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Upper mantle anisotropy at the transition zone of the Saxothuringicum and Moldanubicum in southeast Germany revealed by shear wave splitting

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SUMMARY

The main structures of the mid-European lithosphere, crossing Europe from the Iberian peninsula to the Bohemian Massif, are predominantly formed by the Variscan orogeny. To investigate the anisotropy of the mantle at the transition zone between the two Variscan units, the Saxothuringicum and the Moldanubicum, we carried out a field experiment in SE Germany in 1995–1996: 23 mobile broad-band stations were installed for 6 months in the Vogtland–Oberpfalz–Bavarian Forest area. The station profile crossed the suture zone of the Saxothuringicum and Moldanubicum near the KTB borehole (German Continental Deep Drilling Program). With a mean station spacing of about 10 km, we intended to obtain a high lateral resolution of the anisotropy parameters and to resolve possible changes when passing the suture zone. The analysis of the observed birefringence of *SKS* phases shows E–W directions for the fast polarization. Therefore, the directions deviate only slightly from the strike of the Hercynian mountain belt and from the direction of the absolute plate motion in that region. Indications for the transition zone come from a rotation of the fast polarization direction from $86^\circ \pm 13^\circ$ in the northern part of the profile (Saxothuringicum) to $110^\circ \pm 15^\circ$ in the southern part (Moldanubicum) as well as from strong variations of the splitting parameters with respect to the azimuths of the incoming waves in the middle of the profile. We interpret these variations as an expression of a complex mantle structure formed either by several anisotropic layers with inclined symmetry axes in at least one layer or by a model consisting of inhomogeneous anisotropic layers. A comparison of the azimuthal variations of the splitting parameters in the middle of the profile with those observed at the Gräfenberg station GRA1—situated in the central part of the transition zone approximately 100 km to the west—shows remarkable differences, which may reflect lateral variations in the direction and inclination of the symmetry axes in the transition zone even on a small scale.

Both observations—the change in the fast polarization direction from the northern to the southern part as well as the variations with respect to different azimuths in the middle of the profile—suggest that the transition zone between the Saxothuringicum and the Moldanubicum continues down into the upper mantle.

Key words: anisotropy, Moldanubicum, Saxothuringicum, shear wave splitting, *SKS* phases.

INTRODUCTION

Nowadays, it is widely accepted that seismic anisotropy is a characteristic and important feature of the upper mantle. Diagnostics for an anisotropic medium are azimuthally varying phase velocities or shear wave splitting. In order to resolve the anisotropic properties of the upper mantle, most studies make use of the shear wave splitting of *SKS* or *SKKS* phases (e.g. Vinnik *et al.* 1984, 1992; Kind *et al.* 1985; Silver & Chan 1991; Barruol *et al.* 1997). These core phases are very suitable for resolving mantle anisotropy, since they are free of anisotropic effects from the source-side leg of the ray path and yield good lateral resolution due to their near-vertical incidence at the receiver. However, a shortcoming of the near-vertical incidence is that no constraints can be placed on the depth of the anisotropy. This is also one reason for the ongoing debate about whether the observed anisotropy is related to present-day flow of mantle material in the asthenosphere or to fossil anisotropy in the lithosphere.

The observation of azimuthally varying splitting parameters in several regions of the world requires more complex models than the usually assumed model of one anisotropic layer of transverse isotropy with a horizontal symmetry axis. Silver & Savage (1994) derived analytic expressions for the apparent splitting parameters in the case of two anisotropic layers with different azimuths of horizontal symmetry axes. They were able to fit the azimuthally varying splitting parameters at several stations near the San Andreas fault with a two-layer anisotropy model. Alsina & Snieder (1995), however, explained azimuthally varying splitting parameters at several Netherlands stations by laterally varying anisotropy. A third model was proposed by Sileny & Plomerova (1996) and Plomerova *et al.* (1996). They derived an inversion method to retrieve 3-D anisotropic structures with inclined hexagonal or orthorhombic symmetry axes. Another possible explanation for azimuthally varying splitting parameters was given by Rümpker & Silver (1998). They showed that in the presence of smooth vertically varying anisotropy the apparent splitting parameters are frequency-dependent and azimuthally varying.

In this paper we investigate the anisotropy of the upper mantle at the suture zone between the Saxothuringicum and the Moldanubicum in SE Germany (the Vogtland–Oberpfalz–Bavarian Forest region). The Saxothuringicum and the Moldanubicum are the main tectonic parts of the European Variscides. The European Variscides, crossing Europe from the Iberian peninsula to the Bohemian Massif, were formed between 500 and 250 Myr ago when Gondwana-derived continental fragments of terranes were accreted to the southern margin of Laurasia along prominent collision zones (Ziegler 1984). One prominent collision zone of the Variscan orogeny is the Moldanubian–Saxothuringian transition zone. From geology and seismic reflection profiles, there are indications for a crustal overthrusting of the Moldanubicum onto the Saxothuringicum (Bortfeld *et al.* 1988; Vollbrecht *et al.* 1989). Here, we address the question whether the suture zone of both Variscan units can also be detected in the mantle by analysis of shear wave splitting.

Several studies have already dealt with anisotropy of the upper mantle at the transition zone between the Saxothuringicum and the Moldanubicum in SE Germany and the adjacent area in the Czech Republic. For example Vinnik *et al.* (1994) and Brechner *et al.* (1998) inferred splitting parameters for the Gräfenberg array and the German Regional Seismic Network. Plomerova et al. (1996, 1998) performed a joint analysis of *P*-residual spheres and inversion of shear wave splitting parameters for stations in the Czech Republic and in SE Germany, resulting in a 3-D anisotropic model of the subcrustal lithosphere.

In the first part of the present paper, the field experiment in 1995–1996 in SE Germany is described. The second part gives an overview of the data analysis. After the presentation of the results in the third part, they are discussed in terms of the complex models mentioned above.

FIELD EXPERIMENT

In order to investigate anisotropy at the transition zone between the Saxothuringicum and the Moldanubicum, 23 mobile three-component broad-band stations (A01–A23) were installed from autumn 1995 to spring 1996 in the Vogtland, Oberpfalz and Bavarian Forest region (Fig. 1). The stations formed an approximately 200 km long and roughly N–S-orientated profile that crossed the suture zone, known at crustal depths, in the middle of the profile close to the KTB. With a station spacing of about 10 km we intended to achieve a high lateral resolution and to resolve possible changes of the anisotropy parameters when passing the transition zone. All stations of the experiment were equipped with REFTEK data loggers and the seismometers were either STS2 or GURALP 3T with the exception of one GURALP 40T seismometer. They were running in continuous mode with a sample rate of 20 Hz. The stations of the experiment were complemented by the three-component stations of the Gräfenberg array (GRA1, GRB1, GRC1), by the surrounding stations of the German Regional Seismic Network (BRG, FUR, MOX, WET), by the three-component station of the GERESS array (GEC2) and by the stations of the KTB (NOTT, ROTZ, FALK, NAPF), which unfortunately were only partially in operation during the period of our experiment.

DATA ANALYSIS

SKS phases can be observed without interference from other main phases at epicentral distances between 85° and 130°. The seismic events of our study have been selected and extracted using the PDE catalogue of the US Geological Survey (USGS). We have taken into account all events of magnitude greater than 5.6 in the distance range mentioned that occurred during the installation period of our stations. Altogether, there are 77 events; their locations are plotted in Fig. 2. In order to improve the signal-to-noise ratio, all records were bandpass filtered with a three-pole Butterworth filter between 5 and 30 s. Furthermore, the horizontal components were rotated into radial and transverse components. Phase identification was performed by calculating the phase arrivals using the IASPEI91 tables (Kennett 1991).

Several of the selected events exhibit only weak *SKS* phases or *SKS* onsets distorted by scattering or other noise, and many do not even show an *SKS* phase at all. For only three events were clear and isolated *SKS* phases on the radial component and *SKS* energy on the transverse component observed that allowed us to determine reliable splitting parameters. We also looked for so-called 'null' events, that is, events with an energetic *SKS* phase on the radial and no *SKS* phase on the transverse component. For a reliable determination of null events, a signal-to-noise ratio for the *SKS* on the transverse component of about 5 is required. After careful inspection we did not find any null events. Also, we did not observe any clear splitting of *SKKS*.

Table 1 lists the epicentral parameters of the three events that yielded reliable splitting parameters. Since some of the stations of the KTB network were also in operation in the beginning of 1995, we were able to infer splitting parameters for the KTB stations for another three events, which are also shown in Table 1. Altogether, we obtained 78 individual estimates of splitting parameters (Tables 2 and 3).

Table 1. Events that yield reliable splitting parameters. Epicentres are taken from the PDE catalogue. Baz denotes the mean azimuth to the stations of the field experiment.

Event	Date	Time, UT	Latitude, °N	Longitude, °E	z (km)	m_b	baz
Molucca	Feb. 28, 1996	09:44:08.7	1.711	126.107	100	6.1	70.3
Honshu	Mar. 16, 1996	22:04:06.1	29.002	138.966	476	5.9	44.6
Chile	Apr. 19, 1996	00:19:31.8	−23.744	−69.961	49	6.0	248.7
Samar	Apr. 21, 1995	00:34:46.2	12.169	125.485	23	6.3	64.4
Peru	May 2, 1995	06:06:06.0	−3.829	−76.942	104	6.5	266.9
Chile	Nov. 1, 1995	00:35:32.4	−28.943	−71.390	20	6.3	246.1

To determine the splitting parameters ϕ (the azimuth of fast polarization) and δt (the delay time between split waves), we used the well-known method of Vinnik *et al.* (1984, 1992). In their approach it is assumed that the seismic anisotropy is homogeneous in a single horizontal layer with a horizontal symmetry axis, that the anisotropy is weak and that the medium is transversely isotropic. For such a medium the transverse component of the *SKS* phase behaves in a similar manner to the

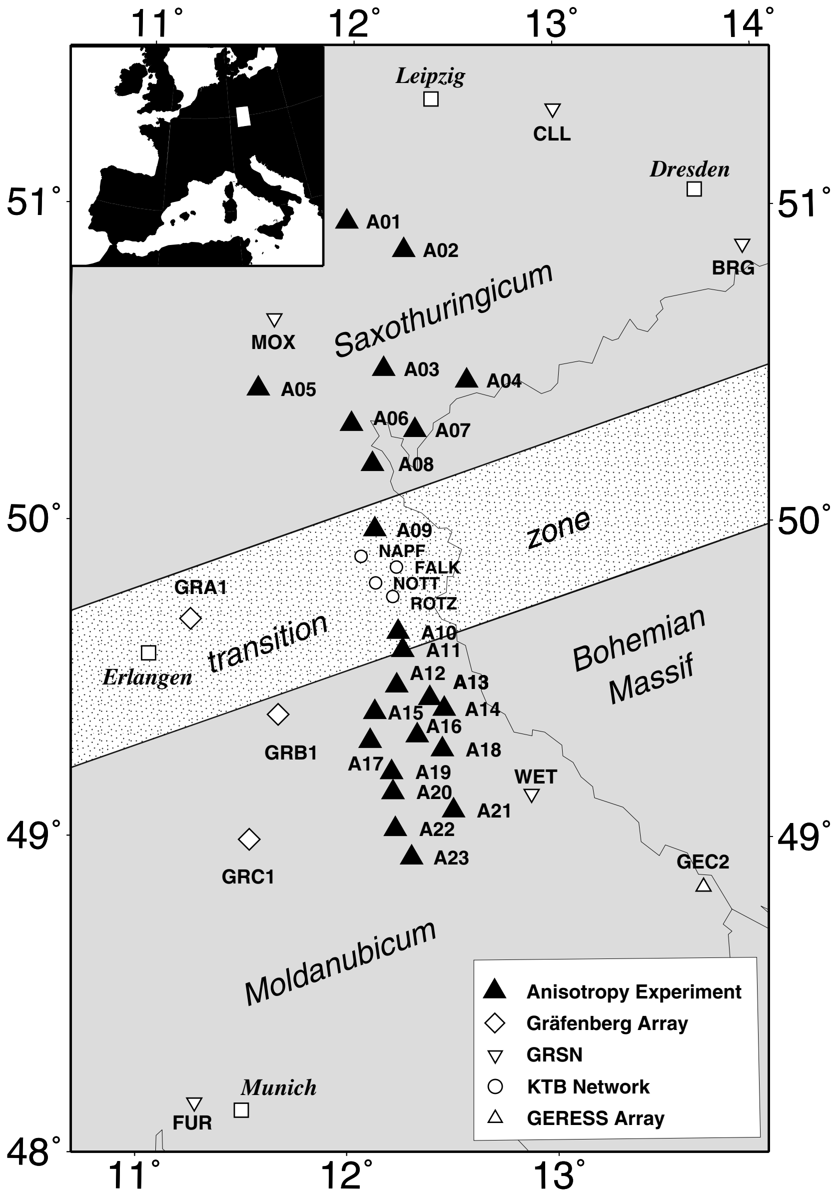

Figure 1. Locations of the 23 temporary broad-band stations of the field experiment in SE Germany (black triangles). They are complemented by the permanent three-component stations of the Gräfenberg array (open diamonds), the surrounding stations of the German Regional Seismic Network (GRSN) (inverted triangles), the stations at the KTB (open circles) and the broad-band station of the GERESS array (open triangle). A rough scheme of the Saxothuringicum and Moldanubicum tectonic units is given. The thin black line denotes the border between Germany and the Czech Republic.

Table 2. Splitting parameters for all stations.

No.	Station	Event	ϕ (°)	δt (s)
1	A02	Honshu, 1996 March 16	64	0.60
2	A02	Molucca, 1996 February 28	248	0.75
3	A03	Chile, 1996 April 19	92	1.15
4	A03	Honshu, 1996 March 16	82	0.90
5	A03	Molucca, 1996 February 28	92	0.75
6	A04	Honshu, 1996 March 16	84	1.35
7	A04	Molucca, 1996 February 28	110	0.80
8	A05	Honshu, 1996 March 16	76	1.35
9	A05	Molucca, 1996 February 28	86	1.05
10	A06	Chile, 1996 April 19	82	1.60
11	A06	Honshu, 1996 March 16	84	0.95
12	A06	Molucca, 1996 February 28	99	1.60
13	A07	Chile, 1996 April 19	84	2.40
14	A07	Honshu, 1996 March 16	74	1.15
15	A07	Molucca, 1996 February 28	90	1.65
16	A08	Honshu, 1996 March 16	100	1.05
17	A08	Molucca, 1996 February 28	120	0.40
18	A09	Chile, 1996 April 19	78	2.10
19	A09	Honshu, 1996 March 16	82	0.95
20	A09	Molucca, 1996 February 28	153	2.40
21	A10	Chile, 1996 April 19	104	1.20
22	A10	Honshu, 1996 March 16	62	1.65
23	A10	Molucca, 1996 February 28	151	0.95
24	A11	Chile, 1996 April 19	98	1.30
25	A11	Honshu, 1996 March 16	74	1.20
26	A11	Molucca, 1996 February 28	143	0.90
27	A12	Chile, 1996 April 19	94	1.40
28	A12	Honshu, 1996 March 16	96	0.90
29	A12	Molucca, 1996 February 28	137	0.85
30	A13	Chile, 1996 April 19	116	1.20
31	A13	Molucca, 1996 February 28	131	0.80
32	A14	Chile, 1996 April 19	116	1.20
33	A15	Chile, 1996 April 19	112	2.35
34	A15	Honshu, 1996 March 16	106	1.20
35	A15	Molucca, 1996 February 28	122	1.45
36	A16	Chile, 1996 April 19	136	1.50
37	A16	Honshu, 1996 March 16	104	0.95
38	A17	Chile, 1996 April 19	86	1.90
39	A17	Honshu, 1996 March 16	100	1.15
40	A17	Molucca, 1996 February 28	106	0.80
41	A18	Chile, 1996 April 19	98	1.50
42	A18	Honshu, 1996 March 16	110	1.45
43	A19	Chile, 1996 April 19	92	1.60
44	A19	Honshu, 1996 March 16	106	1.45
45	A19	Molucca, 1996 February 28	135	0.65
46	A20	Chile, 1996 April 19	98	1.70
47	A20	Molucca, 1996 February 28	126	0.90
48	A21	Chile, 1996 April 19	116	1.05
49	A21	Honshu, 1996 March 16	98	1.55
50	A23	Chile, 1996 April 19	88	1.55
51	A23	Honshu, 1996 March 16	110	1.80
52	A23	Molucca, 1996 February 28	106	0.90
53	ROTZ	Honshu, 1996 March 16	81	0.60
54	ROTZ	Chile, 1996 April 19	106	0.95
55	NOTT	Samar, 1995 April 21	162	1.75
56	NOTT	Peru, 1995 May 2	86	1.25
57	NOTT	Honshu, 1996 March 16	67	1.25
58	FALK	Chile, 1995 November 1	126	1.20
59	FALK	Chile, 1996 April 19	94	1.35
60	GEC2	Chile, 1996 April 19	117	1.40
61	GRA1	Chile, 1996 April 19	90	0.80
62	GRA1	Molucca, 1996 February 28	93	0.85
63	GRA1	Honshu, 1996 March 16	62	1.25
64	GRB1	Chile, 1996 April 19	92	0.80
65	GRB1	Molucca, 1996 February 28	141	0.80
66	GRB1	Honshu, 1996 March 16	114	1.20
67	GRC1	Chile, 1996 April 19	92	0.80
68	GRC1	Honshu, 1996 March 16	78	1.30
69	MOX	Chile, 1996 April 19	82	1.80
70	MOX	Honshu, 1996 March 16	82	1.45
71	MOX	Molucca, 1996 February 28	86	1.55
72	WET	Chile, 1996 April 19	126	1.40
73	WET	Honshu, 1996 March 16	82	1.35
74	WET	Molucca, 1996 February 28	126	0.60
75	BRG	Chile, 1996 April 19	90	1.05
76	BRG	Molucca, 1996 February 28	92	1.80
77	FUR	Honshu, 1996 March 16	66	1.05
78	FUR	Molucca, 1996 February 28	174	2.20

derivative of the radial component. Based on that relationship and using a grid search procedure, in which the splitting parameters are varied over the entire model space, the best-fitting splitting parameters are found by minimizing the difference between synthetic and observed transverse components in a least-squares sense.

An example of a splitting analysis of *SKS* phases for a station in the northern (A03) and in the southern parts (A19) of the profile is given in Fig. 3 for the 1996 February 28 Molucca event. The best fit between synthetic and observed transverse *SKS* is found for $\phi=92°$ and $\delta t=0.75$ s at station A03 and for $\phi=135°$ and $\delta t=0.65$ s at station A19. The contour lines in Fig. 3 offer the possibility of estimating relative errors. Absolute errors are difficult to quantify due to the highly non-linear relationship between the seismograms and the splitting parameters. Based on our *SKS* analysis for the Gräfenberg station GRA1 (Brechner *et al.* 1998), in which we assigned errors in terms of the variances that we obtained for averaged splitting

Table 3. Splitting parameters for those stations of the German Regional Seismic Network (BRG, FUR) and for station GEC2 that are not shown in Fig. 4. The results are from this study and from the work of Brechner *et al.* (1998).

Station	No. of obs.	Range of ϕ (°)	Range of δt (s)	Source
BRG	2	90, 92	1.05, 1.80	this study
BRG	10	88–106	1.05–2.40	Brechner *et al.* (1998)
FUR	2	66, 174	1.05, 2.20	this study
FUR	9	55–175	0.70–2.25	Brechner *et al.* (1998)
GEC2	1	117	1.40	this study

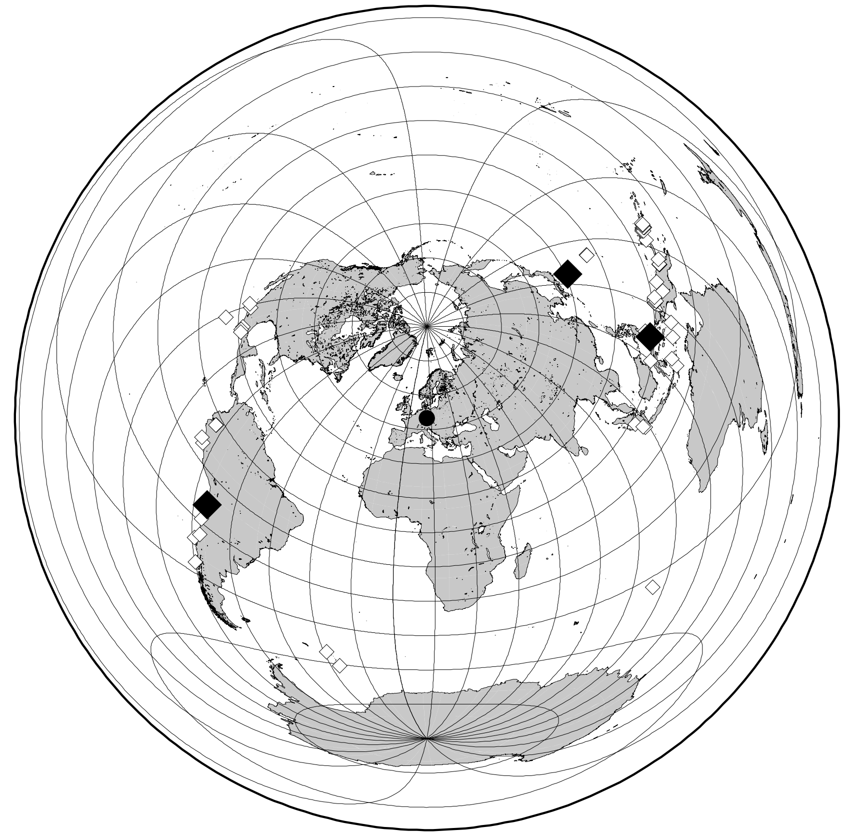

Figure 2. Epicentres of earthquakes (open rhombs) with magnitude >5.6 that occurred during the operation period of the field experiment at epicentral distances between 85° and 130° from the stations of the field experiment. Large black rhombs show those events that were used to determine the splitting parameters for nearly all stations. The black circle denotes the centre of the stations of the field experiment.

parameters for small azimuth ranges with several observations, we estimate the error bars to be smaller than $\pm 15°$ for the fast polarization direction and ± 0.5 s for the delay times.

RESULTS

In this section the estimated splitting parameters for the individual stations are presented. Fig. 4 shows the splitting parameters of the first three events in Table 1 for the stations of the temporary experiment and for most of the surrounding stations. The following characteristics are of interest.

The northern stations (A01–A08) and station MOX exhibit ENE–WSW to ESE–WNW fast polarization directions. The mean azimuth is $86° \pm 13°$ (1σ standard deviation). Delay times vary between 0.6 and 2.4 s; the mean delay time is 1.21 ± 0.46 s. In contrast to the northern stations, the southern stations (A12–A23) and station GRB1 show E–W to SE–NW fast polarization directions. The mean value for the fast polarization is $110° \pm 15°$ and the mean delay time is 1.27 ± 0.41 s. It is obvious that the variations of the fast polarization direction with respect to the different azimuths of the incoming waves in the southern part are slightly more pronounced than in the northern part. In the middle of the profile (A09, A10, A11 and KTB stations), strong variations of the fast polarization directions are observed. The ϕ-direction varies by up to 90°. Therefore, a calculation of a mean value would be meaningless. The splitting parameters for the stations of the GRSN located just outside the central region of our investigation (FUR, BRG, CLL) and for the broad-band station of the GERESS array GEC2 are given in Table 3. For these stations Table 3 also shows the results of a study by Brechner *et al.* (1998), which are based on a greater number of observations. The ϕ–values of our study for stations in the northern part (BRG, CLL) are in the range $90° - 104°$. For station BRG both the ϕ-values and the delay times are in agreement with the measurements by Brechner *et al.* (1998). At station FUR the two events investigated exhibit strongly differing splitting parameters, behaviour that was reported by Brechner *et al.* (1998) and was explained by two anisotropic layers. Station GEC2 shows a fast polarization direction of 117°. This direction is in agreement with the generally observed trend of polarization directions in the southern part.

DISCUSSION OF THE RESULTS

For the interpretation of the splitting parameters we discuss first lateral variations of the splitting parameters and second changes of the splitting parameters at a single station with respect to different events or azimuths. Furthermore, we put constraints on the depth extent of the anisotropic layer by calculating Fresnel zones.

Small-scale lateral variations of the splitting parameters

From our results there is an indication of a clockwise rotation of the fast axis of nearly 25° from the Saxothuringian part in the north to the Moldanubian part in the south. Whereas the northern stations exhibit a mean azimuth of fast polarization of

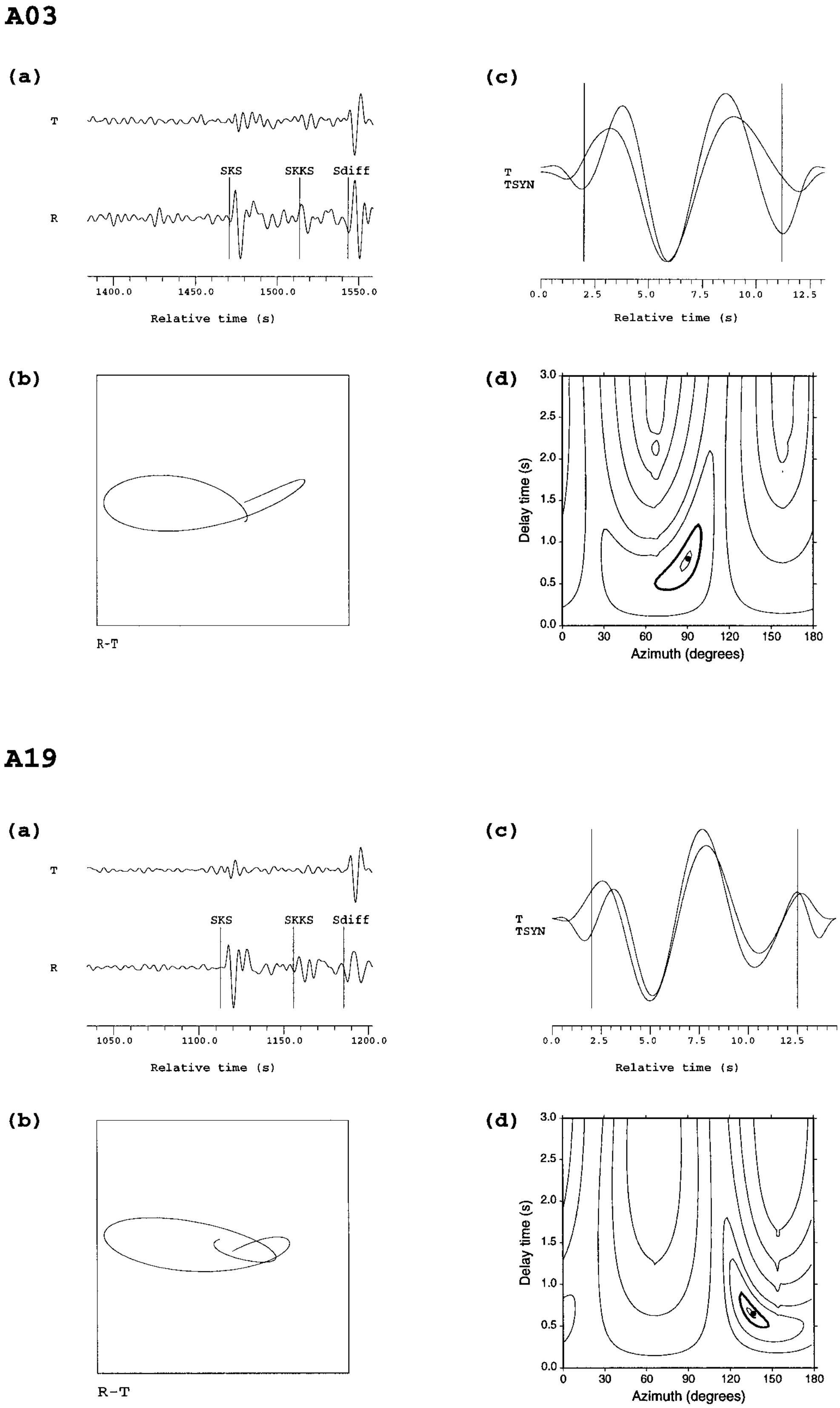

Figure 3. Examples of shear wave splitting analysis for the 1996 February 28 Molucca event (epicentral distance: 103°; backazimuth: 70°) recorded at station A03 and A19. (a) Filtered and rotated seismograms. (b) Particle motion of the *SKS* window. (c) Synthesized transverse component calculated for the splitting parameters found in the inversion and original transverse component. (d) Contour plot of the misfit dependent on delay time and azimuth of the fast polarization direction. The contours denote lines of misfits 0.01, 0.1, 0.5, 1.0, 2.5, 5 and 10 times greater than the misfit of the best model. The best model is marked by a circle. The line with a misfit 0.1 times greater than the best model that we use to estimate error bars is given by the bold line.

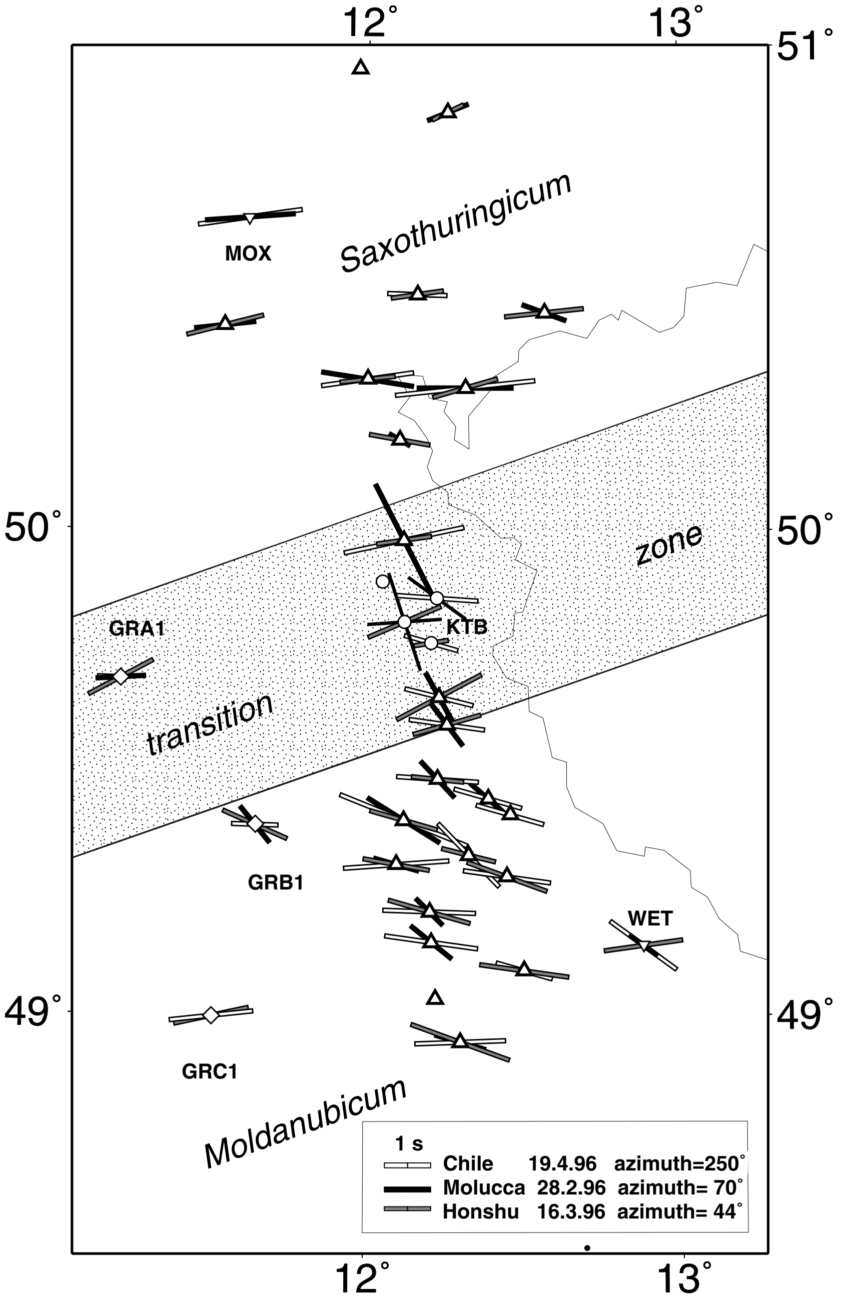

Figure 4. Map of the *SKS* splitting results for the mobile and permanent stations. The straight lines show the directions ϕ of the fast polarization. The magnitude of the delay time, δt, is given by the length of the line.

$86^\circ \pm 13^\circ$, the stations in the south have a mean azimuth of $110^\circ \pm 15^\circ$. The direction of fast polarization in the northern part is roughly parallel to the strike direction of the Hercynian mountain belt ($60^\circ - 80^\circ$) and differs by about 30° from the azimuth of the absolute plate motion of $50^\circ - 60^\circ$ in that region (Montag *et al.* 1995). The similarity of the direction of absolute plate motion and the strike of the mountain belts makes it difficult to decide whether the split *SKS* phases are caused by anisotropy in the lithosphere or in the asthenosphere or by a combination of both. Due to the smaller difference between the strike direction of the Hercynian mountain belt and the direction of fast polarization in comparison to the difference between plate motion and the direction of fast polarization, we suggest a lithospheric source for the observed splitting. However, the direction in the southern part deviates from both the absolute plate motion and the strike of the mountain belts. Two possibilities may account for the different directions of the fast axis in the northern and southern part. On the one hand, the different directions may reflect different frozen directions of anisotropy in the two microplates. On the other hand, the different directions may be the expression of a so-called asthenospheric boundary flow (Bormann *et al.* 1996). According to Bormann, the asthenospheric flow direction is modified by significant topography at the lithosphere–asthenosphere boundary, yielding a lattice preferred orientation of olivine and consequently a direction of the fast split wave that is oriented subparallel to the trends of the depth contours of lithospheric thickness anomalies.

From the analysis of *P* residuals, Plomerova & Babuska (1988) and Babuska & Plomerova (1992) found that the lithosphere in the southern Bohemicum (~150 km) is thicker than the lithosphere of the surrounding areas (80–110 km). From our point of view this finding may support the idea of boundary flow in that region: the lithospheric root of the Bohemian Massif may act as an obstacle for the asthenospheric flow and may cause the flow to deviate around the obstacle. The WNW–ESE direction of fast polarization that we observe in the southern part of our profile is close to the trend of the transition from shallow (80–110 km) to thick lithosphere (~150 km).

Variations of splitting parameters with respect to different azimuths of the incoming waves

The northern stations show only small variations in the azimuths of the fast polarization, with values within the error bars indicated above. The constant values suggest a single anisotropic layer. In the southern part the variations of the fast polarization direction are slightly higher than in the northern part, but still within the error bars. However, strong variations are observed in the middle of the profile close to the KTB (stations A09–A11 and stations of the KTB network), which give an additional indication for a prolongation of the suture zone from the crust into the mantle. In this part, the azimuth of the fast polarization varies by up to 90°. We interpret these variations as an expression of a complex mantle structure formed by several horizontal anisotropic layers and/or by anisotropic layers with inclined symmetry axes. For such media the apparent splitting parameters are strongly dependent on the azimuth of the incoming wave (e.g. Silver & Savage 1994; Brechner *et al.* 1998). Similar complexities were obtained by Plomerova *et al.* (1998) and Babuska & Plomerova (2000) for an experiment with stations approximately 100 km west of our stations.

Unfortunately, shear wave splitting observations with a maximum of three different azimuths do not permit us to resolve more complex models. To obtain more insight into possible models, we compared the apparent splitting parameters for the stations in the middle of our profile with the results of *SKS* splitting for the Gräfenberg station GRA1 found by Brechner *et al.* (1998), since station GRA1 is situated only 100 km west of the stations in the middle of our profile. The database for the Gräfenberg array, spanning more than 20 years, allowed Brechner *et al.* (1998) to infer more than 30 individual estimates of splitting parameters. The splitting parameters of their investigations exhibit considerable variations with respect to different azimuths, which they explained by two anisotropic layers with horizontal symmetry axes. Fig. 5 shows their estimates of splitting parameters for GRA1 and the calculated curves of the effective splitting parameters for the best-fitting two-layer model. The results of this study for station A09–A11 and for stations of the KTB network are also plotted. For three events (Honshu, 1996 March 16, backazimuth 45°; Chile, 1996 April 19, backazimuth 249°; Peru, 1995 May 2, backazimuth 267°) the fast polarization directions more or less fit the general trend. However, considerable differences appear for the Molucca event of 1996 February 28 (backazimuth 70°) and the Samar event of 1995 April 21 (backazimuth 64°). The fast polarization directions for these events vary between 142° and 162°. Therefore, the values are almost 50° greater than those expected for the two-layer model for GRA1. Another argument against adoption of the GRA1 model comes from the comparison of the fast polarization directions for the Molucca and Chile events. The events are from opposite directions, but exhibit strongly differing fast polarization directions. Such behaviour is not compatible with any two-layer model with horizontal symmetry axes, which are characterized by a 90° symmetry of the apparent splitting parameters. The incompatibility with a 90° symmetry for

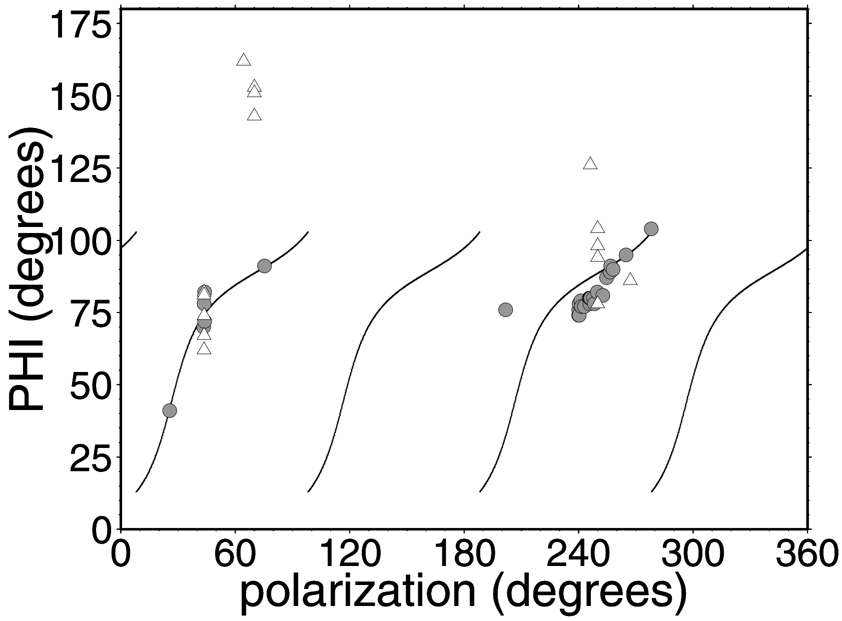

Figure 5. Effective splitting parameters for the Gräfenberg station GRA1 as a function of backazimuth derived from the individual observations (circles) and calculated curves of the splitting parameters (modified after Brechner *et al.* 1998). The calculations of the curves are based on the splitting parameters that the inversion for a two-layer model with horizontal symmetry axis has shown to be the best model (upper layer: $\phi=40°$, $\delta t=1.15$ s; lower layer: $\phi=115°$, $\delta t=1.95$ s). In addition, the splitting parameters are plotted for the stations in the middle of the profile of our field experiment (triangles), where the strongest variations with azimuth occurred.

stations A09–A11 and the KTB stations in the middle of our profile suggests more complex models in that part, such as a two-layer model with at least one inclined symmetry axis or a model consisting of inhomogeneous anisotropic layers, for example. Similar complexity in the anisotropic structures of the upper mantle in that area was observed by Plomerova *et al.* (2000). In their studies based on a joint inversion of *P* residuals and shear wave splitting parameters they found indications for different directions of anisotropic material with inclined axes within the Moldanubian and Saxothuringian parts of the lithosphere. However, more observations are required for future investigations to test the proposed and more elaborate models.

Estimations of the depth extent of the anisotropy

The estimated delay times show a mean value of 1.3 s. Since delay times caused by anisotropy in the crust do not exceed 0.3 s (e.g. Barruol & Mainprice 1993; Crampin & Booth 1985), we conclude that most part of the anisotropic signal of the *SKS* phase is generated in the upper mantle. Due to the near-vertical propagation of the *SKS* phase through the anisotropic medium, it is difficult to constrain the depth of the anisotropy. In the case of lateral variations of the anisotropy parameters it is possible to put further constraints on the probable location of the anisotropy by calculating Fresnel zones (e.g. Alsina & Snieder 1995). Following Alsina & Snieder (1995), Fresnel zones for the ray paths of the events in the present study have been calculated. The Fresnel zones calculated for a mean period of the *SKS* phase of about 8 s include all ray paths that have a traveltime difference from the geometrical ray path of one-sixth of a period. In Fig. 6 the Fresnel zones are shown for 80, 220 and 400 km depth. For simplicity the zones are drawn around the centres of the northern and southern stations. From the figure it is obvious that the Fresnel zones at 80 and 220 km depth do not overlap, whereas at 400 km depth the zones partially overlap. Taking into account both the different mean directions of fast polarization in the Saxothuringian and the Moldanubian parts and the overlap of the Fresnel zones at 400 km depth, we infer that the source of anisotropy is located not much deeper than 400 km. In a recent study, Rümpker & Ryberg (2000) showed that the radius of the Fresnel zones given by Alsina & Snieder (1995) are underestimated by about 40 km. Taking into consideration the greater radius of the Fresnel zones of Rümpker & Ryberg (2000), the maximum depth of 400 km for the source of anisotropy given above is a conservative estimate. It is more likely that the maximum depth is somewhere around 200 km. The source of the strong variations of the splitting parameters in the middle of the profile should be restricted to shallow depth, i.e. to the lithosphere. For a deeper source the variations should also be observed at stations further to the south and north due to enlarged Fresnel zones ,which would interfere with those from the northern and southern stations.

CONCLUSIONS

78 splittings of *SKS* phases from six events have been analysed to study the anisotropy of the upper mantle at the transition zone between the Saxothuringicum and the Moldanubicum in SE Germany. The data are from a profile of mobile stations maintained for 6 months in 1995–1996 and from permanent stations in the surrounding area. If the transition zone between the Saxothuringicum and the Moldanubicum, which is known at crustal depths from several geological and geophysical investigations, continues down into the upper mantle, our investigations have revealed the following results.

(1) The analysis of the observed splitting of *SKS* phases indicates a rotation of the fast polarization direction from 86° in the northern part of the profile (Saxothuringicum) to 110° in the southern part (Moldanubicum). The change in orientation can be interpreted either by different directions of frozen anisotropy in the different microplates or by a boundary flow of the asthenosphere caused by lateral changes in the depth of the lithosphere–asthenosphere boundary in the Bohemicum and surrounding areas.

(2) Furthermore, strong variations of the splitting parameters with respect to the azimuths of the incoming waves are observed in the middle of the profile near the KTB. The azimuthal variations of the apparent splitting parameters suggest the need for a complex structure of the mantle at the transition zone, which might be formed by several anisotropic layers with inclined symmetry axes in at least one layer or by inhomogeneous anisotropic layers.

(3) Both observations—the different directions between north and south (1) and the strong variations of the splitting parameters in the middle of the profile (2)—suggest that the transition zone between the tectonic units extends from the crust into the upper mantle.

(4) A comparison of the azimuthal variations of the splitting parameters in the middle of the profile with those observed at the Gräfenberg station GRA1, a station also situated in the central part of the transition zone approximately 100 km to the west, shows remarkable differences, which may reflect variations of the anisotropic medium in the transition zone even on a small scale. These could be lateral variations in the inclination and/or strike direction of the symmetry axes.

(5) The observed average delay time of 1.3 s indicates that most of the splitting originated from anisotropy in the upper mantle and not in the crust. Calculations of Fresnel zones show that the anisotropy is restricted at most to the upper 400 km of the Earth.

We conclude that analysis of *SKS* phases for stations with narrow spacing is a powerful tool to resolve small-scale variations of anisotropy in the upper mantle and to obtain indications of complex anisotropic mantle conditions. However, it is our experience that a temporary experiment of 6 months duration does not provide enough data to resolve the entire complexity of the tectonics that we expect to be present in the central part of a transition zone such as that between the Saxothuringicum and the Moldanubicum. Longer observation periods, more elaborate analysis methods and more detailed modelling are necessary to obtain more insight into the complexity of anisotropy and tectonics in suture zones.

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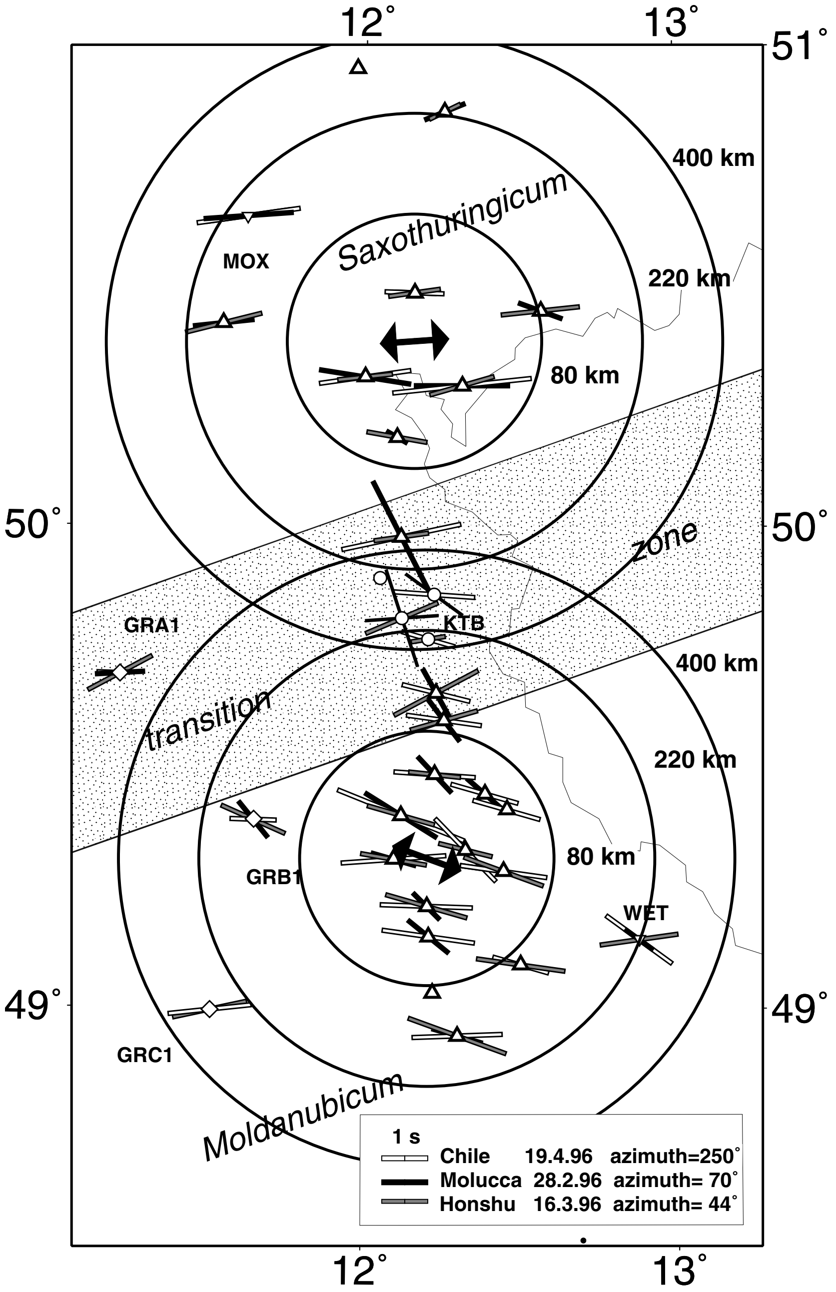

Figure 6. Fresnel zones for *SKS* phases calculated at depths of 80, 220 and 400 km. The Fresnel zones are plotted over the estimated centres of the northern and southern stations. The bold arrows at the centres of the northern and southern stations show the mean splitting parameters for the corresponding regions.

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