S-wave structure of the Lofoten Margin, N. Norway, from wide-angle seismic data: A review

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The seismic S-wave structure of the Lofoten Margin, N. Norway, has been obtained from the modelling of three-component Ocean Bottom Seismograph (OBS) data. The relatively high V_pV_s-ratios estimated for the sediments in most of the area suggest the abundant presence of shales, with the exception of the basin south of the Røst High, where the very low V_p/V_s-ratio indicates a higher sand/shale ratio. The V_pV_s-ratio in the crystalline crust is estimated to 1.75 beneath the continental shelf and seawards to the Vøring Escarpment, and 1.9 beneath the seaward-dipping reflectors (SDR) seaward of the Vøring Escarpment. These values confirm that the crust is of oceanic origin beneath the SDR, and that the crust landward of the Vøring Escarpment is continental. On the continental shelf, a strong S-wave anisotropy is observed in the sediments and in the lower crust, and the modelling of the S-waves also reveals a strong P- and S-wave anisotropy in the upper mantle. The sedimentary anisotropy can be explained by the presence of liquid-filled microcracks aligned vertically along the direction of the present-day maximum horizontal compressive stress in the area, whereas the lower crustal anisotropy might be related to the (steep) alignment of pore space influenced by ductile strain fabrics inherited from Jurassic–Cretaceous and older extension episodes, or by present ductile strain fabrics in case of a still active deformation. The upper mantle anisotropy can be explained by the steep alignment of the strongly anisotropic mineral olivine. The steep inclination of the minerals might possibly be caused by shearing close to a postulated master fault cutting the crust and upper mantle in this area. The OBS-experiment on the Lofoten Margin has shown that S-waves can be easily included in the modelling, and that they provide valuable geological information that cannot be extracted from P-wave studies alone.

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Introduction

Seismic investigations of sedimentary basins and the crystalline crust have traditionally been restricted to the use of (compressional) P-waves. This is related to the fact that P-waves generally provide reliable images of sedimentary and crystalline structures. In more detailed studies, however, the use of P-waves alone has some important drawbacks. One of the most severe limitations in prospecting is the similar P-wave velocity generally observed for different lithologies, e.g. sand or shale.

Laboratory and field experiments have shown that the lithology of sedimentary and crystalline rocks in many cases can be revealed if the (transversal) S-wave velocity is known in addition to the P-wave velocity (e.g. Neidell 1985). A well-consolidated pure sandstone, for instance, has a V_p/V_s-ratio[1] of about 1.6, whereas a (well-consolidated) pure shale has a V_p/V_s-ratio of about 2.0. Another aspect of S-waves is their sensitivity to aligned fluid-filled cracks and pores. In such rocks, the propagating S-wave will split into two or more S-waves with different velocities and polarizations (direction of particle-motion) (e.g. Crampin 1990).

To assure sufficient detection of S-waves, three-component (3-C) receivers (one vertical and two horizontal geophones) are needed. This is because the upward propagating S-waves generally arrive at the surface at very steep angles, even for large offsets, and their polarizations will thus be close to horizontal. In marine surveys, the 3-C receivers must be located at the seafloor, since S-waves are unable to propagate in water.

In 1988, a large seismic experiment by use of 3-C Ocean Bottom Seismographs (OBS) was performed on the Lofoten continental margin, N. Norway (Fig. 1; Sellevoll et al. 1988). One of the main objectives with the experiment was to investigate to what extent S-waves could be recorded, and how information obtained from the analysis of these waves could contribute to the geological understanding of the area. Strong S-waves were observed in the OBS-data recorded on the continental shelf and across the continent/ocean transition. This paper reviews the most significant results from the modelling of the S-waves presented by Mjelde (1992); Mjelde & Sellevol (1993a,b); Mjelde et al. (1995a,b).

Geological framework

The Lofoten Margin in post-Caledonian time was dominated by extensional tectonics. A Late Jurassic–Early Cretaceous extensional episode led to major faulting activity along the entire mid-Norwegian margin, generally creating slightly rotated fault blocks and causing later subsidence along major rift systems (Rønnevik,

[1]V_p and V_s represent P- and S-wave velocities, respectively.

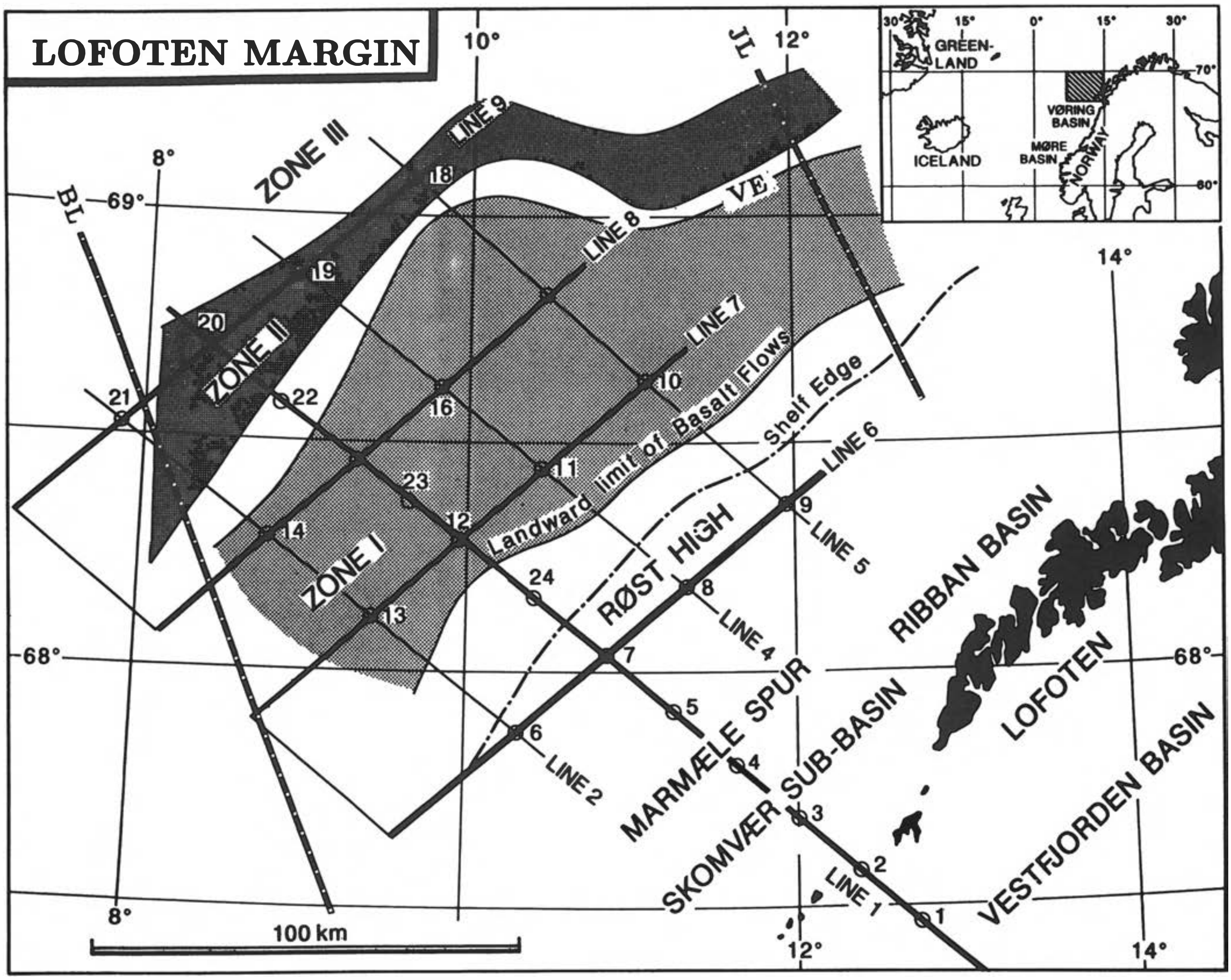


Fig. 1. Main structural elements off Lofoten with position of OBSs (open circles) and seismic reflection and refraction profiles shot during the 1988 survey indicated. The OBS-profiles discussed in this paper are indicated as heavy lines. VE = Vøring Escarpment, BL = Bivrost Lineament, JL = Jennegga Lineament, ZONE I = Early Eocene flood-basalt, ZONE II = Seaward-dipping reflectors, ZONE III = Oceanic crust. (Modified from Sellevoll 1988.)

Eggen & Vollset 1983; Bøen, Eggen & Vollset 1984; Hinz, Dostman & Hansch 1984; Mutter 1984; Skogseid & Eldholm 1989; Mokhtari 1991). Sedimentary sequences of Cretaceous age are preserved within the Ribban Basin on the Lofoten shelf, where they locally exceed 5000 m in thickness (Mjelde et al. 1993).

The final major extensional episode (Maastrichtian–Palaeocene) occurred westward of the Jurassic–Cretaceous episode, and caused continental separation at the Palaeocene-Eocene boundary. The latest rifting was associated with abundant magmatism manifested as flood-basalts on the surface, and as intrusions in the crust (Eldholm, Thiede & Taylor 1987, 1989; Skogseid, Pedersen & Larsen 1992; Mjelde, Kodaira & Sellevoll 1995c).

OBS-data and P-wave model

The acquired OBS-profiles are indicated in Fig. 1. Four air-guns with a total volume of 4800 in^3 operated at a depth of 21 m were used as a source for the data, and the shotpoint interval was 240 m.

The twenty-four analogue OBS instruments used 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 data presented in this paper have been 6–13 Hz band-pass filtered, and they have been plotted with automatic gain control (4 s window) and travel-times reduced by 8 km/s.

P-wave structure beneath the continental shelf

The final P-wave velocity models along Line 1 and 6 derived from ray-tracing (travel-time) modelling of the OBS data, are shown in Figs. 2 and 3. Small amounts of Tertiary sediments (the 1.9 km/s layer) can be inferred to exist in the sedimentary basins on the shelf, but this layer never exceeds 200 m in thickness here (Mjelde et al. 1993).

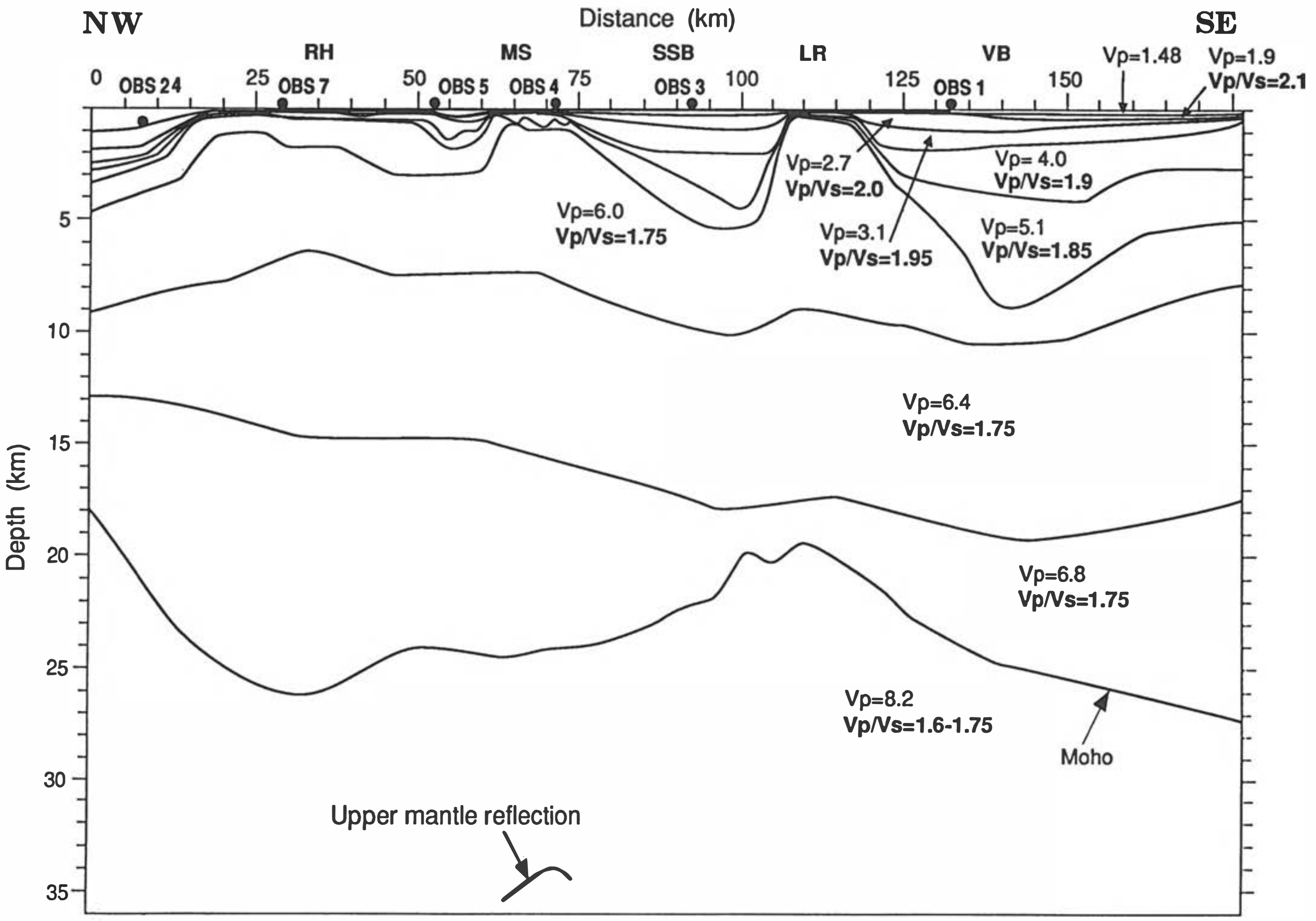


Fig. 2. Model of P wave velocity and V_p/V_s-ratio (V_p in km/s) for the part of profile 1 situated on the continental shelf. RH = Røst High, MS = Marmæle Spur, SSB = Skomvær sub-Basin, LR = Lofoten Ridge, VB = Vestfjorden Basin. (Reprinted from Mjelde & Sellevoll 1993, *Tectonophysics, 22*, 21–32, Elsevier, Amsterdam.)

Large amounts of Cretaceous sediments are present in the basins on the shelf (Fig. 2). Three layers with P-wave velocities of 2.7 km/s, 3.1 km/s and 4.0 km/s have been interpreted as late, middle and early Cretaceous sediments respectively, based on interpretation of multichannel reflection data (Mjelde et al. 1993; Mokhtari 1991) and dredged bedrock samples (Løseth et al. 1989). The 5.1 km/s layer (Figs. 2, 3) has been interpreted as pre-Cretaceous sediments.

The crystalline crust has been divided into three layers with P-wave velocities of 6.0 km/s, 6.4 km/s and 6.8 km/s, respectively. Based on the OBS-data, the upper and middle crust have been interpreted as one rheologically relatively homogeneous (brittle) unit, whereas the strong lateral thickness variations of the lower crust indicate significant lateral ductile flow of material in this portion of the crust (Mjelde et al. 1993).

On two OBSs a strong upper mantle reflector inferred to be situated under the Marmæle Spur, about 10 km below Moho, was observed. This reflection might be related to a seaward dipping master fault cutting Moho under the Lofoten Ridge (Mjelde et al. 1993).

P-wave structure beneath the continental slope

Figs. 4 and 5 show the final P-wave velocity model along the part of profile 1 (Fig. 1) that extends seawards off the shelf, and along the strike-profiles 7, 8 and 9.

On the landward side of the Vøring Escarpment (Figs. 4, 5) the P-wave velocity in the about 2.5 thick flood-basalt increases with depth from 4.4 km/s to 5.2 km/s. Above the crystalline basement there is evidence of a low-velocity layer, which is interpreted as a sequence of sedimentary layers. 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 represents strongly thinned continental crust (Mjelde et al. 1992; Mjelde, Kodaira & Sellevoll 1995c).

On the seaward side of the Vøring Escarpment the velocity in the basalt containing a wedge of seaward-dipping reflectors (SDR), increases with depth from 4.0 km/s to 5.0 km/s (Fig. 4). The crust below the flood-basalt in this part of the area has been divided into an upper 6.7 km/s and a lower crustal 7.3 km/s layer, which is interpreted

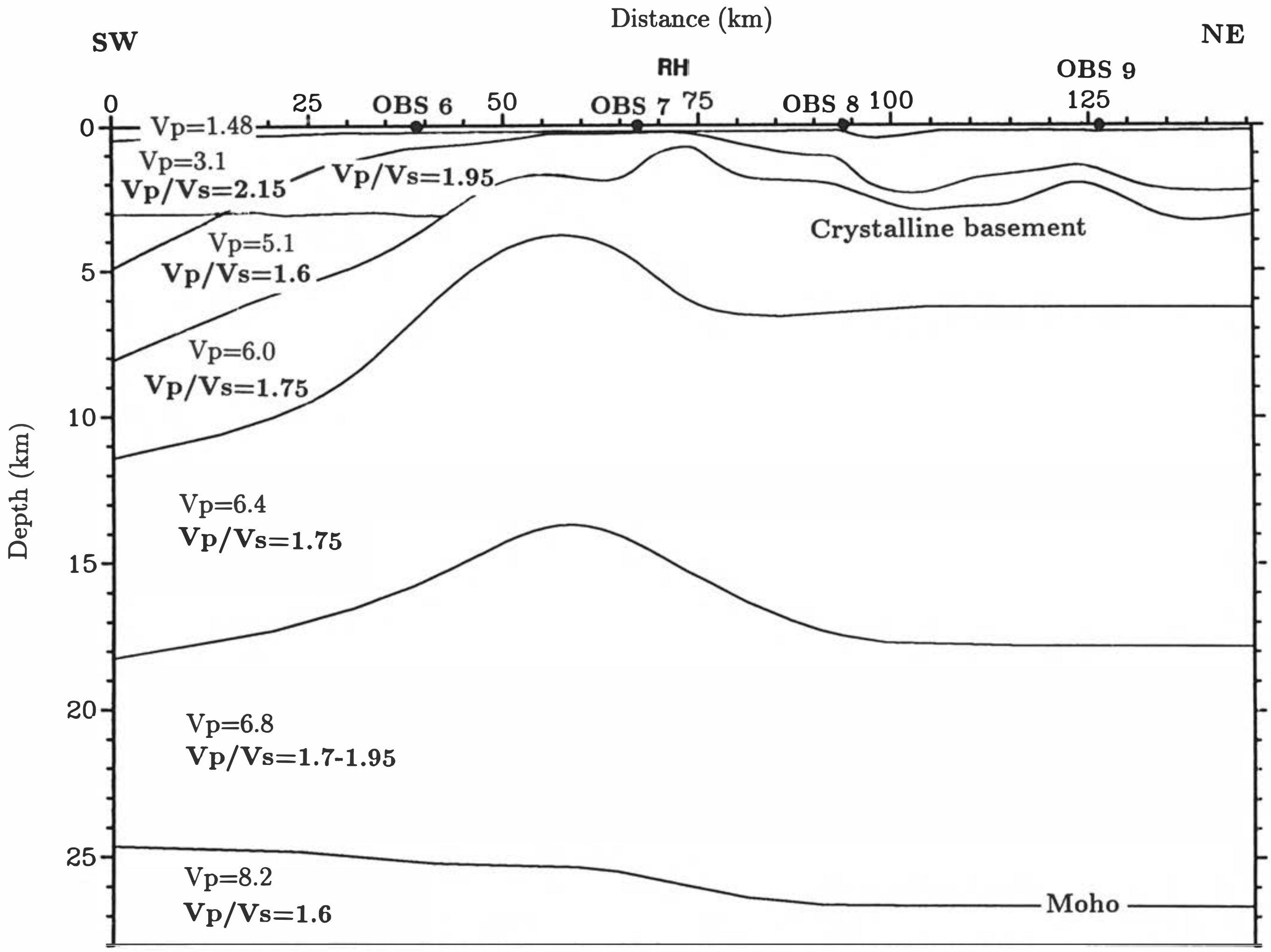


Fig. 3. Model of P wave velocity and V_p/V_s-ratio (V_p in km/s) for profile 6. The horizontal line at 3 km depth in the SW part of the profile represents a vertical change in the V_p/V_s-ratio within the two sedimentary layers ($V_p = 3.1$ and 5.1 km/s respectively). RH = Røst High. (Reprinted from Mjelde 1992. *Geophysical Journal International*, *110*, 283–296, Blackwell, Oxford.)

as magmatic underplating of the crust in concordance with the model of White & McKenzie (1989).

The modelling of the OBS-data shows that the seismic velocities decrease gradually from 'oceanic' beneath the SDRs (line 9; Fig. 4), to 'continental' on the landward side of the Vøring Escarpment (line 7 and 8; Fig. 5). The gradual landward decrease in the upper/middle crustal velocity 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, whereas the landward decrease in the lower crustal velocity can probably be linked to a magmatic underplated body on the western side of the Vøring Escarpment (Mjelde, Kodaira & Sellevoll 1995c).

S-wave model

Continental shelf: lithology

The P-wave model briefly described above, was used as a basis for modelling the S-waves from the horizontal components of the OBS-data. Figs. 6 and 7 show some examples of data with S-wave travel-time curves calculated from 2-D ray-tracing superimposed. The final estimates of the V_p/V_s-ratio are indicated in Figs. 2–5. In the modelling it has been assumed that the waves are P-to-S converted at the seafloor, which represents by far the highest impedance contrast (Mjelde 1992). In addition to waves that have propagated near-horizontally as S-waves, P-to-S reflections are observed.

Along the Røst High the V_p/V_s-ratio in the two sedimentary layers are estimated to 2.15 and 1.95 respectively (Fig. 3). These relatively high values indicate shaly sediments, which is in agreement with results from dredged bedrock samples (Løseth et al. 1989). South of the Røst High the V_p/V_s-ratio is found to be significantly lower than on the shelf: 1.6. This decrease can partly be attributed to the increased compaction of the deepest sediments, and partly to more sandy sediments south of the high (Mjelde 1992).

The relatively high V_p/V_s-ratio in the sediments on the continental shelf is confirmed along the profile 1 (Fig. 2), where the V_p/V_s-ratio for the three Cretaceous sedimen-

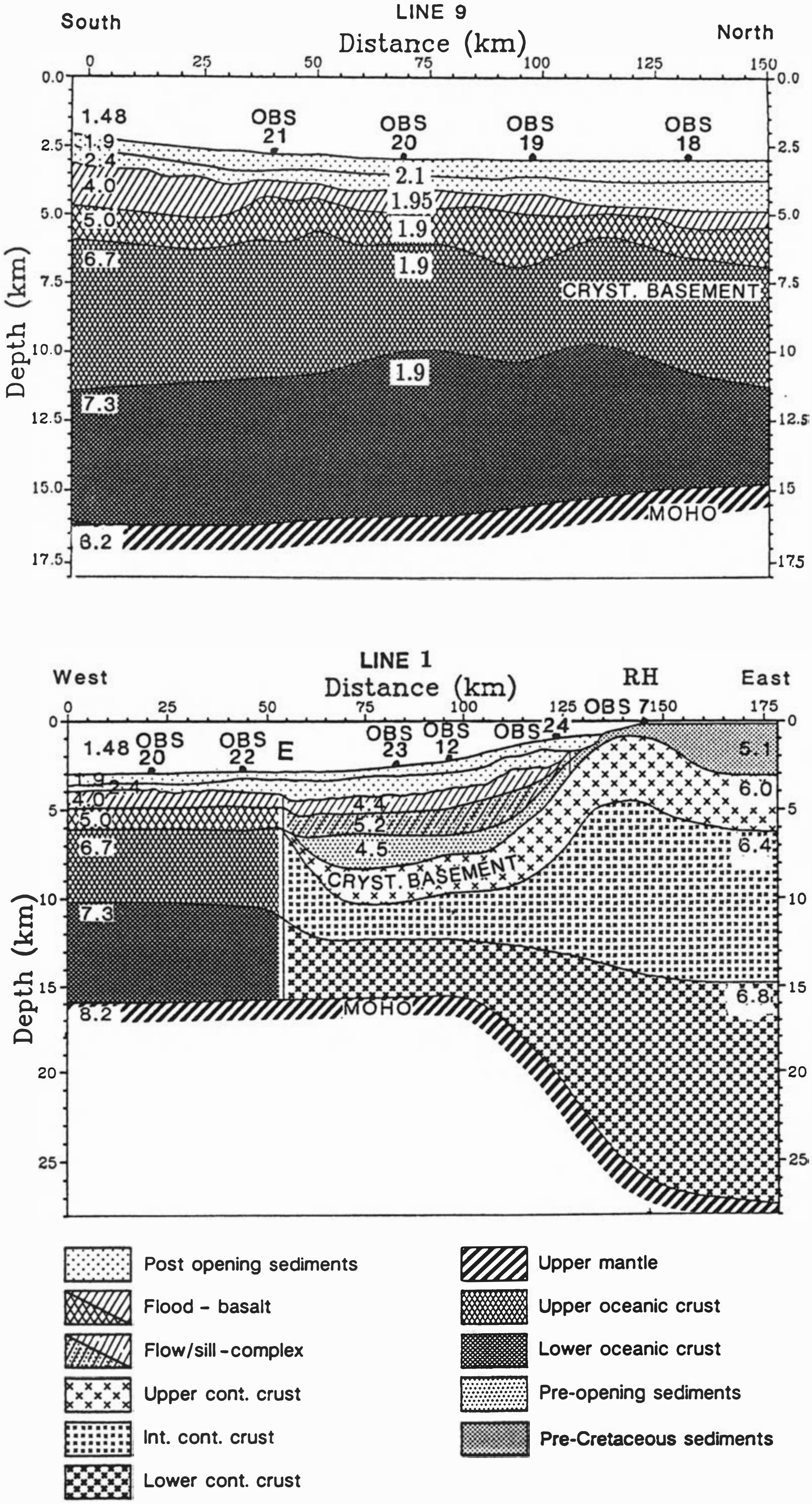


Fig. 4. Velocity models for profiles 9 (on SDRs) and 1 (seaward of the shelf). The P-wave velocities are shown in km/s on the left-hand side of the models, as well as in the central part of the model of profile 1. The V_p/V_s-ratios are indicated in the central part of the model of profile 9. The V_p/V_s-ratios along profile 1 are the same as for corresponding layers in the strike-profiles 7, 8 and 9 (see also Fig. 5) with the exception of the sedimentary layers above the basalt where the V_p/V_s-ratio is 2.0. (From Mjelde et al. 1995b.)

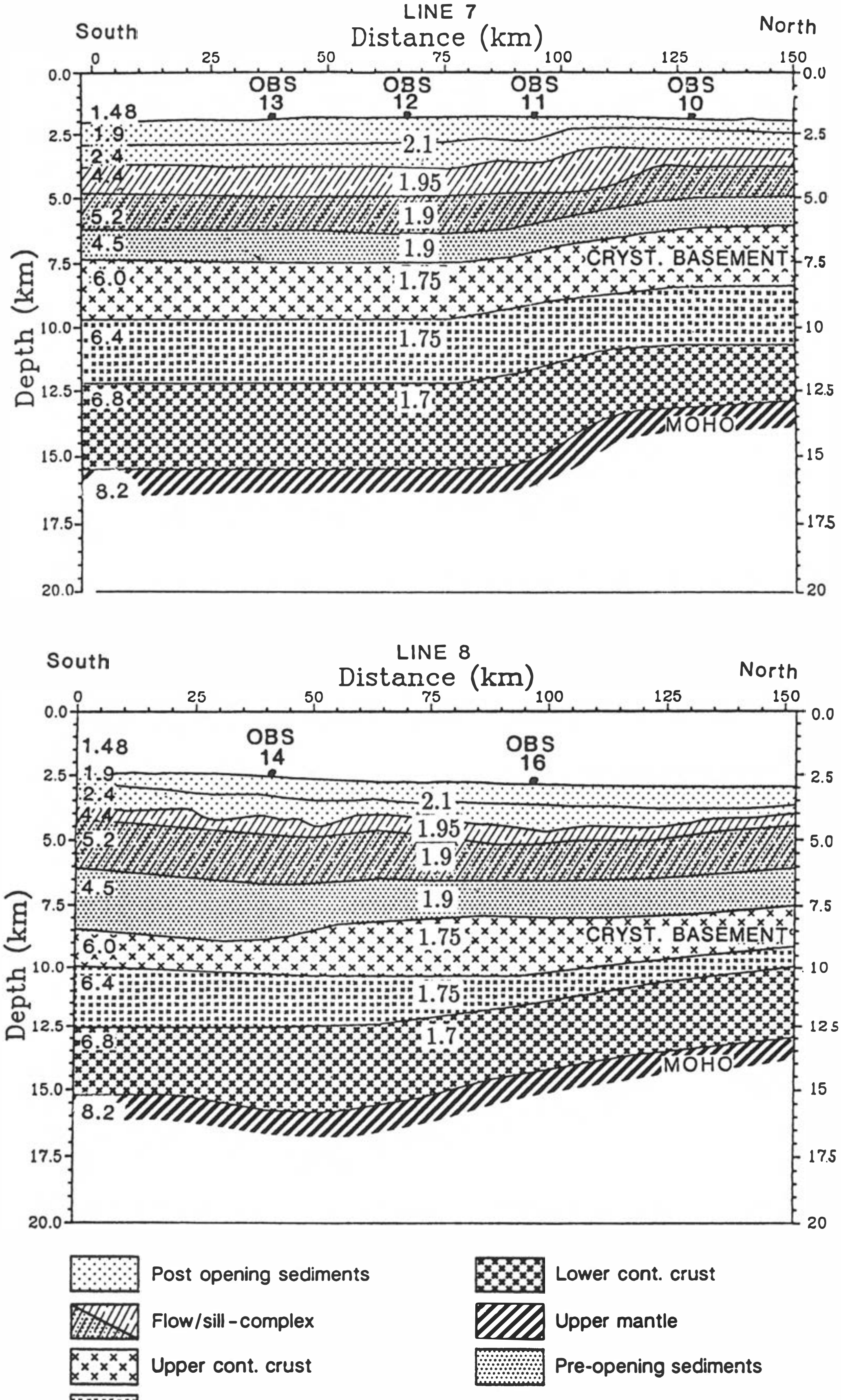


Fig. 5. Velocity models for profiles 7 and 8, landward of the Vøring Escarpment. The P-wave velocities are shown in km/s on the left-hand side of the models, and the V_p/V_s-ratios are indicated in the central part of the models. (From Mjelde et al. 1995b.)

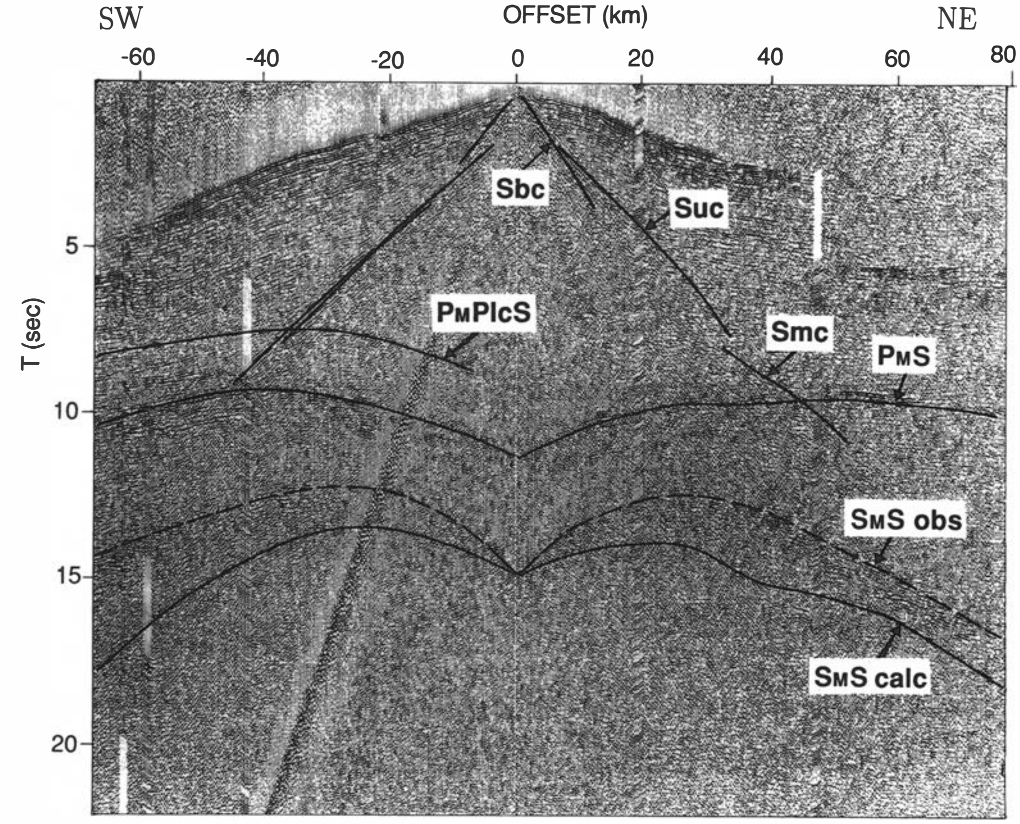


Fig. 6. OBS 7 horizontal component, profile 6, with S-wave travel-time curves from the model in Fig. 3 indicated (calculated from 2-D ray-tracing; reduction velocity 8.0 km/s, 6–13 Hz band-pass filtered, deconvolved). S_{bc} = base Cretaceous refraction, S_{uc} = upper crust refraction, S_{mc} = middle crust refraction, P_M-$P_{lc}S$ = mode conversion at the top of the lower crust, S_MS = Moho reflection, P_MS = mode conversion at Moho. Hatched and heavy lines represent observed and calculated travel-time curves respectively. (Reprinted from Mjelde 1992, *Geophysical Journal International 110*, 283–296, Blackwell, Oxford.)

tary layers is estimated to 2.0, 1.95 and 1.9, respectively, whereas 1.85 is calculated for the pre-Cretaceous sediments. The vertical decrease in the V_p/V_s-ratio from the Cretaceous to the pre-Cretaceous sediments can most likely be explained by the decreasing porosity and microfracturing with depth in the shaly sediments (Mjelde & Sellevoll 1993a).

The V_p/V_s-ratio in the crystalline portion of the crust is estimated to 1.75, with no significant variations in depth. This relatively low value confirms that the crust beneath the shelf is of continental origin, with abundant presence of felsic rocks such as granite, grandiorite or felsic amphibolite facies gneiss (e.g. Holbrook, Mooney & Christensen 1992).

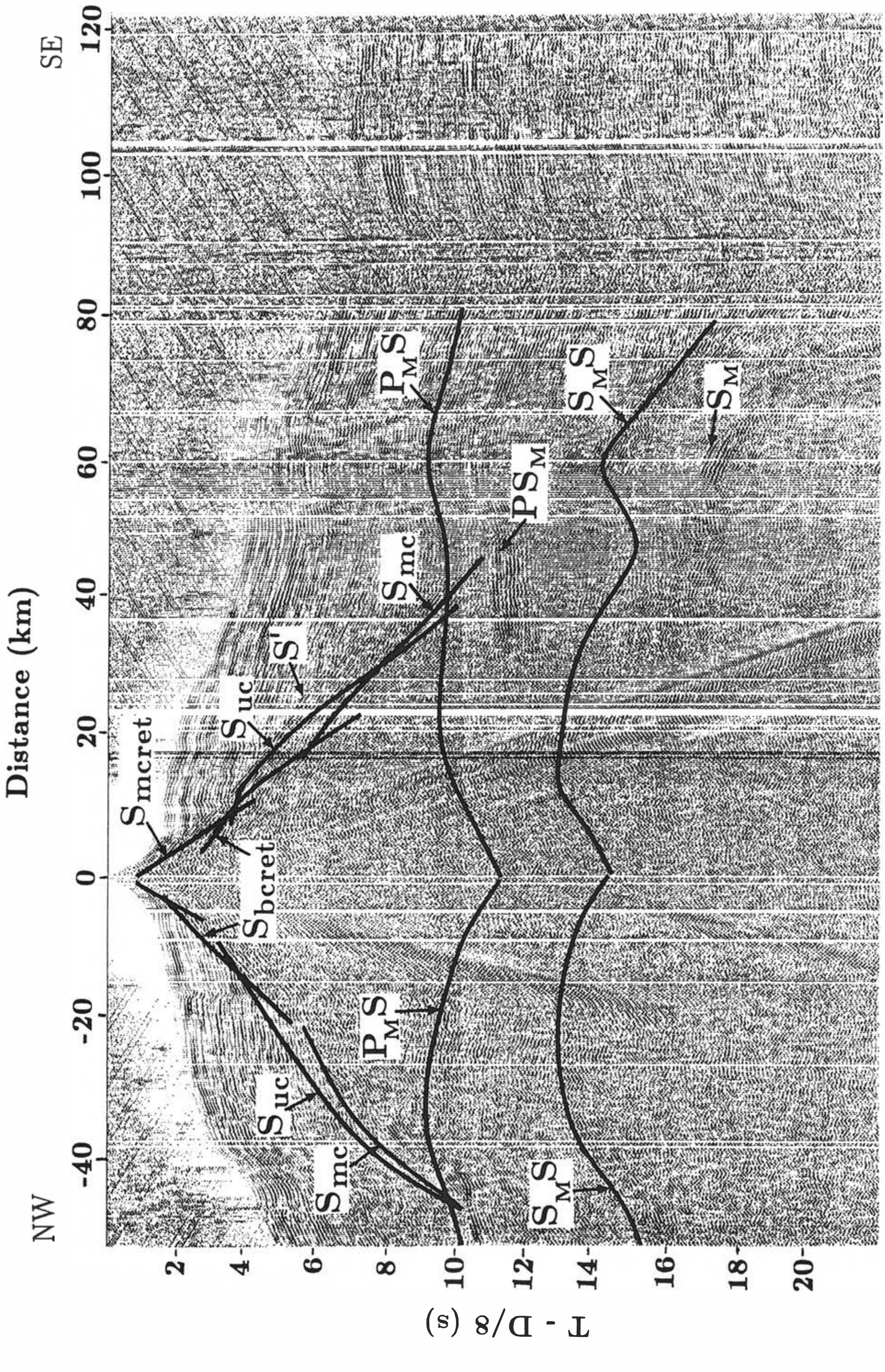
Continental shelf: anisotropy

The V_p/V_s-ratios for the sediments described above, show that the S-wave velocity in the Cretaceous and pre-Cretaceous sediments are, respectively, about 10% and 5% higher along profile 1 than along the perpendicular profile 6. This S-wave anisotropy can be explained by liquid-filled microcracks aligned along the direction of the present-day maximum horizontal compressive stress (Mjelde & Sellevoll 1993a). Fig. 8 shows that this direction of compressive stress (that can be related to push from the Mohns Ridge; Bungum et al. 1990) is close to the azimuth of profile 1, and Fig. 9 shows that an S-wave propagating along the azimuth of the cracks (profile 1) would have higher velocity than a wave propagating perpendicular to the cracks. The dilatancy (mode I) microcracks described here are penny-shaped with a crack density (CD) of 0.1 ($CD = Na^3/v$ where N is the number of cracks of radius a in volume v) and aspect ratio (AR) of 0.05 ($AR = d/a$) where d is the half-thickness of the cracks (Crampin 1978).

The modelling indicates that the anisotropy decreases with depth in the sediments, which can probably be related to decreasing crack-density (number of cracks) with increasing confining pressure (depth). The anisotropy is not observed in the upper and middle crystalline crust, which indicates that the cracks are restricted to the sedimentary layers, or that they close at shallow depths in the crystalline basement; from about 2 to 5 km (Mjelde & Sellevoll 1993a).

The anisotropy for S-waves reappears, however, in the lower crust. This anisotropy is observed as a strong deviation of the observed S-wave reflection from the Moho (S_MS) for the predicted (isotropic) reflection (Mjelde 1992). The modelling of the S_MS phase on OBS 7 (Fig. 6) shows that a V_p/V_s-ratio of 1.95 satisfies the observations for waves propagating near vertically. For larger offsets (wide angles), however, the isotropic model predicts considerably later arrival times than observed, which indicates that the S-wave velocity increases with increasing angle-of-incidence.

This lower crustal S-wave anisotropy observed along profile 6 as variations in S-wave velocity with angle-of-



Distance (km)
NW
SE
-40
-20
0
20
40
60
80
100
120
T - D/8 (s)
2
4
6
8
10
12
14
16
18
20
S_mc
S_uc
P_MS
S_bcret
S_mcret
S'
PS_M
S_MS
S_M

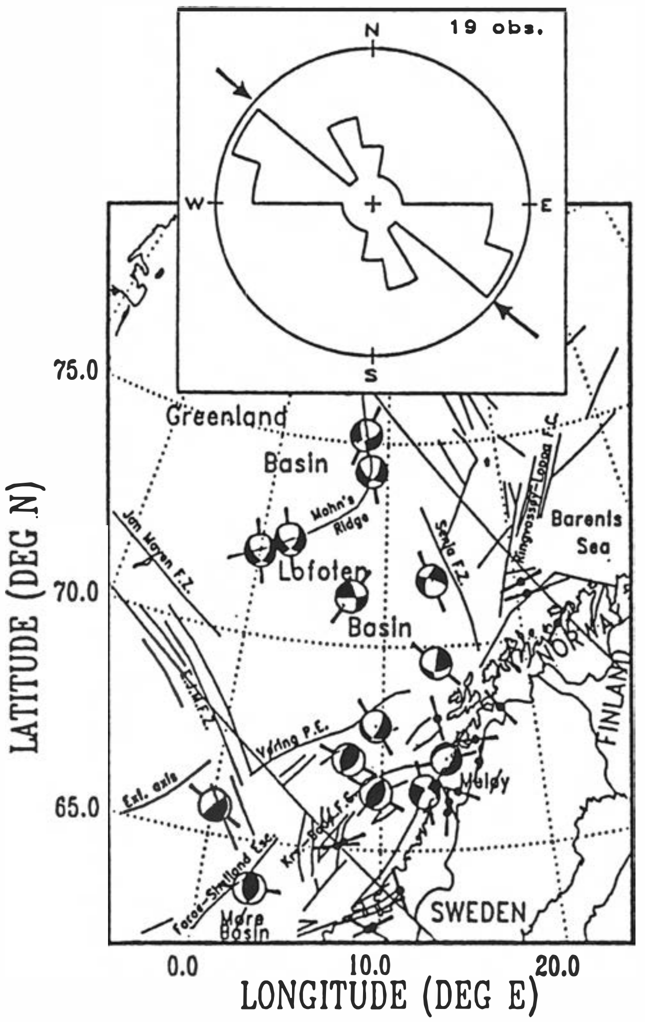


Fig. 8. Focal mechanism solutions and *in situ* stress measurements (solid circles) in the region. The lines (bars) through the focal sphere projections indicate the directions of the P axes (maximum compressive stress). The two parallel NW–SE trending lines across the map are 'ridge push' directions. The rose diagram shows the maximum compressive stress directions from earthquakes in Northern Norway and the Svalbard areas. Arrows indicate the approximate 'ridge push' direction. (From Bungum et al. 1990.)

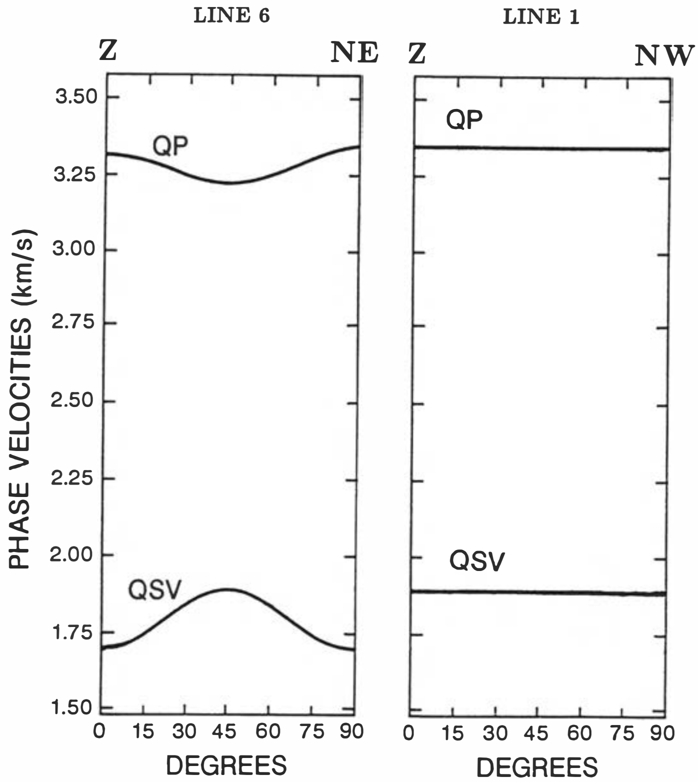


Fig. 9. Variation of theoretical phase velocities with direction of propagation (degrees in angle-of-incidence) for quasi P-waves and quasi SV-waves propagating through parallel liquid-filled microcracks aligned vertically (Z) and striking NW–SE (along profile 1). (Penny-shaped cracks with crack density 0.1 and aspect ratio 0.05.) The left-hand panel is equivalent to wave propagation along profile 6, and the right-hand panel to propagation along profile 1. (Reprinted from Mjelde et al. 1995, *Geophysical Journal International 120*, 87–96, Blackwell, Oxford.)

incidence, is not detected along profile 1 (Mjelde et al. 1995a). These observations can be explained with the same model as for the sediments (Fig. 9); i.e. liquid-filled microcracks (or pore-space) aligned vertically (or steeply) along profile 1. The absence of angle-of-incidence dependent S-wave velocity along profile 1 with this model is explained by the fact that the S-wave in this case always propagate along a plane of symmetry.

The alignment of pore-space in the sediments can, as described above, be related to the present-day stress-field. Although the same geophysical model can also be applied as an explanation for the lower crustal anisotropy, it is difficult to conceive geologically how brittle microcracks can be generated and maintained open by the present stress-field at lower crustal depths.

Multichannel reflection data indicate that significant ductile flow has occurred within the lower crust during the Jurassic–Cretaceous and older extension episodes (Mjelde et al. 1993). Profile 1 is coincident with the inferred direction of maximum ductile flow, and the alignment of pore-space might thus be influenced by ductile strain fabrics inherited from these earlier deformation episodes, or by present ductile strain fabrics in case of a still active deformation (enhanced by the presence of fluids). According to this model, the lower crustal alignment of fluid-filled pore-space might be independent of the present-day stress-field in the area (Mjelde & Sellovell 1993a).

The alignment of fluid-filled pore-space might not, however, be the only possible explanation of the inferred anisotropy. Laboratory measurements on lower crustal rocks exposed on the surface have shown that in many cases these rocks are highly anisotropic due to the align-

Fig. 7. OBS 5 horizontal component, profile 1, with S-wave travel-time curves from the model in Fig. 2 indicated (calculated from 2-D ray-tracing); S_{mcret} = middle Cretaceous refraction, S_{bcret} = base Cretaceous refraction, S_{uc} = upper crust refraction, S_{mc} = middle crust refraction, S_MS = Moho reflection, P_MS = mode conversion at Moho, S_M = upper mantle reflection, PS_M = upper mantle mode conversion, S′ = intra crustal heterogeneities. (Reprinted from Mjelde & Sellevoll 1993, *Tectonophysics 222*, 21–32, Elsevier, Amsterdam.)

ment of minerals (Babuska & Cara 1991). Many highly anisotropic minerals can be excluded in our case, however, since the estimated S-wave anisotropy is at least three times higher than the (non-observable) P-wave anisotropy (Mjelde 1992). Important minerals that have similar P- and S-wave anisotropies (and thus can be excluded) include olivine and chain silicates like pyroxenes and hornblende. Anisotropy due to fine-scaled layering can be excluded for the same reason. The mineral kyanite, however, has an S-wave anisotropy about five times higher than the P-wave anisotropy (Belikov, Aleksandrov & Ryzhova 1970), and certain distributions of this mineral in the lower crust could possibly explain the observations. High concentrations of kyanite has been observed within a ≈ 100 m thick zone in the Gargatis formation, Saltfjellet, and in lower concentrations over a larger rock volume within the Rødingsfjell complex. Kyanite has also been observed locally at Leknes and Sigerfjord in Lofoten, Vesterålen, at up to $\approx 20\%$ concentrations (E. Tveten, NGU, pers. comm.). It is difficult to estimate the concentrations of kyanite needed to explain our observations without performing more laboratory measurements on kyanite-bearing rocks, but the presence of the mineral in the area suggests that it cannot be excluded as a possible cause of the observed anisotropy.

On two OBSs along profile 1, strong arrivals from a dipping structure in the upper mantle are observed (Figs 2, 7). These arrivals include P-wave reflections, S-wave reflections, and P-to-S conversions at the structure itself (Mjelde & Sellevoll 1993b). The modelling of these arrivals suggests the presence of significant anisotropy in the upper mantle. A P-wave anisotropy in the order of 15% with direction of velocity inclined at least 45° from the horizontal, is inferred, whereas the S-wave anisotropy is estimated to be somewhat smaller, in the order of 5–10%. It is important to underline that this anisotropy (also for the P-waves) was discovered when S-waves were included in the modelling.

Seismic anisotropy has been observed frequently in the upper mantle elsewhere (e.g. Hess 1964), and its cause is often related to preferred orientation of olivine due to (frozen) mantle flow (e.g. Francis 1969). Upper mantle anisotropy with dipping symmetry planes, as inferred in Lofoten, has also been postulated under the Alps by Babuška, Plomerova & Granet (1990). These authors argue that the anisotropy probably reflects the inner (anisotropic) structure of the dipping European plate. A similar situation occurred in the Lofoten region during the Caledonian orogeny, when the Laurentia (Greenland) and Baltica (Scandinavia) plates collided. However, the structures resulting from this continental collision may have been significantly overprinted by later extensional episodes. It is thus not very likely that possible steeply dipping Caledonian features have been preserved within large volumes of the upper mantle.

In order to explain the cause of the upper mantle reflection (Fig. 2), Mjelde et al. (1993) suggested the presence of a master fault dipping about 20° seawards and cutting the Moho under the Lofoten Ridge. One possible explanation to the observed anisotropy might be the presence of an abundant secondary set of faults/fractures making an angle of at least 30° with this master fault. According to this model, the steep inclinations of minerals will be explained by alignment due to shearing along these faults during the post-Cadedonian extensional episodes (Mjelde & Sellevoll 1993b).

Continental slope and continent/ocean transition

The modelling of the data in this part of the area suggests that the waves are P-to-S converted mainly at the top of the basalt, which represents the strongest impedance-contrast seaward of the shelf (Mjelde et al. 1995b). In addition, conversion is modelled to occur at the top of the lower crustal 7.3 km/s layer on the seaward side of the Vøring Escarpment (Fig. 4), and at the top of the middle crustal 6.4 km/s layer on the landward side of the Vøring Escarpment (Fig. 5).

Fig. 10 shows that a large portion of the S-wave energy has propagated with an apparent velocity similar to that of the P-waves. These waves have thus propagated within the crust (near horizontally) as P-waves, and they have been converted to S-waves on the way up. In addition to this mode, P-to-S reflections are frequent in this part of the area.

The calculated V_p/V_s-ratio are indicated in the models in Figs. 2–5. The mean V_p/V_s-ratio for the sediments is estimated to 2.1 for the three strike profiles 7, 8 and 9, and to 2.0 for the perpendicular profile 1. These relatively high values can probably be related to a low degree of consolidation of the sediments, and possibly also to the abundant presence of shales. The somewhat higher S-wave velocity along profile 1 compared to the strike-profiles (about 5%), suggests that the S-wave anisotropy for the sediments observed on the continental shelf, to a certain degree, is present over the entire area. It must be emphasized, however, that this possible anisotropy seaward of the shelf is on the limit of the resolution in the modelling.

Along profile 9, situated on the SDRs, the mean V_p/V_s-ratio for the entire crust beneath the sediments is estimated to 1.9, with no significant variations between different layers within the crust (Fig. 4). From the modelled P-wave velocities, Mjelde et al. (1992) concluded that the crust along profile 9 was of oceanic origin. This conclusion is strongly supported by the S-wave model, since V_p/V_s-ratios of 1.9 for crustal rocks clearly falls within the range of gabbro/amphibolite (e.g Holbrook, Mooney & Christensen 1992).

As described above, the detailed modelling of the P-waves suggests that the crustal velocities decreases from 'oceanic' beneath profile 9, to 'continental' beneath the Vøring Escarpment. Unfortunately, the resolution of the S-waves in this part of the area is not high enough to constrain this model further.

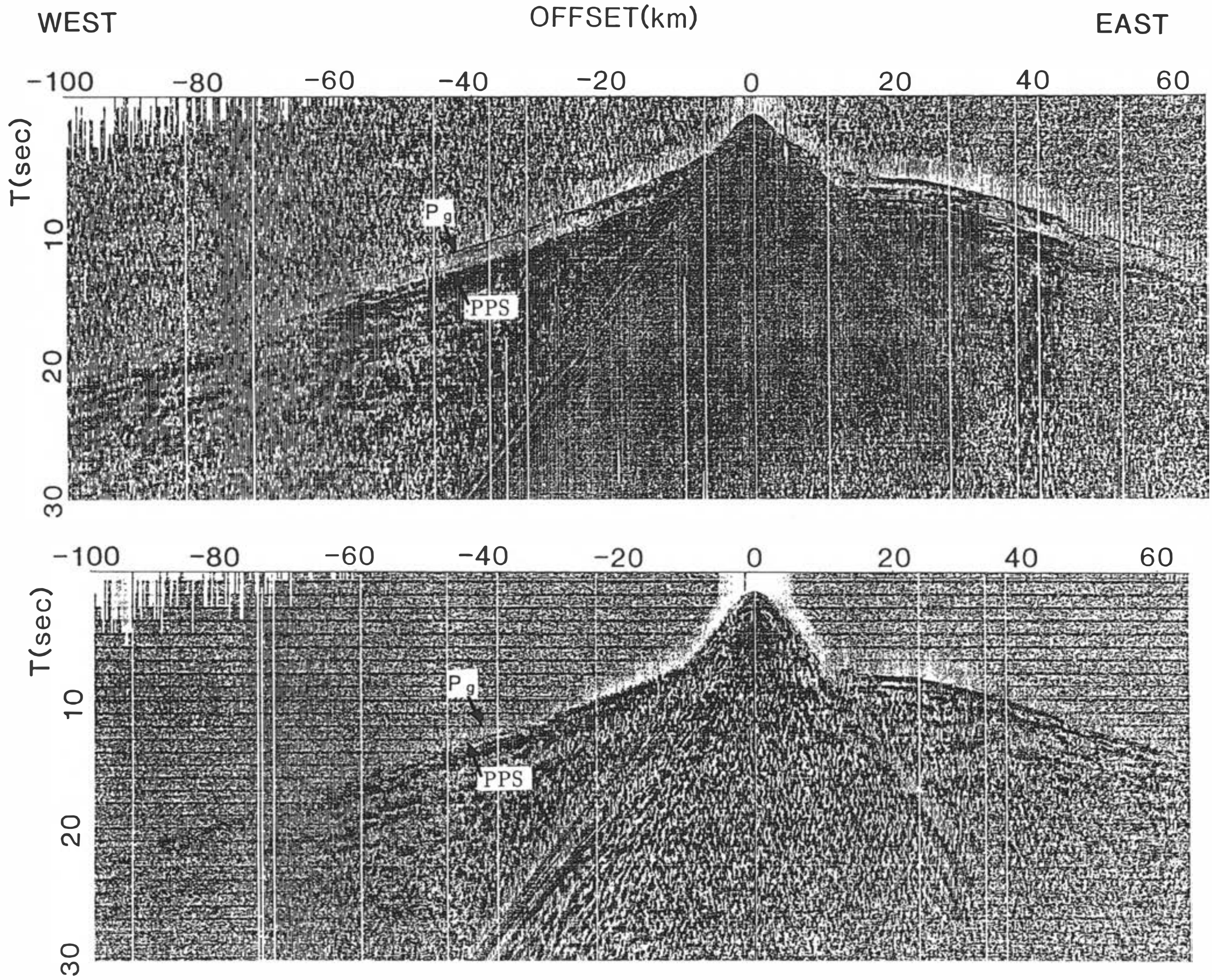


Fig. 10. Comparison between the vertical (above) and one horizontal component (below) of OBS 11, profile 4. On the horizontal component, the P_g-phase (crustal refraction) is very weak, confirming that this arrival is a near vertically polarized P-wave. The later arrival (PPS) is also very strong on the horizontal component, proving that this phase corresponds to an S-wave. The high apparent velocity of the arrival shows that the wave has propagated within the crust (near horizontally) as a P-wave that has been converted to an S-wave on the way up. (From Mjelde et al. 1995b.)

On the landward side of the Vøring Escarpment, the modelling suggests a significantly lower V_p/V_s-ratio for the crystalline crust (Fig. 5). The mean V_p/V_s-ratio of the crust is 1.75, which confirms that the crust on the landward side of the Vøring Escarpment represents strongly thinned continental crust. The modelling suggests a slight decrease in the V_p/V_s-ratio towards the lower crust, from 1.75 to 1.7, but this difference is on the limit of the resolution in the modelling, and should thus not be interpreted in geological terms (Mjelde et al. 1995b).

Conclusions

A model of the seismic S-wave structure from Vestfjorden across the continent/ocean transition off Lofoten has been obtained from ray-tracing modelling of the horizontal components of OBS-data. The modelling indicates that the V_p/V_s-ratio of the sediments is relatively high (1.85–2.15) in most of the area. For the shallowest sediments, these high values are probably related to a low degree of compaction, whereas for the deeper sediments (below about 1 km) the high V_p/V_s-ratios most likely suggest the abundant presence of shales. One important exception is found along a strike-profile along the Røst High, where a significantly lower V_p/V_s-ratio (1.6) south of the high might indicate a much higher sand/shale ratio here.

The V_p/V_s-ratio in the crystalline crust is estimated to 1.75 beneath the continental shelf. These relatively low values suggest granitic/granodioritic lithology, and clearly confirms that the crust is continental with no observable amount of mafic intrusions. The same applies to the area between the shelf edge and the Vøring Escarpment, where flood-basalts, extruded during the Early Eocene opening between Norway and Greenland, are present. Beneath the seaward-dipping reflectors on the seaward side of the Vøring Escarpment, the V_p/V_s-

ratio in the crystalline crust is found to be significantly higher: 1.9. This high value is indicative of a mafic lithology (gabbro/amphibolite) and confirms that the crust in this part of the area is of oceanic origin.

On the continental shelf, a strong S-wave anisotropy is observed in the sediments; the S-wave velocity is estimated to be about 10% higher along the dip-profile than along the perpendicular strike-profile. This anisotropy can be explained by presence of liquid-filled microcracks aligned vertically along the direction of the present-day maximum horizontal compressive stress in the area. The anisotropy is not observed in the upper crystalline crust, indicating that the microcracks are closed at these depths due to the confining pressure.

The same amounts of anisotropy with the same symmetry reappear in the lower crust. This lower crustal anisotropy might be related to the (steep) alignment of pore-space influenced by ductile strain fabrics inherited from Jurassic–Cretaceous and older extension episodes, or by present ductile strain fabrics in case of a still active deformation. Alternatively, the anisotropy might be explained by alignment of some mineral, like kyanite, but it must be emphasized that many highly anisotropic minerals, like olivine, pyroxenes and hornblende, cannot explain the observed anisotropy.

The modelling of the S-wave arrivals from a strong upper mantle reflector reveals a significant anisotropy (both for P-waves and for S-waves) in the upper mantle. This anisotropy can be explained by steep alignment (at least 45° from the horizontal) of the strongly anisotropy mineral olivine. The steep inclination of the minerals might possibly be caused by shearing close to a postulated master fault cutting the crust and upper mantle in this area.

This experiment has shown that high-quality sedimentary and crustal S-waves can be recorded quite easily in marine seismic acquisitions. The S-waves can further be included in the modelling in a straightforward manner, and they provide valuable geological information that cannot be extracted from P-wave studies alone. We thus suggest that S-waves should be included in the analysis of seismic data whenever possible, both in regional crustal studies and in the detailed mapping of reservoirs.

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