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Seismic profiling across the Mendeleev Ridge at 82°N: evidence of continental crust

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SUMMARY

In year 2000, a ship-based expedition carried out a *ca*. 500-km-long geophysical profile ('Arctic-2000') across the Mendeleev Ridge at 82°N, from the Podvodnikov Basin to the Mendeleev Basin. A crustal-scale refraction experiment was combined with shallow reflection and complementary gravity measurements. Bottom samples were also collected.

The reflection survey provided data on the depth to the seafloor and the thickness of the sedimentary cover, the latter being divisible in some areas into three layers (I, II and III) and reaching a maximum thickness of 3.5 km in the Podvodnikov Basin. The composition of the underlying bedrock was investigated by the refraction survey, with the uppermost unit (layer IV) having a velocity Vp of 5.0–5.4 km s^{-1} and a thickness of up to 4 km, being greatest below the ridge. A sharp increase in velocity marks the boundary to the underlying, layer V rocks ($Vp = 5.9$–6.5 km s^{-1}), which are inferred to be crystalline basement, with a general thickness of 1–3 km, reaching 4 km below the axis of the ridge. Layer VI has a velocity Vp ranging downwards from 6.7 to 7.3 km s^{-1} over a thickness of 19–20 km below the arch of the ridge; this decreases to 5–16 km below the western slope towards the Podvodnikov Basin and 7–14 km beneath the eastern slope towards the Mendeleev Basin. These velocities may correspond to the composition of basic granulites. The lowermost unit above the Moho (layer VII), with a Vp of 7.4–7.8 km s^{-1}, is thought to be of mixed crust–mantle composition, perhaps the result of underpating; it has a maximum thickness of 7 km beneath the ridge and thins rapidly to east and west. The base of the crustal section is taken at the boundary with a $Vp = 7.9$–8.0 km s^{-1}, which defines the Moho. The overall thickness of the crust along the 'Arctic-2000' profile varies from a maximum of 32 km below the ridge to 13 km below the Mendeleev Basin and 20 km below the Podvodnikov Basin.

Based on bottom sampling by piston coring and dredging, the lithologies of layer IV have been inferred to be dominated by carbonate and terrigenous sedimentary rocks, with some igneous intercalations. This evidence, taken together with the identification of the immediately underlying layer V with a Vp velocity of 5.9–6.5 km s^{-1} suggests that the Mendeleev Ridge may be composed of continental material that has been substantially altered during the development of the deep Arctic Basin and associated magmatism. The gentle gradient southward across the Kucherov Terrace to the continental shelf suggests that it is an extension of the Eurasian margin and can be compared with other margins with highly attenuated continental crust.

Key words: Arctic Ocean, crustal structure, Mendeleev Ridge, reflection seismology, refraction seismology, seismograms.

1 INTRODUCTION

The Mendeleev Ridge (*ca*. 175°E–175°W and 78°–84°N) has been described to be a part of a coherent morphological province in the Arctic Basin that has been referred to as the 'Central Arctic area of Oceanic Rises' (Gramberg & Naryshkin 2000); it

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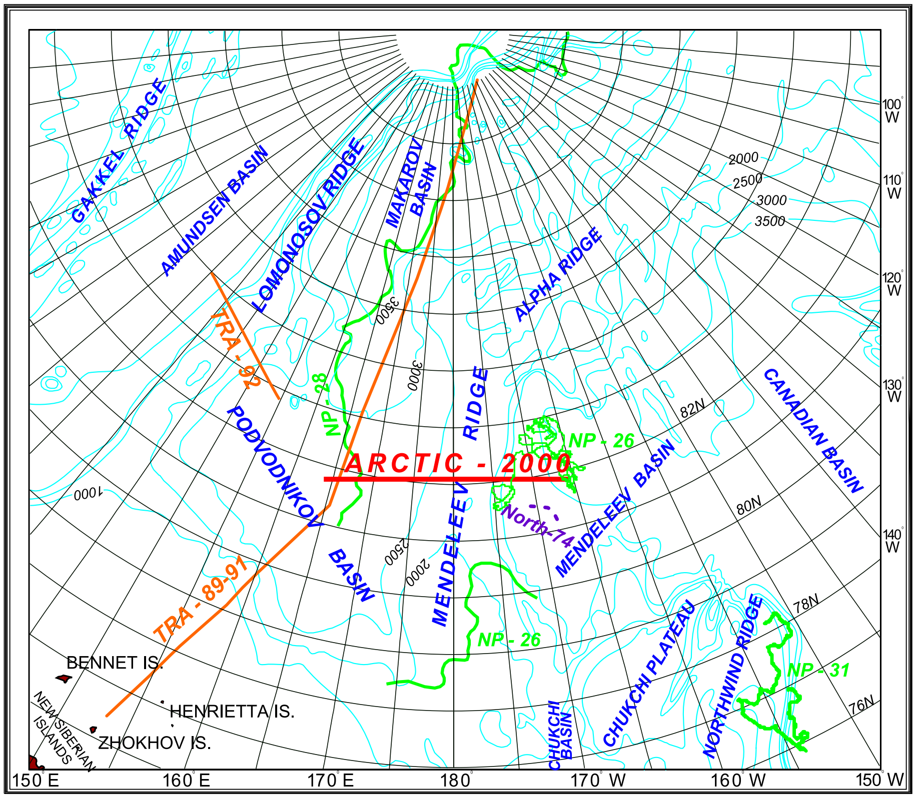

Figure 1. Location of the geotraverse 'Arctic-2000' and the other main geophysical profiles in study area. Combined DSS and reflection geotraverses: TRA-92, TRA-89-91—under the 'Transarctic' program, 'Arctic-2000'. Reflection profiles: NP-26, NP-28, NP-31 and the North-74.

lies within the vast region generally referred to as the Amerasia Basin (Jakobsson *et al.* 2003). It is connected southwards by a gentle slope across the Kucherov Terrace (IBCAO 2004) to the continental shelf of the East Siberian Sea (Fig. 1). The ridge crest dips gently northwards for a distance of *ca*. 600 km from a depth of 1000 m below sea level to 2400 m, this slope being made up of a system of subhorizontal terraces. The levels of the terraces are interrupted by small isolated rises with an amplitude of up to 600 m. At about 84°N, the Mendeleev Ridge passes northwards into the Alpha Ridge across an E–W trending trough (Gramberg & Naryshkin 2000).

The western slope of the Mendeleev Ridge dips gently into the Podvodnikov Basin. The floor of this basin is divided into two levels. The southern part of the basin is between 81°–84°N at depths of 2700–2800 m and northern part is 83°–85°N generally at 3200–3300 m; they are separated by Arlis Gap. The eastern slope of the Mendeleev Ridge is a little steeper than the western one. At southern latitudes (*ca*. 77°N) it passes into the Chukchi Basin, the floor of which is at *ca*. 2200 m below sea level, and further north (81°N) into the Mendeleev Basin, the latter with a depth increasing from south to north from 3200 to 3800 m. The floor of this basin is divisible into two parts, a southern area with an isobath of *ca*. 3200–3300 m, and a northern part at *ca*. 3700–3800 m.

The Mendeleev Ridge, along with most of the 'Central Arctic area of Oceanic Rises', is characterized by magnetic field anomalies (Fig. 2) with amplitudes of 600–1200 nT; in places up to 1500 nT. These anomalies form a complex elliptical, cellular pattern, which differs markedly from the typically oceanic magnetic field of the Eurasia Basin, characterized by long, parallel linear anomalies. The latter are oriented symmetrically on both sides of the axis of the mid-oceanic Gakkel Ridge and have normal seafloor spreading signatures (Vogt *et al.* 1979; Karasik 1980).

Geological interpretations of the magnetic field of the Central Arctic area are highly debated. Some authors (Verba & Petrova 1986; Leonov 2000) consider that the magnetic anomalies are basically similar to those of ancient continental massifs, in particular the Anabar and Canadian shields, and therefore propose that the crust may be continental. Others are inclined to explain the character of the magnetic anomalies to be the result of Mesozoic seafloor spreading and subsequent volcanic activity (Karasik *et al.* 1971; Taylor *et al.* 1981; Gurevich & Mashchenkov 2000).

With regard to the gravity field, three provinces can be distinguished in the deep-water Arctic Basin—the Eurasian, Amerasian and Canadian provinces (Verba *et al.* 2000). An absence of extensive linear elements in the gravitational field is typical of a greater part of the Amerasia province, including the Mendeleev and Alpha Ridges (Fig. 3). Positive Free Air anomalies over the Mendeleev Ridge are appreciably higher than the background of gravity lows of the deep-water basins of the Amerasia province.

Speculations about the composition, structure and origin of the Mendeleev Ridge have included a wide variety of possibilities. Most authors have regarded the Alpha and Mendeleev Ridges to be part of a related system across the high Arctic from the East Siberian Shelf to the Canadian Shelf, north of Ellesmere Island (Jakobsson *et al.* 2003). Whereas some authors (King *et al.* 1966; Johnson *et al.* 1978; Verba & Petrova 1986) have proposed that these ridges may be sunken continental shelf, like the Lomonosov Ridge, others have favoured an oceanic character (Hall 1973; Jackson *et al.* 1986; Forsyth *et al.* 1986; Jokat 2003), maybe related to the Mesozoic

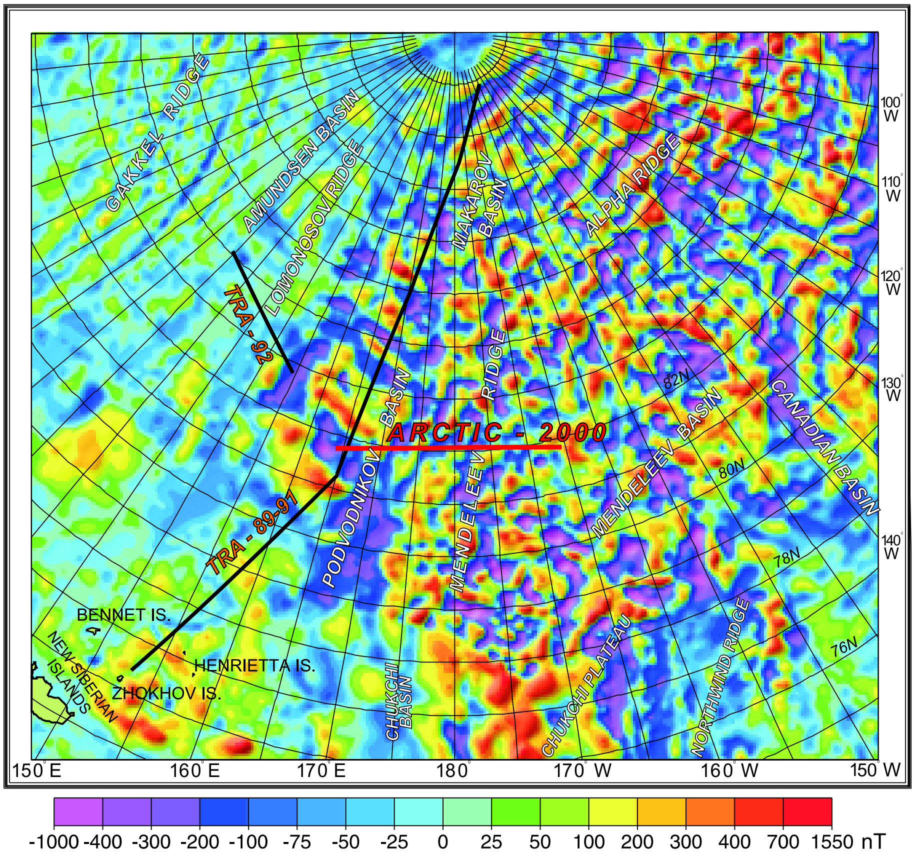

Figure 2. Map of the magnetic field anomalies (from Glebovsky *et al.* 2002). Symbols: red line—DSS profile 'Arctic-2000', black lines—DSS profiles 'Transarctic 1989–1992'.

track of a hotspot that started beneath the Siberia Plate and is now located below Iceland (Lawver & Muller 1994).

Previous Russian seismic research in the high Arctic Basin has been carried out from drifting ice islands, one in particular crossing from the Podvodnikov Plain (Sorokin *et al.* 1999) and extending northwards across the North Pole (Fig. 1) and then southwards to the Jermak Plateau. Other expeditions used fixed-wing aircraft to establish base camps on the ice, from which long reflection and refraction seismic profiles could be carried out. Fig. 1 shows the two main profiles, the one, Transarctic (TRA)-92 (Ivanova *et al.* 2002), crossing the Lomonosov Ridge, and the other TRA-89–91 (Zamansky *et al.* 1999; Lebedeva-Ivanova *et al.* 2004), reaching from the East Siberian Shelf, near the New Siberian Islands, to the North Pole. A part of this transect, over the Podvodnikov Basin, was described by Sorokin *et al.* (1999). Also shown in Fig. 1 is the ship-borne profile 'Arctic-2000', reported here.

Within the area of Fig. 1, western colleagues (see Kristoffersen 2000; Kristoffersen & Mikkelsen 2004, and references therein) have worked on the Gakkel and Lomonosov Ridges and, of particular interest for this paper, on the Alpha Ridge. In 1983, Canadians established an ice-island base above the Alpha Ridge and collected seismic data along two profiles, the one (*ca.* 200 km) along the ridge and the other (*ca.* 175 km) across it (Forsyth *et al.* 1986; Jackson *et al.* 1986). They showed that the crust was about 40 km thick, and that the uppermost sedimentary units ($Vp < 2$ km s^{-1} and less than 1 km thick) were at least in part of Late Mesozoic age. The underlying rocks (Vp *ca.* 5.1 km s^{-1}) were inferred to be basaltic in composition, similar to samples dredged off one of the Alpha Ridge scarps. The underlying velocity structure was compared to that of oceanic features such as the Iceland-Faeroe Plateau and a similar origin was postulated.

Operations from ice islands do not allow comprehensive seismic profiling; they only provide a basis for preliminary assessments of crustal structure. It was therefore decided to carry out a more comprehensive investigation of the Mendeleev Ridge, combining reflection and refraction seismic methods, potential field measurements and extensive bottom sampling. This work was carried out in year 2000 by a team of geoscientists from the Polar Marine Geological Research Expedition (PMGRE) in Lomonosov, the All-Russian Research Institute for Geology and Mineral Resources of the World Ocean (VNIIOkeangeologia) in St Petersburg and the GEON Center in Moscow. 'Arctic-2000' provides a comprehensive investigation of high Arctic crust and the first from the Mendeleev Ridge. The results have been presented briefly by Zamansky *et al.* (2002) and this paper gives a more detailed account, focusing mainly on the seismic acquisition, the velocity structure of the crust and the geological interpretations.

2 DATA ACQUISITION AND MODELLING TECHNIQUES

2.1 The 'Arctic-2000' Expedition

For the first time, in year 2000, major Russian seismic investigations of the high Arctic Basin were ship based. The 'Arctic-2000' transect was carried out by the ice-class ship 'Academician Fedorov' during a period of *ca.* 50 days (20 days on the Mendeleev profile)

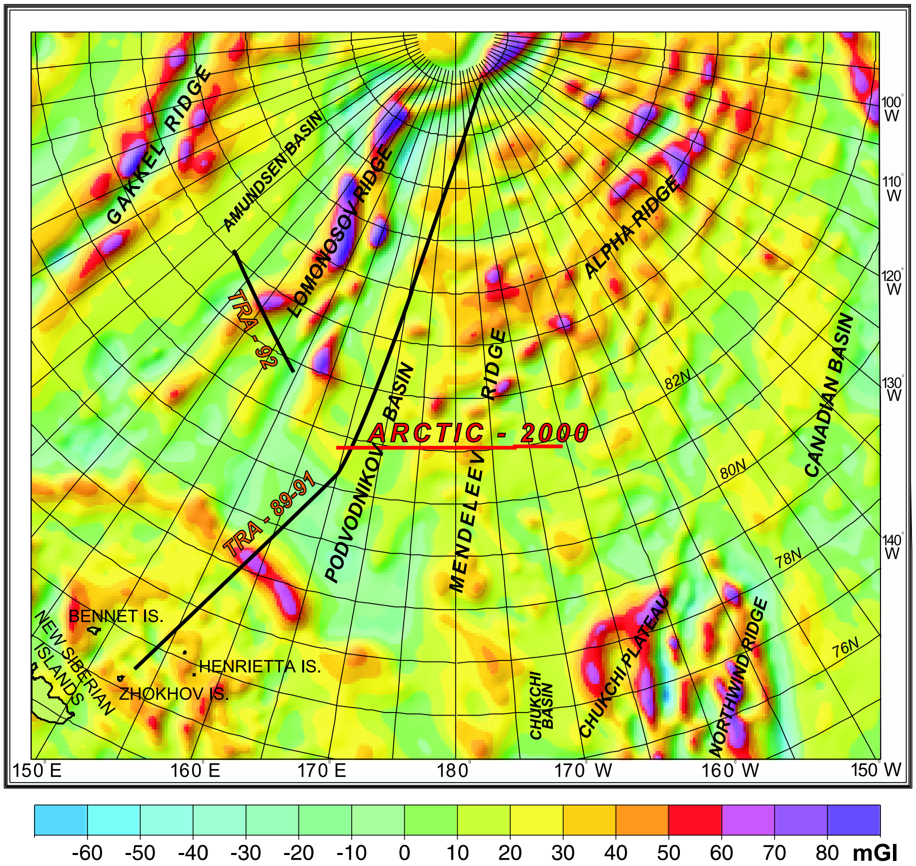

Figure 3. Map of the gravity field—Free Air anomalies (from Glebovsky *et al.* 2002). Symbols: red line—DSS profile 'Arctic-2000', black lines—DSS profiles 'Transarctic 1989–1992'.

in August–September 2000. The nuclear ice-breaker 'Russia' accompanied her from Dikson in western Taimyr (northern Siberia) to the vicinity of Bennett Island and then northeastwards, through the pack-ice, to the Mendeleev Ridge and the 'Arctic-2000' profile at 82°N; thereafter the ship operated alone. Independent operation has never been previously possible in this area by ships of 'Academician Fedorov's class.

Two MI-8 NTV helicopters were based on the 'Academician Fedorov', providing the essential transport facilities for all the geoscience. Good weather forecasting was important for the success of the operation. Previous expeditions (e.g. TRA 89–91) had always been organized in the spring (March to May) to be sure of good weather conditions. The autumn, at the end of the summer melt season was judged a better time for ship-borne operations. On the 'Arctic-2000' expedition, meteorological expertise was essential, supported by satellite data and regional information from the Arctic and Antarctic Institute (AARI) in St Petersburg.

The Mendeleev transect (Fig. 1) crosses the northern part of the ridge, from the Mendeleev Basin to the Podvodnikov Basin along an approximately W–E line from 163°57′W/81°45′N to 165°30′E/81°49′N, a distance of 485 km. Seismic acquisition (Fig. 4) included three components—a comprehensive refraction survey for the whole crust (usually referred to in the former Soviet Union, as Deep Seismic Sounding, DSS) along most of the profile, a short segment (*ca*. 120 km) for targeting the upper crust, and a simple reflection acquisition along the whole profile.

Geological studies involved bottom-sampling by piston coring (Krylov *et al.* 2004) and dredging and subsequent detailed analysis of the lithologies (Andreeva *et al.* 2004; Kaban'kov *et al.* 2004). Bathymetry was controlled by an echo-sounder on board 'Academician Fedorov' (accuracy ± 50 m).

2.2 Seismic profiling—acquisition

Deep Seismic Sounding (DSS) and shallow refraction profiles

The DSS acquisition was designed to define the velocity structure and thickness of the whole crust, from the Mendeleev Basin westwards across the Mendeleev Ridge to the Podvodnikov Basin. The experiment was carried out in three segments, each 125 km long (Fig. 4). A fourth, westernmost segment, of 32 km length, was dedicated to a shallow refraction survey and also acquired some deep crustal data.

The seismic recorders were digital, three-component 'Delta-Geon', SK-IP seismometers. They were placed out along the line by the two helicopters and the shots (seven to eight explosions with 40 km spacing and charges varying from 100 to 1000 kg) were detonated in water depths of 70–100 m.

Ice-drift velocities of up to *ca* 10 km day^{-1}, generally from south to north across the line of profile, introduced some practical problems for the recording and the retrieval of the instruments. Changing weather conditions and poor visibility often hampered the operations. The number of simultaneously installed recorders was limited primarily by the need for rapid deployment, this being necessary to ensure that the line was approximately straight. For the DSS work,

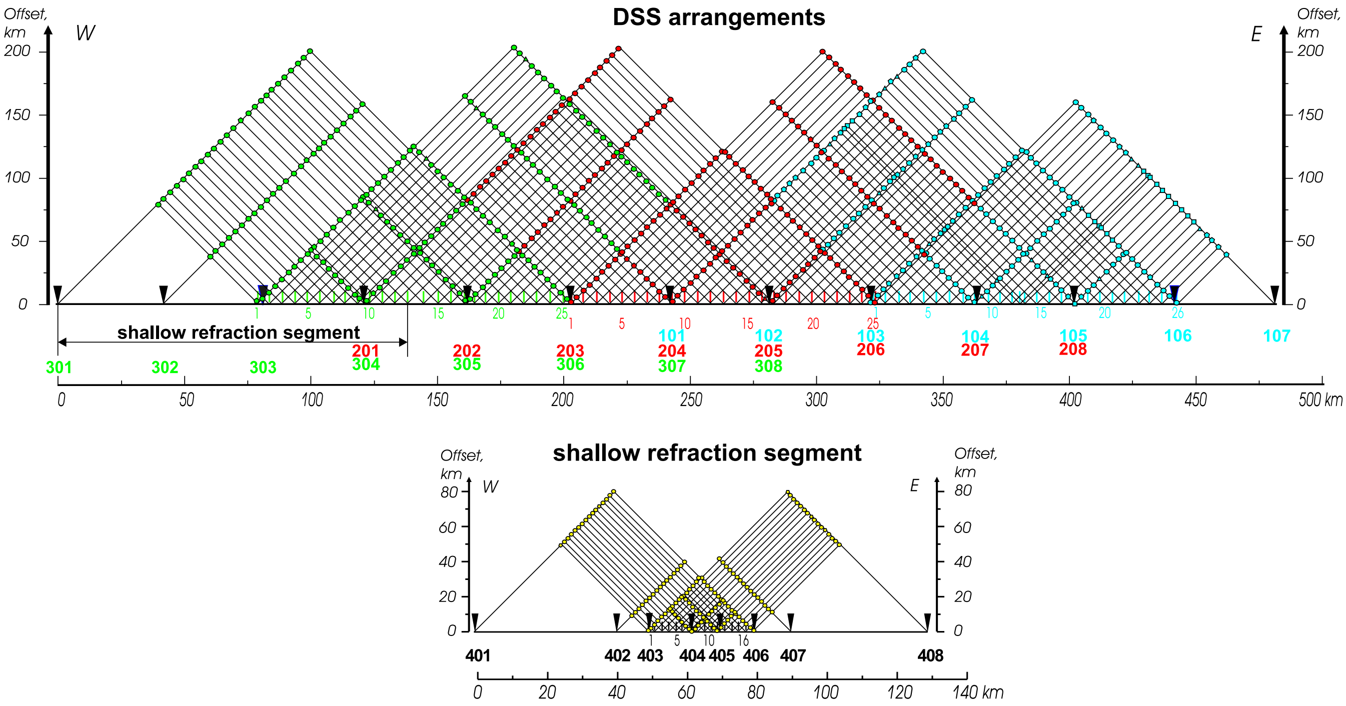

Figure 4. Acquisition configuration of the 'Arctic-2000' profile. 101–107—shotpoints (SP) of first DSS arrangement, 201–208—SP of second DSS arrangement, 301–308—SP of third DSS arrangement, 401–408—SP of shallow refraction segment (fourth arrangement); numerals 1–25 designate the number of points of registration on each arrangement.

an arrangement with 25 recorders distributed along the 125 km line at 5 km intervals during a maximum period of *ca*. 20 hr proved optimal. The position of the recorders of the time of deployment and collection and also the shot points were defined by GPS (accuracy ±100 m). After shooting (at 40 km intervals) and retrieval of the recorders, it was possible to calculate their linear approximate position at the time of detonation of the shots.

Ice conditions were on the whole favourable for the operations. The ice was sufficiently fractured to allow the Academician Fedorov to move along the line to the centre of each of the four segments. The ice thickness of 1.5–2.0 m was suitable for safe helicopter landing and deployment of the instruments. Natural cracks and patches of open water were frequent enough to allow the submergence of the explosives (TNT). Detonation was achieved with electro-detonators.

The three segments of the DSS profile, measured along the transect from east to west, were successfully achieved with the optimal number of recorders and shot points. The quality of the recordings was high, thanks to the reliability of the digital recorders with their 100 dB dynamic range. The maximum frequency of digitization was 140Hz at the time of registration of the signal, and the general working frequency was 1–30 Hz. The receivers measured accurate time by internal clocks, calibrated by GPS UTC time signals before deployment and after collection. The shot times were recorded by a receiver placed close to the shot. The receivers were active for 5 min. in each 15 min. period, and the shots were set off in these periods.

The westernmost, 125 km segment of the 'Arctic-2000' segment, over the Podvodnikov Basin, was dedicated to a shallow refraction experiment to better define the upper crust. The acquisition configuration is shown in Fig. 4, with 16 seismic recording stations being deployed at 2 km intervals along the line.

After acquisition, offsets were calculated, shot gathers were formed and archived in SEG-Y format.

Reflection Survey

Using the same equipment and the same deployment of instruments, the reflection survey was designed to acquire data on the depth to the seafloor and the structure and thickness of the sedimentary cover in the uppermost crust at each of the recording stations, i.e. at 5 km intervals along the entire transect. The measurements were single point recordings made at the time of retrieval of the DSS recorders. The energy was supplied by a 0.4 kg shot of trotyl or 3–10 electro-detonators in a water depth of 8 m; registration was limited to 15 s. The isobaths obtained by the reflection profiling were important for estimating the thickness of the uppermost sedimentary formations; they compared well with the echo-sounder records on board the 'Academician Fedorov'. It was also possible to compare these results with those obtained previously from neighbouring ice stations NP-26 and NP-28, the drifting ice base 'North-74' and 'TRA-89–91' (Fig. 1).

2.3 Processing of seismic data

The reflection data were processed using a commercial software package (ProMax). Processing steps were:

(i) input geometry for each trace;
(ii) minimum phase predictive deconvolution, using a prediction interval of 8 ms and operator length of 200 ms;
(iii) band-pass filter of 15–18 Hz to 50–55 Hz.

DSS seismic data were analysed by using shot gathers. Spectral analysis of the DSS data has shown that the maximum energy of a useful signal falls within a frequency band from 1–3 Hz to 8–10 Hz.

2.4 Modelling procedure and errors

The modelling was made in two steps: firstly the sedimentary cover was constructed using the reflection profile (Fig. 5a); thereafter, forward modelling of layers with velocities greater then 5 km s^{-1} were based on shallow refraction and DSS data, using the sedimentary velocities and boundaries from the first step.

Analysis of the apparent velocities and interpretation of DSS data were made generally using the first arrivals of P waves; refracted and reflected waves of second arrivals were used for interpretation, if their identification was clear. The interactive package SeisWide, provided by Dr. Deping Chian (Bedford Oceanography Institute, Canada), constructed on the basis of a software package by Zelt & Smith (1992), was used for the interpretation. Theoretical and recorded travel-time curves correlate to within RMS 0.1 s. Examples of the interpretation are shown in Figs 6–8 (for all seismograms, see Appendices 1–4).

The accuracy of modelling (velocities and depths) depends on the measuring accuracy (mainly the position of shot points) and on the complexity of the model (dip of boundaries, heterogeneity of the crust and so on). The velocities of the sedimentary cover have been defined with an accuracy of *ca.* 7 per cent; velocities greater then 5 km s^{-1} were defined with an accuracy of *ca.* 0.1 km s^{-1}.

3 RESULTS AND INTERPRETATION

Interpretation of the reflection seismic data was based on the experience of previous work (Langinen *et al.*, in preparation) on the NP-26, NP-28, TRA-89–91 and North-74 profiles (Fig. 1), where the velocities of the sedimentary units were defined. The reflection profile 'Arctic-2000' is crossed by the profiles NP-28 and NP-26 at the points specified in Fig. 5a. Comparable reflectors are present both on the 'Arctic-2000' section and on these profiles (e.g. Fig. 5b).

Time and depth reflection sections were constructed along the DSS profile over a length of 441 km (Figs 5a and 9). Picking of reflectors and their lateral correlation has been difficult due to the long spacing between the traces and the design of the seismic-stations for refraction acquisition. However, it has been possible to construct a seismogeological section along the reflection profile, showing the structure of the sedimentary cover (Fig. 9). On the section, it is possible to trace four reflecting horizons d, d_1, A, A_{F}, that is, approximately from the seafloor surface down to the acoustic basement. Horizon F is traced only locally; probably, it corresponds to the top of the crystalline basement. The sedimentary cover reaches a maximum thickness (3.5 km) on western slope of the Mendeleev Ridge, in the transition zone to the Podvodnikov Basin, and decreases to a minimum on the eastern slope, in the transition to the Mendeleev Basin (2.5–3.0 km). A satisfactory estimation of the thickness of the sedimentary cover is not possible on the arch of the ridge because of difficulties in defining discontinuity F.

A variety of horizons were traced in the 'Arctic-2000' geotraverse section (Fig. 10), these being constructed from the reflection, shallow refraction and DSS data. The units with different seismic velocities include seismic sequences in the sedimentary cover and layering within the consolidated crust. From the top downwards, the following seismic units can be defined:

Layer I ($Vp = 1.7$ km s^{-1}) lies between the reflecting horizons 'd' (the seabed) and 'd_1'. This sedimentary layer is 0.1–0.15 km thick in the lower parts of the slopes, adjacent to the highest parts of the Mendeleev Ridge. Further from the ridge, towards the Podvodnikov and Mendeleev Basins, the thickness increases to about 0.7 km.

Layer II ($Vp = 2.3$–2.6 km s^{-1}) occurs between 'd_1' and 'A' (Fig. 10). Based on the reflection data of the NP-28 and 'TRA-89–91' profiles, it can be divided into two sequences: an upper unit IIa ($Vp = 2.3$ km s^{-1}) between 'd_1' and 'd_2' and lower unit IIb ($Vp = 2.6$ km s^{-1}) between 'd_2' and 'A'. It is probably composed of poorly lithified siliciclastic deposits. The thickness changes from zero on the slopes of the Mendeleev Ridge structural high, mentioned above, to up to 1.7 km in the lower part of the western slope of the ridge. It should also be noted that layer II is appreciably thicker on the western slope of the Mendeleev Ridge than on the eastern side. Horizon A (the base of layer II) is marked by the most clearly defined and extensive reflector; it can be traced practically everywhere in the western part of the Amerasia Basin. It is seen especially clearly in reflection data along the 'NP-28' profile (Fig. 1), where it was interpreted (Butsenko 2001) to mark the base of the Late Oligocene, a time when a sharp drop in sea level has been inferred to have occurred worldwide.

Layer III ($Vp = 3.2$–3.6 km s^{-1}) is interpreted to be a lower, essentially lithified part of the siliciclastic sedimentary section, occurring between horizon A and the top (horizon A_{F}) of the underlying layer IV. The maximum thickness (1.2–1.6 km) of layer III occurs beneath the arch of the Mendeleev Ridge and the lower part of the western slope, towards the Podvodnikov Basin, and the minimum thickness (0.2–0.3 km) is developed in the lower part of the eastern slope of the ridge.

Layer IV extends downwards from the base of the layer III (horizon A_{F}) to K_1 (F) and has a velocity $Vp = 5.0$–5.4 km s^{-1} (up to 5.7 km s^{-1} locally beneath the Podvodnikov Basin). This unit has a thickness of 3.6–4.0 km beneath the Mendeleev Arch and thins both to east and west, for example, to 0.5–0.8 km on the western slope of the ridge. The Vp velocities of layer IV indicate that the density of this unit ranges from 2.62 to 2.71 g m^{-3}. Interpretation of the composition of crustal units with a Vp velocity of *ca.* 5.0 km s^{-1} in oceanic environments is controversial. They may be composed of relatively high-velocity sedimentary rocks (e.g. carbonates); alternatively, basalts of layer 2 of the ocean crust may also have this velocity, if suitably fractured and altered.

Layer V, with a velocity $Vp = 5.9$–6.5 km s^{-1} underlies horizon K_1 (F) and extends down to K_2; it is inferred to compose the upper part of the crystalline crust. The thickness of this unit varies between 1 and 3 km on the slopes of the Mendeleev Ridge, and is up to 4 km thick in the central part. This velocity corresponds to a granitic–granodioritic composition, but the unit could also be composed of other magmatic rocks of somewhat more mafic composition (Christensen & Mooney 1995).

The lowest part of the crust (*layer VI*) between boundaries K_2 and K_{M} has a velocity $Vp = 6.7$–7.3 km s^{-1}. The thickness of this layer varies from 19 to 21 km below the arch of the Mendeleev Ridge to 5–16 km beneath the western slope of the ridge and the Podvodnikov Basin and 7–14 km beneath the eastern slope. The velocity Vp of layer VI corresponds to the composition of basic granulite (Egorov *et al.* 1994), but other compositions, such as gabbro, are possible (Christensen & Mooney 1995).

Layer VI passes down transitionally into *layer VII* ($Vp = 7.4$–7.8 km s^{-1}) between horizons K_{M} and M and is interpreted to be a crust–mantle 'mixed layer', perhaps the result of underplating. Its thickness is up to 5 km on the western slope of the ridge, up to 7 km on the arch and up to 3 km on the eastern slope. The base of the crustal section is taken at the M discontinuity ($V = 7.9$–8.0 km s^{-1}).

The overall thickness of the crust undergoes appreciable fluctuations within the limits of the 'Arctic-2000' profile, with a maximum thickness of 32 km beneath the arch of the Mendeleev Ridge,

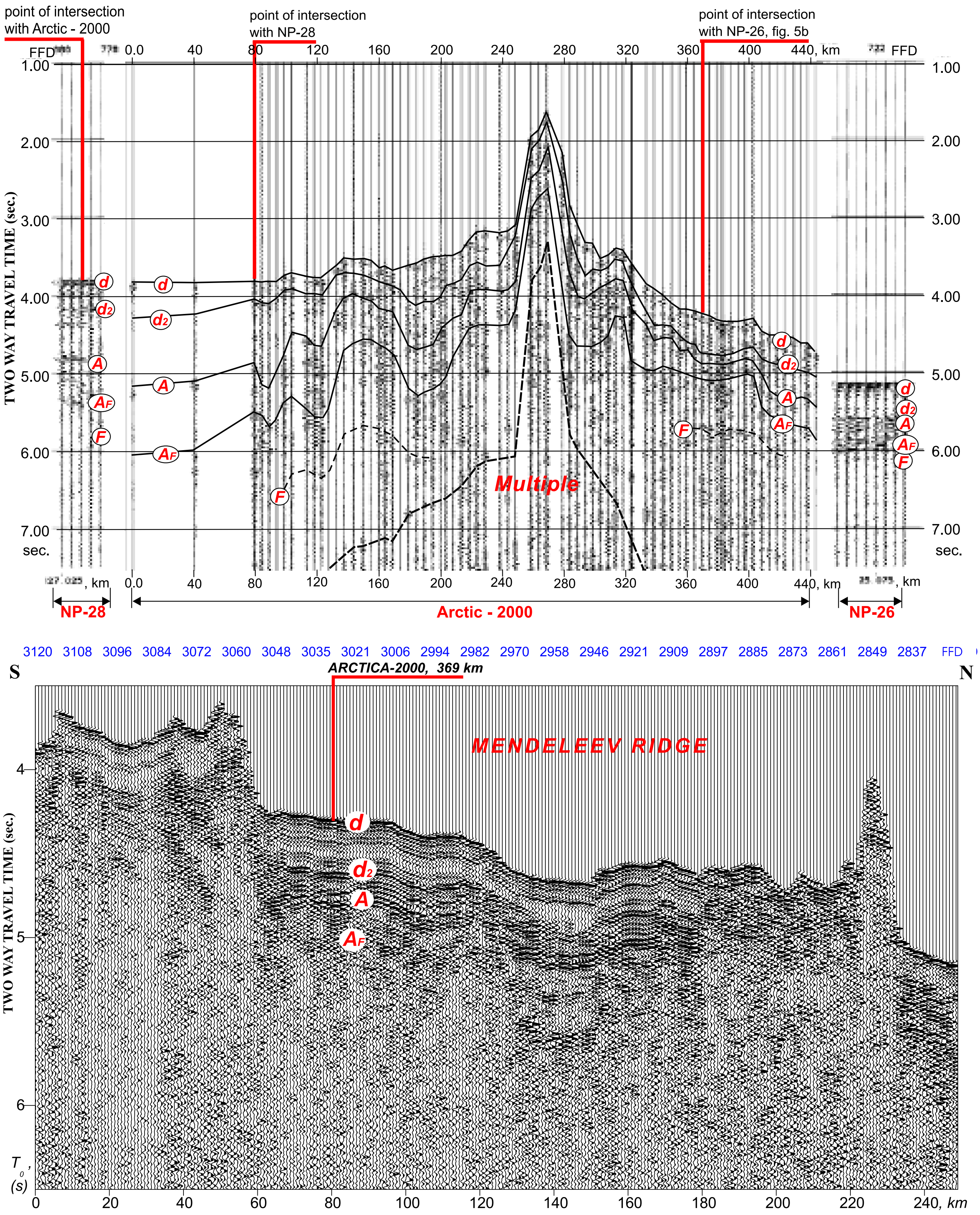

Figure 5. (a) Time reflection section 'Arctic-2000' and fragments of the NP-28 and NP-26 reflection cross-sections (for location, see Fig. 1). Letters refer to the inferred surfaces of the main reflection boundaries within the sedimentary cover. (b) Time section along the NP-26 profile (1985) (location shown in Fig. 1).

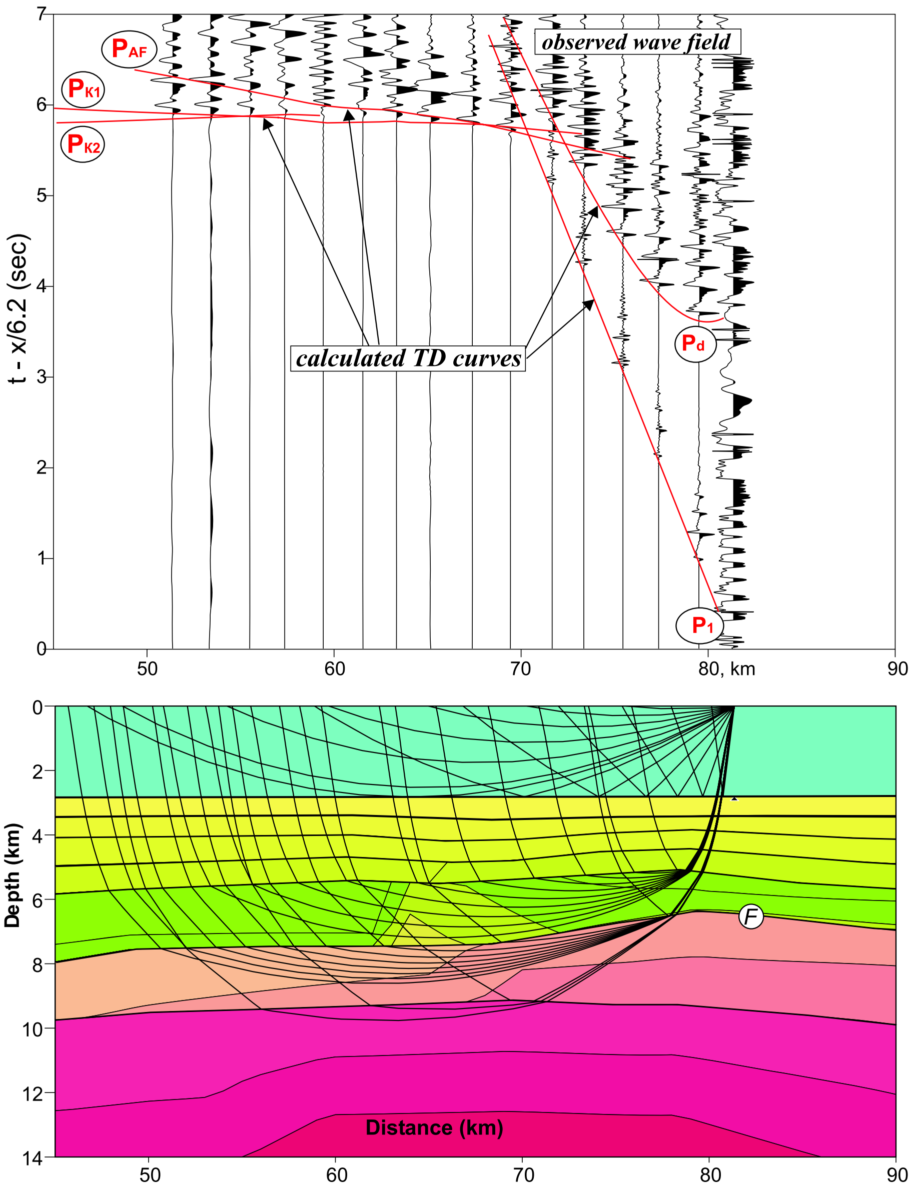

Figure 6. Observed data and ray tracing diagram for SP 406 from the shallow refraction segment. P_1—direct wave; P_d—reflected wave from the surface of the seafloor; P_{AF}—diving wave is related to sediments above boundary F on reflection data; P_{K1}—diving wave in upper crust, interpreted to be crystalline basement (boundary F on reflection data); P_{K2}—diving wave in lower crust, interpreted to be basaltic. Thick lines show seismic boundaries; thin lines are velocity isolines through 0.2 km s^{-1}; values of seismic velocity are given on Fig. 10. F—crystalline basement, M—Moho.

decreasing eastwards to 13 km beneath the Mendeleev Basin and westwards to 20 km beneath the Podvodnikov Basin.

4 DISCUSSION

4.1 Potential field data

Potential field data (Figs 2 and 3) provide additional evidence on the character of the Mendeleev Ridge and adjacent basins. The striking differences between the relatively simple features of the Eurasia Basin and the complexity of the Amerasia Basin are obvious. The typical oceanic linear magnetic anomalies of the Eurasia Basin, arranged symmetrically parallel to the Gakkel Ridge, are absent in the Amerasia Basin, either because they never existed or because they are obscured by younger processes. In the Canada Basin, there is substantial evidence for Mesozoic seafloor spreading (Taylor *et al.* 1981; Kovacs *et al.* 1985; Gurevich & Mashchenkov 2000).

The magnetic anomalies over the region around the Mendeleev Ridge (Fig. 10) have been shown by Leonov (2000) to correlate well with the bathymetry. Local elevations of the sea bottom correspond with maxima in the magnetic field and depressions with minima. This character may result from variations in the relief of the magnetic basement or to basaltic volcanism; perhaps both. Comparison has been made with a similar interrelationship of the AMF with bathymetry on the East Siberian platform, where the anomalies correlate with trap magmatism (Provodnikov 1975).

Gravimetric data acquired along the Mendeleev transect are shown in Fig. 10—both Free Air and Bouguer anomalies. The acquired gravimetric data were used as an independent, additional control in construction of the seismic section of the Earth's crust

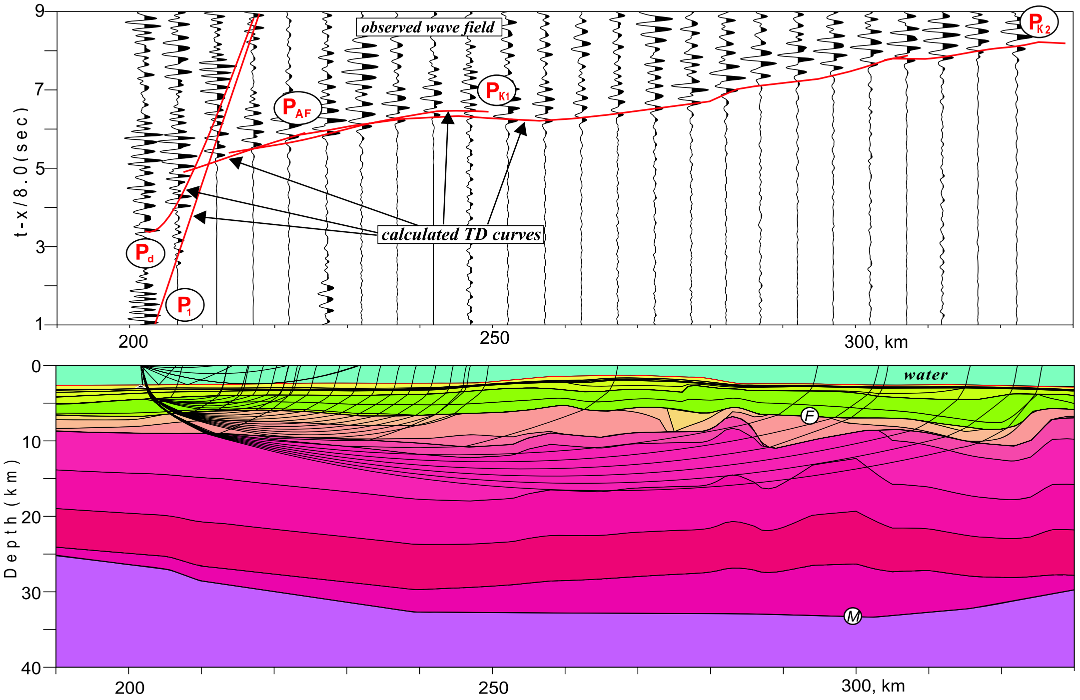

Figure 7. Observed data and ray tracing diagram for SP 203 from the Arrangement 2. P_1—direct wave; P_d—the reflected wave from the surface of the seafloor; P_{AF}—diving wave is sediments above boundary F on reflection data; P_{K1}—diving wave in upper crust, interpreted to be crystalline basement (boundary F on reflection data); P_{K2}—diving wave in lower crust, interpreted to be basaltic; P_n—diving wave upper mantle (M). Thick lines show seismic boundaries on the model of the Earth's crust; thin lines are velocity isolines through 0.2 km s^{-1}; the dotted line is the inferred boundary on the roof of crust–mantle mixed layer. Values of seismic velocity are given on Fig. 10. F—crystalline basement, M—Moho.

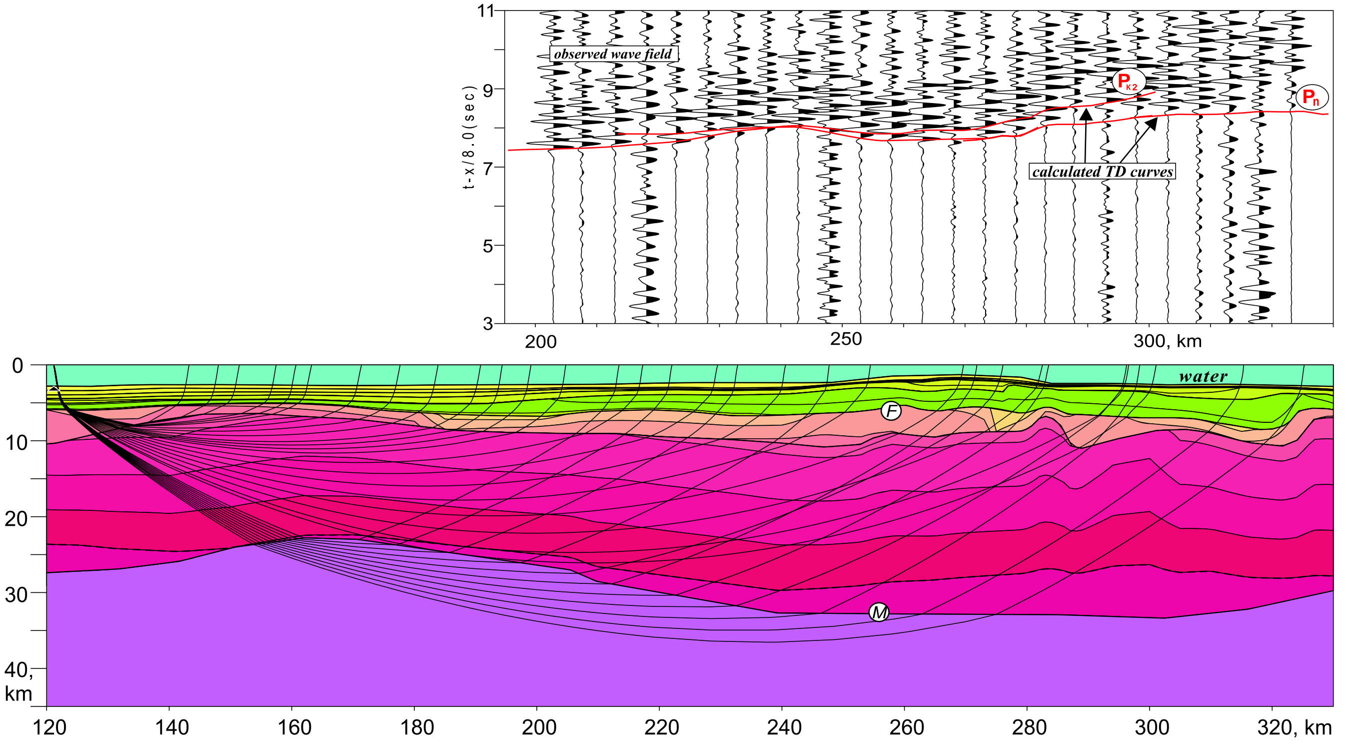

Figure 8. Observed data and ray tracing diagram for SP 201 from the Arrangement 2. P_{K2}—diving wave in lower crust, interpreted to be basaltic; Pn—diving wave upper mantle (M). Thick lines show seismic boundaries on model of the Earth's crust; thin lines are velocity isolines through 0.2 km s^{-1}; the dotted line is the inferred boundary on the roof of crust–mantle mixed layer. Values of seismic velocity are given on Fig. 10. F—crystalline basement, M—Moho.

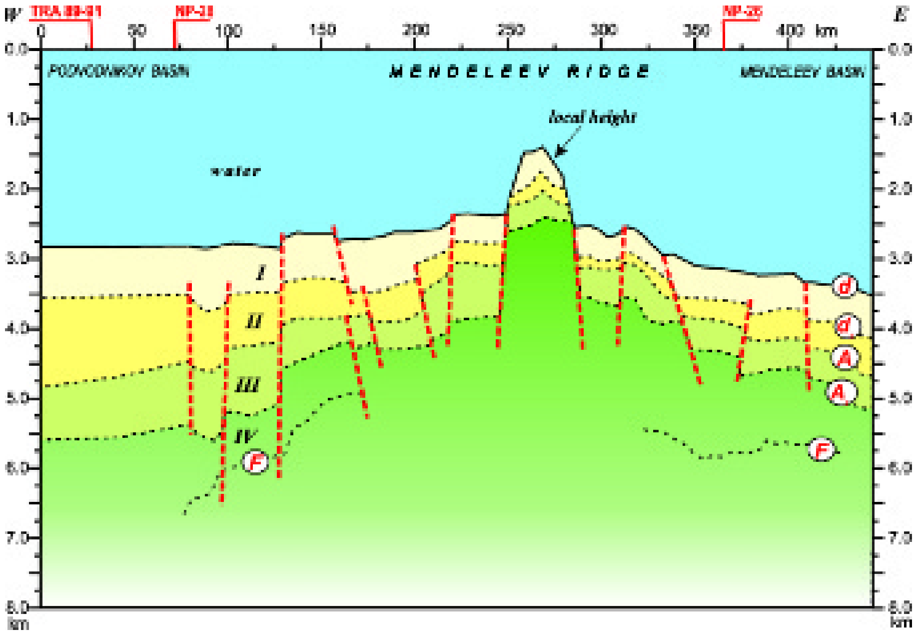

Figure 9. Preliminary geological interpretation of the 'Arctic-2000' reflection profile, based on Fig. 5(a). Letters are assigned to the basic boundaries between sequences I–IV; black dashed lines are interpreted reflectors; red dashed lines are inferred faults.

along the 'Arctic-2000' profile. Both the gravimetric curves and the Free Air and Bouguer ($\sigma = 2$, $3\,\mathrm{g\,cm^{-3}}$) anomalies are given on Fig. 10 for comparison with the seismic section, the latter providing support for the thicker crustal section below the ridge.

4.2 Composition of the Mendeleev Ridge

The velocity structure of the Mendeleev Ridge, presented above, is based on the most modern wide-angle seismic survey that has been carried out in the high Arctic Basin. The character of the sedimentary cover and crystalline basement beneath the Mendeleev Ridge are not uniquely defined by the geophysical data. A crustal structure has been proposed and the composition of some of the different layers is discussed further below.

Beneath the sedimentary layers I–III of the Mendeleev profile, from the soft sediments on the seafloor ($Vp = 1.7$ km s^{-1}) to the more lithified sediments (*ca*. 3.6 km s^{-1}) at depths of up to 4 km, the unit IV (velocity $Vp = 5.0$–5.4 km s^{-1}) is of uncertain composition; it may be of sedimentary (e.g. carbonates) or igneous (e.g. altered basalts) origin; possibly both. One line of independent evidence favours the interpretation that layer IV is dominantly of sedimentary origin, probably with some mafic igneous intercalations, being based on the composition of rock samples collected by piston coring (Krylov *et al.* 2003) and dredging along the line of the 'Arctic-2000' profile (Kaban'kov *et al.* 2001; Andreeva *et al.* 2004; Kaban'kov *et al.* 2004). The density of 23 limestone and dolomite samples collected along the profile ranges from 2.52 to 2.87 g m^{-3}, this variation being due to the presence of siliciclastic material in some of the samples. All the bottom samples that have yielded macro and microfossils are composed of limestone and were collected on the arch of the Mendeleev Ridge. Samples with conodonts and fishes of Devonian age have been found at approximately one hypsometric level (isobath 2200 m), along the base of the structural high. A sample with early Permian foraminifera was found near the crest of the ridge, and samples with Middle Carboniferous fossils occupy intermediate positions (Andreeva *et al.* 2004; Kaban'kov *et al.* 2004). This concentration of mid-Late Palaeozoic samples on the crest and flanks of the ridge favours a local source; it testifies against a derivation (e.g. by ice transport) from a distant source on the continental shelf to the south. However, it should be noted that the reflection seismic profiling (Figs 5 and 9) provides evidence that, if layer IV outcrops on the sea bottom, it does so only near to fault scarps at the crest of the ridge.

Carbonate-dominated samples dredged from the sea bottom elsewhere in the Ameresian Basin have been considered by previous authors (Phillips & Grantz 2001) to be derived by Beaufort Gyre ice transport from the continental shelf of northern Canada and Alaska. This interpretation for the samples of the Mendeleev Ridge, referred to above, appears to be less likely in view of the evidence (Kaban'kov *et al.* 2004) favouring a local source, particularly the stratigraphic order of the samples on the ridge.

Interpretation of the geological nature of layer V (velocity of $Vp = 5.9$–6.5 km s^{-1}) on the 'Arctic-2000' profile is based on evidence from the 'TRA-89–91' submeridional geotraverse (Zamansky *et al.* 1999). The latter reaches from the continental shelf near the New Siberian Islands nearly to the North Pole and crosses the 'Arctic-2000' profile in the Podvodnikov Basin (Fig. 1), close to the picket at 25 km (Fig. 10). On the 'TRA-89–91' geotraverse, layer V has a similar velocity ($Vp = 5.8$–6.3 km s^{-1}). The latter is typically developed below the shelf, and rocks with this velocity (e.g. granites) outcrop on Henrietta Island (Vinogradov *et al.* 1975). Along the 'TRA-89–91' this 'granitic basement' layer thins rapidly and is truncated at the edge of the continental shelf, but is inferred to persist northwards beneath the Podvodnikov Basin with a thickness similar to layer V in the Mendeleev transect. Therefore, this up to 4-km-thick layer is considered to be probably of granitic–granodioritic composition.

4.3 Comparison with other ocean features

In Fig. 11, the velocity structure of the Mendeleev Ridge is compared with that of other high Arctic Ridges and contrasted with that

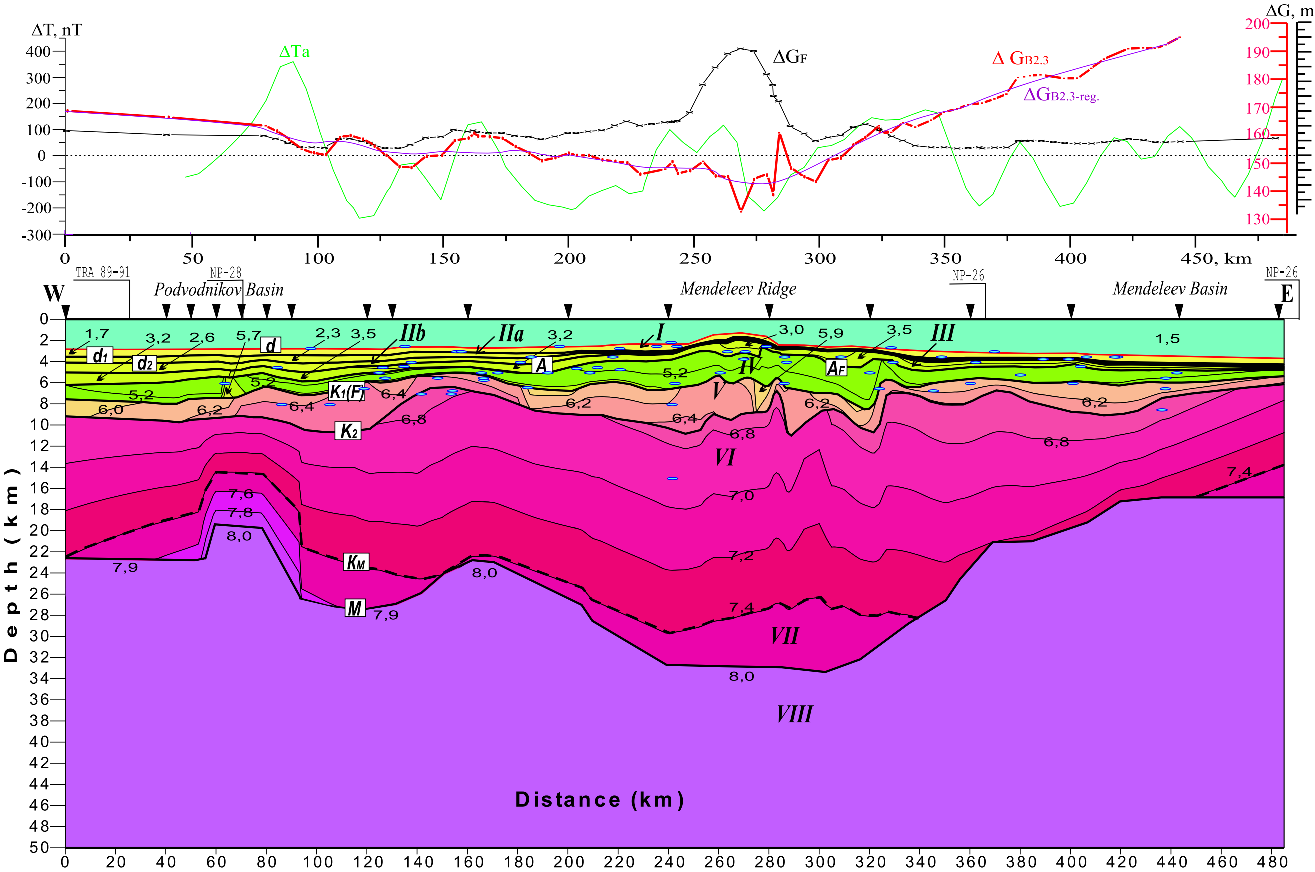

Figure 10. Potential fields and seismic model of the crust along the 'Arctic-2000' geotraverse. Concerning the potential field profiles: ΔG_{F}—Free Air anomalies; $\Delta G_{\mathrm{B2.3}}$—Bouguer anomalies ($\sigma = 2.3$ g cm^{-3}); $\Delta G_{\mathrm{B2.3-reg}}$—regional Bouguer anomalies; ΔTa—magnetic anomalies. Concerning the model of the crust: thick lines show seismic boundaries; thin lines are velocity isolines through 0.2 km s^{-1}; the dotted line is the inferred upper boundary of the crust–mantle mixed layer. Roman numerals mark the seismic sequences of the sedimentary cover and layers of the consolidated crust; letters mark the seismic boundaries; triangles show the locations of explosions. Cover sedimentary sequences, allocated the following velocities on the crustal model: I, IIa, IIb ($V = 1.7$–2.6 km s^{-1}), are friable and weakly lithified deposits. Layers III ($V = 3.0$–3.5 km s^{-1}) and IV ($V = 5.0$–5.7 km s^{-1}) are lithified deposits with various degrees of consolidation. Crystalline layers: V ($V = 5.9$–6.5 km s^{-1})—the upper crust; VI ($V = 6.7$–7.3 km s^{-1})—the lower crust; VII ($V = 7.4$–7.9 km s^{-1})—the crust–mantle mixed layer; VIII ($V = 7.9$–8.0 km s^{-1})—the upper mantle.

of the deeper basins. The Lomonosov Ridge has been inferred to be of continental character (Sweeney *et al.* 1982; Jokat *et al.* 1992; Ustritskiy 1990) and data from the TRA-92 transect (Ivanova *et al.* 2002) supports this interpretation. The Lomonosov crust is *ca.* 26–28 km thick and the section beneath a thin (less than *ca.* 2 km) veneer of little consolidated sediments is dominated by three layers. The uppermost of these, with a velocity (*Vp*) of *ca.* 5.0 km s^{-1}, is about 5–6 km thick and has been shown by reflection seismic profiling to be layered and gently dipping (Kristoffersen 2000) and of probable Mesozoic (Grantz *et al.* 2001) or Palaeozoic age. The middle layer ($Vp = 6.0$–6.4 km s^{-1}) is up to 10 km thick and probably crystalline 'granitic' crust similar to that beneath most continental shelves, and the lowermost unit, *ca.* 12 km thick, has a velocity of *ca.* 7.0–7.3 km s^{-1}, contrasting strongly with the underlying mantle (*ca.* 8.0 km s^{-1}). Although the crust below the Mendeleev Ridge is similar in thickness to that below the Lomonosov Ridge, the lowermost layers (*Vp ca.* 6.7–7.3 km s^{-1}) above the crust–mantle transition (mixed layer, perhaps underpating) are nearly twice as thick. The overlying upper crustal units are comparable in velocity to those beneath the Lomonosov Ridge, but correspondingly thinner.

Comparison of the Mendeleev and Alpha Ridges is more difficult, partly perhaps because of differences in the data acquisition (drifting ice-island operations over the Alpha Ridge) and processing. Below the Alpha Ridge, the uppermost poorly consolidated sedimentary cover and underlying bedrock layer (*Vp ca.* 5.1 km s^{-1}) are similar in thickness to those on the Mendeleev Ridge. Bottom sampling has indicated that the latter is, at least partly, of basaltic composition on the Alpha Ridge. An underlying more felsic crystalline layer has not been reported beneath the Alpha Ridge (though a thin unit with this velocity may be present), but a nearly 15-km-thick layer with a velocity of *ca.* 6.4 km s^{-1} has been identified, itself underlain by a further 12–15 km of higher velocity crust (*Vp ca.* 7.3 km s^{-1}). These thick lower units imply that the total thickness of the Alpha Ridge unit is 10–12 km greater than that below the Mendeleev Ridge. The thick, higher-velocity crust below the Alpha Ridge, along with the basalts collected by dredging, have led to the conclusion (Forsyth *et al.* 1986; Jackson *et al.* 1986) that the Alpha Ridge is an oceanic plateau of uncertain ('problematic') origin. They preferred the interpretation that the ridge developed over a mantle plume.

Magnetic anomalies (Glebovsky *et al.* 2002; Leonov 2000), related to the mafic rocks, indicate that the Alpha Ridge magmatism extended to the south over the Canadian Shelf and perhaps also eastwards to the Lomonosov Ridge. This evidence was suggested by Leonov (2000) to indicate that the Alpha Ridge crustal

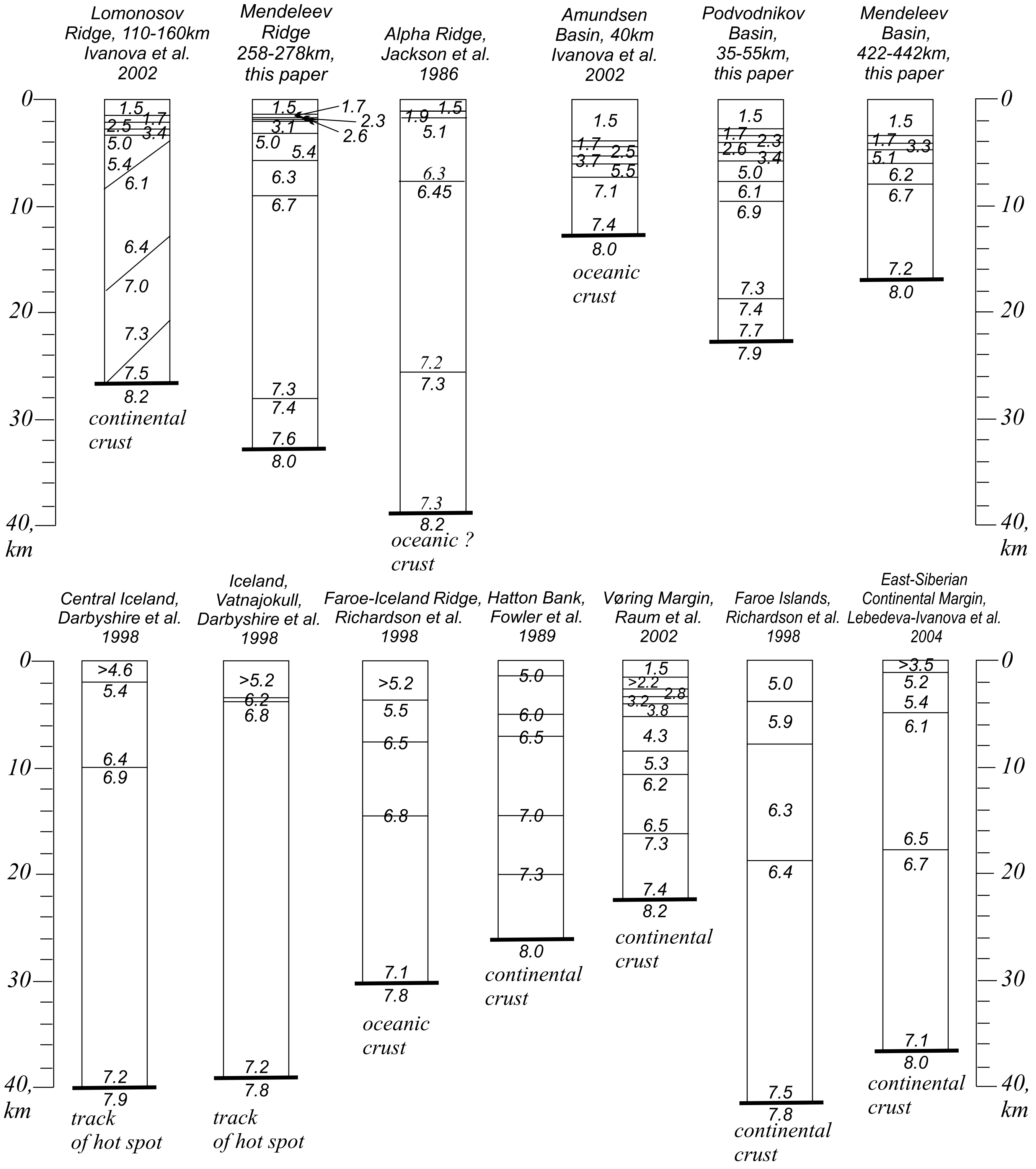

Figure 11. The velocity structure of the Mendeleev Ridge is compared with other Arctic structures.

structure is composite, being composed of both a continental crust and a Large Igneous Province. This interpretation is also possible for the Mendeleev Ridge, if the upper continental layer ($Vp = ca$ 5.0. km s^{-1}) is dominated by basalts and not mainly composed of Palaeozoic limestones and dolomites, as proposed by Kaban'kov *et al.* (2001), Andreeva *et al.* (2004) and Kaban'kov *et al.* (2004).

The crustal structure of the Mendeleev Ridge contrasts strongly with that of some of the deeper basinal areas, particularly the Amundsen Basin, which has typical 12-km-thick oceanic crust (Fig. 11). The Mendeleev and Podvodnikov Basins both have nearly twice as thick crust as the Amundsen Basin and there appears to be a gradual transition between these basins and the Mendeleev Ridge, with each of the layers increasing in thickness towards the arch of the ridge. This evidence, suggests that they are not of normal oceanic character, but may be composed of transitional crust, with some continental components. However, other interpretations are possible, as noted above for the Alpha Ridge.

Comparisons can be made with the continental structure of other ocean ridges and some thinned continental margins e.g. the Faroe-Iceland Ridge (Richardson *et al.* 1998), Galicia Bank (Pérez-Gussinyé *et al.* 2003) and the Vøring Margin (Raum *et al.* 2002). In the case of the the Vøring Plateau, where seaward-dipping reflectors show that basalts dominate in the upper sedimentary successions and crystalline continental crust is only *ca*. 5–10 km thick, there are interesting similarities with the Mendeleev structure. Mesozoic extension of the high Arctic Lomonosov margin (prior to opening of the Eurasian Basin) could have resulted in the development of highly extended fragments of continental crust in the Arctic Basin, similar to those along the margins of the North Atlantic.

5 CONCLUSIONS

The 'Arctic-2000' transect across the Mendeleev Ridge at 82°N in the Amerasia Basin, has shown that the crust is up to *ca*. 32 km thick, and that it thins to the west (20 km) and east (13 km) under the Podvodnikov and Mendeleev Basins, respectively. The Mendeleev Ridge is composed of sediments in the uppermost part (units I–III) that are 3.5 km thick and range in velocity, Vp. from 1.7 to 3.6 km s^{-1}. The underlying basement is divisible into three main layers, an upper one (*ca*. 4 km) with a Vp velocity of 5.0–5.4 km s^{-1} (unit IV), a middle one (*ca*. 4 km) with 5.9–6.4 km s^{-1} Vp velocity (unit V) and a lower one (*ca*. 19–20 km) ranging in Vp velocity from 6.7 to 7.3 km s^{-1} (layer VI). Separating these from the mantle (Vp velocity 7.9–8.0 km s^{-1}), is a layer (up to 7 km thick) of 'mixed' crust–mantle composition (unit VII) with Vp from 7.4 to 7.8 km s^{-1}, which may be the result of underplating.

The velocity structure of the Mendeleev Ridge is consistent with that of thinned underplated continental crust or of thickened oceanic crust. Other continental margins, characterized by highly attenuated continental crust, such as the Vøring Plateau or Galicia Bank, have velocity structures comparable to that beneath the Mendeleev Ridge.

Dredging and piston coring of the sediments on the crest and flanks of the ridge has shown the presence of sedimentary clasts (mainly Palaeozoic carbonates) that are thought to be derived locally. This evidence indicates that layer IV may be made up of Palaeozoic platform sedimentary rocks. The underlying layer V would, therefore, probably be of felsic composition. These lines of evidence, together with the bathymetry indicating a connection between the ridge and the continental shelf via the Kucherov Terrace, favour the conclusion that the Mendeleev Ridge is composed, at least in part, of attenuated underplated continental crust.

ACKNOWLEDGMENTS

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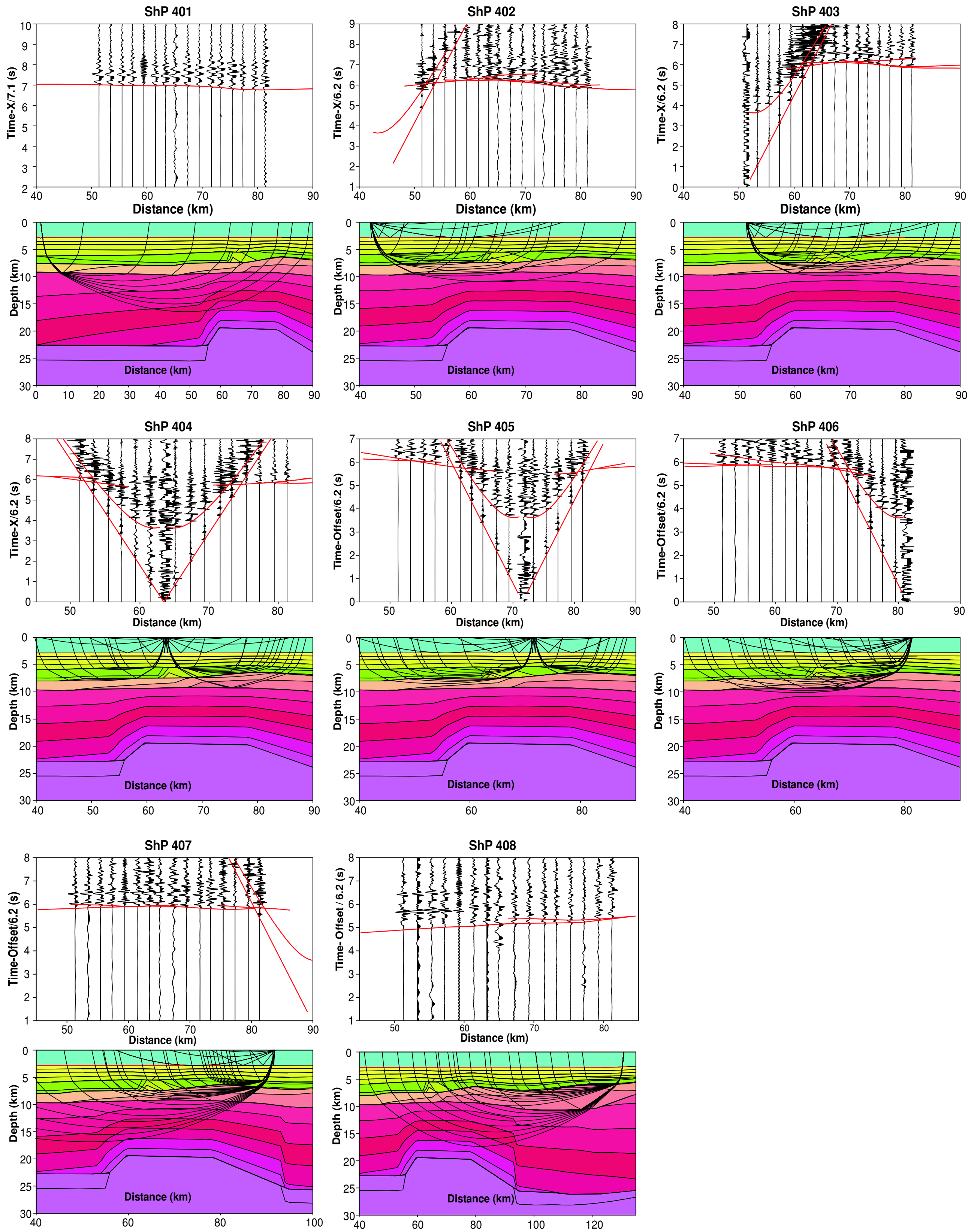
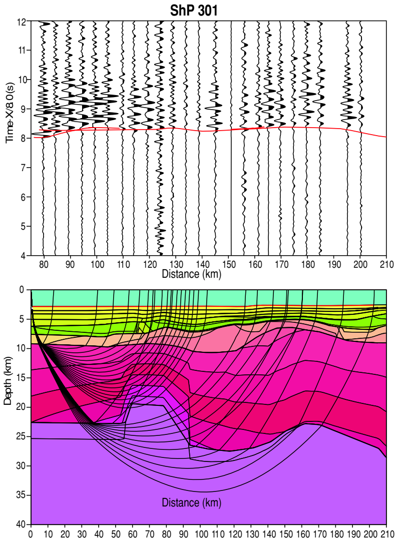
APPENDIX 1

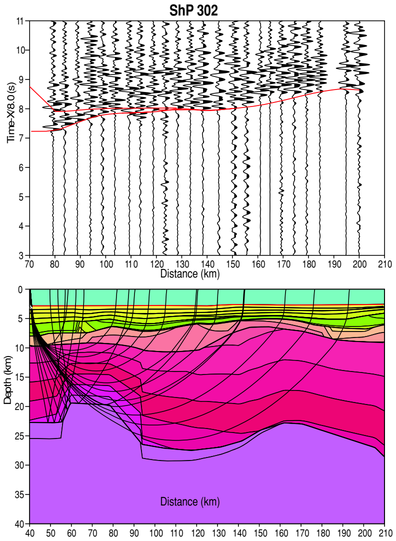
Seismograms and ray tracing for SP 401–408 (shallow refraction segment).

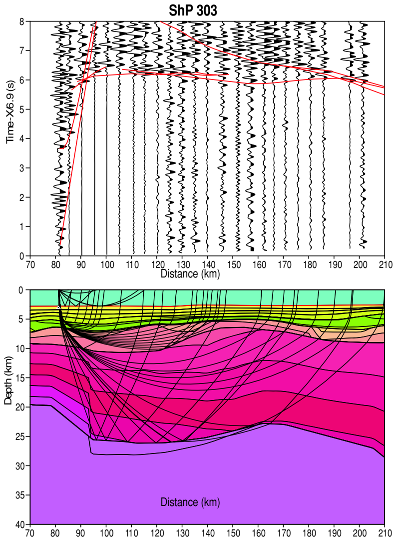


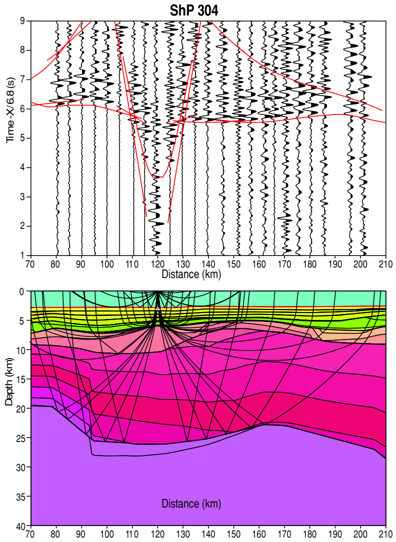
APPENDIX 2

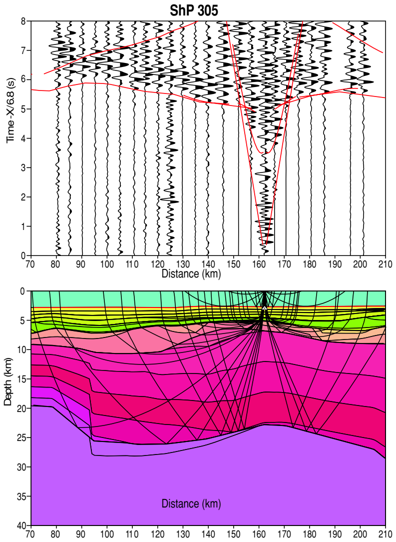
Seismograms and ray tracing for SP 301–308 (third DSS arrangement).

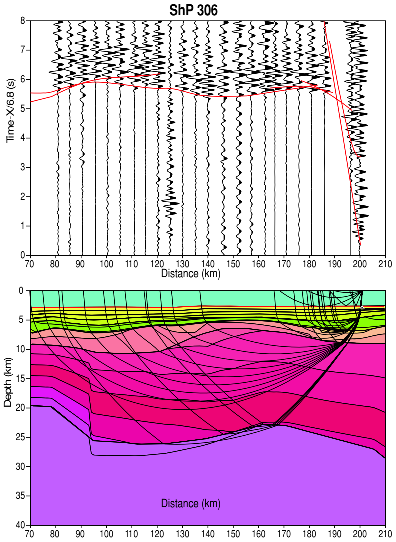


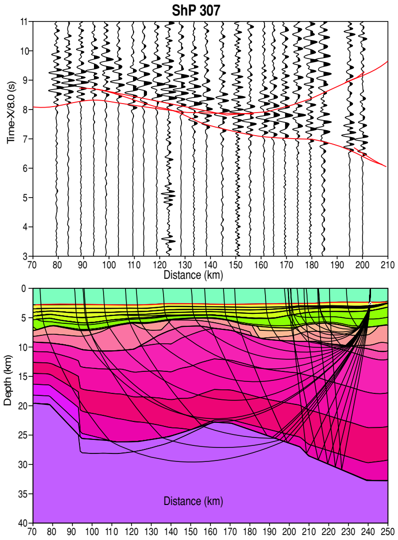


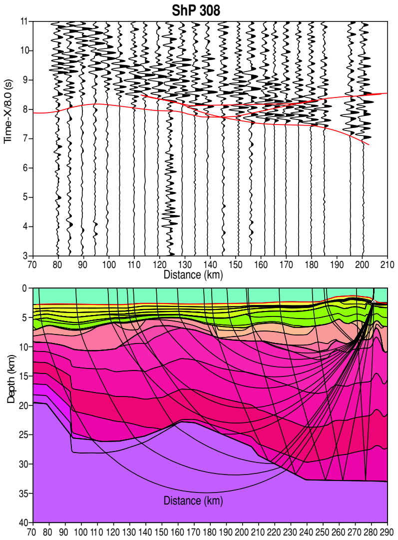






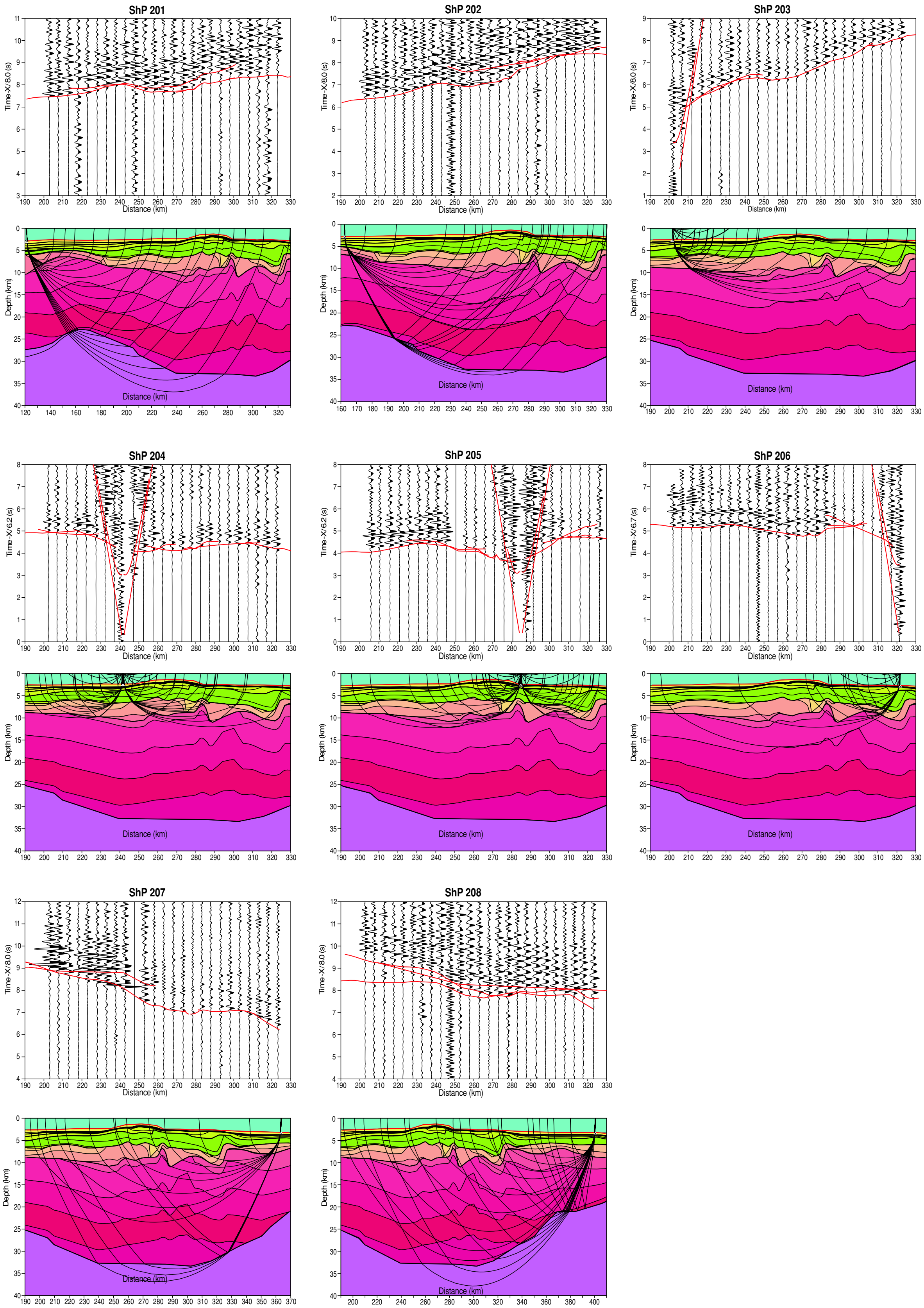






APPENDIX 3

Seismograms and ray tracing for SP 201–208 (second DSS arrangement).



APPENDIX 4

Seismograms and ray tracing for SP 101–107 (first DSS arrangement).