Crustal structure of north-western Spitsbergen from DSS measurements

ABSTRACT: During the Polish Geophysical Expedition in 1985, deep seismic sounding measurements were performed in transition zones between the western Spitsbergen and Knipovich Ridge, as well as between northern Spitsbergen and Yermak Plateau. One hundred and five shots were fired in the sea along five, 200–300 km long, profiles. Two profiles run from the west to the east and three lay in approximately north-south direction. The average distance between shot points was about 5 km. The recording was made by five 5-channel seismic stations deployed in seven places along western and northern coast of the island. Good quality refracted and reflected P waves were recorded along the whole profile length up to a distance of 300 km. The Moho discontinuity was found at a depth of about 25–30 km beneath the land and about 12–25 km beneath the sea. The rift in the Knipovich Ridge was found to occur between continental crustal blocks. Old oceanic crust was not found in the study area. Seismic reflectors were observed in the lower lithosphere at a depth of 40–70 km.

Key words: Arctic, Spitsbergen, crustal structure, 2-D seismic modelling, Knipovich Ridge, Yermak Plateau.

Introduction

Spitsbergen is an island which is part of the Svalbard Archipelago. The Svalbard Archipelago is located at the northwestern corner of the stable Barents Sea continental platform and bordered to the west and north by passive continental
margins (Fig. 1). The development of these margins is strongly connected to the history of rifting and sea-floor spreading in the North Atlantic Ocean (Jackson et al. 1990; Lyberis and Manby 1993a, b; Ohta 1994). The Svalbard continental margin has been studied by geophysical surveys over the last 25 years, mainly based on multichannel seismic reflection, sonobuoy refraction, gravity and magnetic measurements. The previous investigations have only provided very limited information about the crystalline basement and deep crustal structure (Davydova et al. 1985; Faleide et al. 1991; Sellevoll et al. 1991).

This paper presents results of the study of the transition zone between the continental and oceanic crust in the region of northwestern Spitsbergen based on refraction and wide-angle reflection seismic data (Fig. 1). The experiment was carried out in July–August 1985 by geophysical expedition of the Polish Academy of Sciences. Altogether 105 shots of TNT were performed in the sea along five profiles: K1, K2, C1, C2 and C3 (Fig. 1). The explosions were recorded in-line and partially off-line by five 5-channel vertical component seismic land stations located in seven places (I–VII). We have determined two-dimensional seismic models of the crustal structure along the profiles using forward modelling method.

Geology and tectonics of the investigation area

Spitsbergen is composed of sedimentary, igneous and metamorphic rocks ranging all the way from the Precambrian to the Cenozoic time (Birkenmajer 1993; Ohta 1994). The structure of the Svalbard Archipelago is the result of a complex geological history reflecting the relative movements of the Eurasian and the North American plates from the late Precambrian to the present (Eldholm et al. 1987). The tectonic development of the region can be divided into three major events. The first tectonic phase is related to the Caledonian Orogeny (Birkenmajer 1981) whose effects are particularly well recognized in the eastern Svalbard. It seems that a subduction zone was located along the east coast. The next major tectonic phase is called the Late Devonian Svalbardian event. During this event the present-day eastern Spitsbergen moved northward from the vicinity of the today's eastern Greenland by at least 200 km along the Billefjorden Fault Zone to a point north of Greenland (near Queen Elizabeth Islands). It met the present-day western Spitsbergen there. The western Spitsbergen was already in place at that time or moved northward concurrently from a shorter distance (Harland and Cutbill 1974). The N-S trending lineaments which controlled the Devonian sedimentation and tectonism were reactivated in the Carboniferous during a new period of crustal extension (Steel and Worsley 1984), but the North Atlantic region does not appear to have been subjected to large-scale strike-slip motions since the Late Devonian (Torsvik et al. 1985). The last major deformation took place in the Tertiary time when dextral transcurrent movements occurred along a N-S trending fault west of
the Palaeozoic fault lines. At an early stage the deformation was probably transtensional, but it changed to transpressional later when the present margins of the Greenland and Eurasian plates were deformed. This process led to the West
Spitsbergen Orogeny (Harland and Cutbill 1974; Steel et al. 1985). During the orogeny a narrow thrust and foldbelt developed along the west coast of Spitsbergen which led to increased loading along the western margin of Svalbard and turned the epicontinental, littoral basin of central Spitsbergen into a rapidly subsiding foreland basin.

The subsequent tectonic history of Svalbard can be considered in terms of a postorogenic relaxation of tectonic stresses. Consequently, the main depocentre of Neogene sedimentation shifted offshore to the west, where thick clastic wedges have accumulated (Eiken and Austegard 1987). The Cenozoic processes in the Svalbard region reflect the structural history of the western Barents Sea margin. Prior to the Eocene–Oligocene transition, the relative motion between Svalbard and Greenland was along the NNW–SSE trending Hornsund Fault Zone with no accompanying crustal extension in the Greenland Sea. This regional fault zone acted as an incipient plate boundary between the Barents Sea shelf and the emerging Arctic Ocean.

The initial opening of the southern Greenland Sea apparently began in the early Eocene (Faleide et al. 1988), but no significant separation between the two plates occurred until about 36 Ma ago. The seafloor spreading in the Norwegian Sea and the Arctic Ocean began approximately 57–58 Ma ago (Talwani and Eldholm 1977; Vogt and Avery 1974; LaBrecque et al. 1977). The spreading axis in the Greenland Sea today is represented by the Knipovich Ridge. A shift approximately 5–6 Ma ago caused it to be positioned at or just beyond the continental slope. The Hornsund Fault, a prominent feature which parallels the Knipovich Ridge to the east, can be traced from just south of Bjørnøya to about 79°N (Sundvor and Eldholm 1979, 1980). Another main tectonic structure, called the Yermak Plateau is located north of western Spitsbergen (Fig. 1). It is a volcanic body probably connected with an early spreading in the Nansen Ridge (Feden et al. 1979; Jokat et al. 1995).

Field experiment and method of interpretation

The experiment was carried out in July–August 1985 by the Institute of Geophysics of the Polish Academy of Sciences using the ship of Polish Ship Salvage Company, m/s Jantar. One hundred and five explosions were made in the sea along five profiles (K1, K2, C1, C2 and C3) at depths of about 60 m with distances between them of about 5 km. Location of shots was made using satellite navigation. The charges were in the range of 20–120 kg TNT. The explosions were recorded in-line and partially off-line by five 5-channel vertical component seismic land stations, which were deployed in two deployments in seven places (I–VII) along western and northern coast of the island (Fig. 1). Examples of record sections for profiles K1, C2 and C3 are shown in the Figs. 2–4, as well as in the Figs. 5–7,
which show examples of modelling and comparison for travel times and synthetic seismograms.

In general, good quality recordings along all profiles allowed us to make a detailed study of the seismic wave field and crustal structure. First-arrival phases of refracted waves can be clearly recognized for all stations up to about 20–120 km range. The observed arrival times versus range for refracted waves show about 0.6–1.8 s scatter, due to the topography of the seabed and complicated structure of the uppermost crustal sediments. Besides the refracted waves, reflected waves from discontinuities in the crust and from the Moho were correlated, usually at ranges of 40–80 and 60–130 km, respectively. In particular, the PmP waves are characterized by high amplitudes in the distance range of 80–100 km (Fig. 7). The Pn waves refracted in the uppermost mantle and P1 waves reflected in the lower lithosphere are clearly observed up to distances of 120–300 km (see for example Figs. 2 and 5). The correlation of wave groups was based on their kinematic and dynamic properties and was made using the ZPLOT software by C. Zelt modified by P. Środa (Zelt 1994; Środa 1999).

In the present work we have used for interpretation only in-line records, from which we computed two-dimensional seismic models along profiles K1, K2, C2; in interpretation we have combined the C1 and C3 profiles in one longer profile named the C3/C1 profile. To interpret P-wave travel times and relative amplitudes we have used the ray-tracing forward modelling method, specifically the SEIS83
Fig. 3. Example of amplitude-normalized seismic record section for C2 profile, station II. Vertical component; each shot was recorded by 5-channel seismic station with distance interval between seismometers of 200 m; reduction velocity 8.0 km/s; distance from the station in km. Note good quality lower lithospheric waves (P1) recorded up to distance 300 km in reduced time 5–7 s and strong overcritical crustal waves (Pc) in the distance interval 180–280 km.

Wave fields and crustal models: results and discussion

Profile K1. — Profile K1 is 300 km long and it is oriented SEE–NWW at the latitude 78–78.5°N, crossing the Hornsund Fault and the Knipovich Ridge (Fig. 1). The shots were located along line running from the Prins Karls Forland towards the sea. They were recorded by stations III, II and IV. Example of a record section for the station II is shown in Fig. 2. First arrivals are visible up to the end of the profile. The last five traces for station III are noisy and it is difficult to separate a clear wave phase (Fig. 5). We have determined some intracrustal reflected waves but there is almost no reflection from the Moho discontinuity. The Moho refraction, Pn, is visible starting from the distance of about 60 km from stations III and II. The record
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Fig. 4. Example of amplitude-normalized seismic record section for C3 profile, station V. Vertical component; each shot was recorded by 5-channel seismic station with distance interval between seismometers of 200 m; reduction velocity 8.0 km/s; distance from the station in km. Note a complicated shape of the first arrival travel time and strong overcritical crustal waves (Pc) in the distance interval 90–190 km. PmP – Moho reflections; Pn, P1 – lower lithospheric waves.

section for the station IV is difficult to interpret because of the long distance (100 km) between the station and the closest shot point. We can see some refracted and reflected P waves from the Moho boundary but the main signal comes from deeper boundaries.

The continental crust consists of three parts (Fig. 8). We have found two sedimentary layers with P-wave velocities of 3.1 km/s and 4.8 km/s, in the western part of the continental crust where the Hornsund Fault Zone is located. To the east we have found two sedimentary structures at the surface with P-wave velocities of 4.8 km/s and 3.4 km/s. The crystalline basement with P-wave velocities of
Fig. 5. Amplitude-normalized seismic record section from K1 profile, station III (one channel only) and theoretical travel times of P waves calculated for the crustal model (in the middle). Pg – crustal waves; Pn – lower lithospheric waves; PmP – Moho reflections. Reduction velocity 8.0 km/s. The upper diagram shows the synthetic seismograms calculated for the K1 model, which should be compared with data in terms of the relative amplitudes within a trace. The bottom portion of the figure is a diagram with refracted and reflected wave rays in the model. The triangle indicates location of the seismic station.
Fig. 6. Amplitude-normalized seismic record sections from K2 and C2 profiles, stations VI and I, respectively (one channel only) and theoretical travel times of P waves calculated for the crustal model (in the middle). Pg – crustal refracted waves; Pn – lower lithospheric waves; PmP – Moho reflections; P1 – lower lithospheric waves. Reduction velocity 8.0 km/s. The upper diagram shows the synthetic seismograms calculated for the K2 and C2 models, which should be compared with data in terms of the relative amplitudes within a trace. The bottom portion of the figure is a diagram with refracted and reflected wave rays in the model. The triangles indicate location of the seismic stations.
6.2–6.5 km/s is located at the 3–20 km depths but at a distance of about 200 km it reaches the surface at station III. It is probably connected with the Prins Karls Forland. The sedimentary basin at the eastern end of the profile can be connected with the Devonian half-graben west of the Billefjorden Fault Zone (Faleide et al. 1991). The lower crust is characterized by P-wave velocities of the range of 7.1–7.2 km/s. Its thickness decreases toward the east from 15 to 0 km at a distance of 160 km. We were able to determine only one layer with average P-wave velocities of 6.6–6.8 km/s in the crust at the western part of the profile because of the lack of refracted waves in that layer. It is impossible to determine the origin of this layer. We suppose that it is mostly a continental crust. We have found some sedimentary structures above of the layer with P-wave velocities of about 3.1 km/s.

The Moho discontinuity beneath the sea is 16–18 km deep, shallowing to 12 km deep beneath the Knipovich Ridge at a distance of 100 km. The P-wave velocity below the Moho boundary is about 8.1 beneath the Knipovich Ridge and the sea and 8.1–8.2 km/s beneath the transition zone to the land, where the Moho boundary dips to a depth of 30 km. The Moho discontinuity beneath the land is at a depth of about 30 km. The P-wave velocity below it is about 8.6 km/s.

We have found a reflecting boundary below the Moho boundary beneath the sea and the transition zone to the land. It is located at a depth of 26–32 km with the P-wave velocity step from 8.2 to 8.5–8.6 km/s. In addition, we have found two reflecting boundaries in the upper mantle. Their existence and location are based on the data from station IV only (Fig. 10). They are located at depths of the range of 41–60 km and 64–66 km. The velocity field is determined from the relation between amplitudes along each trace only.

Profile K2. — The profile is 220 km long. It is parallel to the K1 profile but it is located about 150 km northward, at the north-western corner of the Spitsbergen island. The shots were recorded by three seismic land station located at the northern coast numbered from the west to the east: VI, I, VII.

First arrivals are clearly visible up to the end of the profile. We have separated travel time branches of refracted and reflected waves. The Moho or below Moho reflections are more or less visible on all record sections. The Pn wave (Moho refraction) is visible from the distance of about 80 km from station VI (Fig. 6) and it is difficult to see the refraction on the other record sections because of significantly strong reflections from deeper boundaries.

We have not found any continent-ocean transition zone along the profile (Fig. 9). The Moho discontinuity is rather flat, varying around 24 km deep. The P-wave velocity below the Moho is rather stable at about 8.05 km/s, being only at the distance 140–150 km of about 8.3 km/s. The crustal structure varies along the profile (Fig. 8). We have determined three layers in the western part of the profile to the 110th km. These are: sediments with the P-wave velocity of 3.6 km/s and the 1–2 km thickness at the 30–90 km distance of the model, the upper crust with the P-wave velocity of about 5.5 km/s extending to the depth of 5–8 km, and the lower
crust with the P-wave velocity of 6.3–6.5 km/s. There are also three layers at distances between 110 and 175-180 km. There are almost no sediments. The first significant layer is the second layer from the previous part of the model. It is 2–4 km thick with the P-wave velocity of about 5.5 km/s. The layer disappears at a distance of 170 km. The second layer is the third layer of the previous part of the model. It shallows to the east, being limited at 6 and 18 km depths in the western part and at the surface and at a depth of 10 km in the eastern part. It disappears at a distance of 175–180 km which can be connected with the Wijdefjorden. The P-wave velocities are in the range of 6.1–6.3 km/s. The lower crust is characterized by the P-wave velocity from 7.1 in the upper part to 7.3 km/s at the western lower side and 7.2 km/s at the eastern lower side. The easternmost part of the crust is composed of two layers only. The first one extends from the top of the model to a depth of 12 km in the place crossed by calculated rays and is characterized by the P-wave velocity of 4.2 km/s. The last layer is the same one as in the previously described part of the model.

We have found two boundaries in the upper mantle (Fig. 10). They are based on reflections from station I and refractions as well as reflections from station VII. The first boundary’s depth varies from 25 to 32 km and this boundary disappears at the 140–150 km distance. The P-wave velocity step is from 8.14 km/s at the western part of the model or 8.1 km/s at the eastern part to 8.3 km/s. The last boundary is a reflector only and its depth shallows to the east from 46 to 29 km.

**Profile C2.** — The profile is 320 km long. A significant part of the profile is located on the land. Shots were located along the first 130 km of the profile from NW to SE in the north of Spitsbergen. The shots were recorded by stations I and II in-line.

First arrivals are clearly visible at station I (Fig. 6) but they are more difficult to determine at station II. We have separated clear Moho reflections at the station I and one intracrustal wave at the station II.

The crustal structure in the sea part of the profile is significantly different from that in the land part. The intracrustal boundaries in the northern part (the sea part) are strongly undulated. We have found three layers in the upper crust (Fig. 8). The first one, located between 20 and 90 km of the model shallowing, from 6 km to the surface southwards. It is characterized by rather sedimentary P-wave velocity of the range of 4.8 km/s. The next layer underlays the previous one with a thickness of 3–4 km thinning, to 0.8 km at a distance of 110–130 km. It is characterized by the P-wave velocity of 6.3–6.5 km/s forming probably a consolidated basement. The third layer extends from the beginning to about 135th km of the model where it disappears. Its thickness increases southwards from 3 to 7–10 km. The lower crust exists along whole the profile with a varying thickness from 7 to 18 km. The P-wave velocity is also strongly varying from 7.3 km/s at the beginning of the model, about 7.0 km/s in the northern part and about 7.1 km/s at the southern part of the profile. The upper crust in the land part of the profile is significantly different (Fig. 9). It
consists of two layers. The first one, with the P-wave velocity of 4.9 km/s and the maximum thickness of about 9 km at a distance of 300 km is probably a sedimentary cover. The next one is likely to be a consolidated basement with the P-wave velocity of 6.1–6.2 km/s and the thickness of about 10 km. At the 270–300 km of the model an 8 km down step appears in the boundary between the upper and the lower crust.

The Moho boundary is at depths of 24–26 km in the northern part and after an abrupt step at depths of about 30–37 km in the southern part. The P-wave velocities below the Moho boundary are 8.4–8.3 km/s in the northern part and about 8.1 km/s in the central part of the profile. A low-velocity body with the P-wave velocity of about 7.9 km/s is located in the southern part of the model. The body underlays the Moho boundary in the range of 120–230 km and covers it from the 230 km to the south. We have found a reflecting boundary below the Moho discontinuity in the northern part of the model (Fig. 10). It is located at depths of 33–43 km dipping to the north. The P-wave velocity step at the reflector is about 0.15 km/s.

**Profile C3/C1.** — The profile is 400 km long. It runs northward along the coast from the latitude of the Bellsund and further to the north toward the Yermak Plateau. The shots were exploded in two groups: the northern one (C3 profile) and the southern one (C1 profile). They were recorded by seismic land stations II, V (C1 profile) and II, V (Fig. 4) and VI (C3 profile).

First arrivals are visible from all the shot points but there is some noise at station V on the C1 profile. We have found refracted and some reflected waves. Moho reflections are not clearly visible; it is rather difficult to separate them. There is almost no Moho refractions visible at the southern profile (Fig. 7). They appear on some last traces only. At the northern profile, however, Moho refractions are visible at the distance of about 50 km from the station. At the first 40 km of the profile we see a significant delay of the signal which suggests an existence of a low-velocity body in that area (Fig. 7).

The model is not well determined in the central part because of the lack of shots in that area. Fortunately, one seismic station (V) is located there, which allowed us to determine a general crustal structure. The crust is composed of four layers. The first one, 3–5 km thick, is characterized by P-wave velocities of about 4.85 km/s. The thickness of the second layer varies from 1 to 5 km and P-wave velocities are in the range of 5.5–5.6 km/s. It forms perhaps the consolidated basement. The next layer reaches to the depth of about 15 km and is characterized by P-wave velocities of 6.2–6.4 km/s. The layer exists only from the model distance of about 195th km to the south. The lower crust is characterized by P-wave velocities of 7.1–7.4 km/s. The Moho depth varies from 27 to 30 km. The P-wave velocity below the Moho boundary is about 8.3–8.4 km/s. We have found a reflecting boundary at a depth of about 52 km shallowing abruptly to the south and north with the velocity step of about 0.3 km/s.
Fig. 7. Amplitude-normalized seismic record section from C3/C1 profile, stations VI and II (one channel only) and theoretical travel times of P waves calculated for the crustal model (in the middle). Pg – crustal refracted waves; Pn – lower lithospheric waves; PmP – Moho reflections; P1, P2 – lower lithospheric waves. Reduction velocity 8.0 km/s. The upper diagram shows the synthetic seismograms calculated for the C3/C1 transect, which should be compared with data in terms of the relative amplitudes within a trace. The bottom portion of the figure is a diagram with refracted and reflected wave rays in the model. The triangles indicate location of the seismic stations.
Fig. 8. Two-dimensional velocity models of the crustal structure along profiles K1, K2, C2 and C3/C1 developed by forward raytracing. Black lines represent seismic discontinuities (boundaries) and colours represent the distribution of P-wave velocity (in km/s). Black triangles show location of stations and crossing points with other profiles (in brackets). Note that boundaries printed here are evidenced not along whole profile.
Fig. 9. Simplified sketch of the crustal structure derived along profiles K1, K2, C2 and C3/C1. Sample P-wave velocity values are posted in km/s. 1 – sedimentary cover; 2 – upper crust; 3 – lower crust; 4 – elements of seismic boundaries obtained from refracted and reflected P waves; 5 – Moho boundary. Black triangles show location of stations and crossing points with other profiles (in brackets).

The extreme parts of the profile are better determined and their structures coincide at the crossing areas with the K1 and K2 profiles (Fig. 8 and 9). The southern part of the profile (C1 profile) is characterized by three near parallel boundaries
shallowing towards the end of the profile. The first layer with a thickness of 2.5 km in the region of station II and up to 6.5 km at a distance of 335 km, thins to 3 km at the end of the profile. The P-wave velocity in this layer is about 4.8 km/s. The next boundary reaches the depth of 19 km beneath the distance of 300 km and then its depth shallows to 8 km at the southern end of the profile. The P-wave velocity of the layer is 6.3–6.5 km/s. The layer probably forms a crystalline basement. The lower crust is characterized by P-wave velocities in the range of 6.6–6.7 km/s. The Moho discontinuity depth decreases from 30 km to 15 km southward. The P-wave velocity below the Moho boundary varies respectively with the depth from 8.00 to 8.15 km/s.

The northern part of the profile (C3 profile) is more complicated. A sedimentary basin with P-wave velocity of 2.9 km/s is located in the region of the first 30 km of the profile. It is 2–5 km thick. A layer with P-wave velocities of about 5 km/s extends to a depth of 10 km and from the beginning of the profile to the distance of 120 km. A thin layer with P-wave velocity of 5.0 km/s is located at distances of 120–150 km. The next layer is characterized by P-wave velocity of 6.2–6.4 km/s and it is 4–10 km
thick at the northern part, and up to 14 km thick beneath the distances of 120–140 km. It forms the lower crust up to the 100th km of the model. Such extremely low velocities in the lower crust are surprising. From the distance of about 100 km south-
ward, the lower crust is formed by a layer with the P-wave velocity of about 7.3 km/s. The Moho boundary is located at depths of 13–16 km at the distance up to 105 with relatively low velocities of about 7.95 km/s. It steps down to the depth of 24–27 km at the 145th km of the profile with the P-wave velocity to 8.05 km/s below the Moho boundary. We have found two reflecting boundaries at depths of 25 and 35–37 km with the velocity steps of about 0.2 km/s (Fig. 10).

Conclusions

During the Polish Geophysical Expedition in 1985 it was realized measurements along a set of deep seismic profiles. This study is the first deep seismic modelling in the region of the north-western Spitsbergen. Using modern modelling methods we have been able to determine continuous two-dimensional lithospheric structure along profiles with complicated seismic velocity distribution.

In this paper we have interpreted in-line recordings and we have determined the seismic structure of the Earth down to the Moho discontinuity or even deeper in the region of north-western Spitsbergen. We have determined especially the Moho depths using well recorded refracted and reflected waves. The crustal thickness is differentiated, about 13 km (Knipovich Ridge and Yermak Plateau) to 25 km (K2 profile) beneath the sea and 24–30 km beneath the land (Fig. 11). These values agree with previous results obtained using seismic and gravimetric studies (Guterch et al. 1978; Guterch and Perchuć 1990; Sellevoll 1982; Vogt et al. 1978).

We have found some reflectors in the lower lithosphere (Fig. 10). They are determined at depths of about 30–40 km in the whole investigation area except of the vicinity of the Kongsfjorden (beneath the station V), where the depth reaches 50 km. We have found two additional deeper reflecting boundaries at depths of about 50 and 65 km along K1 profile.

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