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A Refined Crustal Model and the Isostatic State of the Scandinavian Blue Road Area

St. Goldflam, H.B. Hirschleber, and P. Janle

Institut für Geophysik der Universität Hamburg,
Bundesstr. 55, 2000 Hamburg 13, Federal Republic of Germany

Abstract. In this paper a detailed interpretation of the Blue Road data is presented. Combining the seismic and gravimetric data a refined crustal model is calculated. The Caledonian mountains show a weak mountain root with a Moho depth of 46 km. A further depression of the Moho is detected under the Gulf of Bothnia (44 km).

Isostatic calculations lead to a considerable lithospheric mass deficit in the area of the Gulf of Bothnia. Combining this result with the intensive recent uplift of this area, an ice-isostatic adjustment is proposed which is still active besides the general tectonic upwarping of Scandinavia. From the calculated mass deficits and isostatic Moho depths a thickness of 3.4 km for the original ice cover is estimated. This is in agreement with the recent ice cover of Greenland and the Antarctic.

Key words: Velocity-depth function – Seismic-gravimetric model – Isostasy – Land uplift.

Introduction

The Baltic Shield and the Caledonian mountain range – called Fennoscandia – form one of the oldest parts of the European continent and represent one of the most stable geotectonic units in the earth's history. The inner structure, the process and mechanism of the land uplift constitute one of the main problems of the geodynamic research in Fennoscandia. Maybe the recent land uplift originates from both the orogenic movement and the isostatic compensation after the last ice age.

In 1972 refraction seismic measurements were carried out along the Scandinavian Blue Road traverse crossing the Caledonides, the Svecofennides (Baltic Shield), and the zone of maximum land uplift in the Gulf of Bothnia (Fig. 1).

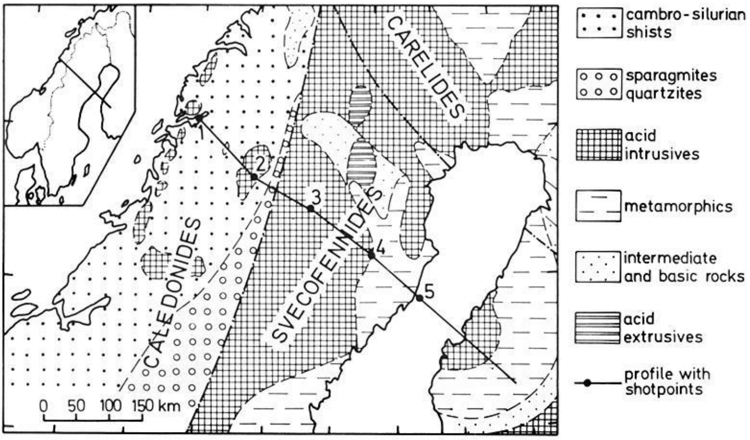


Fig. 1. Simplified geological map with Blue Road profile and locations of shotpoints (modified after Hirschleber et al., 1975)

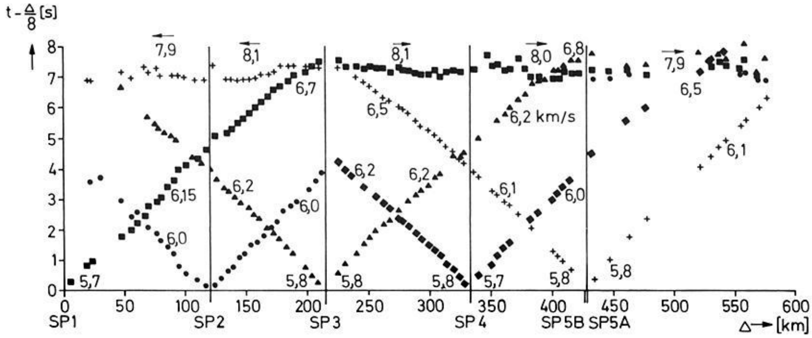


Fig. 2. Arrangement of shotpoints and recording stations with first arrivals and apparent velocities

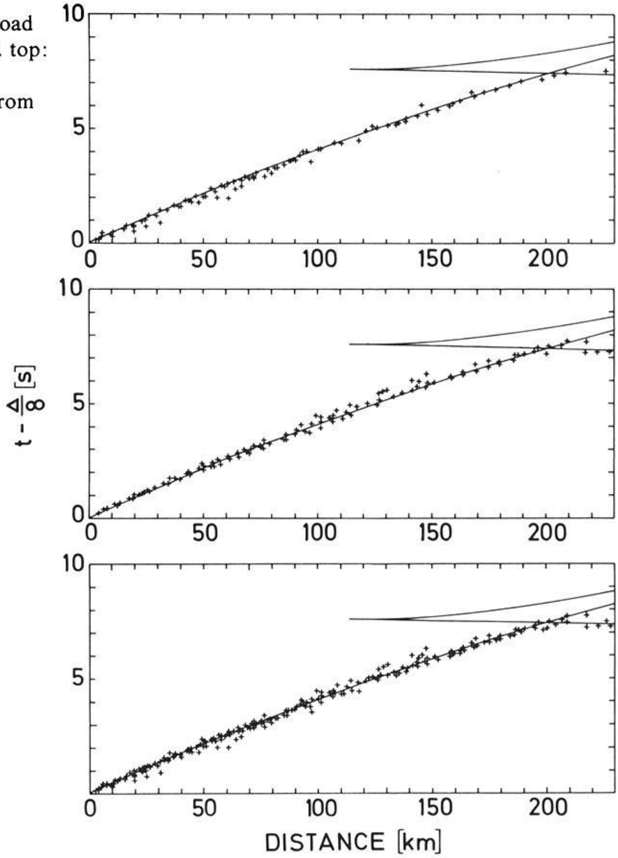
A description of the seismic field work, the record sections, and a first interpretation are given in a paper by Hirschleber et al. (1975). In Figure 2 all first arrivals and different apparent velocities are plotted.

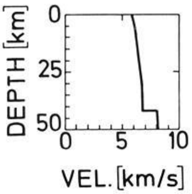
Although excellent first arrivals were found along the whole profile, secondary arrivals were generally weak. No clear subcritical reflections have been detected.

Therefore, velocity-depth models without significant first order discontinuities are given preference. Apart from different structures near the surface the distribution of seismic velocities appears to be very similar within the Caledonides and the Svecofennides. The crust-mantle boundary shows only minor undulations between 37 and 42 km. No distinct roots below the Caledonian mountains were observed. The mantle velocity seems to be constant to depths of about 80 km, – at least it does not increase.

The purpose of this paper is to refine the seismic models with the aid of gravimetric data taken from a map of "Bureau Gravimétrique International"

Fig. 3. First arrivals of the Blue Road profile up to a distance of 230 km. top: the arrivals mainly from the Caledonides, centre: the arrivals from the Svecofennides only, bottom: all first arrivals





(Bouvet, 1971) and the results of a local research by Vogel and Tørne (1975). On the basis of a detailed model of the crust along the profile an isostatic investigation will follow. The reasons of the land uplift will be discussed.

A Refined Model of the Blue Road Traverse

Neglecting lateral velocity changes and dipping of the layers all shotpoints are equivalent. In place of five shotpoints only one is present. For this case all first arrivals up to a distance of 230 km are plotted in Figure 3 (bottom).

The traveltime curve represents a mean velocity depth function for the whole profile:

0.0 km	5.90 km/s
5.5 km	6.10 km/s
30.0 km	6.75 km/s
42.0 km	6.80 km/s
42.0 km	8.1 km/s
50.0 km	8.2 km/s

In Figure 3 (centre) only the arrivals from the Svecofennides are plotted.

The scattering is less than in the general plot below. This may be due to the fact that the Svecofennides represent an ancient homogenous part of the earth's crust impressed by metamorphism at great depths. The first arrivals belonging mainly to the Caledonides are shown in Figure 3 (top). Apart from the larger scattering a lot of onsets are much earlier than the travel time curve up to a distance of 100 km. This indicates a body with a high velocity near the surface. The well known value of 6.6 km/s (gradient 0.005 (km/s)/km) for Scandinavia results from observations of the direct wave. In comparison with the geological map (Fig. 1) we can interprete the high velocity coming from plutonic rocks.

After detailed computations of the local travel time anomalies of the upper crust we have to decide on the course of the crust mantle discontinuity (Moho). In order to reduce the number of possible models gravimetric data were taken into consideration. The calculation of two-dimensional gravity models is justified because the profile transects the geological units nearly at a right angle. Then we have to look for fitting density values to seismic velocities. Using density-velocity diagrams (Nafe and Drake, 1957; Uspenskij, 1970) we get the following relations:

velocity (km/s)	density (g/cm^3)
5.90–6.10	2.78
6.00–6.75	2.80
6.75–6.80	3.01
8.10–8.20	3.37

In order to obtain the best-fitting model a kind of trial and error method is used. The starting depth of the Moho is taken from the seismic data, the course from the Bouguer data. When the computed gravimetric model fits the measured data, travel time curves for possible velocity-depth functions are calculated by the computer. The best model corresponding to the measured arrivals of the seismogram section is selected. Then the seismic model is tested again by the gravimetric data. Comparing continuously the computed models with both the seismic and gravimetric data, an optimal model is found. In this case Figure 4 shows the final model.

In the upper part of Figure 4 one sees the measured first arrivals for shotpoints 1 and 5 and the computed traveltime curves. Here one sees again the larger scattering of the first arrivals in the Caledonian area (SP 1) as compared to the Svecofennian area (SP 5). In the centre one sees the observed and calculated Bouguer anomalies and on bottom the layering with the density values. This model is also consistent with the first arrivals from shotpoints 2–4. Starting on the left with a small root under the Caledonides (46 km), the Moho depth decreases in the eastern direction (38 km) and increases under the Gulf of Bothnia (44 km). The connection between the course of the Moho and the last ice-age including its influence on the land uplift of the Baltic shield will be discussed in the next chapter.

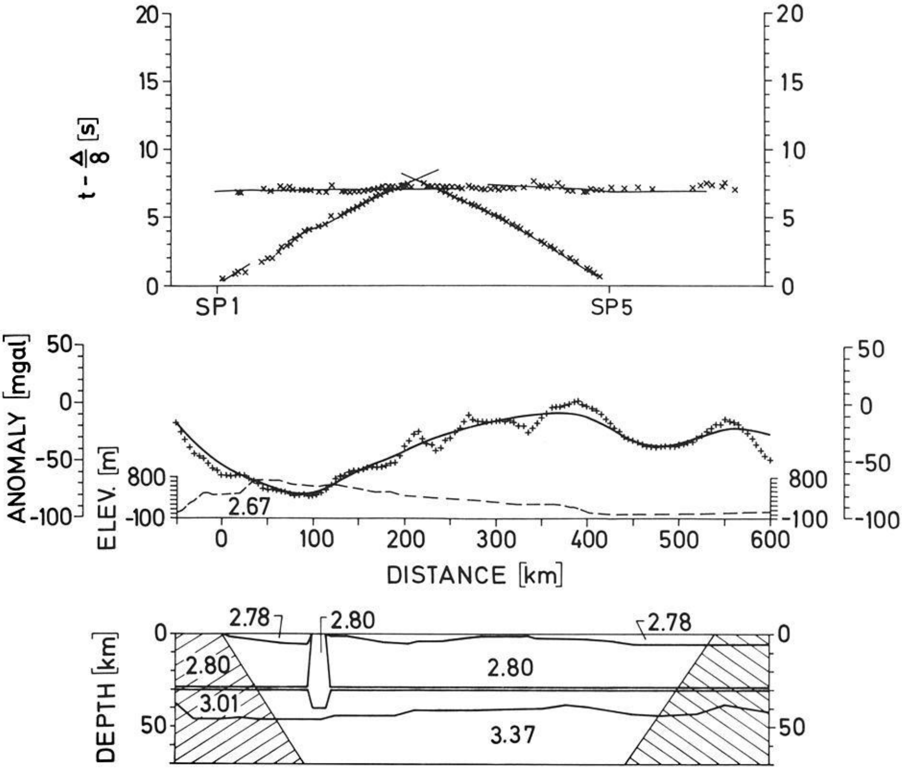


Fig. 4. The final model. top: the traveltime curves for shotpoints 1 and 5 (× = observed arrivals, — = calculated traveltime curve) centre: Bouguer anomaly (+ = observed, — = calculated) bottom: crustal model with density values in g/cm^3 (shaded area: gravimetric data only)

The Isostatic State of the Investigated Area

A significant geophysical phenomenon of Scandinavia is the ancient and recent uplift and its consequences with respect to isostatic questions. Before the investigation of the isostatic state of the derived model some general remarks on isostasy will be made.

The hypotheses of isostasy are closely connected with the density distribution and with the rheologic behaviour of the earth (Jacoby, 1973). While former isostatic calculations only consider the general density distribution of the lithosphere, Janle (1973) and Goldflam (1976) show the advantage of using the local density distribution from crustal models. The density distribution of the investigated area was derived in the previous section of this paper and presented in the final model (Fig. 4). The rheologic behaviour of the earth's lithosphere depends on the length of time considered and on the strength.

Regarding the present hypothesis of plate tectonics, the 200 km thick plates of the lithosphere lie on the asthenosphere of secular fluidity. The lithospheric

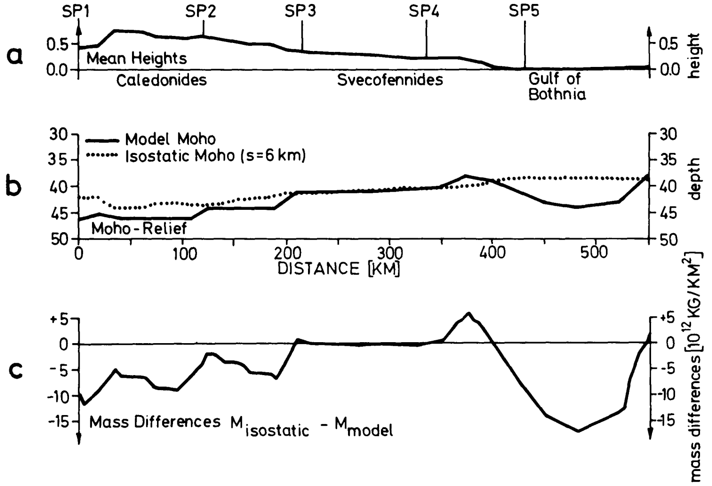


Fig. 5a–c. Isostatic state of the Blue Road area. **a** mean heights; **b** Moho relief, $s = 6$ km: surface of a free floating mantle; **c** mass differences

plates should react nearly ideal-elastically to stress for periods of time less than 10^6 years; for larger periods they may react more visco-elastically with a viscous component of about 10^{24} NS/m^2 (Walcott, 1970). The rheologic behaviour of a stratum is not simply described by viscosity. A minimal stress, called strength (Daly, 1940; Gutenberg, 1940), is needed to permit a flowing movement. Until now, there are only rough estimations of strengths. Barrel's (1915) estimation shows a decrease of strength below 30 km by a factor of 0.6×10^{-1}. Jeffreys (1962) calculated a strength decrease by a factor of 10^{-1} below 50 km.

Considering this decrease of strength at the zone of the Moho the following computations are based on Archimedean floating of solid crustal sections on a secular fluid mantle. Vertically free mobile crustal columns with a base surface of 5×5 km were considered for the investigation of the isostatic state of the derived model. The isostatic Moho depths were calculated for these columns according to Archimedes' principle. For the calculations a depth of 6 km was estimated for a free floating surface of mantle material. This is the Moho depth of deep sea areas with only a minimal cover of crustal material. The use of a free floating mantle is equivalent to the "normal crustal thickness" of the Airy hypothesis.

Outgoing from the model in Figure 4, the masses were summed up until the layer above the Moho was reached. Then the depth of the Moho was varied until hydrostatic equilibrium was obtained with regard to a column of free floating mantle material. The new Moho depth is called "isostatic Moho depth". The total masses down to the model Moho and the isostatic Moho are termed "M_{model}" and "$M_{\text{isostatic}}$". The difference between the depth of the model Moho and the depth of the isostatic Moho is due to the present topography. It does not mean that the model Moho has to rise by the amount of the difference to reach isostatic compensation.

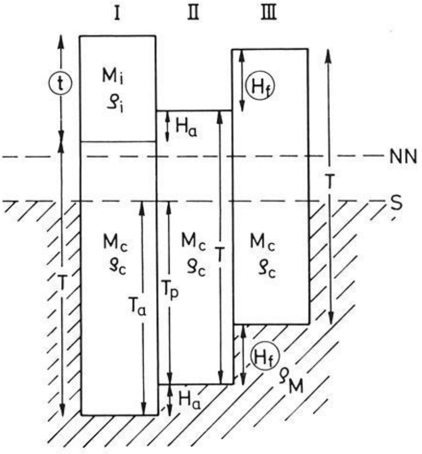


Fig. 6. Illustration for calculations of the future uplift H_f and the thickness t of the original ice cover. *I* original stage with maximal ice cover (isostatically compensated); *II* present stage (not isostatically compensated, mass deficit); *III* future stage after isostatic adjustment; M_c = total mass of a crustal column of the model in Figure 4 (M_{model}); M_i = mass of maximal ice cover; ρ_c = crustal density; ρ_i = ice density; ρ_M = mantle density; s = surface of a free floating mantle (6 km depth); T_a = ancient Moho depth $- s$; T_p = present (model) Moho depth $- s$; T = thickness of a crustal column; H_a = ancient uplift; H_f = future uplift to isostatic adjustment; t = thickness of maximal ice cover

Figure 5b shows the model Moho of Figure 4 and the calculated isostatic Moho; Figure 5c shows the mass differences of crustal thickness between the isostatic compensated crust and the model crust ($M_{\text{isostatic}}$-M_{model}). A similar calculation of masses of crustal columns on profiles was carried out by Janle (1973) for southern Scandinavia.

The calculations of the isostatic Moho and of the mass differences (Fig. 5) permit an estimation: (1) of the uplift to be expected in the future and (2) of the thickness of the original ice cover. The calculations are based on two assumptions:

– the masses of crustal columns remain constant during uplift; erosion is neglected;

– there is Archimedean compensation, i.e. the elastic properties are not considered.

(1) Comparing columns II and III in Figure 6, the following equation is valid for isostatic adjustment:

$$(T_p - H_f)\,\rho_M = M_c$$

$$H_f = T_p - \left(\frac{M_c}{\rho_M}\right)$$

$$\rho_M = 3.37\ \text{g/cm}^3.$$

The following values result for the Gulf of Bothnia from the model in Figure 4 and the calculated mass differences:

$$T_p = 38\ \text{km}$$
$$M_c = 126 \times 10^{12}\ \text{kg/km}^2.$$

The resulting uplift H_f for the future is 600 m.

(2) Comparing I and III in Figure 6, the following equations are valid for isostatic equilibrium:

$$T_a\,\rho_M = \rho_i\,t + T\,\rho_c$$

$$T_a\,\rho_M = (H_a + H_f)\,\rho_M + T\,\rho_c.$$

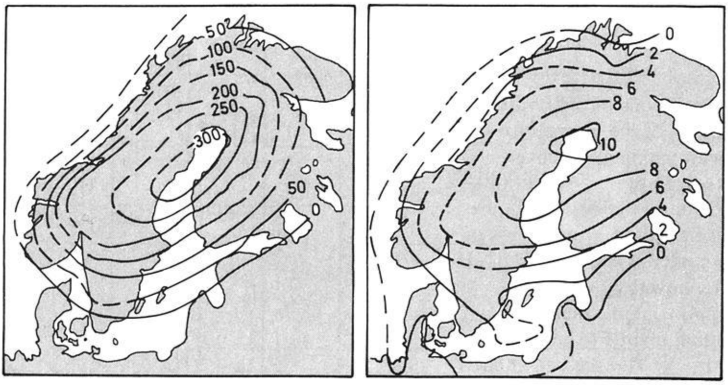


Fig. 7. Left: total ancient uplift in m for the last 7700 years. Right: contour lines of recent uplift in mm/year (Brinkmann, 1967)

These 2 equations lead to

$$t = \frac{\rho_M}{\rho_i}\,(H_a + H_f)$$

$$\rho_i = 0.9\ \mathrm{g/cm^3}$$

$H_a = 300$ m (ancient uplift Fig. 7).

The resulting original ice cover is 3.4 km.

It must be emphasized, however, that the calculated values are maximum values due to the neglect of the elastic properties.

The agreement of the isostatic Moho and the model Moho in Figure 5b indicates an isostatic equilibrium of the crust between SP 3 and SP 4. In the areas of the Caledonides and the Gulf of Bothnia the model Moho lies below the isostatic Moho. These areas must rise to achieve isostatic equilibrium. The mass differences show the same trend in Figure 5c. Negative values indicate mass deficits which can be compensated by an isostatic uplift of the crust. This resulting trend agrees with the ancient and recent crustal uplift (Fig. 7).

After presenting the computed mass deficits and crustal uplift possible causes for these phenomena shall be discussed now. Two components for the uplift have been proposed: a tectonic component has been continously active since the Precambrian; superimposed on this component is an ice-isostatic component (Schwinner, 1928; Heiskanen, 1936; Sauramo, 1939; Daly, 1940; Artyushkov and Mescherikov, 1969). While the tectonic vertical movements amount maximally to 10–15 mm/year, the ice-isostatic uplift starts with more than 10 cm/year and declines rapidly in some 10^4 years to maximally 10 mm/year. Thus, it is difficult to decide whether the recent uplift is due to tectonic or ice-isostatic processes. Mörner (1973) concludes that the ice-isostatic component is nearly terminated.

Janle (1973) and this paper (Fig. 5) show that there is a considerable mass deficit within the lithosphere at least in the area of the Gulf of Bothnia. This mass deficit is interpreted here as a relic of the ice age causing a part of the present uplift. Tectonic vertical movements have their origin in the mantle or, more specifically, in the asthenosphere, caused by convection currents or thermal and mass anomalies. However, there are no hints of recent local tectonic processes within the area of the Gulf of Bothnia such as earthquakes or geologic faults.

Conclusions

The seismic analysis yields a uniform $v-z$ function for the region of the Blue Road. However, there are some differences between the areas of the Caledonides and the Baltic Shield. Differing from the average for the Caledonian mountains a velocity of 6.6 km/s near the surface and a greater scatter of the first arrivals were observed. This effect is explained by: (1) numerous magmatic intrusions, (2) the lesser degree of metamorphism, and (3) the lesser age in comparison to the Svecofennides. The final model (Fig. 4) shows a weak mountain root in the Caledonides. The Moho depression of the Gulf of Bothnia coincides with the region of maximal uplift.

The fact of the considerable crustal mass deficit in the area of the Gulf of Bothnia combined with the maximum recent uplift of 10 mm/year is interpreted as an ice-isostatic adjustment which is still active in addition to the general tectonic upwarping of Scandinavia.

The calculated thickness of the original ice cover agrees quite well with the situation in areas with recent glaciations. The ice cover of Greenland has a thickness of about 3 km (Brinkmann, 1967) and in the Antarctic the ice cover amounts to a maximal thickness of 5 km (Thenius, 1974).

References

Artyushkov, E. W., Mescherikov, Yu. A.: Recent movements of the earth's crust and isostatic compensation. In: The earth's crust and upper mantle, Monograph No. 13, P. J. Hart, ed., pp. 379–390. Washington, D.C.: American Geophysical Union 1969

Barrell, J.: The strength of the earth's crust J. Geol. **1**, XXIII, 27–45, 1915

Bouvet, J.: Anomalies de Bouguer, Europe – Afrique. Paris: Bureau Gravimétrique International 1971

Brinkmann, R.: Abriß der Geologie, Bd. 1. Stuttgart: Enke 1967

Daly, R. A.: Strength and structure of the earth. New York: Prentice-Hall 1940

Goldflam, St.: Ein zweidimensionales Krustenmodell und die isostatischen Verhältnisse auf dem Profil Blaue Straße 1972 in Skandinavien. Diplomarbeit, Institut für Geophysik, Universität Hamburg 1976

Gutenberg, B.: Geotektonische Hypothesen. In: Handbuch der Geophysik, Bd. 3, B. Gutenberg, ed., pp. 442–547. Berlin: Borntraeger 1940

Heiskanen, W.: Das Problem der Isostasie. In: Handbuch der Geophysik, Bd. 1, B. Gutenberg, ed., pp. 878–951. Berlin: Borntraeger 1936

Hirschleber, H. B., Lund, C. E. Meissner, R., Vogel, A., Weinrebe, W.: Seismic investigations along the Scandinavian "blue road" traverse. J. Geophys. **41** 135–148, 1975

Jacoby, W. R.: Isostasie und Dichteverteilung in Kruste und oberem Mantel. J. Geophys. **39**, 79–96, 1973

Janle, P.: Synoptische Bearbeitung des südlichen Teiles von Skandinavien aus seismischen und gravimetrischen Ergebnissen. Hamburger Geophysikalische Einzelschriften. Heft 19, 1973

Jeffreys, H.: The earth. Cambridge: University Press 1962

Mörner, N. A.: Eustatic changes during the last 300 years. Paleogeography, Paleoclimatology, Paleoecology **13**, 1–14, 1973

Nafe, J. E., Drake, C. L.: Physical properties of crustal materials as related to compressional wave velocities. Annual Meeting of Soc. Explor. Geophys., Dallas, Texas, 1975

Sauramo, M.: The mode of the land upheaval in Fennoscandia during late-quarternary time. Soc. Geol. de Finnlande, C. R., No. 13, 1939

Schwinner, R.: Geologische Bemerkungen zu den Norwegischen Schweremessungen. Gerlands Beitr. Geophys. **19**, 107–133, 1928

Thenius, E.: Eiszeiten – einst und jetzt. Stuttgart: Franckh'sche 1974

Uspenskij, D. G.: Study of the earth's crust under the oceans by the gravimetric method. Izvestia, Physics of the solid earth, 429–437, 1970

Vogel, A., Törne, A.: Gravity map of the blue road profile. 2nd Discussion Meeting on the "Blue Road Project" in Uppsala, 1975

Walcott, R. L.: Flexural rigidity, thickness, and viscosity of the lithosphere. J. Geophys. Res. **75**, 3941–3954, 1970

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