NORSAR

NORSAR Scientific Report No. 2-1999/2000

Semiannual Technical Summary

1 October 1999 - 31 March 2000

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Kjeller, May 2000

6.7 Crustal structure of the Barents Sea – important constraints for regional seismic velocity and travel-time models

Introduction

The Barents Sea covers the continental shelf of northwestern Eurasia (Fig. 6.7.1). It is bounded by young passive margins to the west and north that developed in response to the Cenozoic opening of the Norwegian-Greenland Sea and the Eurasia Basin, respectively. The Barents Sea contains some of the deepest sedimentary basins known and it preserves a relatively complete succession of sedimentary strata ranging in age from Late Paleozoic to Quaternary, locally exceeding 15 km in thickness (Faleide et al. 1993, Gudlaugsson et al. 1998).

Deep seismic reflection and refraction data have greatly improved our understanding of the deep basins and the underlying crystalline crust in the Barents Sea and of the crustal transition across the western continental margin (Faleide et al. 1991).

In this report, we review the Barents Sea crustal structure and discuss how the crustal configuration and composition affects regional models for seismic velocities and travel-times.

Geological framework

The western Barents Sea comprises three distinct regions (Faleide et al. 1993, Gudlaugsson et al. 1998):

- The western Barents Sea-Svalbard continental margin consists of three regional segments: a southern sheared margin along the Senja Fracture Zone; a central rifted complex southwest of Bjørnøya associated with volcanism; and a northern sheared and rifted margin along the Hornsund Fault Zone. The continent-ocean transition occurs over a narrow zone along the line of early Tertiary break-up and is covered by a thick Upper Cenozoic sedimentary wedge.
- The Svalbard Platform covered by flat-lying Upper Paleozoic and Mesozoic, mainly Triassic, strata.
- A province between the Svalbard Platform and the Norwegian coast characterised by sub-basins and highs with increasingly accentuated structural relief to the west. Jurassic, Cretaceous, and locally Paleocene-Eocene strata are preserved in the basins.

The eastern Barents Sea comprises two wide and deep north-northeast trending basins of Late Paleozoic-Triassic age separated by a shallow saddle (Johansen et al. 1993).

Direct information on the nature of the crystalline crust beneath the Barents Sea sedimentary basins is scarce, but available, mostly indirect, evidence indicates that the basement underlying much of its central and western parts was consolidated during the Caledonian Orogeny. An older, Baikalian, basement underlies the southeastern Barents Sea (Gudlaugsson et al. 1998).

Upper Paleozoic (Devonian-Permian) rocks in the western Barents Sea are expected to be similar to those of Svalbard and Bjørnøya (Devonian-Carboniferous clastics and Upper Carboniferous-Lower Permian carbonates and evaporites). The eastern Barents Sea had marine conditions earlier with deposition of Devonian and Carboniferous limestones.

The Mesozoic succession comprises mostly clastic rocks. Thick Triassic rocks occur throughout the Barents Sea and comprise coarsening upwards sequences. The Lower-Middle Jurassic interval is dominated by sandstone while shales dominate the Upper Jurassic and Cretaceous interval. Early Tertiary, mostly fine-grained clastics, are only preserved in the southwestern Barents Sea and on Spitsbergen.

In somewhat simplified terms, the post-Caledonian geological history of the Barents Sea has involved (Faleide et al. 1993, Johansen et al. 1993, Gudlaugsson et al. 1998):

- A Devonian tectonic regime in the west comprising both extensional and compressional events, so far known on Svalbard only. Devonian rifting affected the eastern Barents Sea.
- Widespread rifting in the Carboniferous and Permian.
- Gradual development towards non-fault-related regional subsidence in Permian and Triassic times.
- Middle-Late Jurassic and Early Cretaceous rifting in the southwestern Barents Sea, associated with regional magmatism and uplift in the northern Barents Sea.
- Late Cretaceous uplift of most of the Barents Sea, but continued faulting and subsidence in the southwesternmost Barents Sea.
- Early Tertiary continental breakup and margin formation related to the opening of the Norwegian-Greenland Sea and Eurasia Basin.
- Late Cenozoic uplift and glacial erosion.

Data

A comprehensive deep seismic database covers the Barents Sea, including deep seismic reflection profiles recorded to 14-16 s two-way time and deep seismic refraction/wide-angle reflection profiles using both two-ship (ESP) and OBS techniques. We have used the deep seismic data to constrain the first-order crustal structure and deep seismic velocity distribution.

In addition, we have used a regional grid of conventional seismic reflection profiles recorded to 6-10 s twt and a large number of sonobuoy refraction profiles to elucidate the shallow structure.

Gravity and magnetic data have also been useful constraining the deep basin configuration and crustal structure.

Important geological information is also obtained from exploration wells and outcrops onshore (Svalbard, Franz Josef Land, Novaya Zemlya, Finnmark-Kola).

Velocity structure

The large number of velocity-depth profiles plotted in Fig. 6.7.2 show the wide range of velocities measured at various depths in the Barents Sea compared to the regional velocity model of Kremenetskaya and Asming (1999). To reveal the large lateral and vertical velocity variations in the Barents Sea region we need a regional 3D velocity model.

Fig. 6.7.3 summarises a generalised velocity structure for the Barents Sea including depth ranges to some of the key interfaces in the Barents Sea subsurface:

- The geology at the top of the bedrock (beneath a thin cover of Quaternary sediments) varies laterally because of varying Late Cenozoic uplift and erosion. The surface (top of bedrock) velocity varies typically between 2 and 4 km/s depending on the amount of missing overburden due to erosion. The highest velocities and erosion estimates are found in the northwestern Barents Sea including Svalbard.
- Mesozoic strata (mainly sandstones and shales) reveal a velocity gradient reaching velocities of typically 4-4.5 km/s at the base of the Triassic.
- Upper Carboniferous-Lower Permian carbonates (mainly limestones and dolomites) and Upper Permian silicified clastics are characterised by high velocities (~6 km/s). Detailed measurements (sonic logs) in wells reveal considerable variations within this unit but parts of it have velocities in the order of 6 km/s irrespective of burial depth. Depths to the top of this high-velocity layer ranges between 0-10 km.
- A velocity inversion occurs below the carbonate platform. Carboniferous and Devonian clastic rocks have velocities of 5+ km/s. The velocity inversion is difficult to detect by standard interpretation techniques applied to the seismic refraction data. This may cause errors in the depth estimates for underlying interfaces such as top of the crystalline basement and moho at the base of the crust.
- The crystalline basement has velocities of 6+ km/s. Depths to top basement ranges between 0-20 km.
- Magmatic underplating characterised by 7+ km/s velocities are probably present east of Svalbard (Høgden 1999).
- 8+ km/s are measured in the upper mantle. Moho-depths typically range between 20-40 km).

Crustal transects

Differences in crustal structure are illustrated by a series of regional transects which are based on an integrated interpretation of the deep seismic data supplemented with conventional seismic reflection and refraction profiles. In order to bring out the primary crustal features, only the main structural elements and sedimentary units of the upper crust are shown.

The moho relief and structure of the lower crust are mainly constrained by the deep seismic reflection and refraction data. In the interpolation between the deep crustal reflectors and/or refractors we have used results from gravity modelling along some of the transects.

Two regional crustal transects across the Barents Sea have been constructed between the Novaya Zemlya test site and the seismic arrays SPITS and ARCES respectively (Figs. 1 and 4). The most prominent features in both transects are the wide and deep East Barents Sea basins. The deeper fault-controlled part of these basins, interpreted as being either Devonian (Johansen et al. 1993) or Carboniferous-Permian (Verba et al. 1992) in age, is associated with crustal thinning and high seismic velocities in the crust (Verba et al. 1992) indicating an extensional tectonic setting. The total sedimentary thickness reaches 17 km and the average depth to moho is about 35 km. The velocities in the upper crystalline crust are 5.8-6.4 km/s and in the lower crust they are 6.8-7.0 km/s and higher (Davydova et al. 1985).

The areal configuration of the East Barents Sea basins and their Late Permian-Early Triassic subsidence, contemporaneously with inversion and folding on Novaya Zemlya (Ulmishek 1982), suggests that the primary driving forces of the regional subsidence may be related in some way to active-margin and continental-collision processes culminating in the Uralian Orogeny at the eastern Barents Sea margin (Vågnes et al. 1994, Gudlaugsson et al. 1998).

The geology of the western Barents Sea exhibits distinct regional differences (see N-S transect in Fig. 6.7.4). South of 74°N, the southern Barents Sea sedimentary basin province is characterised by a number of sub-basins and highs. This region is dominated by Late Paleozoic to early Tertiary extensional events. The structural relief becomes increasingly accentuated towards the margin, reflecting westward retreat of the areas affected by rifting with time. North of about 74°N, a relatively flat-lying succession of Upper Paleozoic and Mesozoic strata reflects a general platform setting in a region largely unaffected by the late Mesozoic extension.

A series of crustal transects across the western continental margin is shown Fig. 6.7.5. The change in crustal type, from continental to oceanic, occurs over a narrow zone and is closely related to the primary shear and rift structures along the margin.

In a regional sense, continental breakup took place within two distinctly different provinces, the Mesozoic sedimentary basin region in the southwestern Barents Sea, and the platform further north comprising Svalbard and the Svalbard Platform. In the platform province Mesozoic and Upper Paleozoic strata cover a thick crystalline crust. The base of the crust is well defined in the deep seismic reflection profiles and corresponds to an 8+ km/s velocity at a depth of 30-35 km in the deep seismic refraction data. In contrast, the basinal region exhibits an accentuated basement relief with thick local sediment accumulations. Moho depths range from 20 to 30 km. Within the basins, continuous reflectors interpreted as sedimentary sequence boundaries are observed down to a maximum depth of 9.5 s twt, or approximately 20 km. An extended crystalline crust of only a few kilometres in thickness exists beneath the basin axis, suggesting that the Cretaceous rifting almost reached breakup (Faleide et al. 1993, Breivik et al. 1998).

The oceanic crust has a normal thickness (5-8 km) but higher velocities associated with top basement (6-7 km/s) than normal oceanic crust. Depths to moho in the oceanic domain typically ranges between 10-15 km (Jackson et al. 1990, Faleide et al. 1991). Oceanic basement is overlain by a 5-7 km thick sequence of Cenozoic sediments (Faleide et al. 1996).

The continent-ocean transition is less clear at the rifted margin segment (Fig. 6.7.5, transect 2) because volcanic extrusives mask most of the underlying structures. Two deep reflectors may bound an underplated magmatic body but we do not have velocity control to support this interpretation.

The northern transects (3-5) which represent breakup within a platform region reveal significant differences in crustal thickness, structural style and sediment accumulation with respect to the southern transects. Both the deep seismic reflection and refraction data define the moho at depths of 30-32 km beneath the western Svalbard Platform.

On Svalbard, moho is well defined as a fairly horizontal and continuous reflector at the base of the reflective crust at a depth of 32 km (Fig. 6.7.5, transect 4). It deepens to 35 km under the foldbelt in western Isfjorden. Further west, rapid crustal thinning towards the continent-ocean transition is observed. The large variations in crustal structure around Svalbard will affect seismic travel times for local and regional events recorded at the SPITS array. For example, between the plate boundary (Knipovich Ridge) in the Greenland Sea and SPITS the moho depth varies between 10-35 km over a distance of 200-250 km.

Gravity modelling, constrained by the deep seismic data, indicate lateral density (and velocity?) variations in the upper mantle (Breivik et al. 1999).

Further work

Further work may include:

- Calculation of synthetic travel-times along 2D transects and comparing these to travel-time predictions from the Barents Sea regional velocity model.
- Analysis of wide-angle profiles recorded at SPITS and ARCES using commercial and academic seismic surveying (mainly with airguns but also explosives) as source. Such data sets have proven useful focusing on the velocity structure of the lower crust and uppermost mantle (Høgden 1999, Schweitzer 2000).
- Construction of a regional 3D crustal velocity model.

Summary

The crustal and seismic velocity structure of the Barents Sea varies significantly:

- Thickness of sedimentary cover varies between 0 – 20 km
- Depth to moho varies between 20 – 45 km
- Thickness of crystalline crust varies between 10 – 45 km

The crustal heterogeneity of the Barents Sea region should be revealed by regional velocity models.

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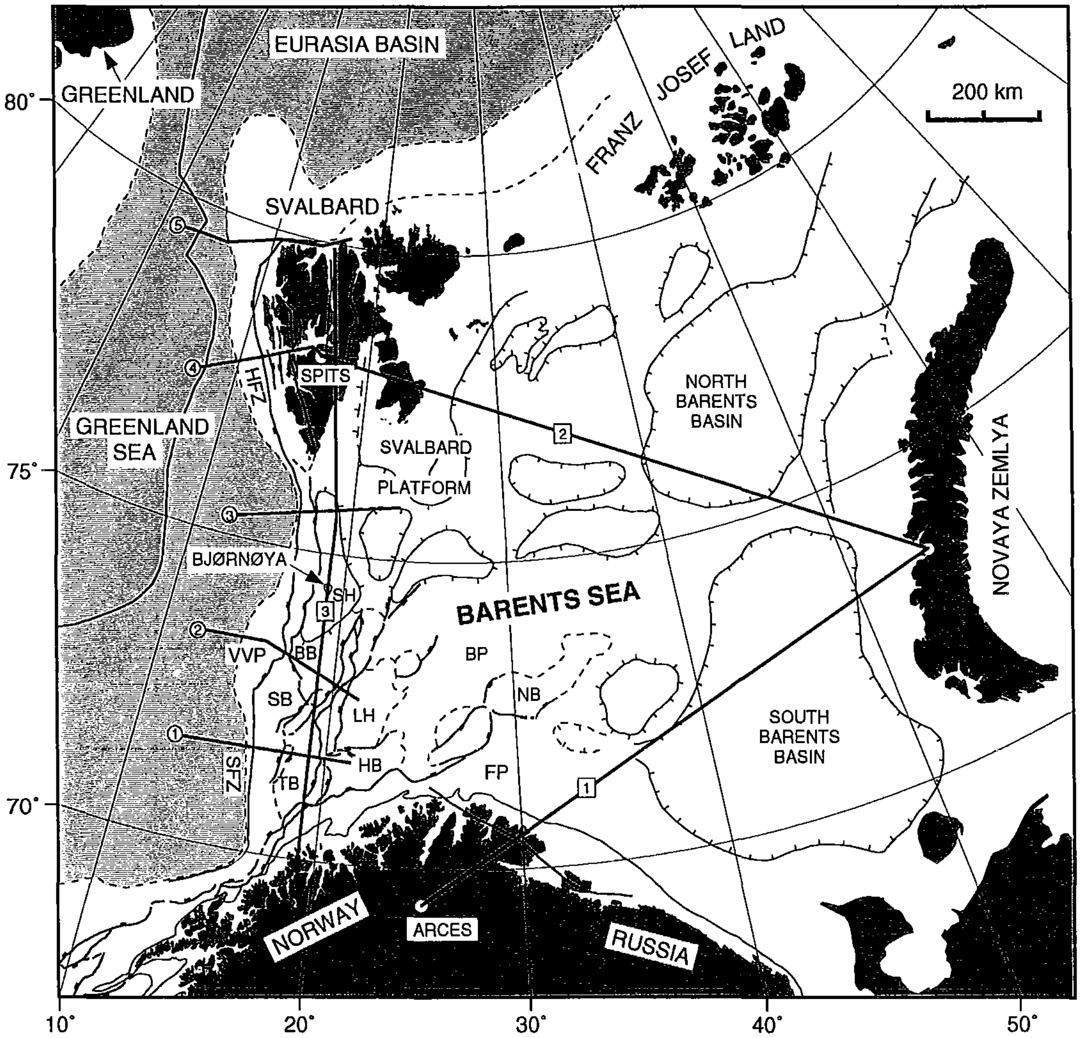

Fig. 6.7.1. *Regional setting – main geological provinces and structural elements in the Barents Sea and surrounding areas. Location of crustal transects in Figs. 4 and 5 and the seismic arrays SPITS and ARCES also shown. BB = Bjørnøya Basin, BP = Bjarmeland Platform, FP = Finnmark Platform, HB = Hammerfest Basin, HFZ = Hornsund Fault Zone, LH = Loppa High, NB = Nordkapp Basin, SFZ = Senja Fracture Zone, SB = Sørvestsnaget Basin, SH = Stappen High, TB = Tromsø Basin, VVP = Vestbakken Volcanic Province.*

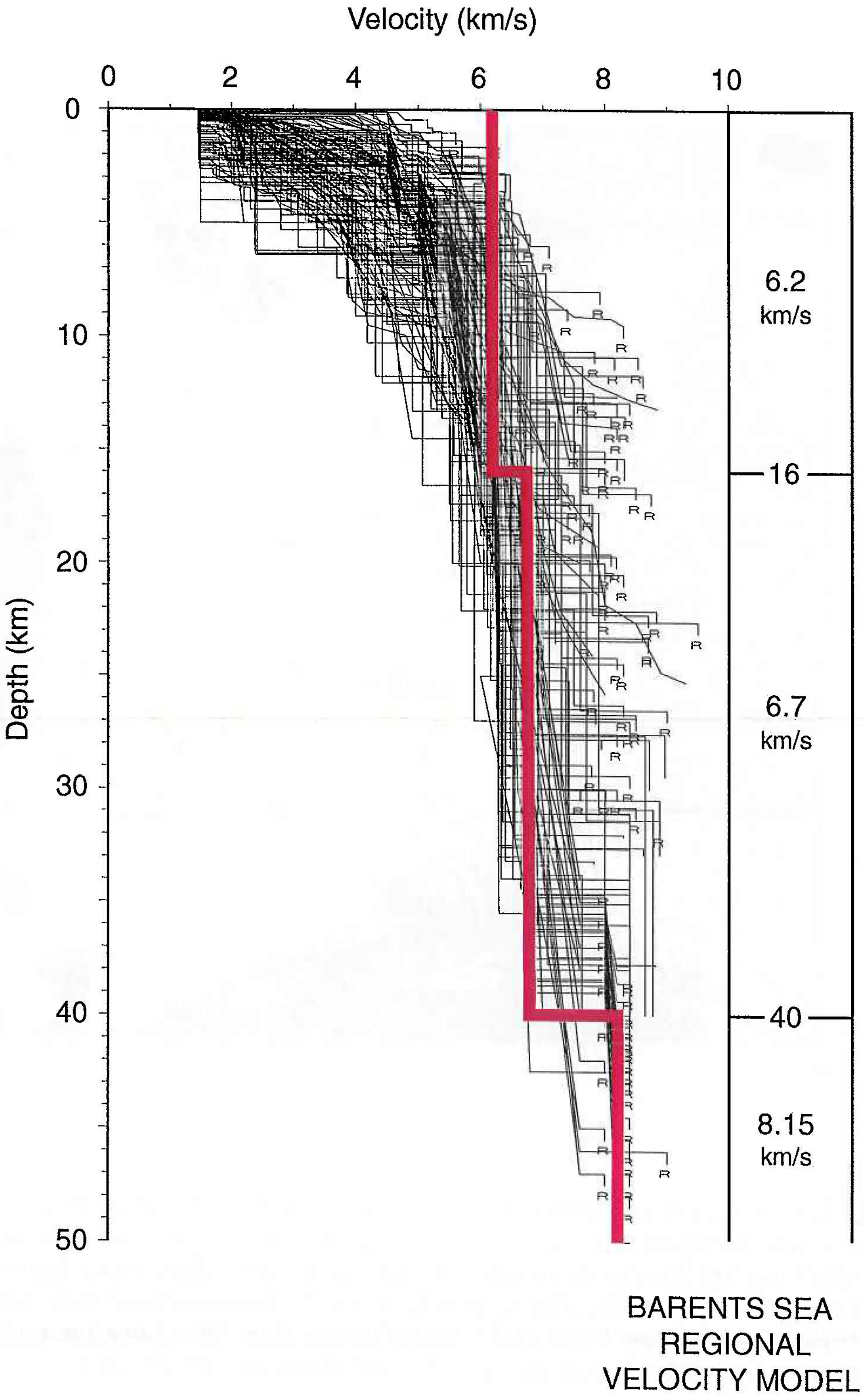

Fig. 6.7.2. *Velocity-depth profiles from most of the Barents Sea (stored in the VELO database compiled by the University of Oslo) compared to the Barents Sea regional velocity model of Kremenetskaya and Asming (1999).*

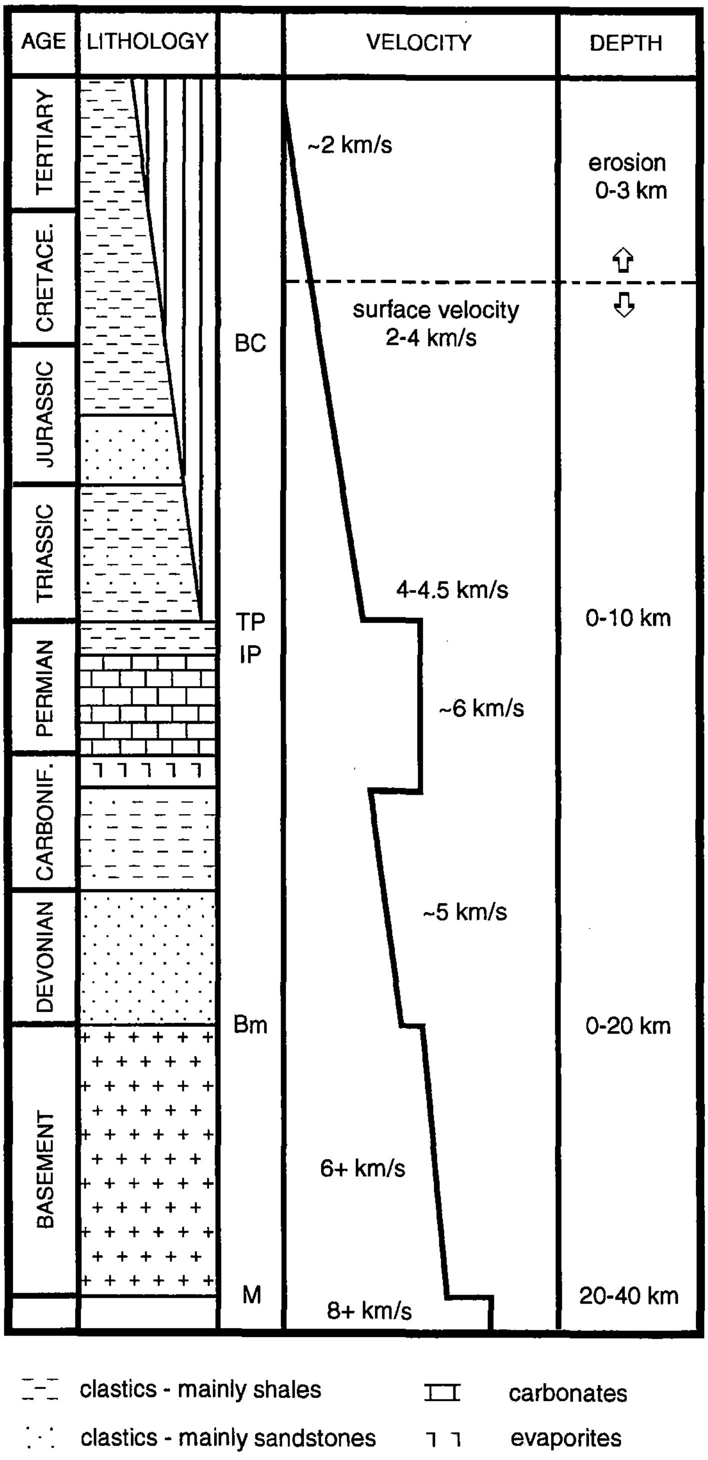

Fig. 6.7.3. *Generalised velocity-depth structure in the Barents Sea showing typical velocities and depth ranges of the main sedimentary and crustal units.*

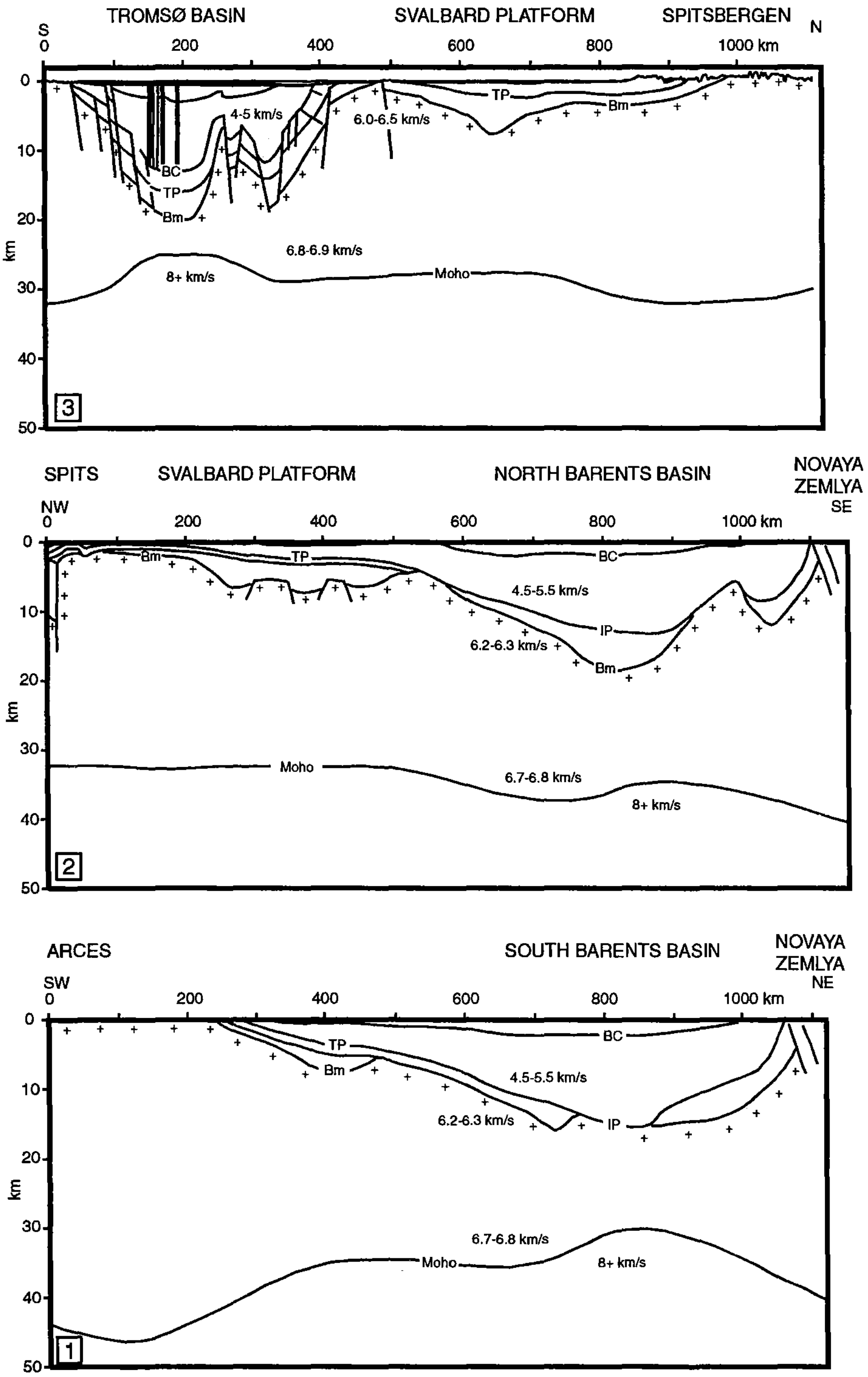

Fig. 6.7.4. *Regional crustal transects across the Barents Sea. (1) ARCES to the Novaya Zemlya test site, (2) SPITS to the Novaya Zemlya test site, and (3) N-S profile in the western Barents Sea from the coast of Norway, across Bjørnøya, to the northern coast of Svalbard. See Fig. 6.7.1 for location and Fig. 6.7.3 for identification of the main interfaces in the Barents Sea subsurface.*

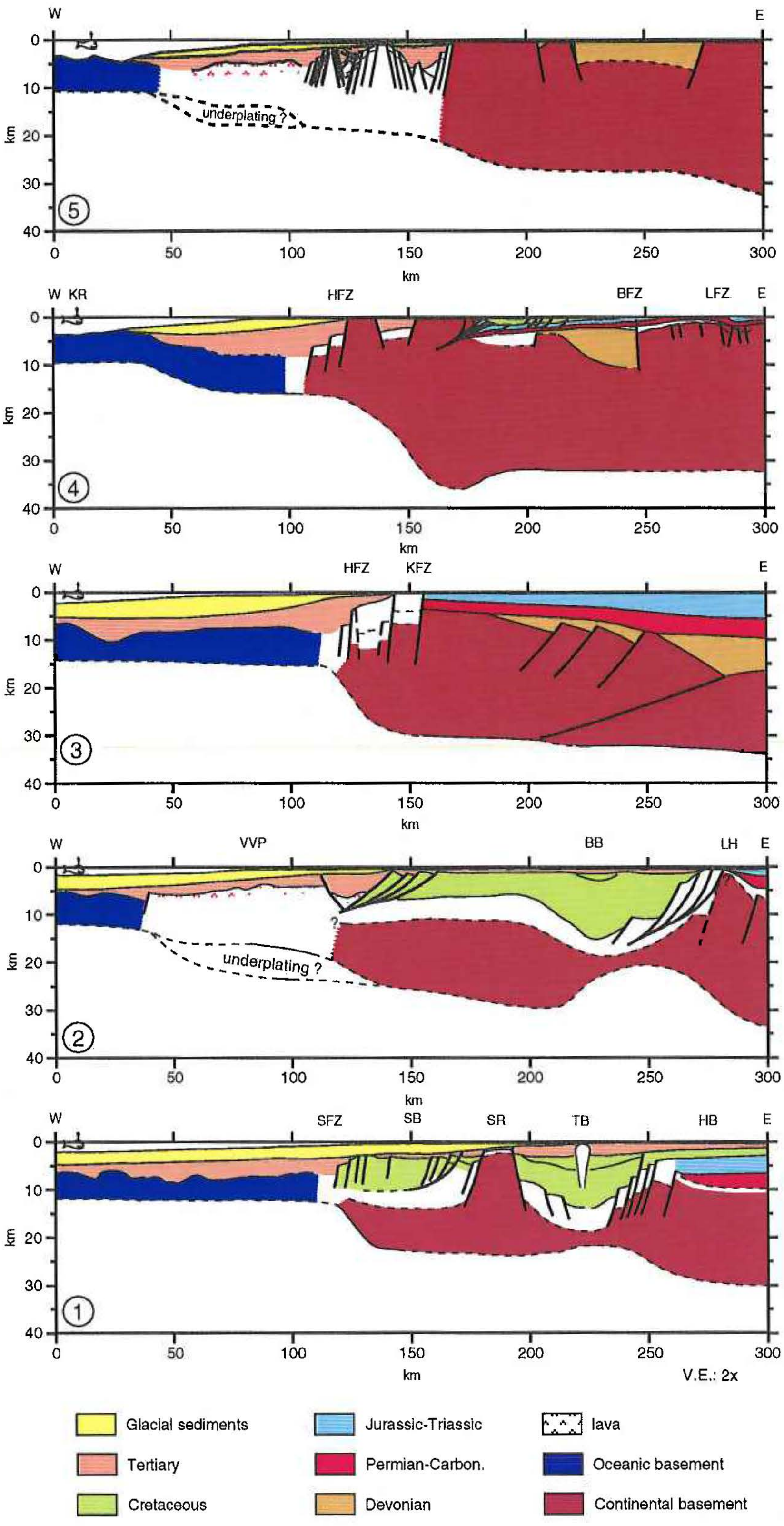

Fig. 6.7.5. *Regional crustal transects across the western Barents Sea-Svalbard margin. See Fig.6.7.1 for location.*