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# Lithosphere-asthenosphere system in shield areas of North America and Europe

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**Abstract**

In previous papers surface dispersion data have been combined with the results of deep seismic refraction data to derive a regionalization of the lithosphere-asthenosphere system and to investigate the presence of significant heterogeneity down to depths of 350 km along two profiles in the North European Fennoscandian area; a regionalized upper mantle model for the whole area down to more than 400 km is given as cross sections. We have extended that approach to North America. The older part of the shield shows lid thickness up to more than 100 km with, if any, weak shear velocity contrast to the underlying layer. The surrounding areas are characterized by a thinner lid; a stronger low-velocity zone to lid contrast may be found in peripheral areas. A map of the lithosphere-asthenosphere system has been derived, permitting a better regional resolution of the shear-wave velocity distribution with depth beneath different regions of North America. The correlation between the lithosphere-asthenosphere system structure and other geophysical data is commented as well as the results for North America and those obtained for the corresponding North European area, in order to outline the geophysical characteristics of shield areas that might give useful constraints for the geodynamic behaviour of the plates to which they belong.

**Key words** *North America – Fennoscandia – shield – lithosphere-asthenosphere – surface waves*

## 1. Introduction

An important issue in resolving the depth of continental roots is the depth of lateral variations between and within continents. There is evidence that structural differences within continents extend well below 200 km.

A picture of the extent and magnitude of lateral variations in seismic velocity throughout the upper mantle will certainly help in mapping the course of its evolution. However, such a picture is hard to derive from comparison of the results of different types of studies in different regions of the world. In fact it is not easy to sort out true variations in structure from apparent variations, for example, caused by differences in methodology. To overcome this problem, we applied a unique methodology to different regions, in order to outline possible lateral variations. We focused our attention on areas of North Europe and North America, that in the predrift configuration were contiguous parts of Pangea; both areas include Precambrian shields that play an important role in geodynamic processes.

In previous papers surface dispersion data have been combined with the results of deep seismic refraction data to derive an upper mantle model for some parts of the north European

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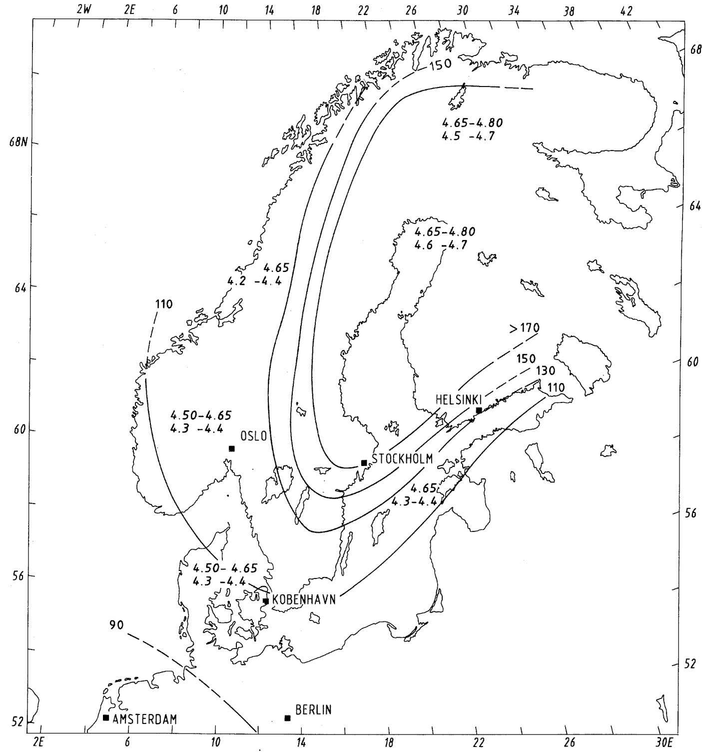

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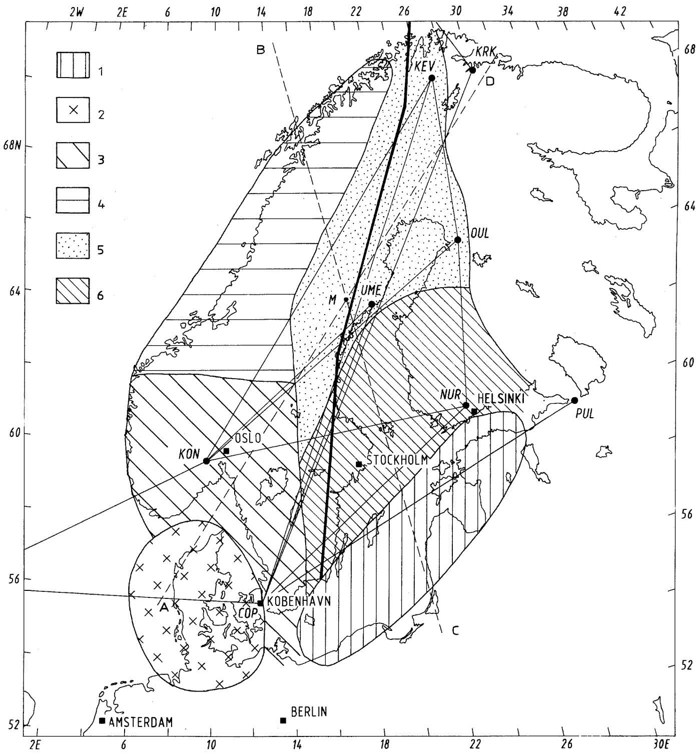

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**Fig. 1.** Lithospheric thickness and shear-wave velocity in Fennoscandia. Upper and lower lines indicate, respectively, lid and channel shear-wave velocity (after Calcagnile, 1982).

**Fig. 2.** Long-period seismographic stations, profile coverage and regionalization of Fennoscandia; the location of the Fennolora profile is shown by a bold line. 1) Baltic sea; 2) Danish area; 3) Southern Norwegian-Swedish area; 4) Caledonides; 5) Northern Bothnia area; 6) Southern Bothnia area. AD and CB show the location of the sections considered.

Fennoscandian area (*e.g.*, Calcagnile, 1982, 1991; Calcagnile *et al.*, 1990) down to a depth of about 400 km.

In this work we will give the results of the investigations for the upper mantle in the whole Fennoscandian area by means of inversion of regionalized Rayleigh wave dispersion relations; we will also report the results obtained extending the same methodology to North America, where over the past years the study of *P*- and *S*-wave velocities in the upper mantle has been the subject of intensive research work (*e.g.*, Durrheim and Mooney, 1994) using many different methodologies.

## 2. North European area

The analysis and subsequent inversion of the available dispersion profiles (Calcagnile, 1982) allowed a regionalization of the lithosphere-asthenosphere system (fig. 1) which indicates that the Fennoscandian area is characterized by a significant lateral heterogeneity in the first 200 km of the upper mantle. Namely, the upper mantle in the north-central part of the area has no low-velocity zone or in the extreme case this is virtually absent down to depths of about 200-250 km. The results for the peripheral area indicate an upper mantle structure with a low-velocity zone well developed beneath the Caledonides and the Baltic Sea while it may be much milder in the Danish and Sveconorwegian area. The inversion of new phase velocity dispersion results (fundamental mode up to about 250 s and first two higher modes up to about 70 s) (Calcagnile, 1991) suggested the presence of significant lateral heterogeneity down to depths of about 350 km moving from the older Precambrian shield (COP-KEV/COP-KRK) to the peripheral area (NUR-COP) (see fig. 2).

In view of the significant variation of the upper mantle structure along Fennolora (fig. 2), on the basis of available DSS results (*e.g.*, Guggisberg and Berthelsen, 1987), a global approach has been attempted (Calcagnile *et al.*, 1990) by means of inversion of all available Rayleigh wave dispersion relations regionalized following a procedure adopted by Panza *et al.* (1980), (see Calcagnile, 1982).

Besides giving average *S*-wave velocity at different depths in the upper mantle, that approach suggested that the average bottom of the asthenosphere beneath Fennolora is at a depth of about 320 km, thus giving an asthenosphere thickess ranging from about 200 km in the southern part to about 100 km, and less contrasted, in the northern one. Below that depth slight differences, if any, have been found, thus giving the depth to which the heterogeneity might extend. The mantle transition zone seems to be in average at the same depth of about 450 km for the south, central and north segment of Fennolora.

The use of the aforementioned regionalization procedure for Fennoscandia (Calcagnile *et al.*, 1990) discloses dispersion relations in the area regionalized according to previous results and tectonic setting (fig. 2).

Due also to the availability of long period higher mode dispersion data having a good geographical distribution and very deep DSS data, we succeeded in extracting regionalized information on upper mantle characteristics down to more than 400 km. Therefore, besides the map of the lithosphere-asthenosphere system for the uppermost 200 km, we can show the inversion results in shape of cross sections (fig. 3) down to the so-called «400 km-discontinuity».

The Baltic Sea region is characterized by a lithosphere 120-130 km thick (on average) overlying a clear-cut low velocity layer ($\beta_{\mathrm{LID}}$ = 4.65 km/s; $\beta_{\mathrm{LVZ}}$ = 4.30-4.40 km/s). Adding the subchannel, we find the so-called «400 km discontinuity» at about 450 km (however it could be of transitional type).

The Caledonides region displays the same characteristics as the Baltic Sea upper mantle.

The Southern Bothnia-Finland area is characterized by a thin, if any, LVZ ($\beta_{\mathrm{LVZ}}$ = 4.40-4.60 km/s) with a lithosphere about 180 km thick. The deep discontinuity is still at about 450 km.

The northern Bothnia-Finland region has no LVZ ($\beta_{\mathrm{LID}}$ = 4.50 km/s; $\beta_{\mathrm{LVZ}}$ = 4.50-4.80 km/s). The deep discontinuity seems to be at a depth of about 450 km.

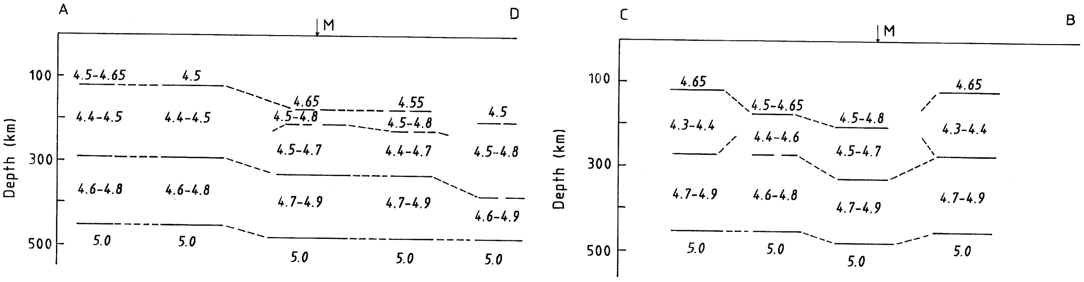


**Fig. 3.** Velocity-depth model of the upper mantle along the lines AD and CB of fig. 2.

The Danish and Southern Norwegian-Swedish areas seem to have intermediate characteristics as the LVZ is concerned ($\beta_{\rm LID}$ = 4.50-4.65 km/s; $\beta_{\rm LVZ}$ = 4.40-4.50 km/s): it is not well developed as in the first two areas. The lithosphere is about 120 km thick. Also in this case the so-called «400 km-discontinuity» seems to be at a depth of about 450 km.

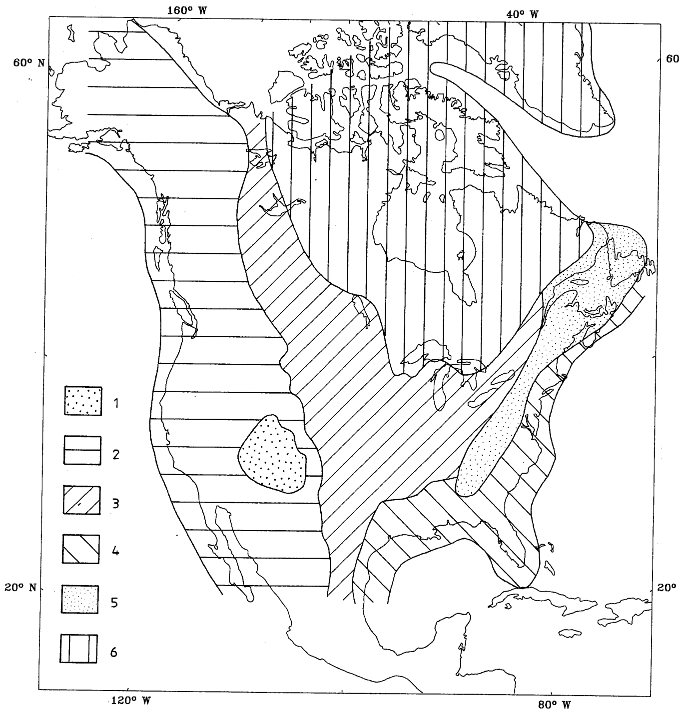
## 3. North American area

In North America over the past years the study of *P*- and *S*-wave velocities in the upper mantle has been the subject of intensive research work using different methodologies, *e.g.*, *S* station anomalies (Wickens and Buchbinder, 1980), waveforms and traveltimes for *S* and *SS* (Grand and Helmberger, 1984; Grand, 1987) and for *P* (Massé, 1987; LeFevre and Helmberger, 1989; Catchings and Mooney, 1991; Beghoul and Mereu, 1992), shear wave splitting (Silver and Chan, 1988), tomographic study (Hearn *et al.*, 1991). To these studies many others based on surface wave dispersion analysis must be added (*e.g.*, Brune and Dorman, 1963; McEvilly, 1964; Biswas, 1971; Wickens, 1971; Biswas and Knopoff, 1974; Godlewski and West, 1977; Okal, 1978; Cara, 1979; Mitchell and Hermann, 1979; Chen, 1985; Al-Khatib and Mitchell, 1991).

However, a global picture of the extent and magnitude of lateral variations in seismic velocity throughout the upper mantle is hard to derive from a comparison of the results of different types of studies in different tectonic regions. No comparable amount of higher mode dispersion data (nor for geographical distribution nor for periods range) is available for North America, as it is for North Europe. Therefore, we attempted to exploit available surface wave dispersion data in order to extract, with the same methodology used in Fennoscandia, the first map of the lithosphere-asthenosphere system showing the distribution of heterogeneity down to a depth of about 200-250 km. For this purpose we carried out a detailed investigation, to the extent tha data permit, of the lithosphere-asthenosphere system in North America by means of the inversion of the Rayleigh wave dispersion relations regionalized following the procedure adopted by Panza *et al.* (1980). This method consists in drawing a set of isophase velocity maps wherefrom regional dispersion relations are extracted (see also Calcagnile, 1982). This procedure minimizes the limitations that are posed by the direct inversion of dispersion curves obtained for paths crossing heterogeneous areas as is the case of the considered area: fig. 4 sketchily shows the very large tectonic variations in North America (Eardley, 1951; Bally *et al.*, 1989).

## 4. Data

Figure 5 shows the long-period seismographic stations used in this study together with the path lines or «profiles» along which the phase velocity of Rayleigh waves has been measured by several authors with the two-sta-



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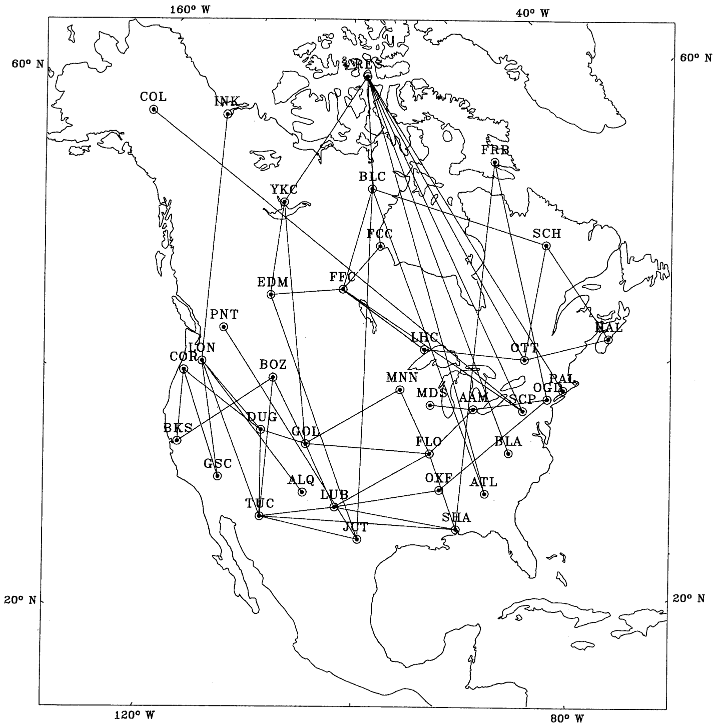

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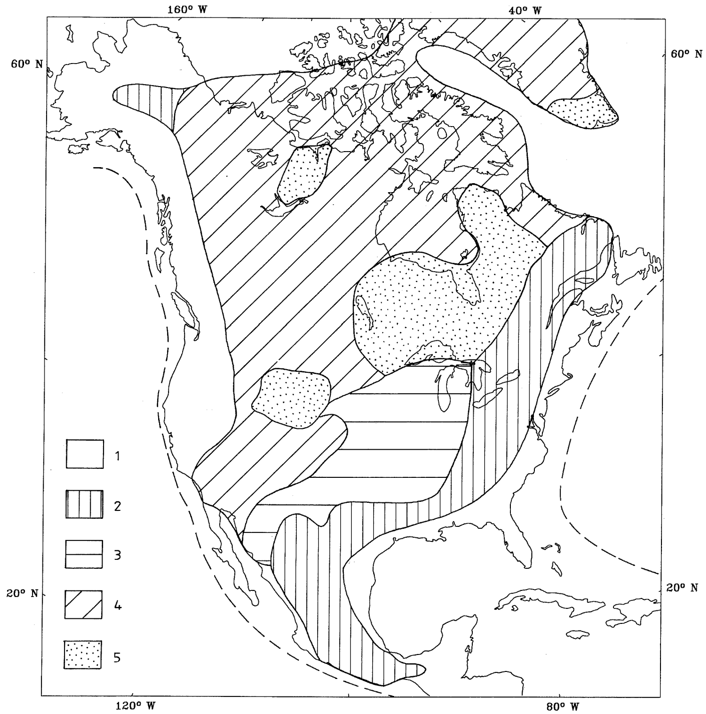
**Fig. 4.** Tectonic map of North America (after Bally *et al.*, 1989, simplified). 1) Colorado Plateau; 2) Cordilleran orogen; 3) Central stable region; 4) Gulf and Atlantic coastal plain; 5) Appalachian belt; 6) Canadian shield.

**Fig. 5.** Long-period seismographic stations and profile coverage.



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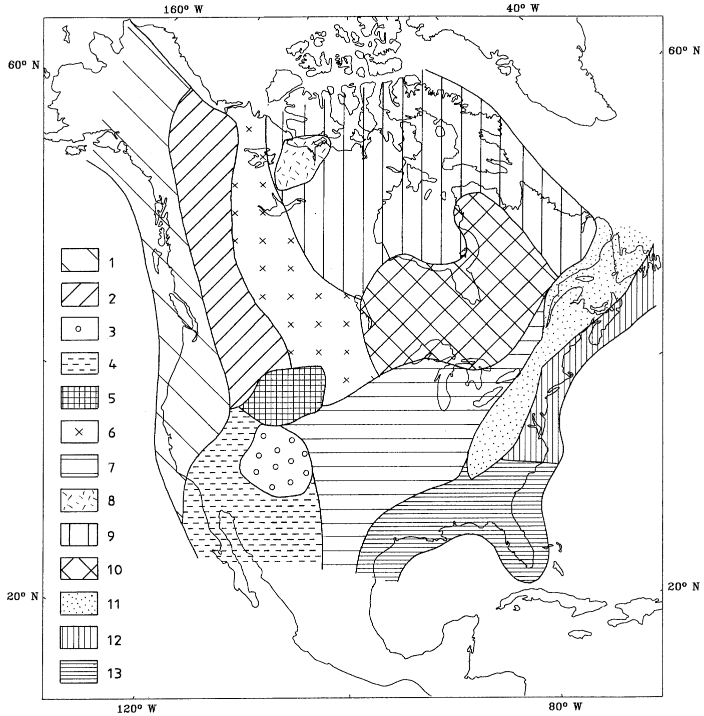

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**Fig. 6.** Major crustal provinces of North America excluding anorogenic provinces (after Condie, 1976, modified). Ages, in billion of years: 1) ≤ 0.7; 2) 0.7-1.2; 3) 1.2-1.5; 4) 1.5-2.5. 5) ≥ 2.5.

**Fig. 7.** Sketch map of the regionalization of the investigated area. 1) Western Cordilleran; 2) Eastern Cordilleran; 3) Colorado Plateau; 4) Southern Cordilleran; 5) Wyoming basin; 6) Northern central stable region; 7) Southern central stable region; 8) Slave; 9) Canadian shield; 10) Superior; 11) Appalachian belt; 12) North Atlantic coastal plain; 13) Gulf and South Atlantic coastal plain.

**Table I.** Seismic station pairs used and reference.

| | |
|---|---|
| Brune and Dorman (1963) | RES-OTT; RES-PAL |
| Wickens (1971) | BLC-FFC; EDM-FFC; FCC-FFC; FFC-LHC; HAL-SCH; OTT-HAL; OTT-LHC; OTT-SCH; RES-BLC; RES-YKC; SCH-BLC; YKC-EDM |
| Biswas and Knopoff (1974) | AAM-FLO; AAM-MDS; BKS-BOZ; FLO-GOL; FLO-LUB; FLO-SHA; GOL-BOZ; GOL-DUG; GOL-MNN; GSC-LON; LUB-GOL; MNN-FLO; OGD-AAM; OGD-OXF; OXF-LUB; SHA-LUB; SHA-TUC; TUC-BOZ |
| Okal (1978) | COL-SCP |
| Chen (1985) | ATL-BLC; ATL-RES; BLA-RES; FFC-SCP; GOL-YKC; JCT-BLC; JCT-PNT; LON-INK; OGD-FRB; SCP-RES; SHA-FRB; TUC-LON |
| Al-Khatib and Mitchell (1991) | ALQ-LON; BKS-COR; COR-GSC; DUG-COR; JCT-EDM; JCT-TUC; LON-DUG; LUB-TUC; TUC-DUG |

tion method. The list of the station pairs is reported in table I with the appropriate references.

The results presented in this paper must be viewed in the light of the station and profile coverage; for example, it is clear that a proper regionalization of phase velocity in North America will require more observations in some areas.

The regionalization has been carried out on the basis of the tectonic map of North America (fig. 4), using crustal radiometric provinces (fig. 6) (Condie, 1976) as a guideline to delineate «homogeneous» subregions (fig. 7); the boundary of the subregions has no actual «geological» meaning, but represents a purely indicative separation of possible different «homogeneous» areas.

Figure 8 shows some examples of isophase velocity maps. The derived phase velocities may differ in detail, especially in view of non-uniqueness of the procedure, although the overall picture does not change significantly within the estimated uncertainty.

In this way dispersion relations shown in fig. 9 were obtained; it is possible to group these dispersion relations into three classes. The highest values, and an almost linear trend in the period range 40-120 s, correspond to the North-Eastern Canada area (top left of the figure); at the opposite extreme (bottom of the figure) the Western America and South Atlantic regions are characterized by the lowest values with a relatively flat portion in the period range 70-100 s; the other regions form a third group which has intermediate characteristics.

## 5. Inversion

The inversion was carried out using the «hedgehog» procedure by Keilis-Borok and Yanovskaya (1967) (*e.g.*, Biswas and Knopoff, 1974). The starting models of the inversion were prepared on the basis of the resolving power of the information contained in the available data (*e.g.*, Panza, 1981).

Average phase velocity values of the whole data set which were used in the inversion step are given in table II together with the associated errors $\varepsilon$. The model is rejected if the difference $\Delta C$ between computed and observed phase velocities exceeds $\varepsilon$ at any individual period, or if the rms difference between the observations and the computations for the parametrized structure is greater than a fixed value $\sigma$. The values of $\varepsilon$ and $\sigma$ are consistent with the precision in the data sets constructed from maps like those in fig. 8.

The mantle parametrization used in the inversion is given in table III. For each region, the average crustal thickness was fixed on the basis of the map given in fig. 10 (Mooney and

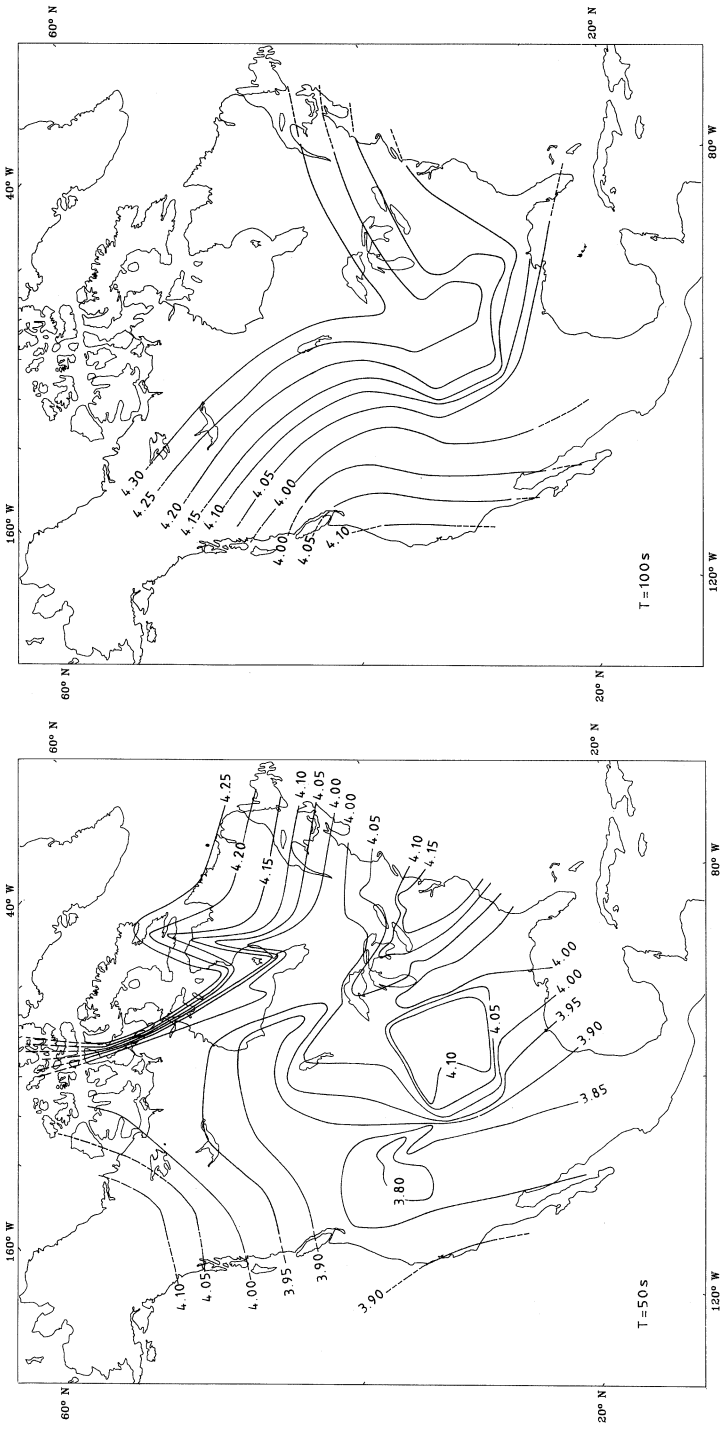


**Fig. 8.** Example of contour lines of equal phase velocity (isotachs) for Rayleigh wave: fundamental mode at 50 s (left) and 100 s (right).

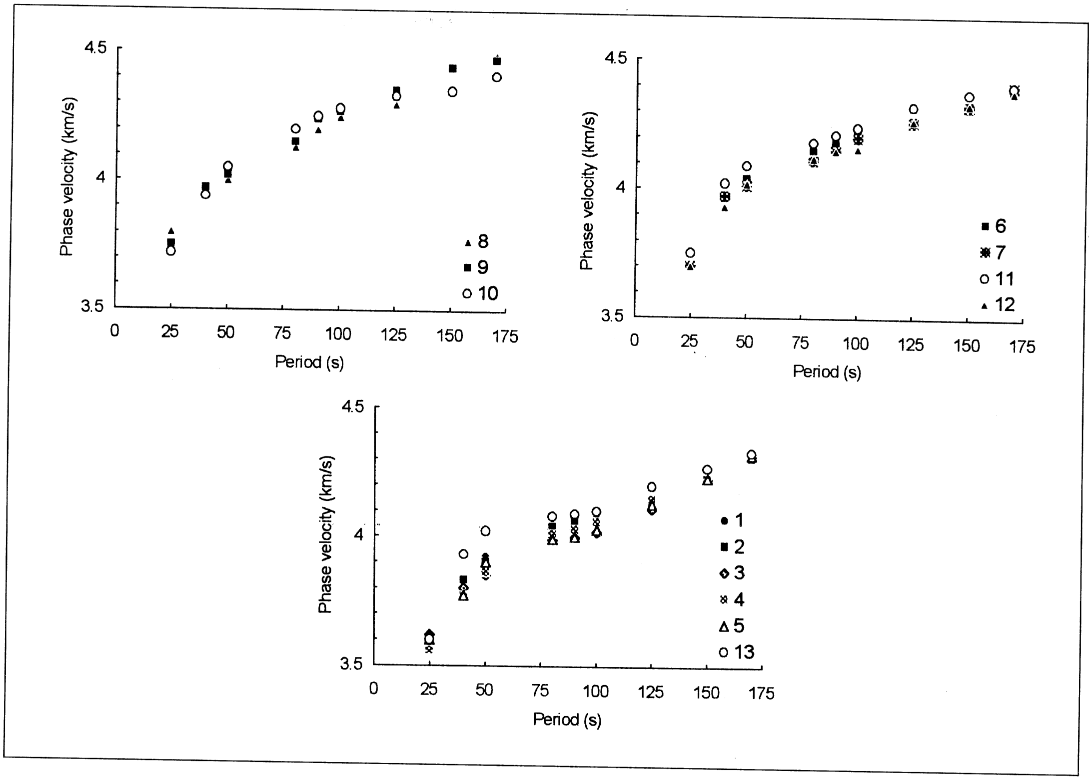


**Fig. 9.** Regional dispersion relations. Numbers identify regional dispersion relations according to the region numbers in fig. 7.

**Table II.** Phase velocities (km/s) and errors $\varepsilon$ (km/s) for different periods $T$(s) used in the inversion for the 13 subregions (see fig. 7).

| $T$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | $\varepsilon$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 25 | 3.58 | 3.60 | 3.62 | 3.56 | 3.60 | 3.70 | 3.70 | 3.80 | 3.75 | 3.72 | 3.75 | 3.70 | 3.60 | 0.08 |
| 40 | 3.83 | 3.83 | 3.80 | 3.77 | 3.77 | 3.97 | 3.97 | 3.95 | 3.97 | 3.94 | 4.02 | 3.93 | 3.93 | 0.06 |
| 50 | 3.92 | 3.90 | 3.85 | 3.86 | 3.90 | 4.04 | 4.01 | 4.00 | 4.02 | 4.05 | 4.09 | 4.02 | 4.02 | 0.06 |
| 80 | 4.05 | 4.04 | 3.99 | 4.01 | 3.99 | 4.15 | 4.11 | 4.13 | 4.15 | 4.20 | 4.18 | 4.12 | 4.08 | 0.06 |
| 90 | 4.07 | 4.06 | 4.00 | 4.03 | 4.00 | 4.18 | 4.15 | 4.20 | 4.24 | 4.25 | 4.21 | 4.15 | 4.09 | 0.06 |
| 100 | 4.09 | 4.10 | 4.02 | 4.06 | 4.03 | 4.21 | 4.20 | 4.25 | 4.27 | 4.28 | 4.24 | 4.16 | 4.10 | 0.06 |
| 125 | 4.15 | 4.13 | 4.11 | 4.15 | 4.13 | 4.27 | 4.26 | 4.30 | 4.35 | 4.33 | 4.32 | 4.27 | 4.20 | 0.06 |
| 150 | 4.23 | 4.23 | 4.23 | 4.23 | 4.23 | 4.33 | 4.32 | 4.44 | 4.44 | 4.35 | 4.37 | 4.33 | 4.27 | 0.08 |
| 170 | 4.32 | 4.31 | 4.32 | 4.32 | 4.32 | 4.39 | 4.40 | 4.49 | 4.47 | 4.41 | 4.40 | 4.39 | 4.33 | 0.08 |

**Table III.** Mantle parametrization used in the inversion; $h_c$ is crustal thickness.

| Depth (km) | Thickness (km) | $\beta$ (km/s) | $\alpha$ (km/s) | $\rho$ (g/cm$^3$) |
|---|---|---|---|---|
| $h_c$ | | | | |
| | P4 | P1 | 8.10 | 3.50 |
| $h_c$ + P4 | | | | |
| | P5 | P2 | 8.45 | 3.40 |
| $h_c$ + P4 + P5 | | | | |
| | 440 – $h_c$ – P4 – P5 | P3 | 8.80 | 3.50 |
| 440 | | | | |
| | 250 | 5.00 | 9.80 | 4.00 |
| 690 | | | | |
| | 400 | 6.10 | 11.15 | 4.40 |
| 1090 | | | | |
| | $\infty$ | 6.40 | 11.80 | 4.60 |

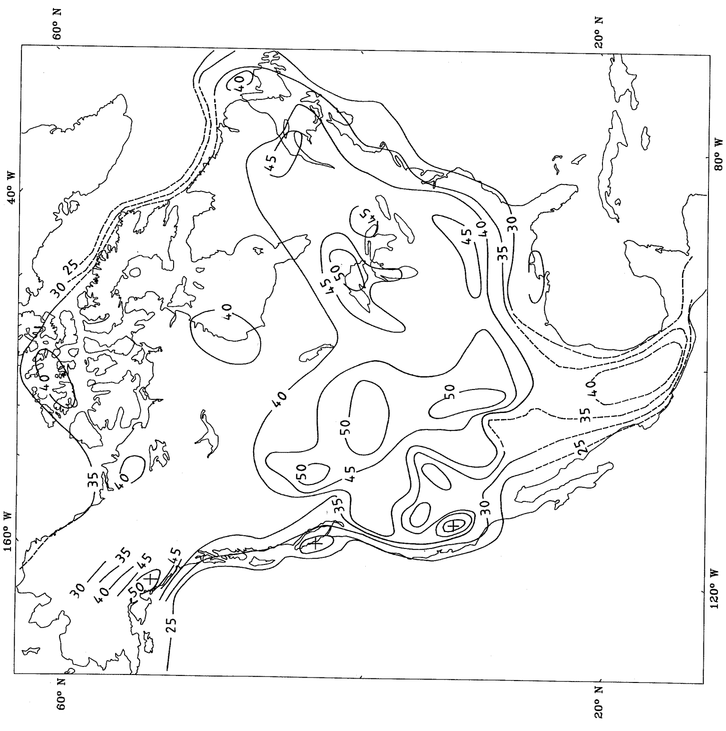
$\sigma = 0.065$ km/s.
Single point rejected if $|\Delta C| > \varepsilon$.

| Parameters | Range |
|---|---|
| P1 (km/s) = $\beta_{\mathrm{LID}}$ | 4.3-4.8 |
| P2 (km/s) = $\beta_{\mathrm{LVZ}}$ | 4.1-4.7 |
| P3 (km/s) = $\beta_{\mathrm{subLVZ}}$ | 4.4-5.1 |
| P4 (km) = $h_{\mathrm{LID}}$ | 5-95 |
| P5 (km) = $h_{\mathrm{LVZ}}$ | 100-250 |

Braile, 1989); the details of the different crustal models are suggested by results of available DSS and relevant geophysical data (*e.g.*, Mooney and Braile, 1989; Braile *et al.*, 1989). Small to moderate fluctuations in crustal properties do not have a significant influence on the results of the inversion for the upper mantle properties at the periods we are dealing with. In general, the density $\rho$ and the compressional wave velocity have been kept fixed in all layers using standard values; however, data from body wave studies have been used whenever possible.

To have a much more immediate insight into the lateral variations in the upper mantle, and henceforth into the depth range of interaction in the area, we have sketched a map of the lithosphere-asthenosphere system in fig. 11. When interpreting this map, it must be borne in mind that it represents only an approximate solution of the inverse problem and is subject to inherent uncertainties, *e.g.*, 15 to 20 km in lithospheric thickness (see Panza, 1981). The first row of each set of numerals refers to the possible range of the average *S*-wave velocity, $\beta$, from the Moho to the depth indicated by isolines (lower lithosphere or lid), while the second row describes the possible range of the average *S*-wave velocity below that depth (upper asthenosphere or low velocity channel); only in areas where a marked contrast exists between the values in the two rows, can the isolines be considered representative of the lithospheric thickness.

From the figure, the presence of strong variations, both in thickness and in *S*-wave velocity, is evident. The older part of the shield area (the old craton) shows maximum lithospheric thickness and no low velocity zone or in the extreme case this is virtually absent, down to a



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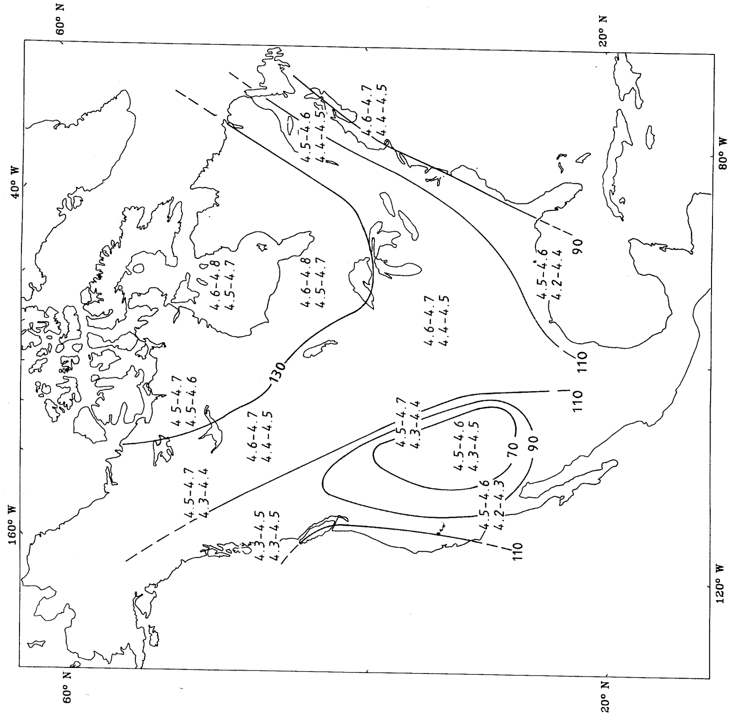

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**Fig. 10.** Map of the average crustal thickness in North America (after Mooney and Braile, 1989, modified).

**Fig. 11.** Schematic map of lithospheric thickness and shear-wave velocities in North America; upper and lower lines indicate, respectively, lid and channel shear-wave velocity.

depth of about 200-250 km. The surrounding areas are characterized by thinner lithosphere in the western and southeastern regions with a relatively well-developed low-velocity zone (excluding the Colorado Plateau-Sierra Nevada area, where low velocity material such as 4.4 km/s may almost rise up to the Moho); in the central stable and eastern regions the contrast may be much milder with higher velocities.

These results area similar to those found in North Europe, both being predrift contiguous parts of Pangea; the more complex picture in the western part of North America might reflect the overriding of North America over the «Pacific Ridge».

## 6. Comparison with other geophysical results

Some qualitative considerations may be drawn from the comparison of our results with other geophysical features, even if a more quantitative approach will be the subject of a forthcoming paper.

If we compare heat-flow values in North America (*e.g.*, Lachenbruch and Sass, 1977, 1980; Mareschal, 1991) and electrical conductivity (*e.g.*, Porath, 1971; Gough, 1973) with lithospheric-asthenospheric structure, we see a rather good correlation of lithospheric thickness and shear-wave velocity distribution with high and low heat-flow values, thus pointing toward a potential deep origin of a significant part of the observed heat-flow features, as well as the association of a decrease in resistivity occurring at some depth ranges with a decrease in shear-wave velocity. This constitutes a rather important argument in favour of the presence of process of partial melting in the upper mantle (on a global scale electrical conductivity and the velocity of *S*-wave of the Earth's mantle are both controlled by thermal conditions, the closer the temperature in the mantle is to the melting point, the lower is the *S*-wave velocity). Similar results have been found in North Europe (*e.g.*, Calcagnile, 1982; Calcagnile and Panza, 1987).

Furthermore, from the comparison of our results with the gravimetric field, isostatic and Bouguer gravity field in North America (Woollard, 1972; Simpson *et al.*, 1986; Hanna *et al.*, 1989), it seems that the general characteristics of the gravimetric data might be correlated with lower velocity in the western part even if one should bear in mind that they have a more complex interpretation, particularly the Bouguer anomalies of crustal-upper mantle origin.

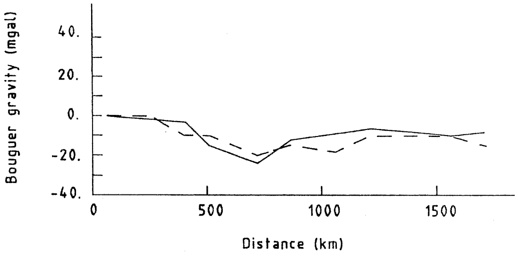

**Fig. 12.** Computed (solid line) and measured (dashed line) Bouguer gravity anomalies along the Fennolora profile area from north to south.

However in North Europe, in the Fennolora area there is a first interesting quantitative result. The inversion of the Bouguer anomalies, characterized by a northwards very weak gradient (about 1 mGal/150 km) and small negative values (about 10 mGal), shows that in order to obtain an acceptable fit with experimental data (fig. 12), we have to assume that the density contrast between lithosphere and asthenosphere must be very low, less than 0.05 g/cm$^3$; no other important lateral density variation is present at greater depths.

## 7. Conclusions

The analysis and subsequent inversion of the available dispersion profiles in North Europe and North America, using the same methodology, have allowed a regionalization of the lithosphere-asthenosphere system which indicates that these areas, in the predrift configuration contiguous parts of Pangea, are characterized by significant lateral heterogeneity in the upper mantle. Namely, the upper mantle in the north-central part of the two areas has no low velocity zone or in the extreme case this is virtually absent, down to a depth of about 200-250 km with a very rapid transition in the lithospheric thickness going from the peripheral area to the central part of the shield.

Moving toward the peripheral area, upper mantle structures with a relatively well-developed low velocity zone or somewhat milder are found; in Western North America, *e.g.*, Colorado Plateau, low velocity material may almost rise up to the Moho. The more complex picture in western North America might possibly reflect its overriding over the «Pacific Ridge».

Due also to the availability of the long period higher mode dispersion data for Fennoscandia, the average bottom of the asthenosphere beneath Fennolora is identified at a depth of about 320 km and the upper mantle structure for the area can be followed down to the so-called «400 km discontinuity» mantle transition that actually seems to be in average at about 450 km, while the inversion results suggest the presence of significant lateral heterogeneity down to depths of about 350 km.

Other geophysical features like heat-flow, gravity anomalies and electrical conductivity correlate qualitatively rather well with the characteristics of the lithosphere-asthenosphere system.

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