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Seismological evidence for a very sharp Sorgenfrei-Tornquist Zone in southern Sweden

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Abstract – A passive seismological experiment across the northern boundary of the Tornquist Fan was carried out from December 1994 until April 1995 along a 100 km long profile in Denmark and Sweden. Observed PS converted seismic waves indicate an abrupt increase in Moho depth of 4–5 km within 5 km horizontal distance at about 50 km to the northeast of the Øresund. This is a much sharper jump than that inferred from the wide-angle data of EUGENO-S line 1. Preliminary analysis of seismic shear wave anisotropy indicates asthenospheric mantle flow parallel to the Sorgenfrei-Tornquist Zone. These parallel directions are already observed between the Elbe Line and the Sorgenfrei-Tornquist Zone while further south in central Europe the flow directions follow the trend of the Alpine belt.

1. Introduction

The Trans-European Suture Zone (TESZ) has been subject of intensive geophysical research especially in the projects EGT (European Geotraverse, e.g. Blundell, Freemann & Mueller, 1992) and BABEL (Baltic and Bothnian Echoes from the Lithosphere, e.g. BABEL working Group, 1993). One previous result we will address in this paper is the crustal thickening towards the northeast across the Sorgenfrei-Tornquist Zone (STZ) (Berthelsen, 1992) inferred from wide-angle seismic data along the EUGENO-S line 1 (EUGENO-S Working Group, 1988; Ansorge, Blundell & Mueller, 1992) located very close to our profile. Another problem we will address is the structure of the asthenosphere in the region of the TESZ and central Europe. The lithospheric thickness was studied by Zielhuis & Nolet (1994) using tomographic methods, by Calcagnile *et al.* (1990) using surface waves, and by Schweitzer (1995) using regional seismic phases. We will address the structure of the asthenosphere in the region of the TESZ and central Europe by studying seismic anisotropy.

2. Data and results

Up to 26 seismic broadband stations of the GeoForschungsZentrum (GFZ) Potsdam were set up along a southwest–northeast profile across the Sorgenfrei-Tornquist Zone in Denmark and Sweden (Fig. 1). The station spacing was about five kilometres. Reftek data loggers and STS-2 and CMG-3 broadband seismometers were used. The data were continuously recorded with 20 samples/sec on 540 Mbyte discs. Discs were changed about every three weeks. The 12 STS-2 stations were operated in Denmark from December 18, 1994 until April 10, 1995. The 14 CMG-3 stations in Sweden

were operated in the period from March 8 until April 20, 1995. All stations were located inside buildings. The main technical problems encountered were malfunctions of battery chargers.

As an example we show the data for the following event:

Origin time: 17 April 1995 07:14:35.2

Location: 33.763N 38.576W Northern Mid-Atlantic Ridge

Figure 1. Location map of seismic broadband stations temporarily deployed across the Sorgenfrei-Tornquist Zone (STZ) in Denmark and Sweden.

Source depth: 10 km

Magnitude: 6.2 M_w

The epicentral distance of station SW01 is 37.6° and the backazimuth is 264.9°.

Figure 2 shows the vertical (Z), radial (R) and transverse (T) components of the P and the S phases of this event, respectively. Each component is plotted on the same amplitude scale to facilitate direct comparison. Only the stations in Sweden were operating at the time. The stations SW01 to SW07 are located on young sediments with Precambrian basement at about 4 km depth, a geological situation similar to that at the locations of the

Figure 2. Broadband records of the stations in Sweden shown in Figure 1 for the event on April 17, 1995. Origin time: 07:14:35.2, epicenter: 33.763N and 38.576W, source depth 10 km, M_w 6.2, Northern Mid-Atlantic Ridge (after PDE Monthly Listing). Top panel: vertical component of the P arrivals, lower panels: radial and transverse components of the S arrival. The waveforms do not change significantly across the Sorgenfrei-Tornquist Zone. There is a clear difference in the seismic noise on the horizontal components at both sides of the Sorgenfrei-Tornquist Zone (between stations SW07 and SW08), caused by a sedimentary layer in the southwest.

stations in Denmark. The stations SW08 to SW14 were located on very thin sediments or directly on the basement rocks of the Scandinavian Shield. Effects of that on the noise conditions can be seen by inspecting the horizontal-component R and T seismograms. The noise prior to the S wave arrival at stations SW01 to SW07 is clearly much higher than at stations SW08 to SW14, while there are no differences in the noise conditions on the vertical component seismograms. Stations SW08 to SW14 reach about 30 km into the Scandinavian Shield and the stations SW01 to SW07 reach about the same distance away from the shield border into the sediment covered area with deep basement. In this distance range of about ± 30 km to both sides of the shield border we see no significant change of the waveforms of the P and S phases on the Z, R and T components, respectively (Fig. 2), as could be expected to occur across such a major geological heterogeneity as the border of the Scandinavian Shield.

2.a. Converted phases

The receiver function technique is commonly used for studies of the shear wave velocity structure of the lithosphere. A description of the method and an application to the stations of the German Regional Seismic Network (GRSN) was given by Kind, Kosarev & Petersen (1995). In this technique use is made of P waves from distant events. Part of the P wave signal is converted to S waves at the Moho and crustal interfaces. The PS converted phases are identified on Q-component seismograms or receiver functions, that is, the component perpendicular to the incident P wave and lying in the vertical plane through station and epicentre. Since the method uses

Figure 3. Receiver functions for the same event as in Figure 2 recorded at the stations in Sweden. Times are relative to the maximum of the deconvolved P wave signal at zero time. The PS converted phases from the Moho are marked by the dashed lines between about 4 and 5 seconds. The jump in the Moho is clearly visible between stations SW07 and SW08, the location of the Sorgenfrei-Tornquist Zone. The stations SW01 to SW07 show effects of the sedimentary layer also. The PS conversion at the base of the sedimentary cover is marked by the long dashes between zero time and 1 second.

teleseismic waves arriving with a very steep angle of incidence, the lateral resolution is higher than in the wide-angle seismic method. The result of the processing of the data is shown in Figure 3. Two phases can be identified, one originating from the base of the sediments, and one originating from the Moho.

The conversion at the bottom of the sediments can only be seen at the stations SW01 to SW07 at arrival times of less than 1 sec. There is no energy at this time at the stations SW08 to SW14, which suggests that underneath these stations basement practically reaches the surface. This is a second indication that the Sorgenfrei-Tornquist Zone is located exactly between the stations SW07 and SW08 and that it is a very sharp feature with rapid lateral changes in between 5 km or less. The first indications were the changing seismic noise conditions between these stations (see Fig. 2).

The second major feature in Figure 3 is the conversion at the Moho arriving between 4 and 5 seconds after P. This phase can clearly be seen in all traces. The arrival time difference of this phase relative to P decreases by

Figure 4. Receiver functions (top) and P wave signals (bottom) of the event described in Figure 2 observed at a number of European broadband stations (the station locations are shown in Fig. 5). The PS Moho conversion is observed at each station in the top panel.

about 0.5 sec between SW01 and SW07, indicating a rising Moho. There is a jump of the Moho conversions between SW07 and SW08 of about 0.5 sec. This is evidence for a sudden 4–5 km increase of Moho depth to the northeast within less than 5 km horizontal distance followed by a slight further increase of the Moho depth towards SW14. An explanation of the jump in the Moho conversions by a change in average crustal velocities would require higher velocities beneath stations SW01 to SW07 compared to stations SW08 to SW14. Because of the absence of low-velocity sedimentary layers beneath the latter stations this explanation is regarded as unlikely. The EUGENO-S data (EUGENO-S Working Group, 1988; Ansorge, Blundell & Mueller, 1992) also show an increase of the Moho depth towards the northeast at the Sorgenfrei-Tornquist Zone, however, we infer from our data a much sharper, possibly a fault-like step.

We have also searched for the Moho conversions at records of the same event at permanent European broadband stations. This was done to confirm that these observations are indeed caused by effects underneath the station and not somewhere else. Figure 4 shows the data for these records. The Q component records (top, PS converted energy) clearly show at all stations a Moho conversion indicating the crustal thickness at each station. The stations are sorted by increasing Moho depth from TNS to KONO. The station KONO has a very similar Moho depth (40–50 km) to the stations SW08 to SW14 in Figure 3 (5–6 seconds conversion time). There is no energy on the L component (bottom Fig. 4, P energy) at the time of the Moho conversion on the Q component, indicating that this observation is really caused by a PS conversion under the station. The time variations of the Moho conversions are also an argument against source effects. The results shown in Figures 3 and 4 also indicate that it is possible to obtain easily estimates of crustal thickness beneath seismograph stations.

2.b. Anisotropy observations

Seismic anisotropy is thought to be an indicator of mainly asthenospheric mantle flow. Bormann *et al.* (1996) have discussed central European anisotropy directions in relation to the influence of the Alpine Belt and the East European Platform on the asthenospheric flow. The clearest way to observe mantle anisotropy is to use the splitting of SKS waves. However, in the operational period of our experiment we did not observe SKS phases with sufficient signal-to-noise ratio. Therefore we attempted to use relative information obtained from shear wave polarizations of mantle S waves from the same event discussed so far, also observed at a number of European stations with known anisotropy properties. Figure 5 shows the particle motion diagrams of the S phases recorded at European seismic broadband stations. Most stations belong to the German Regional Seismic Network (GRSN) and to the GEOFON network of the GFZ and of partner institutions.

Figure 5. Map of central European broadband stations and particle motion diagrams of the mantle S phase of the event shown in Figure 2. The particle motion diagrams can roughly be divided into two groups, northeast and southwest of the line connecting the two dashed arrows. This is very likely caused by a change in the direction of mantle anisotropy.

The particle motion diagrams in Figure 5 can clearly be divided into two groups. One group has linear particle motion in an east–west direction (all diagrams to the left of Fig. 5 with the exception of WLF) and the other group has elliptical polarization with the long axis oriented 75° to 90° from north to east (right of Fig. 5). The Elbe Line is roughly dividing both groups. This could indicate that asthenospheric flow directions change along the Elbe Line and not along the TESZ. There is possibly no significant change across the TESZ in the asthenospheric flow pattern. This is supported by preliminary results obtained from SKS for the GEOFON station SUW (Perchuc, Wylegalla & Bock, pers. comm.) that indicate a value near 110° for the fast anisotropy direction, which agrees with directions to the south of the TESZ (Vinnik *et al.* 1994). Although the GRSN stations closest to the TESZ (HAM and BRNL) are very noisy, the particle motion there is similar to that at the neighbouring stations of the GRSN. The stations KONO and SW14 are located on the Scandinavian Shield and they show similar polarization to that of the neighbouring GRSN stations in northeast Germany. The polarization of S does not depend on the

backazimuth and distance of each station, indicating that source or source side polarization is an unlikely cause.

Vinnik *et al.* (1994) and Brechner (S. Brechner, unpub. Dipl. thesis, Univ. Erlangen, 1996) have determined anisotropy parameters for the stations of the GRSN network. They found a trend of the fast polarization axis (meaning asthenospheric flow direction) in the southwestern part of the network of 50–70° and in the northeastern part of 100–120°. The splitting between these two different directions roughly follows the Elbe Line. Our observations of particle motions in Figure 5 confirm the existence of such a division along the Elbe Line. The TESZ does not seem to be the dominant dividing feature in the anisotropy. However, it is still too early for a final discussion as the data across the TESZ are insufficient.

3. Conclusions

We draw the following geological conclusions from our seismological data:

The northeastern limit of the Sorgenfrei-Tornquist zone (STZ) in Sweden is characterized by two main seis-

mological features. First, a sharp fault-like step in the Moho was resolved with the downthrown side of the Moho being located 4–5 km deeper to the northeast. Second, the significant near-surface sedimentary layer to the southwest ends directly at the same surface position where the Moho step is observed. Both these features are located about 50 km northeast of the Øresund.

Asthenospheric mantle flow seems to be parallel to the TESZ between the Elbe Line and across the Sorgenfrei-Tornquist Zone. So far there are only insufficient data on anisotropy on the Scandinavian Shield. Asthenospheric mantle flow to the southwest of the Elbe Line is dominated by the Alpine orogeny.

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References

- ANSORGE, J., BLUNDELL, D. & MUELLER, ST. 1992. Europe's lithosphere – seismic structure. In *A Continent revealed* (eds D. Blundell, R. Freeman and St. Mueller), pp. 33–69. Cambridge: Cambridge University Press.
- BABEL WORKING GROUP 1993. Deep seismic reflection/refraction interpretation of crustal structure along BABEL profiles A and B in the southern Baltic Sea. *Geophysical Journal International* **112**, 325–43.
- BERTHELSEN, A. 1992. From Precambrian to Variscan Europe. In *A Continent revealed*, (eds D. Blundell, R. Freeman and St. Mueller), pp. 153–64. Cambridge: Cambridge University Press.
- BLUNDELL, D., FREEMAN, R. & MUELLER, ST. (eds) 1992. *A Continent revealed*. Cambridge: Cambridge University Press, 275 pp.
- BORMANN, P., GRÜNTAL, G., KIND, R. & MONTAG, H. 1996. Upper mantle anisotropy beneath central Europe from SKS wave splitting: effects of absolute plate motion and lithosphere–asthenosphere boundary topography? *Journal of Geodynamics* **22**, 11–32.
- CALCAGNILE, G., BERRY, P., DEL GAUDIO, V. & MUELLER, S. 1990. A two-dimensional velocity model for the upper mantle beneath FENNOLOGRA from seismic surface waves and body waves. In *The European Geotraverse – Integrative Studies* (eds D. Blundell, R. Freeman and S. Mueller), pp. 49–66. Strasbourg: European Science Foundation.
- EUGENO-S WORKING GROUP 1988. Crustal structure and tectonic evolution of the transition between the Baltic Shield and the North German Caledonides (the EUGENO project). *Tectonophysics* **150**, 253–348.
- KIND, R., KOSAREV, G. L. & PETERSEN, N. V. 1995. Receiver functions at the stations of the German Regional seismic Network (GRSN). *Geophysical Journal International* **121**, 191–202.
- SCHWEITZER, J. 1995. Blockage of regional seismic waves by the Teisseyre-Tornquist Zone. *Geophysical Journal International* **123**, 260–76.
- VINNIK, L. P., KRISHNA, V. G., KIND, R., BORMANN, P. & STAMMLER, K. 1994. Shear wave splitting in the records of the German Regional Seismic Network. *Geophysical Research Letters* **21**, 457–60.
- ZIELHUIS, A. & NOLET, G. 1994. Shear-wave velocity variations in the upper mantle beneath central Europe. *Geophysical Journal International* **117**, 695–715.