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Structure of the Earth's Crust in Fennoscandia as Revealed from Refraction and Wide-Angle Reflection Studies

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Abstract

The crustal structure in Fennoscandia has been intensively studied by seismic methods over the last one and half decade. The features and differences of the crustal structure are discussed by reviewing examples of velocity models from the seismic profiles for the different regions in Fennoscandia. It is shown that crustal thickness varies from 40 to 65 km in the shield, the thickest values are found in the middle of the shield, in Central Finland. Generally the crust in the shield can be divided into three layers, namely: upper, middle and lower crust. P-wave velocity in the upper crust varies from about 6.0 to 6.4 km/s, in the middle 6.6-6.7 km/s and in the lower one from 7.0 to 7.4 km/s. The sedimentary layer is thin or missing. The ratio of P-wave velocity to S-wave velocity increases with depth from about 1.7 in the upper crust to 1.77 in the lower crust. Outside the shield in the North German Lowland the crust is only 30-35 km thick. Here a layer with a velocity higher than 7.0 km/s is missing, so that the crystalline crust consist only of two layers. The sedimentary layer is of considerable thickness ranging in some areas to a thickness of almost ten kilometres. The Moho contour map has been updated. This map gives a quick view of the general behaviour of crustal thickness variation in the area.

Key words: crustal structure, Fennoscandia, refraction, wide-angle reflection, Moho-map

1. Introduction

The first seismic refraction studies were performed in FENNOSCANDIA in the late 1950s and 1960s (e.g. *Penttilä et al.*, 1960; *Sellevoll* and *Penttilä* 1964). The most comprehensive refraction experiment in the 1960s was the Trans-Scandinavian Seismic Profile of 1969 (Fig. 1), the results of which and reviews of the earlier deep seismic soundings in Scandinavia and the neighbouring countries were published in the proceedings of a colloquium held in Uppsala 1969 (*Vogel*, 1971). The field work of the Blue Road Profile 1975 (*Hirschleber et al.*, 1975) was the most important seismic profile in the 1970s before the long FENNOLORA profile 1979 (*Guggisberg*, 1986).

The FENNOLORA profile (Fig. 1) was the first one in which the spacing of the recording stations was equal or shorter than 3 km. Three international profiles were

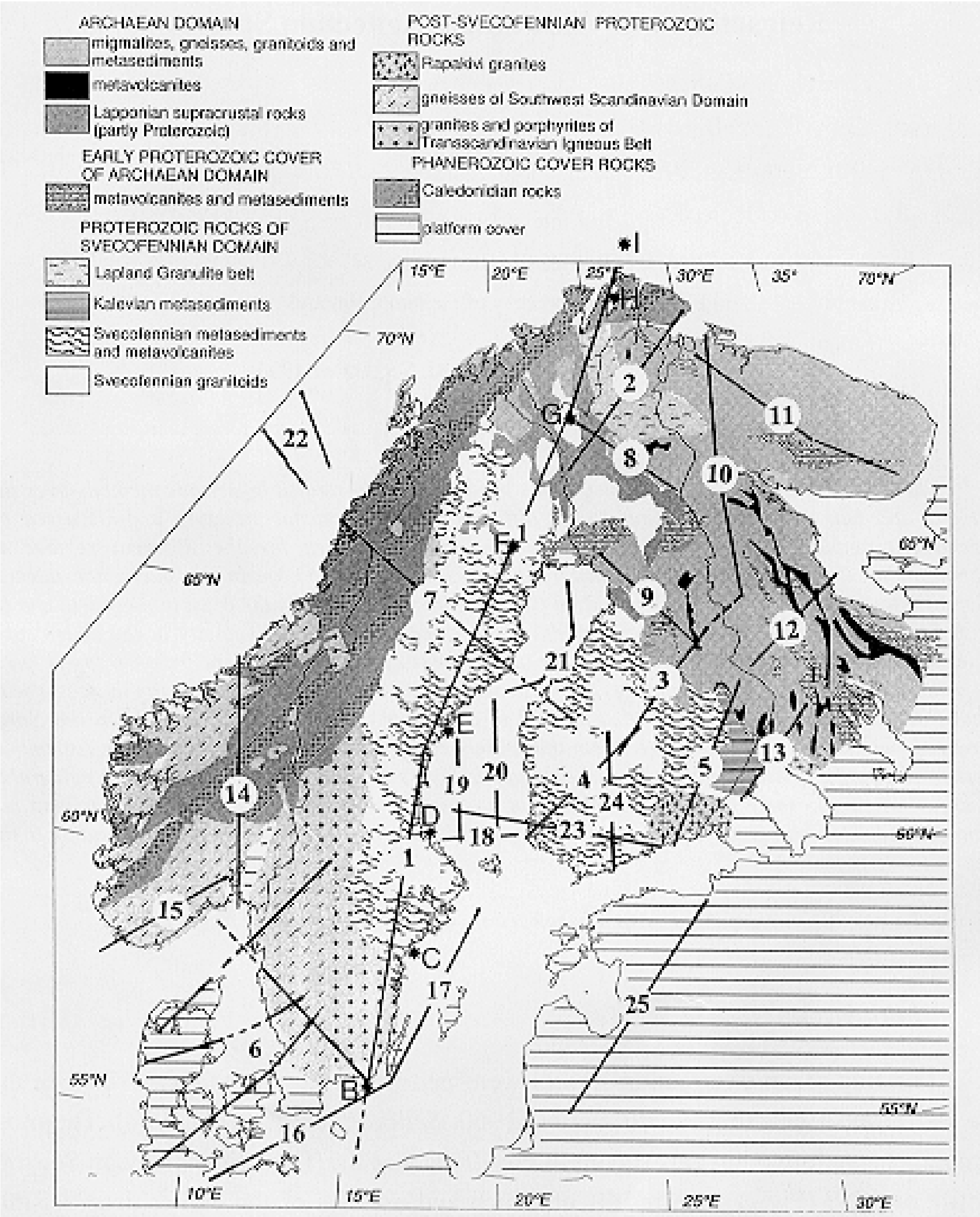


Fig. 1. Locations of seismic refraction and wide-angle profiles on the geological map modified after Gaal and Gorbatschev (1987): 1 - FENNOLORA, 2 - POLAR, 3 - Sveka'81, 4 - Sveka'91, 5 - Baltic, 6 - EUGENO-S, 8 - FINLAP, 9 - Bothnian, 10 - Petsenga-Kostomuksha, 11 - Umbozero, 12 - Kem-Tulos, 13 - Ladoga, 14 - Transcandinavian Seismic profile, Section 3-4, 14 - North Sea-southern Norway, 16 - BABEL A, 17 - BABEL B, 18,19 and 20 - BABEL lines 7,6 and 1 respectively, 21 - BABEL lines 2, 3 and 4, 22 - Lofoten, 23 - Sylen-Porvoo, 24 - FENNIA, 25 - Sovetsk-Kohtla-Jaerve. Capital letters from B to I refer to FENNOLORA shotpoints. The capital letters from B to I refer to FENNOLORA shot points. (For references and descriptions of the profiles see *Luosto* 1991, *Babel Working Group*, 1993a and 1993b, *Luosto et al*., 1994 and *Heikkinen et al*., 1995)

performed in Finland in the 1980s, namely SVEKA'81 in 1981 (e.g. *Luosto et al*., 1984; *Grad* and *Luosto*, 1987); the Baltic profile in 1982 (*Luosto et al.*, 1985; *Luosto et al.*, 1990); the POLAR profile in northern Finland and Norway performed in 1985 (*Luosto et al*., 1989). The last one was a part of the European Geotraverse program (EGT). The EUGENO-S profiles in Southern Scandinavia belonged also to the EGT program. During the BABEL marine seismic survey in 1989 (e.g. *BABEL Working Group*, 1990) more than 2000 km of deep reflection profiles in the Baltic Sea and Gulf of Bothnia were collected. The shots of the marine airgun source were also recorded at more than 50 seismic stations on islands and on land around the Gulf of Bothia and the Baltic Sea. In 1991 field work for the SVEKA'91 profile, a southwest extension of the SVEKA'81, was carried out (*Luosto et al*., 1994). In 1993 the refraction profile FENNIA was surveyed in the southern Finland (*Heikkinen et al*., 1995).

Syntheses of the seismic data from the Fennoscandian Shield (Baltic Shield) were made earlier by *Luosto* (1991), *Kinck et al*. (1993) and *Sharov* (1993) including e.g. references to DSS studies and Moho maps.

In this paper results of the FENNOLORA profile and five later ones are reviewed in some details including those of the wide angle reflections of the BABEL marine survey. Variations of the crustal structure and thickness in the region are also discussed in the light of what is known from the contour thickness map of the lower crust and of the updated Moho contour map.

2. Methods

Since the FENNOLORA profile of 1979 almost identical methods have been used to produce seismic signals and to interpret all the refraction and wide-angle reflection data. Charges ranging from 100-1600 kg were fired in small lakes with mutual distances of 60-80 km for crustal studies. To get structural information from the deeper mantle to the depths more than 400 km (FENNOLORA profile) larger charges of few tons were fired in the sea. In most of the profiles the spacing of the recording stations between the shotpoints was about 2 km, but for the FENNOLORA profile it was 3 km. The length of the FENNOLORA profile was about 1800 km and that of the other profiles 250-400 km. During the BABEL profile airgun shots were fired every 75 meters enabling to improve the signal to noise ratio by summing neighbouring traces. After the field surveys the data were jointly processed to plot record sections (see Fig. 2). The seismograms were filtered with different band pass and reducing velocities for P- and S- waves.

In the first stage simple 1-D methods were used to determine depths of reflectors and 1-D velocity-depth functions for each shotpoint. The subsequent 2D-models were achieved using modern kinematic and dynamic ray tracing programs. An example of the method is shown in Fig. 2.

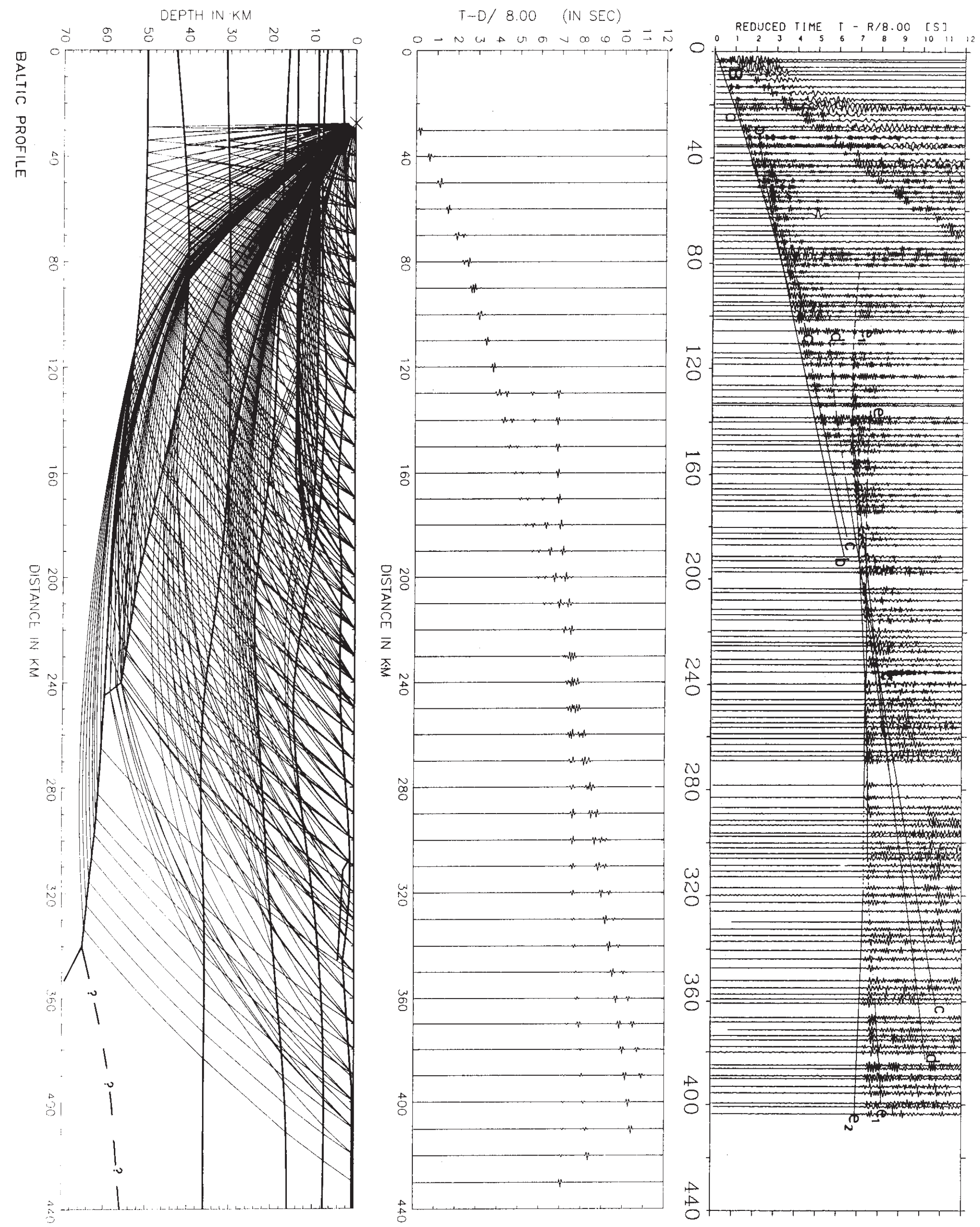


Fig. 2. An Example of the ray tracing method: a) P-wave record section for shotpoint B on the Baltic profile with calculated traveltime curves of the model superimposed; the letters a to f refer to the different travel time branches: a and b-b are phases connected to the upper crust, c-c to to the middle crust, d-d to the lower crust, e-e to the mantle, respectively. b) synthetic record section for the shotpoint, c) ray paths of the arrivals and synthetic record sections shown in Fig 2a and 2b.

Because the interpretation is based on the interactive forward modelling it is difficult to give quantitative estimates of the accuracy. The most reliable results in the models are the velocity distribution and the behaviour and depth of the Moho boundary. Generally the errors in the depths are hardly greater than 5 per cent. The resolution and ambiguity of the models are strongly bound with the density of the recording system.

3. *Results from selected profiles*

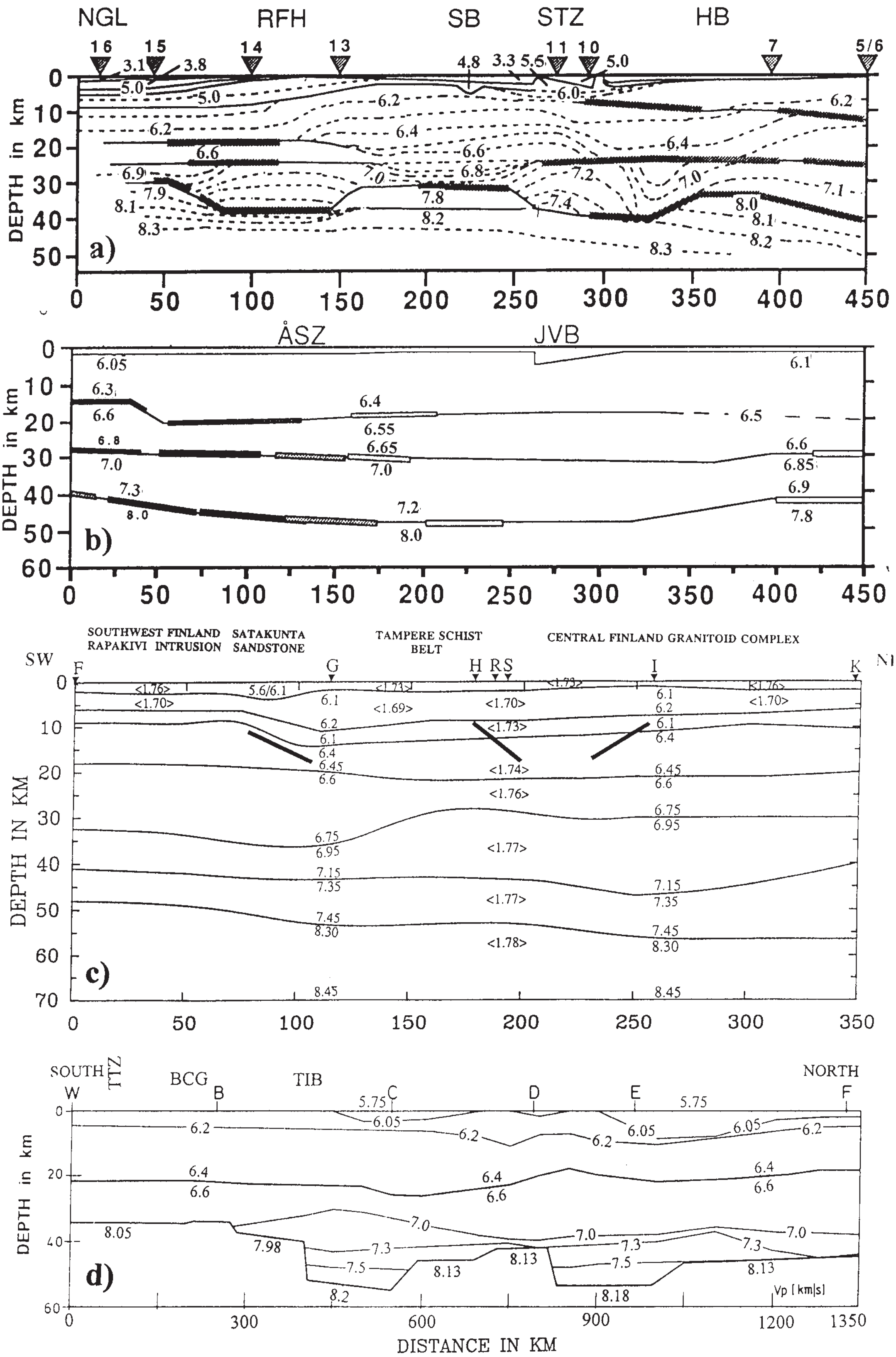
The models of the profiles FENNOLORA, BABEL A, BABEL B, Sveka'91, Sveka'81, POLAR and FENNOLORA covering the area from the South to the North are chosen to be reviewed. The interpretation of data in those cases has been also rather similar. The locations of the profile lines are seen in Fig. 1 and the velocity models along the profiles in Fig. 3. The BABEL A profile (Fig. 3a) (*BABEL Working Group*, 1993a) represents the transition from the North German Lowlands in the SW to the Baltic Shield in the NE. It is seen that crustal thickness is gradually increasing from 30 km outside the shield to 40 km and more underneath the Baltic Shield (northern part of the profile). At the same time the thickness of the sedimentary layer decreases from about 8 km to 1 or 2 km. The typical Palaeozoic crystalline crust of the North German Caleonides is divided into two layers: in the upper one the P-wave velocity varies from 6.0 to 6.3 km/s, and in the lower one from 6.6 to 6.9 km/s. In contrast the crust of the Precambrian Baltic Shield has a three-layer structure. The P-wave velocity in the lowest layer is higher than 7.0 km/s. Clearly this structure starts at the Sorgenfrei-Tornquist Zone (STZ) even if there are some relics of this high velocity layer in the Rinkøping-Fyn-High (RFH). According to the interpretation of wide angle data of the BABEL B line (Fig. 3b) the crustal thickness varies from 40 km in the SW to 48 km in the central part and decreases to 42 km in the northern part of the profile. The Åseda Shear Zone is seen as an increase of the thickness of the sedimentary layer. The interpretation of the northern half is not so detail because of lacking recording stations.

The next profile to the north described here is the SVEKA'91 (*Luosto et al.*, 1994), Fig. 3c. In the SW the crust is 48 km thick and gradually thickens to the NE reaching 56 km under the northeastern end of the profile. The crust can be divided into upper crust (P-wave velocity 5.6-6.45 km/s), middle crust (velocity of 6.6-6.75 km/s) and lower crust with velocities of 6.95 - 7.45 km/s. At the bottom of the lower crust a layer with a velocity higher than 7.35 km/s can be separated. The P-wave velocity under the Moho boundary in the mantle is about 8.3 km/s. In the upper crust a 3-5 km thick low-velocity zone was found at depths of 6 to 14 km. Below the Southwest Finland Rapakivi intrusion the velocities in the upper crust are higher than elsewhere in the upper crust. Intensive reflections from inclined reflectors are observed in several record sections. These reflectors do not coincide with seismic boundaries but they are rather so-called floating reflectors, in this case probably associated with gabbro intrusions or diabase dykes. They are located below the Satakunta Sandstone formation, the Tampere Schist belt and south from shot point I. The V_p/V_s ratio generally increases with depth from about 1.7 in the upper crust to 1.77 in the lower crust with the exception of the uppermost 1-2 km where higher values of 1.73 to 1.76 were observed. The higher values in the lower crust are interpreted as being associated with temperature and pressure increasing with depth and with the transition from a felsic to a more mafic composition (*Kern et al.*, 1991).

Figure 3d shows a simplified model for the crust along the FENNOLORA profile between shotpoints W (in Germany, outside the map in Fig. 1) and F (*Guggisberg,* 1986). The crustal thickness varies from 35 km in the southern end to 55 km in the deep depressions of the Moho boundary between shot points B and C or D and E. The C-boundary (originally called Conrad discontinuity, where P-wave velocity reaches a value of about 6.5 or 6.6 km/s) with a velocity of 6.6 km/s was found throughout the profile with a varying depth of 16-24 km. In the shield (from B to the north) the P-wave velocity is over 7.0 km/s in the lowermost crust reaching a value of 7.5 km/s in the deep depressions.

The SVEKA'81 profile was the first continuous and reversed seismic refraction experiment in Finland. The first interpretation (*Luosto et al*., 1985) of the good quality data was made applying the traditional DSS methods used in Poland in the 1960s and 1970s. The cross-section presented in Fig. 3e is, however, a reinterpretation of the data using modern ray tracing techniques (*Grad* and *Luosto*, 1987). The most surprising result from the Sveka profile was the large crustal thickness of almost 60 km, in such a low altitude area. This result was later confirmed by similar results obtained from the Baltic Profile *(Luosto et al.*, 1990), BABEL line 1 (*BABEL Working Group*, 1993b) and SVEKA'91 discussed above. According to Fig. 3d the thickness of the crust varies from 55 to 59 km. In the upper crust a low velocity layer with a thickness of 2-7 km was found at a depth of 5-9 km, as well as a body with higher velocities around the Iisalmi Block. Similar to Sveka'91 the ratio of V_p/V_s increases in the crust with depth from 1.72 to 1.77. In the upper crust, in the Archean granodioritic basement gneiss, the ratio is only 1.67. A detailed study of fracturing and velocity distribution of the crystalline uppermost crust along the profile revealed that in the uppermost 1 km the V_p/V_s values are high, varying from 1.76 to 2.0 (*Grad* and *Luosto*, 1994). The relative small S-wave velocities in the uppermost 1 km are interpreted as being probably due to the fracturing of the basement.

The field work of the POLAR Profile was carried out in 1985. A special international workshop was established in Espoo, Finland, to interpret the obtained seismic data together with other geophysical and geological data from the area. The refraction interpretation of P-wave recordings by the refraction Working Group was published by *Luosto et al.* (1985). In Fig. 3e, however, a velocity model based on a combined interpretation of P- and S-wave interpretations (*Walther* and *Flüh*, 1993) is presented. The interpretation of S-waves has also led to small changes in the boundaries but the main features are rather similar compared with the model of the Working Group. The crust here is much thinner than in the central Fennoscandian Shield, only 42-45 km in the middle of the profile, the greatest depth of 49 km being in the SW part of the profile almost below shot point B. The structure of the upper 10 km is very complicated evidently caused by greenstone and granulite belts in the area. A P-wave velocity as high as 6.55 km/s was found in the upper crust in a body below the Sirkka line. Also in the body related to the Karasjok-Kittilä Greenstone Belt and the Lapland Granulate Belt P-


NGL
RFH
SB
STZ
HB
DEPTH in km
a)
ÅSZ
JVB
b)
SOUTHWEST FINLAND RAPAKIVI INTRUSION
SATAKUNTA SANDSTONE
TAMPERE SCHIST BELT
CENTRAL FINLAND GRANITOID COMPLEX
SW
DEPTH IN KM
c)
SOUTH
TTZ
BCG
TIB
NORTH
d)
Vp [km/s]
DISTANCE IN KM

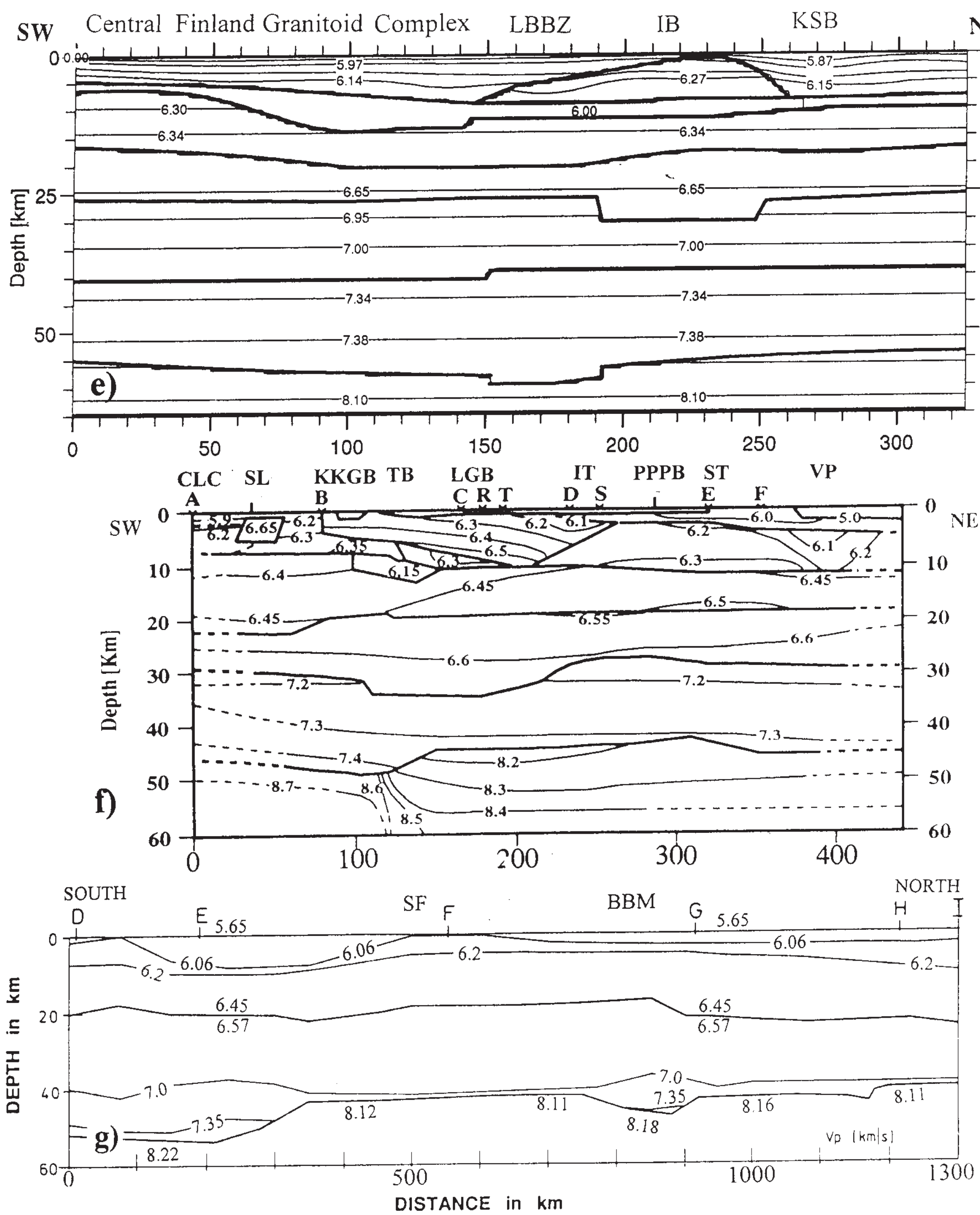


Fig. 3. Adapted crustal sections from different profiles: a) BABEL line A, b) BABEL line B (BABEL Working Group, 1993a,b), c) Sveka'91 (Luosto & al., 1994), d) FENNOLORA between W and F (Guggisberg, 1986), e) Sveka'81 (Grad and Luosto, 1987), f) POLAR (Walter and Flüh, 1993), g) FENNOLORA between D and I (Guggisberg, 1986). NGL - North German Lowlands, RFH - Ringkøbing-Fyn High, SB - Skurup Basion, STZ - Sorgenfrei-Tornquist Zone, HB - Hanö Basin, ÅSZ - Åseda Shear Zone, JVB - Jothnian to Vendian Basin, TTZ - Teysseyre-Tornquist Zone, BCG - Blekinge Coastal Gneiss, TIB - Transsandinavian Igneous Belt, BB - Bergslagen volcanic Belt, LBBZ - Ladoga-Bothnian Bay Zone, IB - Iisalmi Block, KSB - Kainuu Schist Belt, CLC - Central Lapland Complex, SL - Sirkka Line, KKGB - Karasjok-Kittilä-Greenstone Belt, TB - Tanaelc Belt, LGB - Lapland Granulite Belt, IT - Inari Terrain, PPPB - Polmak-Pasvik-Petchenga Belt, ST - Sørvaranger Terrain, VP - Varanger Terrain.

waves velocities are higher than in the neighbouring areas reaching from 6.1 km/s near the surface to 6.5 km/s at the bottom of the granulite at the depth of 10 km. A small low velocity layer was found at a depth of 10 km between shot points B and C. The velocity contrast between the upper and middle crust at a depth of about 20 km is only small. At the boundary between the middle and lower crust the velocity contrast is marked. The P-wave velocity in the lower crust (30-45 km) is over 7 km/s. The velocity distribution in the mantle below the Moho is remarkable. In the southern part of the model the velocity is more than 8.6 km/s, but in the central and northern part only 8.2 km/s. The ratio V_p/V_s increases from 1.71 in the upper crust to 1.78 in the lower crust. However, in the greenstone belts and the granulite the value is smaller, being only 1.69. In the upper mantle the ratio is 1.8.

Figure 3g shows a simplified model for the crust along the FENNOLORA profile between shot points D and I (*Guggisberg*, 1986). The crustal thickness varies from 55 km underneath the shot point E to 40 km in the northern end of the profile. A smaller Moho depression is seen below the Baltic-Bothnian-Megashear suggested by *Berthelsen* and *Marker* (1986). In the Moho map (Fig. 4), however, this trough is connected to the almost E-W trending depression. The C-boundary with a velocity of 6.6 km/s was found throughout the profile with a varying depth of 17-24 km. In the lower crust the P-wave velocities vary from 6.6 to 7.0 km/s with exception of the deep depressions where velocities reaching a value of 7.35 km/s are found.

4. General view of the structure

To get a general overview of the Moho behavior in Fennoscandia Moho depth maps have been calculated (*Luosto*, 1990 and 1991, *BABEL Working Group*, 1993b, *Korja et al.*, 1993). Depth values were collected from recent refraction and wide-angle reflection profiles. For the updated version of Figure 4 the additional results were added from SVEKA'91 profile (*Luosto et al.*, 1994) and from a preliminary interpretation of the FENNIA profile (*Heikkinen et al.*, 1995). One can see that in Central Finland and in central Sweden the crust is unusually thick being 55-60 km with an abrupt thinning to the east approximately along the Archean-Proterozoic border. In Lapland there is an almost E-W trending 46-50 km depth trough. Elsewhere, the thickness of the Svecofennian crust varies mainly from 40 to 45 km with a rapid thinning along the western edge of the Svecofennian domain in SW and under the Caleonides. An almost E-W oriented zone of thinned (or normal depth) crust is recognized along the Rapakivi formations in Southern Finland and an another area of "thinned" crust beneath the Bothnian Bay and north-central Sweden. When moving from the shield to the Palaeozoic in SW the crust thins to 30-35 km, which is the typical crustal thicknesses in the Central Europe. The most radical crustal thinning is, however, seen in the North-West in the transition from the continental crust to the oceanic one.

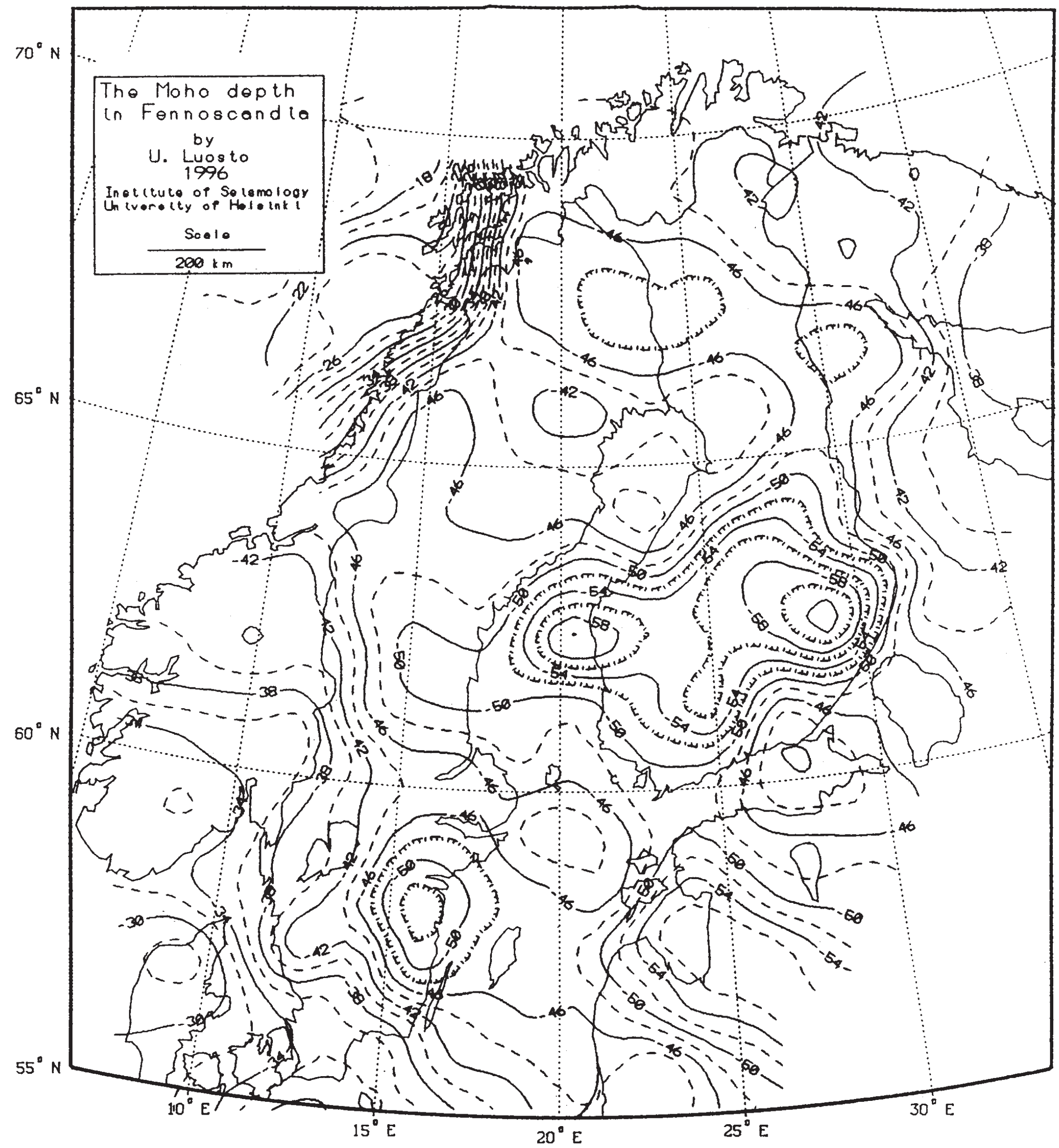


Fig. 4. Moho depth map calculated from the crustal thickness values of the profiles shown in Figure 1. Depths are given in km as negative values from the Earth's surface. The contour interval is 2 km. Pins in closing contour lines gives the direction of increasing Moho depth.

Figure 5 shows the thickness of the lowermost crust with P-wave velocity higher than 7.0 km/s (*Korja et al.*, 1993). A comparison with the Moho map reveals that this layer accounts for most of the variations in crustal thickness. The layer is more than 20 km thick in Central Finland but is almost zero when approaching the Palaeozoic in the SW or the oceanic crust in the NW.

Tectonic implications of the Moho depth map and thickness of the lowermost high velocity crustal layer was discussed recently by *A. Korja* (1995) and *Korja et al.* (1993). The most comprehensive overview of the Precambrian evolution of the Fennoscandian Shield is given by *Gaal* and *Gorbatschev* (1987).

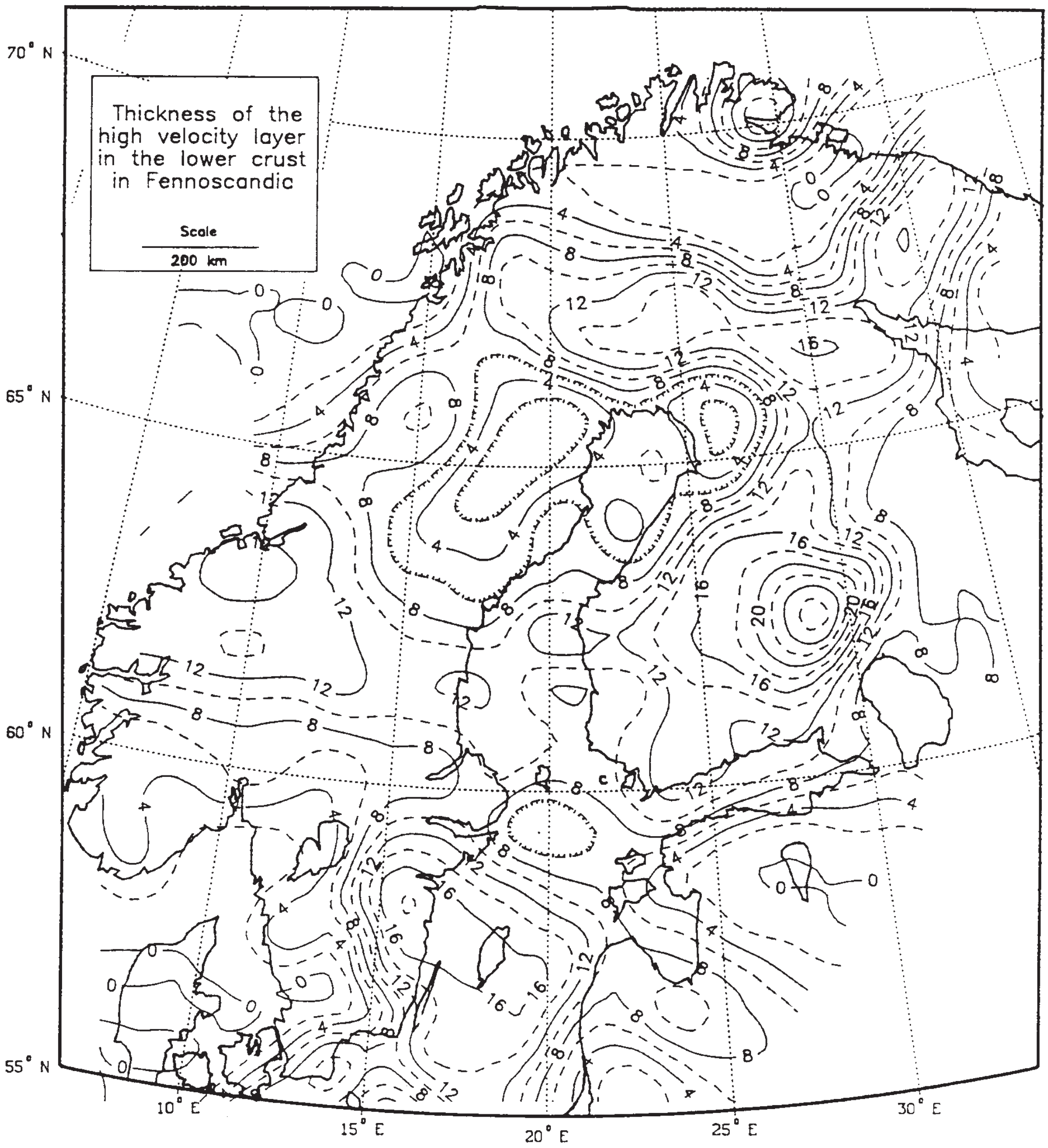


Fig. 5. Thickness (km) of the lowermost high-velocity crustal layer in Fennoscandia (Adopted from *Korja* et *al*., 1993).

5. *Conclusions*

During the last one and half decade the structure of the Earth's crust was studied along many seismic refraction and wide-angle reflection profile lines in Fennoscandia, and the resulting field data interpreted using modern ray tracing methods. It was found that the crustal thickness varies in the shield from 40-64 km and 30-35 km in the southern off-shield area in southern Baltic Sea and in Danish area. The Archean crust in the East is 38-46 km thick. The transition from the continental crust to the oceanic crust produces a radical thinning in the crustal thickness in the study area from 40 to 16 km. In the shield the crust can be divided into upper, middle and lower crust with P-wave velocity distributions roughly of 6.0-6.4, 6.5-6.7 and 7.0-7.4 km/s, respectively. The lowest high velocity layer disappears when moving off the shield and the crystalline crust in Central Europe consists of only two layers. The layer is also thinner or has smaller velocities in the Archean crust. The unusual big variations of the crustal thickness are due mainly to thickness variations in this layer

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