Crustal structure of the Lofoten Margin, N. Norway, from normal incidence and wide-angle seismic data: a review

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The crustal structure of the Lofoten continental margin, off Norway, has been obtained from multichannel seismic reflection data and wide-angle Ocean Bottom Seismograph (OBS) data. The shallow sedimentary sequences on the shelf are well imaged on the seismic reflection data, whereas deeper structures are mapped with confidence from the OBS-data. The area west of the shelf edge is covered with flood-basalts, associated with the Paleocene/Eocene break-up between Norway and Greenland. The flood-basalts, which are essentially opaque on conventional multichannel reflection data, can be penetrated with the OBS-method. A total thickness of up to 4.0 km of pre-opening sediments is indicated below the 1.0–2.5 km thick basalts. The crust is inferred to be of continental origin from the shelf to a sequence of seaward dipping reflectors (SDR) seaward of the Vøring Escarpment (VE). Gradual decrease in crustal velocities from 'oceanic' beneath the SDRs to 'continental' at the Vøring Escarpment is interpreted in terms of landward decrease in the content of magmatic intrusions in the crust, and the presence of a lower crustal magmatic body terminating close to the escarpment.

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Introduction

The multichannel seismic reflection technique is currently considered as the most efficient method in geophysical exploration, both in the search for hydrocarbons and in scientific investigations of the crust. This near vertical reflection technique generally provides a detailed image of sedimentary layers and structures. The relatively small distance between source and receiver, however, limits its efficiency at greater depths. In deep sedimentary basins, for instance, it is often difficult to image the top of the crystalline basement, which represents a problem in subsequent geological modelling.

Some of the penetration problems inherent in the near vertical reflection technique can be elucidated by the use of wide-angle seismic data. A detailed velocity image of the crust can be obtained by the use of refracted or diving waves, and modelling of wide-angle data by ray-tracing and finite-difference methods assists the interpretation of the data and provides a more complete crustal resolution. The increasing number of publications on the successful use of wide-angle seismic data (e.g. Mooney & Brocher 1987; Holbrook et al. 1988, 1992) indicates that the best seismic model of the crust in many areas would be achieved by combining the two techniques.

In some areas, however, the multichannel reflection technique has proved to be inefficient. One province of such a kind is the outer continental margin of NW Europe, dominated by flood-basalts and basaltic intrusions associated with the early Tertiary break-up between Eurasia and Greenland (Eldholm, Thiede & Taylor 1987, 1989). On the Lofoten margin the entire area beneath the continental slope is covered with flood-basalts that are almost impenetrable with the conventional reflection technique. Several geophysical investigations have been performed on this margin during the last two decades (Eldholm, Thiede & Taylor 1989; Sellevoll 1983; Avedik et al. 1984; Drivenes et al. 1984; Mutter, Talwani & Stoffa 1984; Mokhtari, Sellevoll & Olafsson 1987; Mokhtari, Pegrum & Sellevoll 1989; Goldschmidt-Rokita et al. 1988; Sellevoll et al. 1988).

This paper addresses a seismic velocity model of the Lofoten margin from Vestfjorden, across the continental shelf and slope, to the continent/ocean transition. Beneath the shelf the model is obtained by combining high quality multichannel seismic reflection data and wide-angle data acquired by the use of three-component Ocean Bottom Seismographs (OBS) (Fig. 1). The crustal velocity model beneath the slope – i.e. in the region covered with basalts – is based entirely on OBS-data (Mjelde et al. 1992).

The seismic reflection profile across the shelf (Line 1, Fig. 1) was acquired by the Norwegian Petroleum Directorate (NPD) in 1987, whereas the acquisition of the OBS data was performed in 1988 by the Institute of Solid Earth Physics, University of Bergen, Norway, in cooperation with the Laboratory for Ocean Bottom Seismology, Hokkaido University, and the Geophysical Institute, University of Tokyo, Japan (Sellevoll 1988).

In this paper we present a review of the most significant crustal scale features that can be derived from the seismic data (Mjelde et al. 1992, 1993).

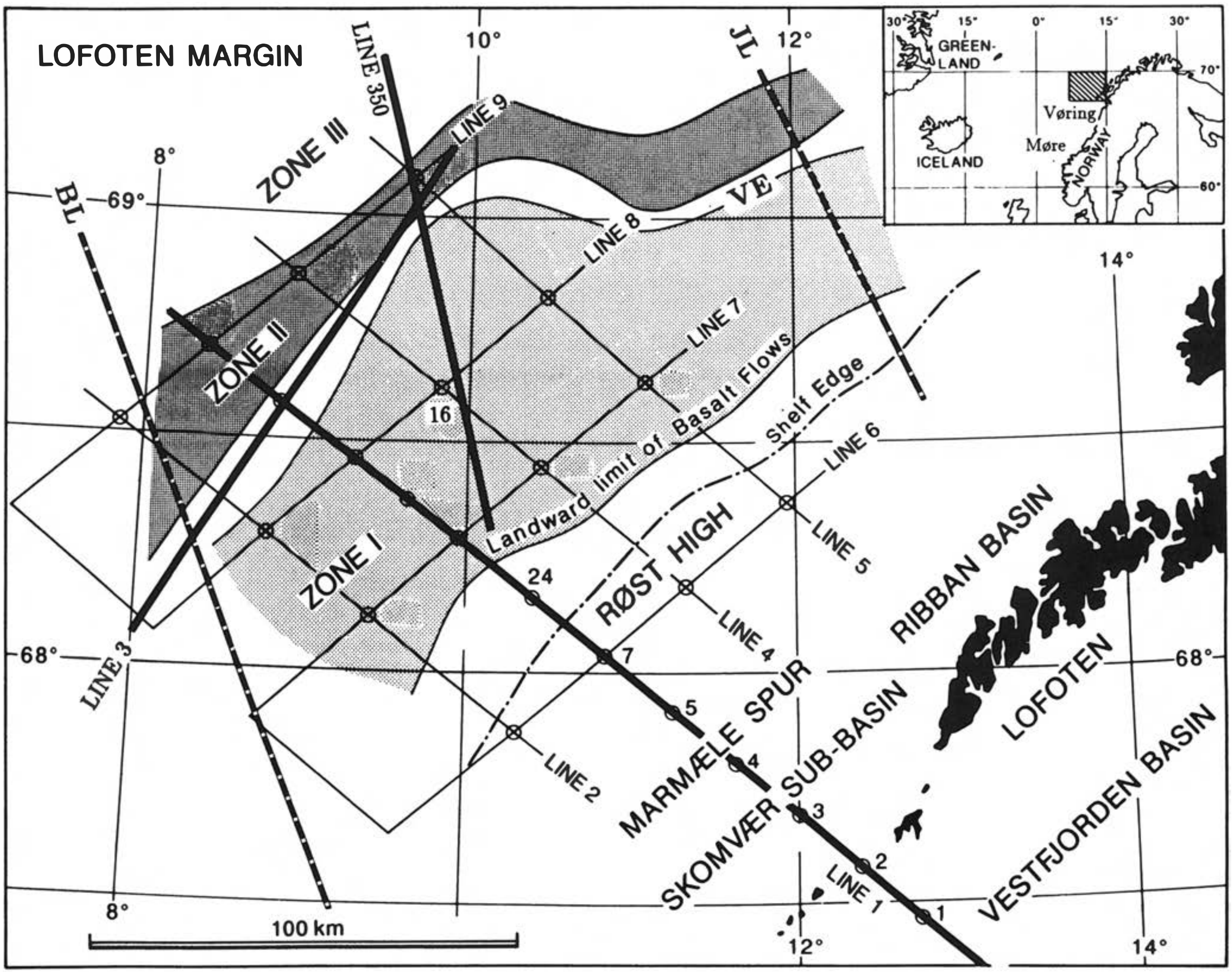

Fig. 1. Main structural elements off Lofoten with position of OBSs (open circles) and seismic reflection and refraction profiles shot during the 1988 survey indicated. The position of the reflection profile shot by GECO in 1987 (line 1) and described in this paper is indicated as a heavy line. The OBS-profile acquired during the experiment seaward of the 1988 survey is also indicated as heavy line (line 3). VE = Vøring Escarpment, BL = Bivrost Lineament, JL = Jennegga Lineament, ZONE I = Early Eocene flood-basalt, ZONE II = Seaward-dipping reflectors, ZONE III = Oceanic crust. The positions of the Vøring and Møre Margins are indicated in the upper right corner. Modified from Sellevoll (1988).

Geological framework

The present Lofoten Margin was centrally located and probably strongly affected by compression during the Silurian to Early Devonian Caledonian Orogeny (Bukovics et al. 1984; Bøen, Eggen & Vollset 1984; Gage & Doré 1986). The crystalline basement in Lofoten is believed to represent an exhumed deep section of the continental crust (Chroston & Brooks 1989).

The Lofoten Margin as well as the Vøring and Møre Margins to the south (Fig. 1) have, in post-Caledonian time, been dominated by extensional tectonics. The Vøring margin has been extensively studied through acquisition of seismic reflection data (Bøen, Eggen & Vollset 1984; Skogsied & Eldholm 1989), seismic refraction data (Eldholm & Mutter 1986; Mutter, Talwani & Stoffa 1984; Mutter, Buck & Zehnder 1988), commercial drilling on the continental shelf (Spencer et al. 1984, 1986; Dalland, Worsley & Ofstad 1988) and scientific drilling on the Vøring Plateau (Talwani et al. 1976; Eldholm, Thiede & Taylor 1987, 1989). No deep boreholes have been drilled on the Lofoten margin, and the present model (Mokhtari 1991) has been based primarily on the gross stratigraphic relationships observed along the shelf, as well as on results from bedrock samples and shallow wells (e.g. Løseth et al. 1989).

A number of Late Palaeozoic–Early Mesozoic extensional episodes between Eurasia and Greenland have been documented. Late Carboniferous–Early Permian regional rifting, Mid to Late Triassic block faulting and Late Triassic–Early Jurassic growth faulting with detachment in Triassic evaporites are reported (Bukovics et al. 1984; Surlyk et al. 1984; Ziegler 1988; Skogseid, Pedersen & Larsen 1992). No sediments of certain Palaeozoic age have been observed on the Lofoten margin, however, and only relatively thin pre-Cretaceous

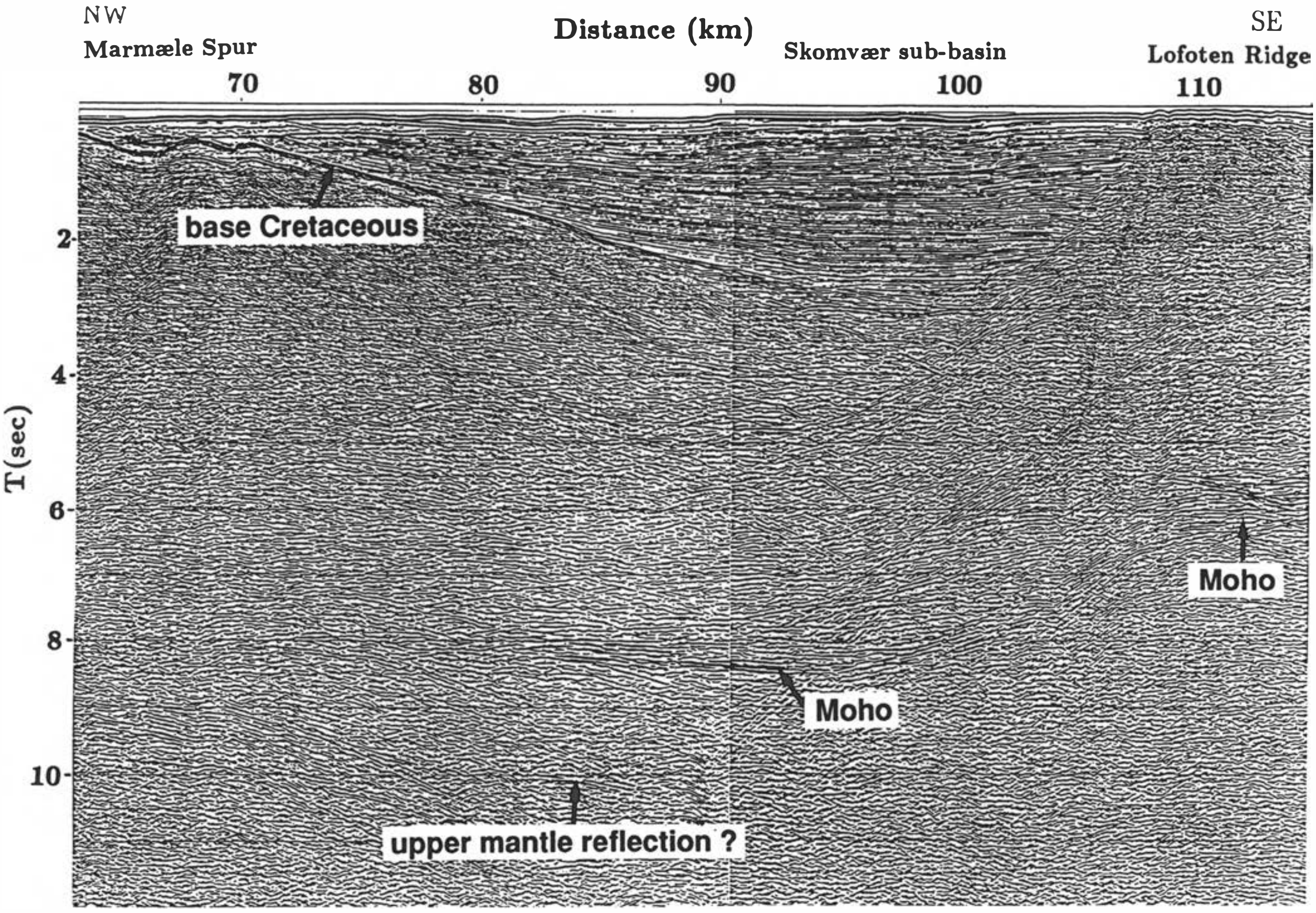

Fig. 2. Part of multichannel reflection profile shot in 1987 by GECO. See Fig. 1 for location (line 1). Unmigrated. From Mjelde et al. (1993).

sequences have been inferred locally beneath the shelf from multichannel reflection data (Mokhtari 1991).

During Late Mesozoic times a Late Jurassic–Early Cretaceous extensional episode led to major faulting activity along the entire mid-Norwegian margin, partly as reactivation of older fault zones, generally creating slightly rotated fault blocks and causing later subsidence along major rift systems (Bøen, Eggen & Vollset 1984; Hinz, Dostman & Hansch 1984; Mutter 1984; Rønnevik, Eggen & Vollset 1983; Skogseid & Eldholm 1989; Mokhtari 1991). Sedimentary sequences of Cretaceous age are also preserved within the Ribban Basin on the Lofoten shelf, where they locally exceed 5000 m in thickness (Fig. 1).

The final major extensional episode occurred during Maastrichtian–Palaeocene time, and led to continental separation at the Palaeocene-Eocene boundary (Skogseid, Pedersen & Larsen 1992). The extension axis shifted westward with respect to the Jurassic–Cretaceous episode.

Tertiary sediments are very thin or absent over the Lofoten shelf. It is uncertain whether Palaeogene sediments are eroded by post-depositional uplift or whether the shelf remained emergent through this period. The Lofoten shelf appears to have been a sediment by-pass area in the Neogene.

Data acquisition

The NPD multichannel reflection line (Line 1) was acquired using a 4452 in^3 airgun array, a 3000 m streamer with 25 m group interval, 50 m shotpoint interval, and a record length of 15 s.

During the acquisition of the OBS-data the scientific program comprised seismic reflection, seismic refraction and gravimetric measurements performed simultaneously (Fig. 1). Seismic reflecion data were not acquired along line 1 during this acquisition, since this line coincides with the high-resolution seismic reflection line acquired by the NPD. During a separate OBS-experiment more data were acquired seaward of the 1988 survey (Fig. 1, line 3; Kodaira et al. 1995).

Four airguns with a total volume of 4800 in^3 operated at a depth of 21 m were used as source for the OBS-data. The shotpoint interval was 240 m.

Twenty-four analogue OBS instruments were used to acquire the seismic refraction data. These instruments were developed and built by the geophysical institutes at Hokkaido and Tokyo universities (Shimamura 1988). The instruments have three orthogonal components (4.5 Hz gimbal mounted geophones); one vertical and two horizontal. The instruments have a capacity of

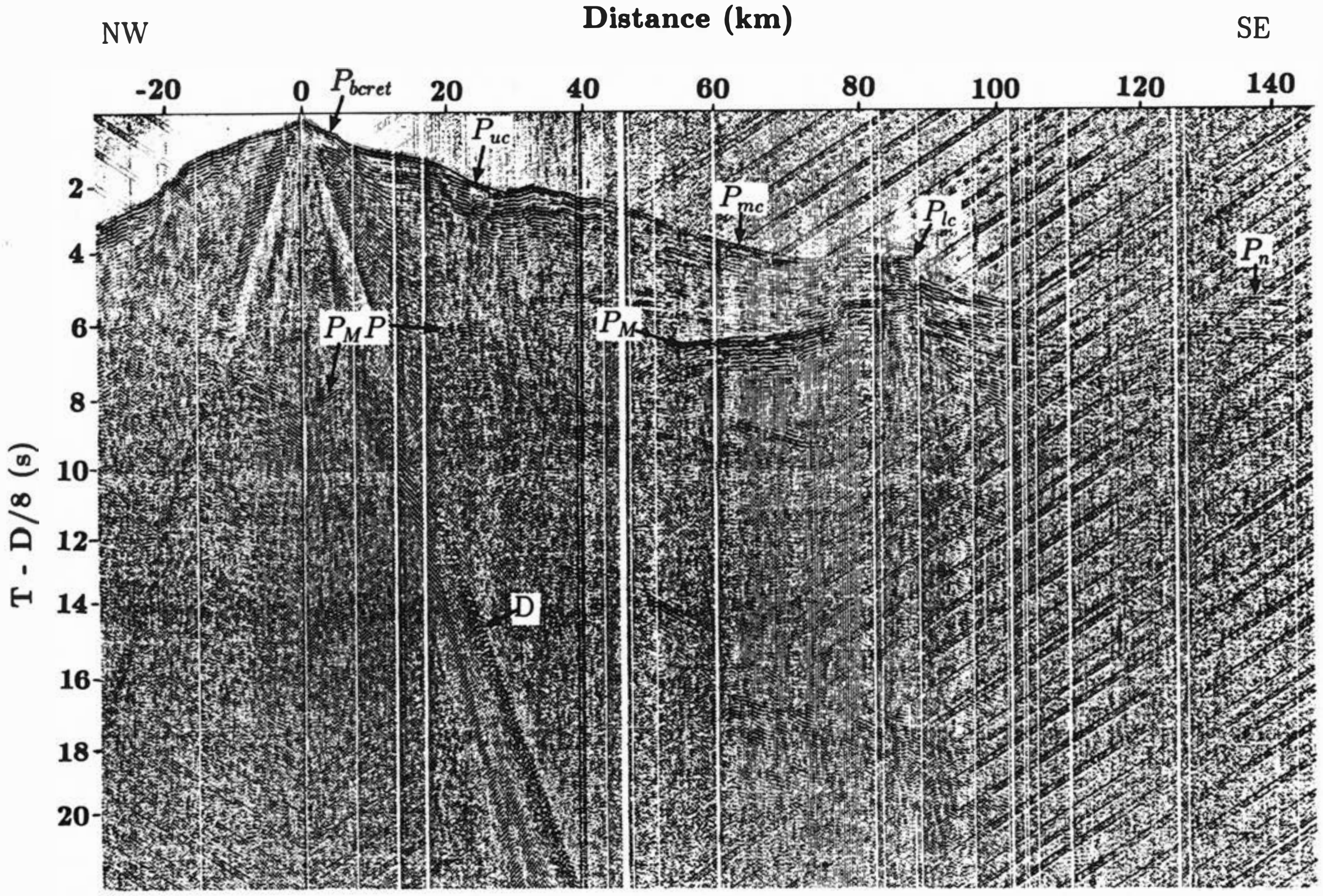

Fig. 3. OBS 7, line 1, vertical (high-gain) component (reduction velocity 8.0 km/s). 6–13 Hz band-pass filtered. D = direct water arrival and surface waves, P_{bcret} = base Cretaceous refraction, P_{uc} = upper (crystalline) crustal refraction, P_{mc} = middle crustal refraction, P_{lc} = lower crustal refraction, P_MP = Moho reflection, P_n = Moho refraction, P_M = upper mantle reflection. From Mjelde et al. (1993).

recording continuously for 14 days within the frequency range from 1 to 30 Hz (− 3 dB).

Data processing

The seismic reflection profile has been processed with considerable efforts made to remove multiples through the application of different deconvolution schemes.

The OBS-data were digitized at Hokkaido and Tokyo universities and are of very high quality. The digital data processing have thus been limited to conventional band-pass filtering (6–13 Hz). The data are plotted with automatic gain control (4 s window), and the interpretation of the data is done on displays with travel-times reduced by 8 km/s.

Crustal structure beneath the continental shelf

Reflection profile

In the multichannel reflection data the base Cretaceous reflector is very prominent and easily definable in the Skomvær Sub-basin (Fig. 2), and westwards to the Røst High. In the landward Vestfjorden Basin the interpretation is less certain, and it is not possible to identify with confidence the base Cretaceous reflector, nor the top of the crystalline basement (Mjelde et al. 1993). This is also the case above the basement highs where no information concerning the total sedimentary thickness can be obtained from the reflection data. The main reason for the lack of observed reflections from pre-Cretaceous sedimentary sequences and from the upper crystalline crust is probably related to significant shot-generated noise (sea-floor multiples) due to the very high impedance of the well-consolidated Cretaceous sediments found at the sea floor along the entire profile. This problem is most severe on the Røst High where at least ten sea-floor multiples can be identified, masking any real reflections for this part of the profile (Mjelde et al. 1992).

The deeper parts of the crust, however, are strongly reflective. The lower crust consists of short, discontinuous reflections that can be observed along the entire profile, although they are most easily observed below and immediately west of the Lofoten Ridge. A distinct relatively continuous reflector representing the lower boundary of the reflective lower crust is used as the definition of the Moho. The depth to the Moho is less certain under the Vestfjorden Basin. The Moho reflector

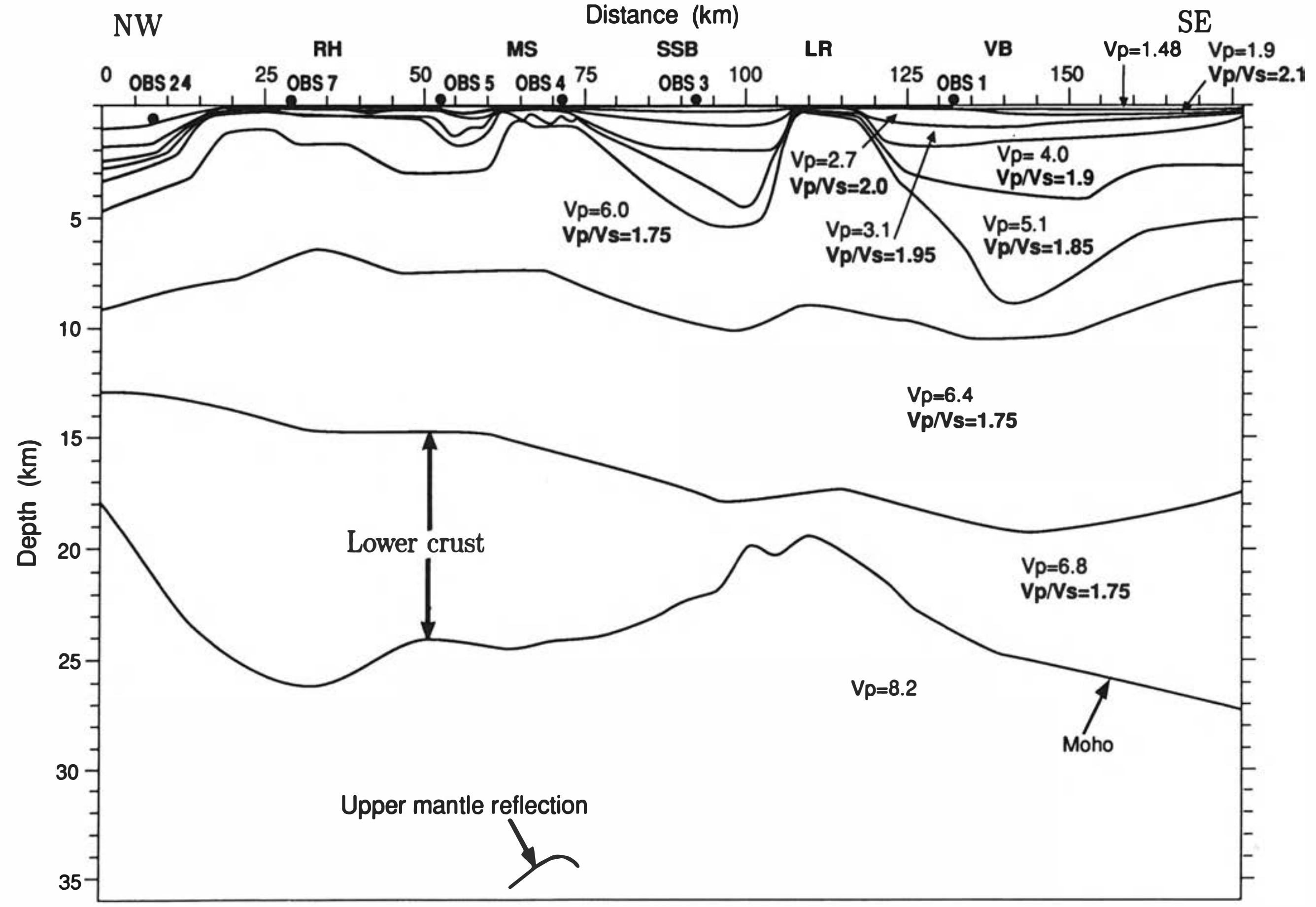

Fig. 4. P wave velocity model (in km/s) for profile 1 (landward of the shelf edge). The V_p/V_s ratio is also indicated. RH = Røst High, MS = Marmæle Spur, SSB = Skomvær Sub-basin, LR = Lofoten Ridge, VB = Vestfjorden Basin. From Mjelde et al. (1993).

appears to be relatively horizontal in the time-section which, according to Warner & McGeary (1987), may indicate local isostatic equilibrium along the profile. An exception exists under the Lofoten Ridge where a significant structure is observed in the Moho interface (Fig. 2).

Wide-angle (OBS) profile

The records from OBS 7, profile 1, are shown in Fig. 3 as an example of the wide-angle data. The depth-converted version of the interpretation of the multichannel reflection data was used as a base for 2-D kinematic (travel-time) ray-tracing modelling of the OBS-data. The depth-conversion was based upon the strongest and most continuous interfaces (intra-Cretaceous, base-Cretaceous and Moho) only, and the velocities used were based on the mean velocities found from the OBS-data along line 6 (Fig. 1).

From ray-tracing (travel-time) modelling of the OBS-data the final P-wave velocity model along Line 1, and a geological interpretation of the velocity model is shown in Figs. 4 and 5, respectively. The uncertainty of the velocities is estimated to be ±0.1 km/s, except for the 6.4 km/s and 6.8 km/s iso-velocity surfaces, for which it is estimated to be ±0.2 km/s. The uncertainty of the Moho depth is estimated to be ±1 km. A more detailed analysis of uncertainities is found in Mjelde et al. (1992).

Tertiary sediments

The 1.9 km/s layer that can be associated with Tertiary sediments has significant thickness only beneath the continental slope (Figs. 4 and 5). Small amounts of Tertiary sediments can be inferred to exist in the sedimentary basins on the shelf, but this layer never exceeds 200 m in thickness along the profile.

Cretaceous sediments

The Skomvær Sub-basin and Vestfjorden Basins have similar maximum thicknesses of the 2.7 km/s layer (maximum 0.7 km thick), 3.1 km/s layer (maximum 1.2 km thick) and 4.0 km/s layer (maximum 2.5 km thick), which are inferred to represent late, middle and early Cretaceous sediments, respectively. The 2.7 km/s and 4.0 km/s layers appear to be absent in the small sub-basin to the west of Marmæle Spur, whereas the 3.1 km/s layer in this sub-basin has similar thickness to that inferred in the Skomvær Sub-basin.

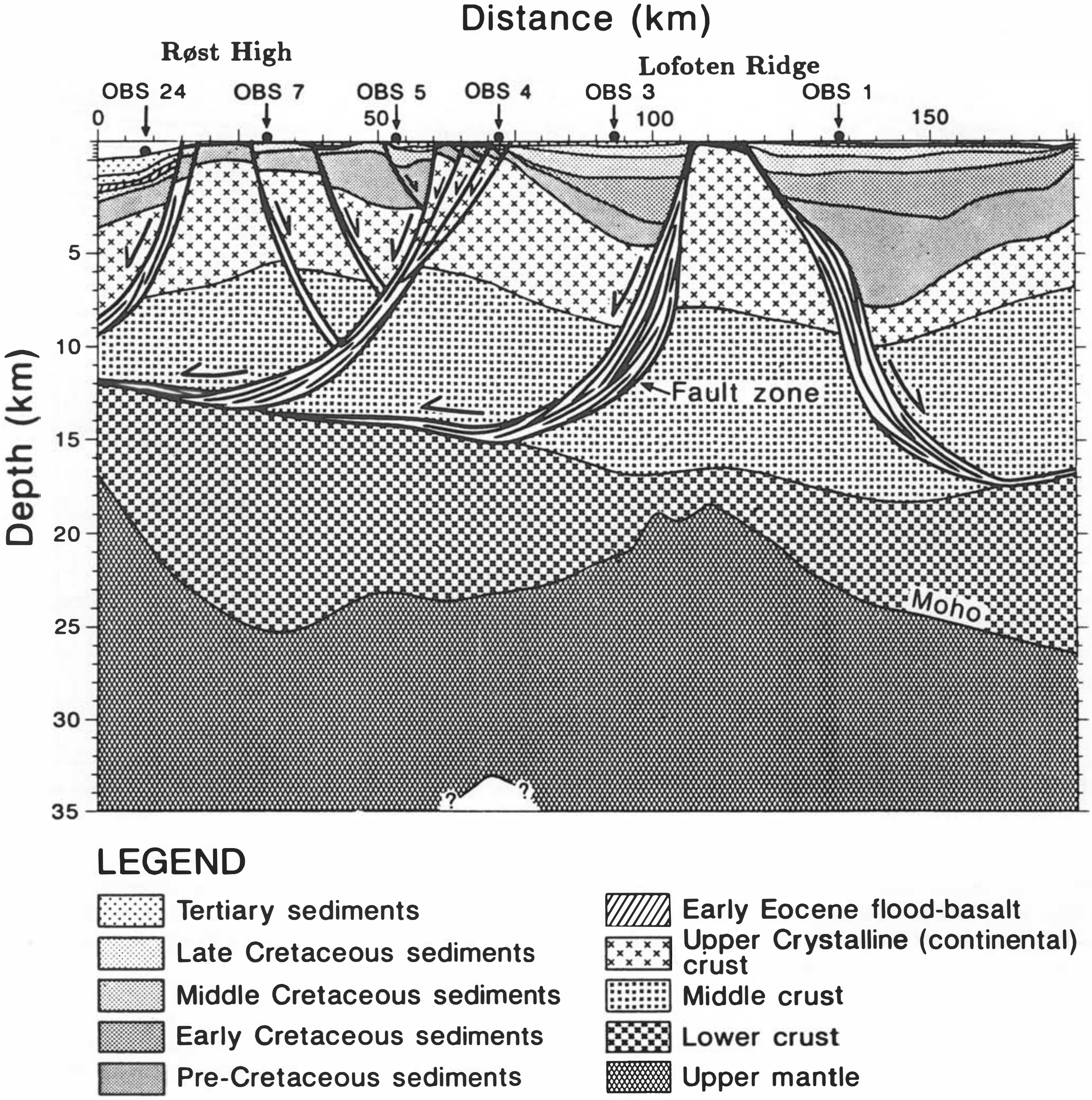

Fig. 5. Geological model for profile 1 (landward of the shelf edge). From Mjelde et al. (1993).

The top of the 5.1 km/s layer between the Røst High and the Lofoten Ridge coincides with the base-Cretaceous reflector interpreted from the reflection profile. In the Vestfjorden Basin, however, where the interpretation from the reflection profile is less certain, the top of the 5.1 km/s layer is situated significantly shallower than the interpreted base-Cretaceous reflector (Mjelde et al. 1993). In addition, it is observed that the shape of the 5.1 km/s iso-velocity surface is significantly different from the shape of the base-Cretaceous reflector. The most likely explanation for the misfit between the two datasets is that the interpretation of the reflection seismic data is not correct in this basin, and hence that the actual base-Cretaceous location is best mapped with the wide-angle technique in the Vestfjorden Basin.

The relatively high sea-floor (Cretaceous) velocities across the Lofoten Margin indicate that most of the area experienced a marked burial during the Cretaceous period, and that significant uplift and erosion have taken place during Tertiary times.

Pre-Cretaceous sediments, upper and middle crystalline crust

The top of the 6.0 km/s interface along line 6 (Fig. 1) coincides with the depth to magnetic basement (Langnes, Statoil, pers. comm.), and is thus interpreted to represent the top of the continental crystalline crust (Mjelde et al. 1992). Following this interpretation it can be seen from Figs. 4 and 5 that pre-Cretaceous sediments of about 1 km thickness are present on the Røst High, whereas no significant amount of sediments of this age is found under the Marmæle Spur and the Lofoten Ridge. In the Skomvær Sub-basin a maximum thickness of 1.5 km pre-Cretaceous sediments is inferred; this thickness increases to 2.5 km in the sub-basin to the west of Marmæle Spur, but the largest amount of pre-Cretaceous sediments is found in the Vestfjorden Basin, where a maximum thickness of about 5 km is inferred. The pre-Cretaceous sediment probably relates to the Late Palaeozoic–Early Mesozoic rift development between Eurasia and Greenland, and their lateral distribution across the Lofoten Margin may provide important information on this development.

The 6.4 km/s and 6.8 km/s iso-velocity surfaces, representing the top and bottom of the middle crust respectively, are not very well constrained along the profile. The modelling indicates, however, that these velocities can be tied with well-constrained 6.4 km/s and 6.8 km/s layers observed as first-order discontinuities along line 6 (Fig. 1) (Mjelde et al. 1992). It must be underlined that the division of the crust into upper, middle and lower crust, is based on the seismic observations. It is well known that the rocks at the surface in Lofoten represent rocks exhumed from middle to lower crustal depths (e.g. Griffin et al. 1978; Chroston & Brooks 1989). This might suggest that the seismic velocities for shallow crustal rocks are more sensitive to aspects like porosity and the presence of microcracks than to lithology and metamorphic grade.

The depth to the top of the crystalline basement (6.0 km/s) on the basement highs increases gradually westwards from the Lofoten Ridge, where crystalline basement outcrops (Figs. 4, 5). The basement relief, however, decreases considerably westwards; the depth to the crystalline basement in the basins thus increases gradually landwards. A landward dip is also observed in the 6.4 km/s and 6.8 km/s layers, which indicates that the upper and middle crust represent one rheologically relatively homogeneous landward-dipping unit (Mjelde et al. 1993). The faults defined from the multichannel reflection data (Mokhtari, 1991) are interpreted to be listric faults bounding upper- and middle-crustal brittle or semi-brittle blocks (Fig. 5).

Lower crust and upper mantle

For the Moho interface (top of the mantle), there is very good agreement between the wide-angle and reflection data from the Lofoten Ridge westward; the Moho dips downwards from about 20 km under the Lofoten Ridge to about 26 km under the Røst High. It is revealed, however, that the Moho structure under the Vestfjorden Basin differs considerably in the two data-sets (Mjelde et al. 1993). Since the interpretation of the reflection data is uncertain in this area, we assume that the reason for the misfit is, as for the base Cretaceous reflection, that the position of the Moho inferred from the reflection data is not correct.

From Figs. 4 and 5 it is clear that the lower crustal 6.8 km/s layer varies considerably in thickness; from about 11.5 km under the Røst High to about 2 km under the Lofoten Ridge. The lower crust thus seems to have rheological properties that are markedly different from that of the shallower crust; the lateral thickness variations of the lower crust indicate significant lateral ductile flow of material in this portion of the crust.

On OBS 7 (Fig. 3) and OBS 5 a strong upper mantle reflection is observed. The modelling indicates that this event represents a dipping reflector situated under the Lofoten Ridge about 10 km below Moho, based on an upper mantle velocity of 8.2 km/s (Fig. 4). The cause of the reflection cannot be unequivocally determined from studies of these data alone, but one possibility is that the reflection is related to a seaward dipping master fault cutting Moho under the Lofoten Ridge. The reflection is stronger than the reflection from Moho, implying a very strong impedance contrast. One possible explanation for the strong impedance contrast might be the presence of layers of partially hydrated peridotite (Warner & McGeary 1987; Mjelde & Sellevoll 1993).

Crustal structure beneath the continental slope

Fig. 6 shows the final P-wave velocity model along the part of the profile 1 (Fig. 1) that extends seawards of the shelf (Mjelde et al. 1992). The sea-floor reflector, a mid-Tertiary reflector and the top flood-basalt reflector have been digitized from the seismic reflection data acquired simultaneously with the OBS-data and depth-converted using velocities achieved as a result of earlier studies (Drivenes et al. 1984; Fig. 7).

On the landward side of the Vøring Escarpment (Figs. 6 and 7) the flood-basalt velocity is found to be 4.4 km/s. The 4.4 km/s layer is approximately 500 m thick in the west and thickens eastwards to a maximum thickness of about 1 km. Below this, a 5.2 km/s layer is observed. The total thickness of these two layers, about 2.5 km, seems to remain relatively constant until they pinch out eastwards towards the Røst High. The 5.2 km/s layer can be interpreted in two ways; either as flood-basalt, or as a package of high-velocity sills intruding the pre-opening sediments. Sills intruding Mesozoic sediments have been documented more than 200 km on the landward side of the Escarpment on the Vøring margin (Skogseid, Pedersen & Larsen 1992), and we assume that sills might also be abundant off Lofoten, particularly close to the Vøring Escarpment.

Above the crystalline basement we find evidence for a low-velocity layer (Fig. 6) of which the top may be inferred from reflections (Mjelde et al. 1992). This low-velocity layer is interpreted as a sequence of sedimentary layers in accord with earlier interpretations (Mokhtari,

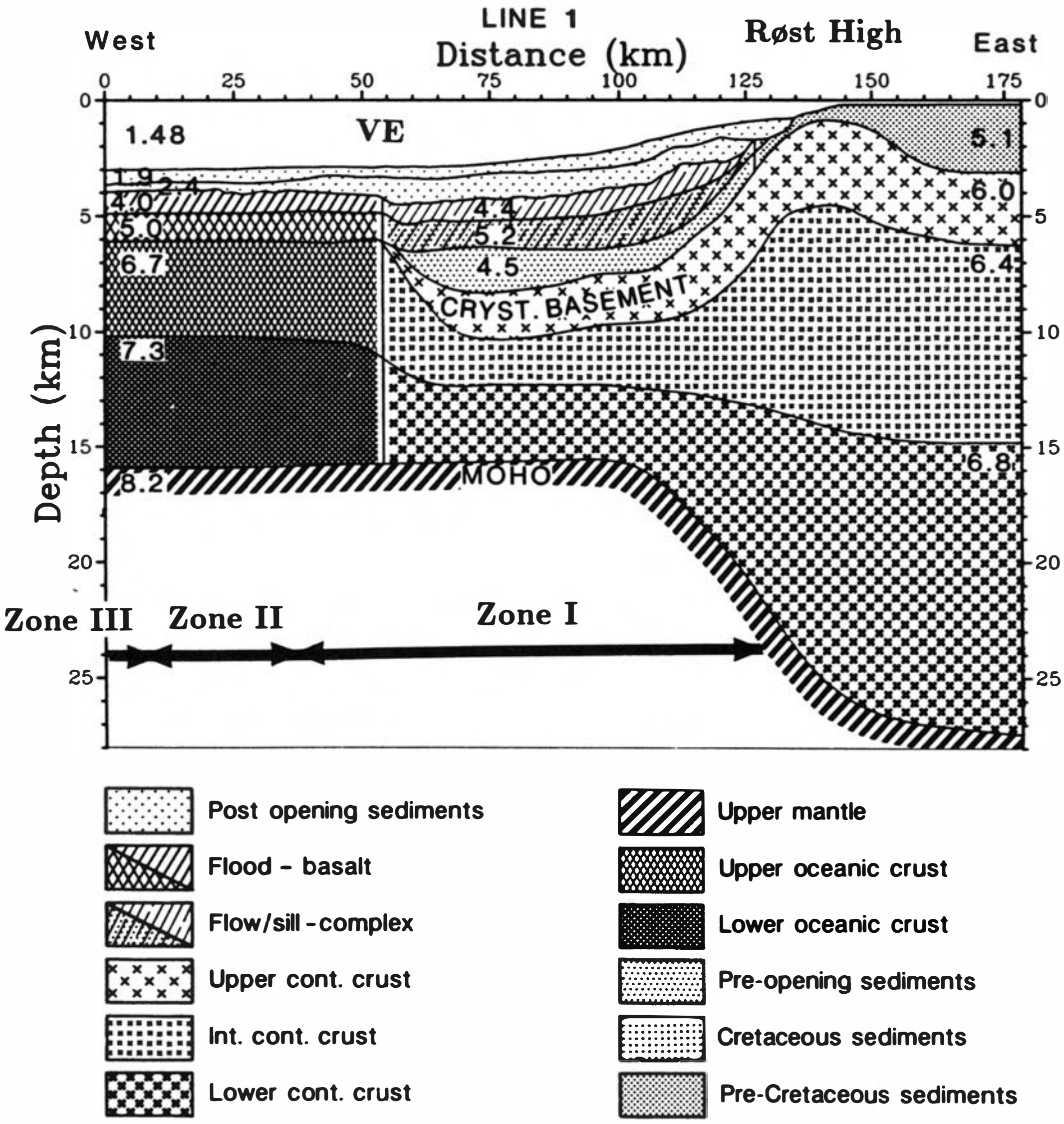

Fig. 6. P wave velocity model (in km/s) for profile 1 (seaward of the shelf edge). ZONE I = Early Eocene flood-basalt, ZONE II = Seaward-dipping reflectors, ZONE III = Oceanic crust. From Mjelde et al. (1992).

Pegrum & Sellevoll 1989). The low-velocity layer has a maximum thickness of about 2.5 km in the southern part of the study area, immediately to the east of the Vøring Escarpment. The maximum thickness of the sediments below the flood-basalt might be considerably greater than 2.5 km if the reflection believed to represent the top of the low-velocity layer is interpreted as a reflection from a high-velocity sill within the sediments. In this case as much as the lowermost $\approx$ 1.5 km of the 5.2 km/s layer can represent sediments intruded by high-velocity sills at the same time as the eruption of the basalts.

The velocities of the crystalline portion of the crust are found to be similar to those observed under the continental shelf (6.0 to 6.8 km/s), which implies that the crust east of the Vøring Escarpment is of continental origin. The crystalline crust is strongly thinned in this area, showing a minimum thickness of about 6 km. On the seaward side of the Vøring Escarpment a 0.5–1 km thick layer with a velocity of 4.0 km/s is found in the uppermost part of the flood-basalt. Below this layer a 1.2–2 km thick 5.0 km/s layer is observed (Fig. 6).

An important wedge of seaward-dipping reflectors (SDR) is situated within the 4.0 and 5.0 km/s layers (Fig. 7). A similar wedge was drilled on the Vøring Plateau (Eldholm, Thiede & Taylor 1989), and it was confirmed that the SDRs represent a sub-aerially constructed complex of transitional mid-oceanic tholeiitic lava flows and interbedded volcanoclastic sediments. The vertical velocity increase from 4.0 to 5.0 km/s in the inferred basaltic sequence can probably be attributed to the increasing alteration of the basalt and the formation of secondary minerals filling the pores (Flovenz 1980).

The crust below the flood-basalt on the seaward side of the Vøring Escarpment has been divided into an upper 6.7 km/s layer and a lower crustal 7.3 km/s layer. The lower crustal high-velocity layer (about 7.3 km/s) ob-

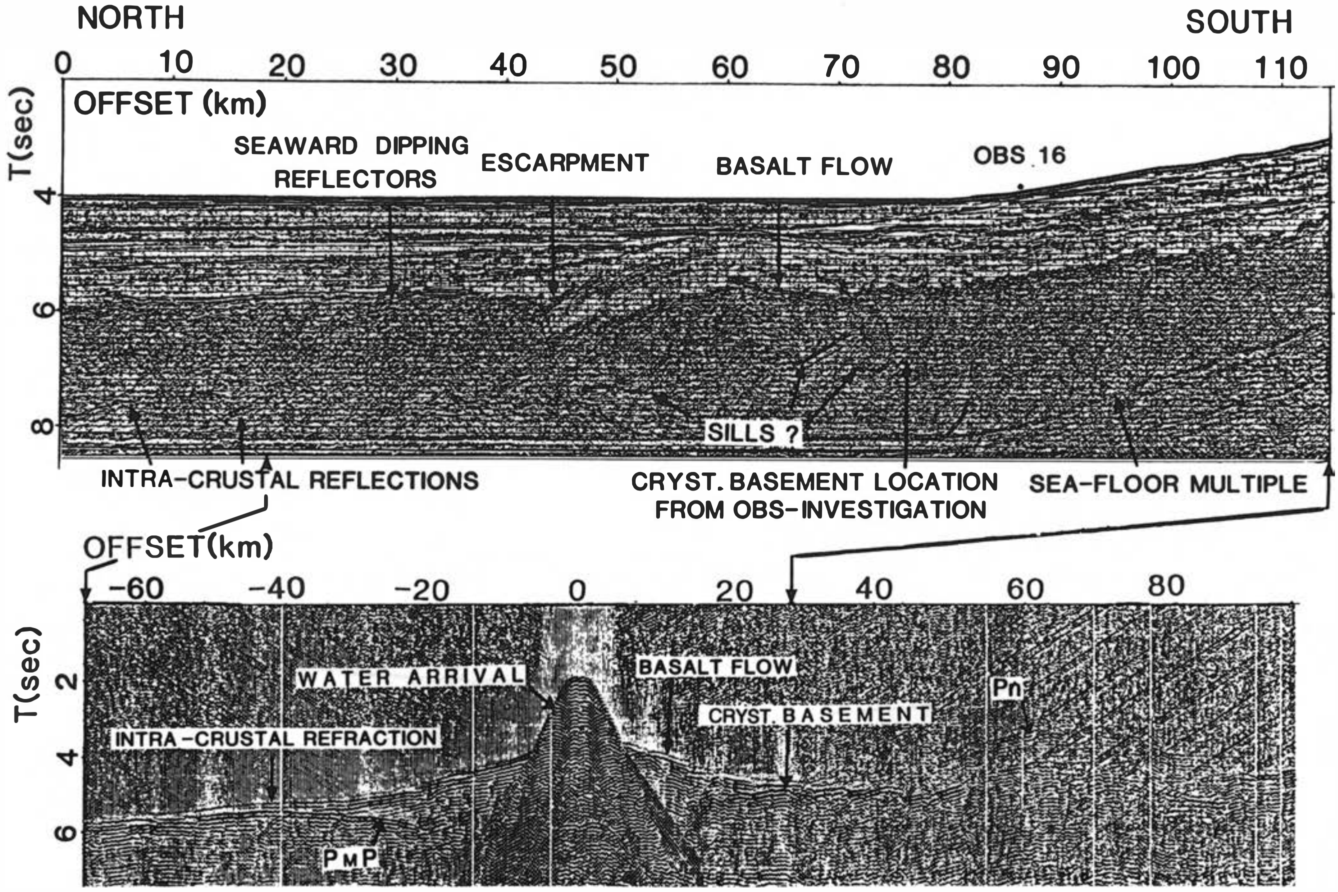

Fig. 7. Comparison between seismic reflection line 350 (top) and OBS 16 (bottom) shot along line 4 (Fig. 1). The crystalline basement is not observed in the reflection profile. However, it is clearly observable in the OBS data. From Mjelde et al. (1993).

served off Lofoten has also been observed at the Vøring and Møre margins (Mutter, Buck & Zehnder 1988; Olafsson et al. 1992), and has in these areas been interpreted as magmatic underplating of the crust (Skogseid, Pedersen & Larsen 1992; Olafsson et al. 1992) in concordance with the model of White and McKenzie (1989). These authors explain the formation of volcanic continental margins by assuming the presence of a mantle plume beneath the lithosphere with temperature raised 100–200°C above normal. As the mantle rises passively beneath the rifting continental lithosphere, huge amounts of melts are generated by decompression melting of the hot asthenospheric mantle. The melt migrates rapidly upward until it is partially extruded as basalt flows and partially intruded into, or beneath the crust. Melt generated from abnormally hot mantle is more magnesian than that produced from normal mantle. This results in an increase in the seismic velocity of the igneous rocks emplaced in the crust, from typically 6.8 km/s for normal mantle temperatures to 7.2 km/s or higher.

Continent/ocean transition

The modelling of the OBS-data shows that the seismic velocities are 'oceanic' beneath the SDRs (line 9), and 'continental' on the landward side of the Vøring Escarpment (line 8) (Mjelde et al. 1992). Profile 3, which crosses the SDR/Escarpment area obliquely, indicates that the crustal velocities decrease gradually from 'oceanic' to 'continental' across the zone (Fig. 8) (Hassan, 1994). There exists hence no sharp velocity boundary between the continental and oceanic crust in this area.

The gradual landward decrease in the upper/middle crustal velocity from 6.7 km/s to 6.0–6.4 km/s can most likely be interpreted in terms of a landward decrease in the content of magmatic intrusions in the crust over an approximately 50 km wide zone. The landward decrease in the lower crustal velocity from 7.3 km/s to 6.8 km/s can probably be linked to a magmatic underplated body on the western side of the Vøring Escarpment.

Another implication of the model is that the Vøring Escarpment can be interpreted as a landward-dipping fault. This follows from mechanical considerations; the heavy load on the crust represented by the thick flood-basalt complex will, at least partly, be compensated by the underplated body on the western side of the Vøring Escarpment. This compensation does not exist on the landward side of the Vøring Escarpment, and the differential forces may cause faulting at the Escarpment.

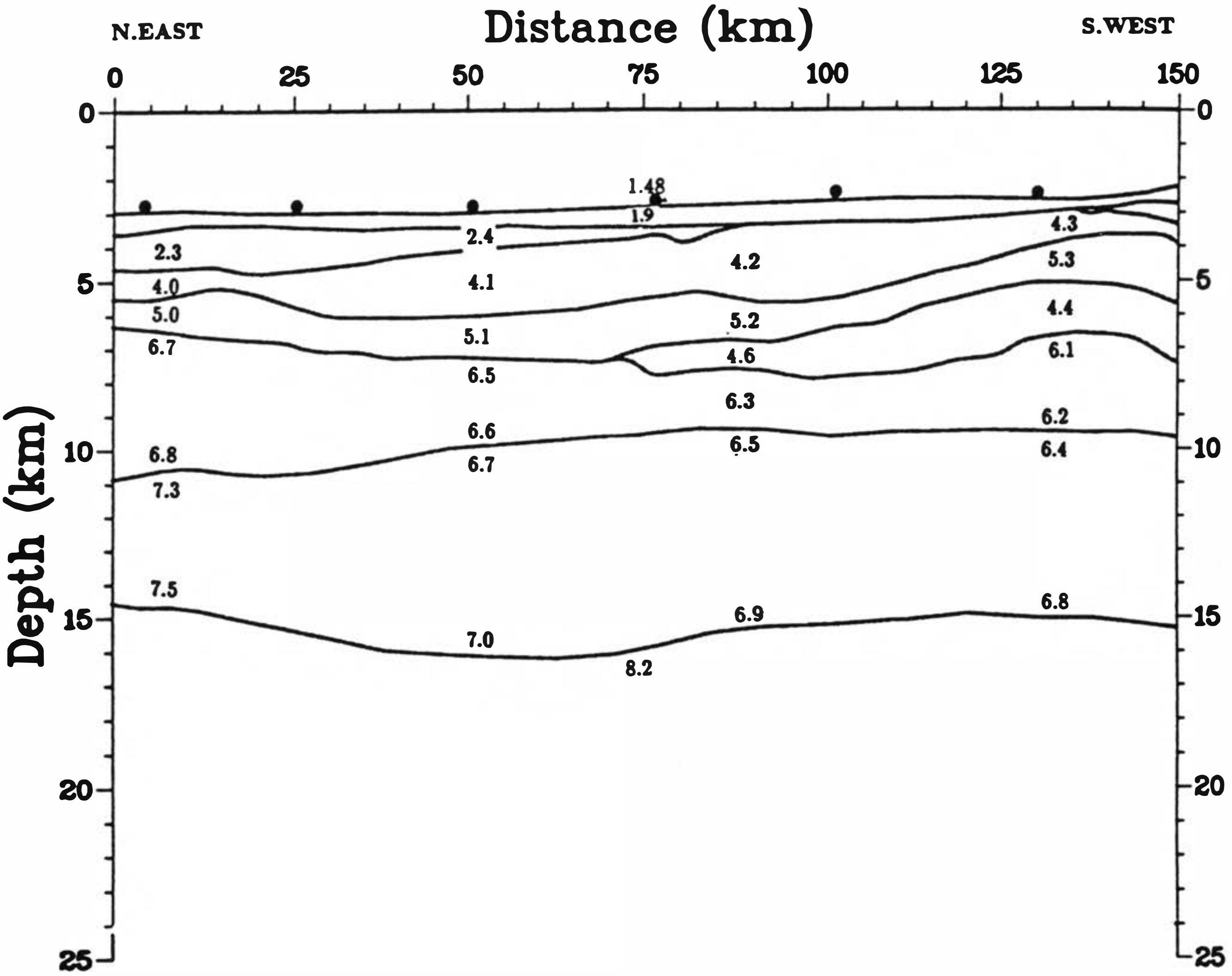

Fig. 8. P wave velocity model (in km/s) for profile 3 (Fig. 1; Hassan 1994), acquired during an experiment seaward of the 1988 OBS-survey (Kodaira et al. 1995).

Conclusions

A model of the crustal structure from Vestfjorden to the continental shelf edge off Lofoten has been obtained from combining high-quality seismic multichannel reflection data and wide-angle (OBS) data. The multichannel reflection data provide a detailed image of the shallow sedimentary (Cretaceous) structures, and also of the lower crust and Moho in some parts of the area. The wide-angle (OBS) data, however, provide important information on deeper sedimentary, upper and middle crustal, and upper mantle structures. In addition, the OBS-data give independent information about the shallow sedimentary basins and the Moho structures. This study has shown that the integrated use of the multichannel reflection, and the wide-angle (OBS) techniques, provide information about the crustal structure that could not have been achieved with the use of only one of the techniques.

An important scientific aspect in the use of the OBS-data was to investigate whether this method could be used to map structures below flood-basalts characterizing the outer NE Atlantic Margins. On the Lofoten Margin these flood-basalts extend almost to the continental shelf, up to 100 km landward of the continent/ocean transition, and are essentially seismically opaque on conventional multichannel reflection data.

The interpretation of the OBS-data has been verified by 2-D ray-tracing modelling, and it is shown that the OBS-data contain considerable information about deeper structures. A total thickness of up to 4.0 km of pre-opening sediments is indicated below the 1.0–2.5 km thick flood-basalt. The crystalline portion of the crust is strongly thinned in this area; the minimum thickness is about 6 km. The crustal velocities on the landward side of the Vøring Escarpment are found to be similar to those observed under the continental shelf (6.0–6.8 km/s), which indicates that the crust here is of continental origin.

The crustal velocities beneath the seaward-dipping reflectors (SDR) are typical of oceanic crust, ranging from 6.7 km/s to 7.3 km/s in the upper and lower crust, respectively. The gradual decrease in crustal velocities from 'oceanic' to 'continental' from the SDRs to the

Vøring Escarpment, can most likely be interpreted in terms of a landward decrease in the content of magmatic intrusions into the crust, and the presence of a lower crustal magmatic body terminating close to the Vøring Escarpment.

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