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Shear wave splitting across Tornquist-Teisseyre zone in Poland

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Abstract *The area of Poland consists of two large geological units, the East- and West- European Platforms separated by a zone called Tornquist-Teisseyre Zone. With several modern seismological broadband stations, SKS splitting analysis was performed as to look into any differences in the splitting parameters from one platform to another, across the Tornquist-Teisseyre Zone. Although the results found are rather similar for all the five stations analyzed, a more close-up view of the results reveals two-layered anisotropic structures under both platforms and possibly a still more complicated situation in the Tornquist-Teisseyre Zone itself. The overall effective values of SKS fast split wave direction are in accord with the results known for other seismic stations nearby, namely in the Eastern part of Germany and in the Bohemain Massif.*

Keywords: *SKS Wave Splitting, Mantle Anisotropy, Tornquist-Teisseyre Zone*

INTRODUCTION

Results of shear wave splitting of SKS are generally understood to provide information on the anisotropy of the subcontinental mantle (Vinnik *et al*., 1992). Global patterns of mantle anisotropy show a variety of directions in different parts of the world, yet data from stations located in a relatively confined area often show similar directions of anisotropy (Vinnik *et al*., 1989). This result has been proven also by methods using waves other than SKS (Hiramatsu and Ando, 1995). With respect to Central Europe a good example of such similarity of directions of fast shear waves is provided by Wylegalla *et al*. (1999), which covers the SKS splitting results obtained from TOR project carried out 1996/97 in Germany, Denmark, Southern Sweden and surrounding areas. The TOR project was especially aimed at the Sorgenfrei-Tornquist Zone separating the Western European and Scandinavian Platforms. The main findings of that paper is the predominantly east-west direction of fast split waves in Germany and weak or even absence of splitting in Sweden. Little if any data was supplied from the Sorgenfrei-Tornquist Zone itself, which is a rather narrow structure in comparison with its southeasterly extension, the Tornquist-Teisseyre Zone.

At the time of the TOR project on the territory of Poland there were only a few modern broadband digital seismic stations that could provide reliable data for analysis. Bock *et al*. (1997) performed analysis of the few earthquakes that could be used for the purpose using Suwalki data, finding result similar to the one for most German stations. The temporary station at Czajcze, Poland has provided little data - badly enough there were few large earthquakes at the 100º - 120º epicentral distance, best for SKS analysis. Makeyeva *et al*. (1990) present a result of 120º and 0.9 s time delay for KSP. This result is in accord with the result for nearby stations in Germany and Bohemia, yet it should be treated with care. Makeyeva *et al*. (1990) state a rather wide range for split wave direction (80º to 140º) and the basis for their study were recordings on nowadays obsolete equipment used in the 1970's and 1980's. The data was recorded in analogue on magnetic tapes, thus the digitization of data could be an additional source of errors.

This paper aims to be a continuation of the work by Wylegalla *et al.* (1999), taking opportunity of the substantial amount of data gathered by SUW and other digital broadband stations that have been put in operation in Poland after 1996.

DATA AND METHOD OF ANALYSIS

Modern digital broadband seismic recording in Poland has been started in late 1995 with the erection of a station at Suwalki (SUW) in Northeast Poland on the East European Platform. Ksiaz (KSP) observatory in Southwest Poland (on West European Platform) started broadband recording in 1997. In the period of 1997-1999 existed the temporary station at Czajcze (CZA) (Wiejacz, 2000) in the northwestern part of the Tornquist-Teisseyre Zone. Since mid-1999 a new station at Kalwaria Paclawska (KWP) was put into operation (Wiejacz *et al.*, 2001). Though located several kilometers within the Carpathians, it can be treated as situated on the Tornquist-Teisseyre Zone, because the Carpathian structures near their front form only the top few kilometers of the crust, under which the structures belonging to the Zone are presumed. This data can be complemented by the digital station at Warsaw (WAR). The station has been working in digital since 1996 using BB-13 seismometers, analogue filtered lowpass at 2 Hz. Luckily, the procedure of SKS splitting analysis usually involves filtering of the signal lowpass at 3 or 5 s, so this limit on the frequency band does not hamper the usefulness of the data for SKS splitting analysis. The problem with Warsaw data was however the urban noise, as the station is located in the center of the city. Due to this problem, for many of the weaker events, especially those during day hours, Warsaw data was useless. The source coordinates of the stations used in this study are given in Table 1.

Table 1. Station parameters of station used in this study

Station code	Station name	Latitude	Longitude	Elevation	Time of operation	Comment
SUW	Suwalki	54.0125N	23.1808E	152 m	Nov.1995-present	
CZA	Czajcze	53.2293N	17.0963E	169 m	Aug.1997-Jun.1999	temporary station within project TOR
KWP	Kalwaria Paclawska	49.6314N	22.7075E	448 m	Jun.1999-present	
WAR	Warszawa	52.2417N	21.0236E	110 m	Jul.1996-present	analogue filtered lowpass at 2 Hz; exists since 1939, analogue to 1996
KSP	Ksiaz	50.8428N	16.2931E	353 m	Jan.1997-present	exists since 1970, analogue broadband prior to 1997

Poland is an exceptional area where SKS waves of earthquakes from different parts of the world can be registered. Large earthquakes do not take place uniformly distributed around the world, the special situation of Poland is a result of its geographical location in respect to the seismically active zones of Central and South America and the Indonesia - Philippines region. The stations in Western Europe have smaller epicentral distances in respect to the American earthquakes and often these distances happen to be too small for effective SKS splitting analysis. In addition to the two forementioned regions, epicentral distance for earthquakes from South Sandwich Islands and South Indian Ocean also allowed reliable SKS splitting analysis. This data was supplemented by few SKKS data from the South Pacific earthquakes. The distribution of earthquakes used in the splitting analysis is shown in Figure 1 while the location of the Polish seismological stations are shown in Figure 2.

The splitting analysis is based on the fact that the radial (R) and transverse (T) components of a harmonic component of SKS can be written as:

$$R(t) = \cos^2\beta * e^{i\omega t} + \sin^2\beta * e^{i\omega(t-\delta t)}$$

$$T(t) = -0.5 * \sin(2\beta) * (e^{i\omega t} - e^{i\omega(t-\delta t)})$$

where t is time, ω is circular frequency, β is the angle between the fast direction of wave propagation and the direction of the ray, and δt is traveltime delay between the split waves. Hence, having the radial component, assuming certain values of β and δt, we can calculate a theoretical transversal component and check it against the real observed transversal component. We repeat this procedure for different values of beta and dt until our theoretical transversal component fits the best. We then take the corresponding values of β and δt as our result.

The actual data seldom happen to be so good that no filtering is needed. Usually at least the high frequency noise has to be filtered out. In the calculations a standard third order Butterworth bandpass filter between 30 s and 3 s was used. In a few more stubborn cases, a narrower bandpass of 20 s to 5 s was used. Taking the M=6.1 event from Bolivia (September 15, 1999, 03:01:24, 20.934S 67.275W 218.0 km depth) recorded at SUW (distance 106.93 degrees, back azimuth 257.71), after being filtered, the SKS pulse is identified and the particle motion is checked (Fig.3) to be uniform and uncontaminated by possible other signals. The energy on the T component of SKS is confirmed by the elliptical shape of the particle motion, this is perhaps visible still better if the components are rotated to radial and transversal. Then the seismograms are rotated to radial and transversal components. The splitting analysis is performed following the method described by Vinnik *et al.* (1992), and Silver and Chan (1991), on the fragment of data relevant to the SKS wave particle motion. Having the results, a theoretical transversal component is constructed out of the radial one. The "theoretical" particle motion is shown in Figure 4 while the radial, observed transversal and theoretical transversal components of the SKS pulse are shown in Figure 5.

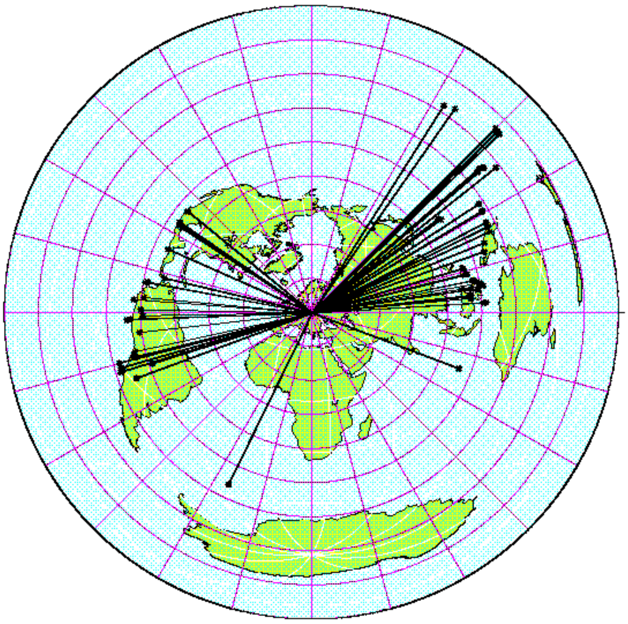

FIG. 1. Distribution of events used in the splitting analysis of SKS and SKKS. Figure is actually for the centermost of the Polish stations, WAR, yet the differences for the other stations are negligible.

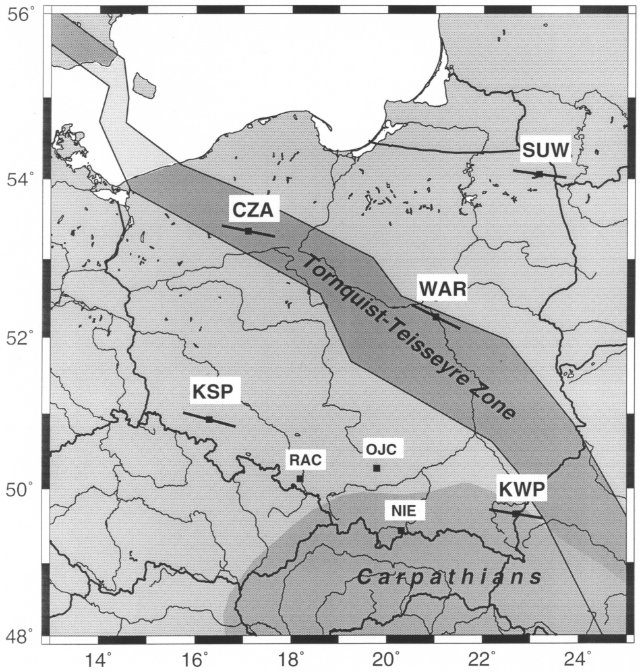

FIG. 2. Location map of the Polish seismological stations. The stations used in this study are marked with large lettering and showing the obtained direction of fast split wave. Other Polish observatories are marked with smaller lettering. The boundaries of the Tornquist-Teisseyre Zone are schematically plotted running from Northwest towards Southeast.

The result of this SKS splitting analysis was 0.4 s delay time and 107.8 azimuth for the fast split wave direction.

Similar calculations have been performed on data from different earthquakes recorded at the Polish digital broadband seismic stations. However, it was not always possible to obtain a satisfactory result due to noise or epicentral distances unsuit for the analysis at some of the stations. In some cases, the particle motion have shown to be erratic and those data was eliminated. In other cases, the observed transversal component has proven to be almost null, therefore the algorithm of determining the delay and fast split wave direction was bound to fail. The splitting analysis was not performed in such cases.

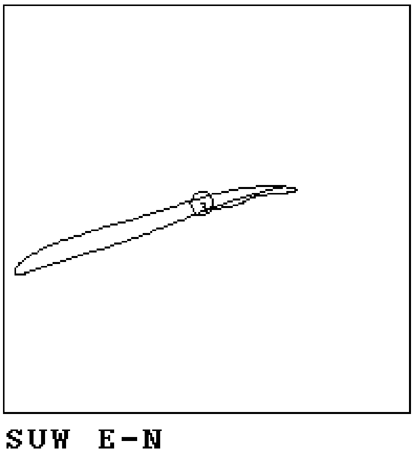

FIG. 3. Example of observed particle motion of SKS on horizontal components

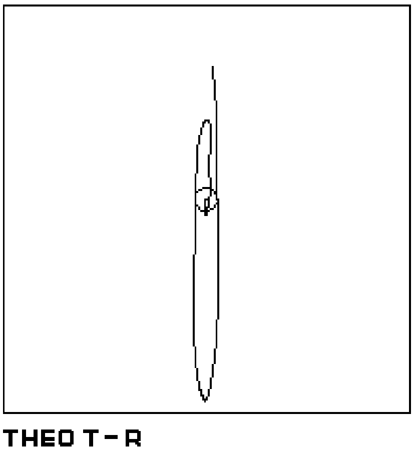

FIG. 4. Example of theoretical particle motion of SKS, radial vs. transversal components, of the same event

RESULTS OF SKS SPLITTING

SKS splitting analysis was performed on data of 62 earthquakes recorded by the Polish seismic stations. Not all earthquakes at all stations have given results. There have been problems in identification of SKS from some smaller earthquakes especially at WAR. In cases of some events, the epicentral distance was unsatisfactory for SKS analysis at some of the stations. In a few cases where SKKS waves were clearly seen, they have been used for the analysis. In cases of some events, even though SKS wave could be identified, after performing rotation the observed transversal component got lost in the noise, or there have appeared serious differences between the observed and the obtained theoretical transversal waveforms. Such results have been eliminated.

Results of SKS splitting analysis are summarized in Table 2

Although individual scatter of SKS results from different earthquakes seems rather large, statistics of these results give fair estimations of SKS splitting.

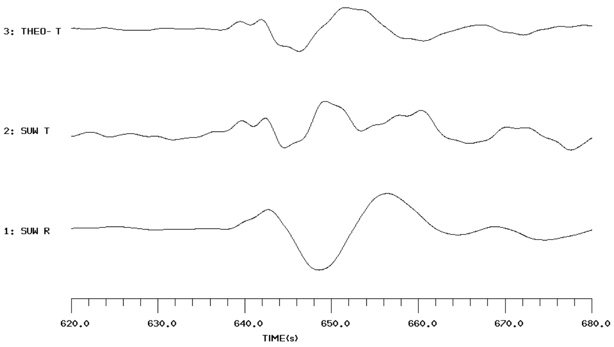

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FIG. 5. Radial, observed transversal and theoretical transversal components of the same event. Please note the similarity of the two transversal components.

Table 2. Results of SKS splitting obtained in this study

DATE	TIME	REGION	Mag	LAT	LON	Z	STA	DIST.	AZIM	DT	FI	rem
960101	080510.83	Minahassa	7.8	00.729N	119.931E	24.0	SUW	93.39	84.12	1.2	105.83	
960221	125101.30	Peru	7.5	09.593S	079.587W	10.0	SUW	105.21	274.39	-	-	
960225	030815.87	Mexico	7.0	15.978N	098.070W	21.1	SUW	94.23	304.46	-	-	
960228	094410.92	Molucca Sea	6.4	01.756N	126.048E	115.5	SUW	96.13	78.53	0.7	108.62	
960317	144856.71	Vanuatu	6.6	14.705S	167.297E	164.4	SUW	131.79	49.52	-	-	SKKS
960416	003054.67	Fiji	7.1	24.061S	177.036W	110.9	SUW	146.47	34.88	-	-	SKKS
960502	133428.99	Solomon Islands	6.6	04.548S	154.833E	500.0	SUW	117.00	56.75	0.8	116.82	
960609	011216.76	Mariana Islands	6.5	17.444N	145.458E	149.0	SUW	93.46	53.95	0.6	94.03	
960617	112218.54	Flores Sea	7.9	07.137S	122.589E	587.3	SUW	101.27	86.60	0.5	126.68	
960715	165122.07	Mariana Islands	6.2	18.726N	145.628E	176.5	SUW	92.44	53.18	0.5	93.25	
							WAR	94.55	51.49	-	-	
960716	100736.65	Minahassa	6.6	01.016N	120.254E	33.0	SUW	93.35	83.69	0.8	103.78	
960722	141935.77	Minahassa	7.0	01.000N	120.450E	33.0	SUW	93.48	83.54	0.9	103.63	
							WAR	94.99	81.93	0.9	142.00	
960805	213916.25	Ecuador	6.2	01.996S	081.001W	33.0	SUW	99.93	280.37	0.4	80.38	
							WAR	98.93	278.32	0.8	118.41	
961105	094134.77	Kermadec	6.7	31.160S	179.999W	369.4	SUW	151.73	45.45	0.6	95.52	SKKS
961112	165944.03	Peru	7.7	14.993S	075.675W	33.0	SUW	107.18	268.10	-	-	
							KSP	102.70	261.91	0.7	102.00	
970111	202839.10	Mexico	7.1	18.270N	102.510W	45.8	SUW	94.34	309.29	1.0	119.29	
970123	021533.10	Jujuy	6.4	22.030S	065.850W	285.3	SUW	106.96	255.92	-	-	
							WAR	105.25	253.80	0.7	103.88	
970311	192213.20	Philippines	6.9	07.840N	127.870E	15.6	SUW	92.23	73.56	-	-	
							WAR	94.00	71.91	-	-	
970521	141034.20	Vanuatu	6.4	20.560S	168.920E	68.2	SUW	137.64	51.53	0.4	81.61	SKKS
							KSP	142.90	45.58	-	-	SKKS
970525	232244.00	Kermadec	6.1	32.010S	179.500W	346.0	SUW	152.68	45.54	0.7	85.62	
							WAR	154.85	44.50	-	-	
							KSP	157.85	37.83	0.6	77.91	
970624	230459.80	Halmahera	6.4	01.880S	127.120E	40.5	SUW	99.70	79.77	0.8	99.86	
							WAR	101.31	78.32	0.8	108.40	
							KSP	104.51	74.78	1.2	94.87	
970706	095412.00	Chile	6.5	30.200S	072.280W	15.0	SUW	117.20	255.49	-	-	
							WAR	115.17	252.75	-	-	
							KSP	111.92	248.90	1.0	88.99	
970719	142217.80	Guerrero	6.7	15.730N	098.250W	15.0	SUW	94.53	304.48	0.5	104.49	
							WAR	94.42	302.59	-	-	
							KSP	92.59	298.73	1.0	128.82	
971015	010345.30	Chile	6.8	30.940S	071.430W	73.6	SUW	116.98	253.96	0.5	154.02	

Table 2 (continuation). Results of SKS splitting obtained in this study

DATE	TIME	REGION	Mag	LAT	LON	Z	STA	DIST.	AZIM	DT	FI	rem
							WAR	115.22	251.60	0.8	141.66	
							CZA	113.30	249.26	-	-	
971028	061529.70	Peru	6.9	04.480S	076.570W	125.3	SUW	99.34	275.26	-	-	
							KSP	95.25	269.39	-	-	
							CZA	95.76	270.25	-	-	
971115	185933.40	Vanuatu	6.6	14.920S	167.260E	122.1	SUW	131.96	49.70	-	-	SKKS
971125	121445.60	Minahassa	6.8	01.440N	122.760E	32.6	SUW	94.48	81.40	0.7	101.49	
							KSP	99.23	76.23	0.8	106.31	
							CZA	98.18	76.52	-	-	
971128	225349.30	Peru/Bolivia	6.3	13.580S	068.980W	603.3	SUW	102.12	263.65	0.7	103.74	
							WAR	100.60	261.61	0.7	121.69	
							KSP	97.45	257.78	0.6	107.86	
							CZA	98.42	258.72	-	-	
971222	020602.80	Papua	6.7	05.680S	148.070E	188.6	SUW	114.54	63.81	-	-	
							WAR	116.50	62.56	-	-	
							KSP	119.76	58.75	0.8	98.82	
							CZA	118.09	58.39	0.8	88.48	
980403	220148.25	Peru/Brazil	6.0	08.148S	074.238W	164.6	SUW	100.90	271.17	0.4	111.26	
							WAR	99.61	269.13	0.8	119.21	
							KSP	96.59	265.26	0.6	115.33	
							CZA	97.26	266.17	-	-	
980521	053425.50	Minahassa	6.2	00.207N	119.584E	33.0	SUW	93.61	84.70	0.6	104.79	
							KSP	98.22	79.52	0.7	109.60	
							CZA	97.31	79.84	-	-	
980522	044850.44	Bolivia	6.5	17.731S	065.431W	24.0	KSP	98.46	252.47	0.8	102.55	
							CZA	99.63	253.44	0.5	93.53	
980717	132802.96	Papua	7.0	02.961S	141.926E	10.0	SUW	108.96	67.79	1.0	97.88	
980729	071424.08	Chile	6.2	32.312S	071.286W	51.1	SUW	117.93	252.84	0.6	92.93	
							KSP	112.87	246.67	0.6	96.75	
							CZA	114.25	248.18	0.5	108.25	
980729	180029.99	Irian Jaya	6.0	02.693S	138.901E	33.0	SUW	107.07	70.29	0.8	140.35	
980804	185920.10	Ecuador	7.1	00.593S	080.393W	33.0	SUW	98.44	280.68	-	-	
							WAR	97.46	278.69	-	-	
							KSP	94.69	274.81	0.8	124.89	
							CZA	94.96	275.64	-	-	
980823	135715.28	Mexico	6.0	11.663N	088.038W	54.6	SUW	92.70	293.90	0.4	133.99	
							WAR	92.20	292.09	0.6	142.17	
							KSP	89.91	288.35	0.4	118.45	
							CZA	89.61	288.97	0.9	119.07	
980902	083739.91	Mindanao	6.7	05.410N	126.764E	50.0	SUW	93.58	75.85	0.6	135.91	
							WAR	95.29	74.23	0.7	134.30	
							KSP	98.53	70.59	0.7	100.67	
							CZA	97.28	70.73	0.7	121.00	
981129	141031.96	Molucca Sea	7.6	02.071S	124.891E	33.0	SUW	98.55	81.71	0.7	111.80	
							WAR	100.11	80.24	0.9	110.33	
							KSP	103.29	76.71	0.4	106.79	
							CZA	102.26	76.84	0.6	106.92	
981206	004713.45	Molucca Sea	6.2	01.253N	126.198E	33.0	SUW	96.63	78.70	0.6	108.79	
981227	003826.76	Fiji	6.0	21.632S	176.376W	144.3	SUW	144.42	32.32	-	-	SKKS
							WAR	146.61	30.37	-	-	SKKS
							KSP	149.20	23.49	-	-	SKKS
990206	214759.47	Santa Cruz Isl.	7.3	12.853S	166.697E	90.1	SUW	129.88	49.09	1.0	109.15	
990403	061718.36	Peru	6.2	16.660S	072.662W	87.2	SUW	109.07	267.82	0.9	97.92	
							WAR	107.67	265.54	0.8	115.62	
							KSP	104.53	261.58	0.7	101.67	
990405	110804.00	New Britain	7.4	05.591S	149.568E	150.0	SUW	115.25	62.36	0.8	112.44	

Table 2 (continuation). Results of SKS splitting obtained in this study

DATE	TIME	REGION	Mag	LAT	LON	Z	STA	DIST.	AZIM	DT	FI	rem
							WAR	117.24	61.11	-	-	
							KSP	120.49	57.24	-	-	
990406	082214.27	Papua	6.4	06.527S	147.007E	33.0	SUW	114.68	65.29	0.9	115.36	
							KSP	119.88	60.30	-	-	
990420	190408.32	Kermadec	6.5	31.888S	179.04W	95.7	SUW	152.77	44.67	0.8	84.75	SKKS
990516	005120.46	New Britain	7.0	04.751S	152.486E	73.7	SUW	116.04	59.13	0.9	99.20	
							WAR	118.08	57.83	0.9	127.89	
							KSP	121.31	53.85	0.9	113.91	
							CZA	119.49	53.52	0.7	83.61	
990517	100756.45	New Britain	6.9	05.160S	152.877E	27.0	SUW	116.59	58.98	1.0	89.06	
							CZA	120.04	53.35	0.7	93.43	
990615	204205.93	Mexico	6.5	18.386N	097.436W	70.0	SUW	91.85	303.15	0.7	45.20	
							CZA	89.23	300.24	-	-	
990618	105525.75	Mindanao	6.1	05.514N	126.639E	33.0	SUW	93.42	75.89	0.5	105.97	
							KSP	98.37	70.63	0.8	100.71	
							CZA	97.12	70.97	-	-	
990915	030124.34	Bolivia	6.1	20.934S	067.275W	218.0	SUW	106.93	257.71	0.4	107.79	
							KWP	105.64	256.11	0.7	106.19	
							KSP	102.02	251.76	0.8	101.84	
990930	163115.69	Mexico	6.5	16.059N	096.931W	60.6	SUW	93.60	303.55	0.4	93.57	
							KWP	95.76	302.87	-	-	
							KSP	91.59	297.88	-	-	
991229	132919.62	Santa Cruz Isl.	6.8	10.860S	165.354E	33.0	SUW	127.52	49.43	1.0	89.50	
							KWP	130.54	51.65	-	-	
000423	092723.32	Argentina	6.9	28.307S	062.990W	608.5	SUW	110.25	249.67	0.4	79.77	
							KWP	108.38	247.90	0.8	87.99	
							WAR	108.39	247.54	-	-	
							KSP	105.12	243.82	0.8	103.90	
000512	184323.80	Jujuy	7.0	22.988S	066.743W	244.1	SUW	108.22	255.98	0.6	86.07	
							KWP	106.81	254.29	1.2	114.29	
							WAR	106.51	253.82	0.8	43.84	
							KSP	103.27	250.02	0.8	104.19	
000618	144413.31	South Indian Oc.	7.5	13.810S	097.410E	10.0	SUW	92.04	110.69	-	-	
							WAR	92.66	109.06	1.1	99.07	
000807	143355.91	Banda Sea	6.5	07.018S	123.357E	648.5	KWP	102.21	86.46	0.7	96.55	
							WAR	103.07	84.55	1.2	154.61	
000809	114147.90	Michoacan	6.5	18.198N	102.480W	45.8	SUW	94.39	309.23	1.1	49.27	
							KWP	96.91	308.50	1.1	148.59	
							WAR	94.47	307.34	-	-	
							KSP	92.87	303.46	-	-	
000815	043008.80	Kermadec	6.6	31.511S	179.725E	357.7	SUW	151.92	46.24	0.5	96.31	SKKS
							KWP	155.02	52.14	-	-	SKKS
							WAR	154.09	45.23	-	-	SKKS
							KSP	157.19	38.37	-	-	SKKS
000828	150547.91	Banda Sea	6.5	04.110S	127.394E	16.0	SUW	101.65	80.85	0.5	150.91	
							KWP	102.62	81.40	0.7	91.50	
001107	001806.14	South Sandwich	6.7	55.176S	028.736W	33.0	KSP	112.11	205.98	-	-	
001108	065959.03	Panama	6.3	07.052N	077.885W	17.0	SUW	90.80	283.05	-	-	

Entries from left are: date and time of event, its source region, magnitude, latitude, longitude, depth, then station at which the event was analyzed. Following the station code are the epicentral distance, back-azimuth, split wave delay (in seconds), fast split wave direction, and possibly, remark in case SKKS waves were basis for the calvulations. In cases when the event rendered a null transversal SKS component, or if the theoretical transversal differs from the observed, the results are disregarded and the appropriate fields for time delay and fast split wave direction are left blank. In case the earthquake was analyzed at more than one station, earthquake origin data is given only for the first station on list (usually SUW).

The station KSP (Ksiaz) is located in Southwestern Poland and its results for SKS splitting are quite similar as those obtained for the German stations (Brechner *et* al., 1998; Plenefisch *et al.*, 2001), which are located on the same Palaeozoic Platform as KSP is. The mean values of azimuth of fast direction and of the delay are 104.9º and are in accord with the earlier findings for the area (Silver, 1996).

The station SUW (Suwalki) located on Eastern European Platform has yielded a 102.9º degree result. This, however, after the elimination of the several exceptionally large (above 140º for the fast split wave direction) results goes down to 97.8º. This seems to be in accord with Bock *et al.* (1997).

There have been three stations in the Tornquist-Teisseyre Zone, working for limited time only (CZA, KWP) or noisy (WAR). CZA was thought to be most promising as this was a modern station running for almost two years in good recording conditions and the station location was selected so it was right atop the Tornquist-Teisseyre zone. Yet, CZA data proved to be somewhat disappointing, there have been few events good for SKS analysis in the period of activity of the station and then the usual case is that the observed transversal component is of rather small amplitudes. The result for CZA is 101.8º for the fast split wave direction. KWP has yielded only 7 satisfactory results, of which the mean is 112.2º, however, this goes down to 99.3º if the two exceptionally high values above 140º are rejected. The resultant direction of fast split wave for KWP looks parallel to the Carpathian front, a fact that cannot be called unexpected since at some stations in Western Europe, the fast split wave direction was found parallel to the Alpine front (Nicholas, 1993; Smith and Ekstrom, 1999). The centrally located WAR results in 118.9º, down to 115.9 after exclusion of exceptionally high or exceptionally low values. The scatter of the results for WAR is also the highest, this can be attributed to the relatively poor recording conditions.

The delay time in cases of all the five stations in question is of the order of 0.7 - 0.8 s, highest for KWP and WAR (0.82 s), lowest for CZA (0.67 s), though the scatter is relatively high. The splitting results are collected in Table 3. The distribution of the obtained results versus the back azimuth is shown in Figures 6 (the fast split wave direction) and 7 (delay time).

The fact that the obtained SKS splitting results are alike may be noticed at first glance and it seems interesting in view of the stations being situated atop three different geological structures. Figure 6 for KSP (bottom) shows a possible interesting property of the fast wave direction being a function of back azimuth. Such situation is possible in case there are two (or perhaps) more anisotropic layers with different fast split wave directions (Vinnik *et al*, 1994) and the azimuthal distribution of these directions should have the property of 90º periodicity. Figure 8 shows all the KSP fast split wave directions brought to the back azimuths from the first quarter.

Table 3. Average results of SKS splitting obtained in this study

Station	fast azimuth	fast azimuth error	delay time	delay time error
	(deg)	(std. deviation, deg)	(s)	(std.devaition, deg)
SUW	97.8	2.6	0.71	0.12
KWP	99.3	4.3	0.82	0.38
WAR	115.9	3.2	0.82	0.26
KSP	104.9	2.3	0.75	0.16
CZA	101.8	4.7	0.67	0.24

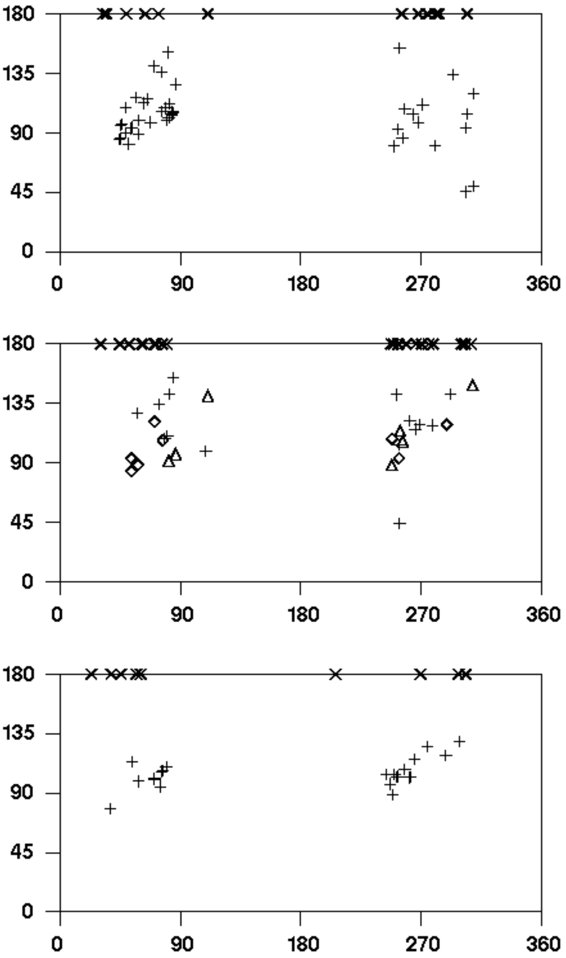

FIG. 6. Azimuthal distribution of the observed fast split wave direction versus back azimuth for SUW (top), KSP (bottom) and the Tornquist Teisseyre Zone stations (middle) CZA - diamonds, WAR - crosses, KWP - triangles. X's on the border of the graphs mark the back azimuths of the event that yielded no results for the splitting.

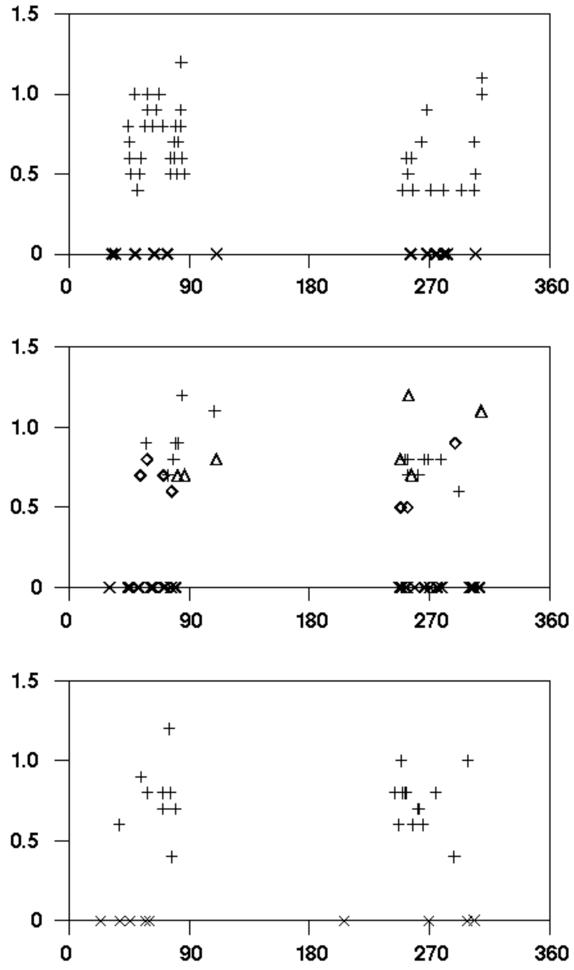

FIG. 7. Azimuthal distribution of the observed delay time versus back azimuth for SUW (top), CZA, WAR, KWP (middle) and KSP (bottom). Notations as in Figure 6.

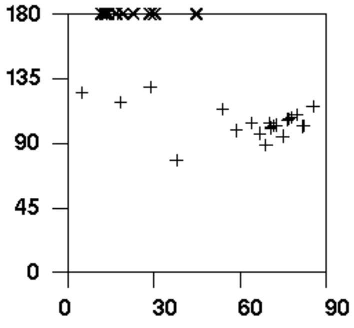

FIG. 8. Azimuthal distribution of fast split wave directions for station KSP brought to the back azimuths from the first quarter of the circle.

Definitely, there seems to be some correlation, but it is difficult to tell where the fast split wave angle has its minimum or maximum. Most likely there is a maximum around 30º and a minimum just above it, a situation similar to the one found at GRF (except that the minimum there was found to be at 15º). Badly enough, the other four stations in this study do not show a correlation of this sort.

DISCUSSION

The results of SKS splitting obtained in this study for the Polish seismic stations SUW, KWP, WAR, KSP and CZA all yield a similar direction and with the exception of WAR all fall within maximum errors of one another. The individual differences could be easily attributed to crustal anisotropy (Bormann *et al*., 1993; Bormann *et al*., 1996). The obtained results could be interpreted as all the stations registering the same SKS splitting anomaly and the effect of the Tornquist-Teiseyre Zone is invisible in the SKS wave splitting. The somewhat different value obtained for WAR could be attributed to the local conditions, namely the location of the station on a rim of a 30 m high embankment of the valley of Wisla River. All stations yield a similar delay between the split waves. Since this delay must be tied to the thickness of the anisotropic layer (Sileny and Plomerova, 1996), this thickness of the anisotropic layer should be understood as more or less the same for all the stations. This is however in conflict with the findings of Babuska and Plomerova (1992), where the thickness of the lithosphere increases from about 140 km at KSP to over 200 km at SUW. This seems to present an extra evidence that the model with single anisotropic layer is too simple for the area.

A close-up look at Figure 8 shows a dependency of the obtained fast split wave direction on the azimuth. This correlation for station KSP shows the 90º self-similarity, a feature that may indicate two layers of different anisotropy, as discussed by Vinnik *et al.* (1994) for the stations in Germany. A similar correlation seems to exist also for the station SUW, but only in case of the earthquakes from Southeast Asia, in the azimuths below 90º, while for the American events (azimuths around 270º) the data shows pure scatter (Fig. 6 top). Similar scatter can be observed for all earthquakes observed at WAR (Fig. 6 middle; crosses), while for CZA and KWP the number of data is too few to draw any conclusions but does not seem to show any trend. A possible explanation of the phenomenon at SUW could be that the seismic waves from Asian earthquakes do not pass through the Tornquist -Teisseyre zone and are only a subject to a two layered anisotropic structure similar to the one at KSP, though the directions of anisotropy do not have to be the same. However, in view of the similar result of fast split wave direction and their similar dependence on azimuth, one would expect these directions to be also similar. The slight difference - if it at all exists - could be even attributed to a different depth of one of the anisotropic layers, resulting in a slightly different "effective" value of direction of SKS splitting. In view of this, the fact of the scatter of SKS splitting results for American earthquakes observed at SUW looks puzzling. This scatter looks the same as the results of SKS splitting obtained for the three stations in the Tornquist-Teissyre Zone (CZA, WAR and KWP). The seismic waves reaching SUW from America are likely to pass through the zone, while for the stations located in the zone, all rays pass through the zone.

The Tornquist-Teisseyre Zone therefore seems to show rather bad properties for studying SKS wave splitting. As the Tornquist-Teissyere Zone is a contact zone between East- and West-European Platforms, one could expect the material in the contact zone either to be "crushed" into smaller clusters of possible different orientations of olivine crystals each, or - for some area - the East- and West- European structures lay atop one another in vertical. If each of them consists of two anisotropic layers, the overall effect of this would be a four anisotropic layer structure, or possibly a three layered structure on assumption that the differentiation of the material between the platforms does not go that deep and that the two "share" a common lower anisotropic layer. The theory of shear wave splitting by multiple anisotropic layers is given by Silver and Savage (1994) and is furtherly described by Rumpker and Silver, 1998. However, it is not certain which model of anisotropic layers should be used and it seems likely that there may be also horizontal differences in anisotropy, especially in the Tornquist-Teisseyre Zone. Identification of the individual time delays and fast split wave directions for the different layers, remains beyond the possibility of this study not only because of this problem. In fact, the main issue is that earthquakes do not happen in all azimuths on uniform basis, there hasn't been a single earthquake recorded in the azimuths from 100 to 240º and from 320º to 30º within the period covered by this study. With such insufficient data coverage, any form of modeling to solve this problem is bound to fail.

Another issue to discuss might be the few events that yielded abnormally high results for fast split wave direction and were eliminated from the statistics. These are most likely errors, most of these events have rather small epicentral distances or, on the contrary, these distances are exceptionally large and the SKS signal could have had contribution from some other wave, not big enough to show up in the particle motion, but sufficient to wreck the solution.

The obtained results of SKS splitting parameters, whether they should be treated "effective" or not, are in accord with the results known for other stations in the region, namely for the German stations (BRG, CLL, RUE, MOX), the stations in the Bohemian Massif (DPC, KHC) and the station OLDS on Oeland Island in the Baltic Sea.

CONCLUSIONS

The performed SKS splitting analysis for the Polish seismic stations has yielded a similar result for all the stations, namely, about 100º fast split wave direction and about 0.7 s time delay, only in case of WAR the fast split wave direction was found somewhat greater, at 115.9º. However, in case of station KSP located on Western European Platform, there is indication of a possible two layered anisotropic structure. Similar indication exists also for station SUW on the other side of the Tornquist-Teisseyre Zone, but only in case of seismic waves incoming from the East. The stations located on top of the Tornquist-Teisseyre Zone do not show a dependence of the fast split wave direction on the back azimuth of observation. This may indicate that the mantle structure of the Tornquist-Teisseyre Zone consists of several anisotropic layers or perhaps clusters of materials of different crystal orientations and that the observed resultant values for fast split wave direction and time delay are their effective values to which all the different blocks have their contributions. Discerning for the different anisotropic layers, attempt to calculate their individual crystal orientations and time delays remains beyond the possibility of this study because of large gaps in azimuthal distribution of earthquake sources and, possibly, insufficient data quality in case of some smaller events.

The effective SKS splitting parameters for the stations in Poland are in accord with the data from nearby stations in Germany and in Czech Republic, known from earlier publications.

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