GEOPHYSICAL RESEARCH LETTERS, VOL. 16, NO. 5, PAGES 409-412, MAY 1989

ANISOTROPY BENEATH 9 STATIONS OF THE GEOSCOPE BROADBAND NETWORK AS DEDUCED FROM SHEAR-WAVE SPLITTING

Valérie Ansel and Henri-Claude Nataf

Département de Géologie, Ecole Normale Supérieure, Paris

Abstract. Polarization of SKS, ScS and S waves has been analyzed on digital 3-components seismograms recorded at 9 stations of the recently installed GEOSCOPE broadband network. Splitting was observed for about 15 records, and is interpreted as being due to seismic anisotropy beneath the stations. From every record, it is possible to retrieve the fast direction at the station, and the time difference between the fast and slow polarization directions. Some 30 observations of quasi-linear S-pulses also help constrain the direction of fast velocity. Synthetic seismograms were built to test the validity of the method used to retrieve the parameters of anisotropy. Typical time-differences are about 1 sec, corresponding, for example, to a 80 km-thick zone of perfectly oriented pyrolite. The fast directions obtained at 3 continental stations in America (Westford, Santa Cruz, Heredia), could be related to plate tectonic processes. On the other hand, the fast directions found in 3 oceanic islands (Kipapa, Papete, La Réunion) differ strongly from the oceanic plate velocity direction there.

Introduction

Seismic anisotropy could provide important constraints on convective motions in the mantle. It is indeed widely accepted that the crystallographic axes of olivine (a strongly anisotropic mineral) are preferentially oriented, according to their shear history in a convective mantle (Christensen, 1984, Ribe, 1989). Anisotropy appears to be an important component of lateral velocity variations in the upper mantle. A better understanding of anisotropy at the regional scale is therefore essential for improving seismic tomography models.

A striking consequence of anisotropy is the splitting of shear-waves : when a linearly polarized S-pulse encounters an anisotropic zone, it splits in two orthogonaly polarized pulses that travel with different velocities. This property has been studied in detail by Crampin (e.g. 1984). Observations of shear-wave splitting caused by anisotropy in the mantle have been described by Fukao (1984), Ando (1984), Vinnik et al. (1984), and Silver and Chan (1988).

In this paper, we present the first results of a systematic study of shear-wave splitting observed on the GEOSCOPE network.

Method

We have computed synthetic seismograms in order to test and illustrate the method we use for retrieving the parameters of anisotropy from the observed splitting of shear waves. Let us consider a linearly polarized S-pulse entering a known homogeneous anisotropic zone, defined by its 6 x 6 symmetric matrix of elastic constants. Crampin (1984) showed how the eikonal equation reduces to an eigenvalue problem. For a given polarization azimuth and a given angle of incidence, the fast and slow S-velocities and corresponding eigenvectors are easily computed. The incident S-pulse projects on the two perpendicular eigenvectors, which correspond to the fast and slow polarizations. The two components travel in the medium with different velocities, until they get out of the anisotropic region. If we then observe the S-pulse in the transversal plane, we no longer have a linearly polarized pulse.

Figure 1 shows how an incident, horizontally polarized (SH), synthetic pulse looks like after it has travelled vertically across a 80 km-thick homogeneous anisotropic zone. That zone consists of perfectly oriented pyrolite, as computed by Estey and Douglas (1986), with the fast axis North and horizontal. The SH polarization is directed N135. The projection of the SH-pulse on the fast eigenvector arrives first and projects back on the SH and the orthogonal SV directions, with the amplitudes and arrival time indicated by the first vertical bars on the left of Figure 1. One second later arrives the projection of the SH-pulse on the slow eigenvector, as shown by the second bars. A similar behaviour is found when more realistic anisotropy models are considered. A larger thickness is then required to explain the same time delay.

A realistic incident S-pulse is built by convolving a triangular displacement time function

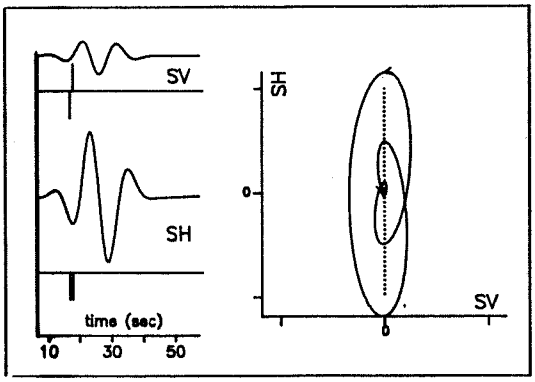

Fig. 1. Synthetic seismogram of an incident SH-pulse that has travelled across an anisotropic region defined in the text. The source duration is 3.2 sec. The seismogram has been filtered with the same low-pass Butterworth as used for the observed data of Figure 3. The particle motion is drawn on the right.

Paper number 89GL00610.
0094-8276/89/89GL-00610$03.00

for the source, an S-attenuation filter, and the receiver response (e.g. Deschamps et al., 1980). The consequence of anisotropy is that the particle motion in the S-plane (right of Fig. 1) is not linear but semi-elliptical instead. The effect of splitting is different for the SV and SH components, so that the resulting signals are not identical in shape. However, the two signals are identical if the particle motion is projected on the fast and slow eigenvectors.

Following Ando (1984), the projection axes are rotated until the two projected signals "look alike", that is the maximum cross-correlation of the projections is closest to 1. Using the signals of Figure 1, a maximum cross-correlation of 1 is obtained for an angle of 45°, and the time-shift needed to put the signals in phase is 1.0 second. Two parameters related to the anisotropy of the zone are thus obtained: the direction of fast velocity, and the time-shift between the fast and slow directions. Here, the retrieved parameters are in agreement with the input values for the synthetic. The original pulse, as it was before entering the anisotropic zone is reconstructed by suppressing the time-shift in the rotated frame, and rotating back to the SV-SH axes. Figure 2 shows that the signal thus obtained is indeed linearly polarized, in the theoretical direction (here pure SH).

However, synthetics show that the method can be dangerous when the polarization of the incoming S-wave happens to be close to the fast (or slow) direction of the anisotropic zone. In that case, the particle motion is not far from linear; a spurious fast direction can be inferred. In the present study, special care was taken to avoid such an artefact. In order to qualify, the splitting should lead to a particle motion far from linear; the maximum cross-correlation versus rotation angle curve should have a well-defined maximum; and the reconstructed incident pulse should have the polarization computed from the event's focal mechanism.

Data analysis

The Geoscope network (Romanowicz et al.,1984), now runs more than 15 broadband digital 3-components stations which are particularly suited for the analysis of shear-wave polarization. The sampling rate is 5 per second, and periods ranging from about 0.6 seconds to several hundred seconds are retrieved. Sufficient data could be collected for 9 of these stations. Ideally, one would like to use only SKS-type phases. These waves travel as P waves in the core and therefore convert to purely SV polarized at the base of the mantle. If splitting is observed, it must have been acquired on the way up to the station (Vinnik et al, 1984), and cannot be due to possible anisotropy at the source. However, in order to increase the coverage, we also processed ScS and S phases. Then, part of the splitting could be due to source region. In order to avoid splitting due to free surface effects, we disregarded all phases with an incidence angle larger than 25° (Bowman and Ando, 1987). More than 200 records have been analyzed. Data analysis included a careful phase identification step, a check of the P-arrival time, and computation of the theoretical travel time, polarization and amplitude of the shear waves. The data were often low-pass filtered to enhance the shear phases.

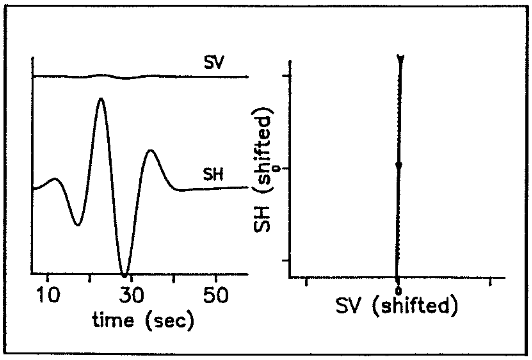

Fig. 2. Seismograms and particle motion for the synthetics of Figure 1, after removing the time-shift deduced from the cross correlation technique and rotating back to the SV-SH axes.

TABLE 1. Earthquakes used in this study (from PDE)

#	DATE	TIME	LAT	LONG	DEPTH	M
1	1986/05/26	18:40:44	-21.819	-179.079	583	6.1
2	1986/08/30	21:28:35	45.547	26.316	132	6.9
3	1986/09/16	18:20:17	19.376	146.301	48	6.7
4	1986/10/30	01:28:54	-21.702	-176.616	188	6.4
5	1986/11/23	01:39:23	-3.342	-77.411	106	6.4
6	1987/02/10	00:59:28	-19.489	-177.456	395	6.2
7	1987/03/05	09:17:05	-24.388	-70.161	62	7.3
8	1987/03/22	02:49:15	51.594	-173.574	20	6.0
9	1987/04/01	01:48:08	-22.767	-66.205	249	6.1
10	1987/04/20	09:31:37	-21.654	-179.137	570	5.4
11	1987/04/25	12:16:54	16.066	120.301	107	6.3
12	1987/05/19	12:56:25	-30.284	-71.484	36	6.0
13	1987/05/30	16:54:04	-6.064	130.518	138	5.6
14	1987/06/15	21:05:11	-19.074	-63.910	591	5.4
15	1987/07/08	22:56:02	46.437	149.558	152	5.4
16	1987/08/13	15:23:06	-17.897	-70.931	37	6.4
17	1987/08/15	18:04:23	-28.135	-70.884	37	6.1
18	1987/10/03	03:35:10	-17.950	-69.247	149	5.8
19	1987/10/06	04:19:06	-17.940	-172.225	16	7.3
20	1987/10/27	21:58:17	-28.676	-62.929	605	6.0
21	1987/10/29	20:23:41	4.817	127.688	153	6.1
22	1987/11/03	08:15:00	-17.204	-173.757	88	6.1
23	1987/11/06	18:47:35	-22.801	-63.583	538	5.8
24	1987/11/07	16:23:55	5.634	126.614	80	6.2

Some 45 reliable polarizations were obtained. Table 1 lists the earthquakes that yield reliable results at one or more stations. We obtained about 15 clearly split shear waves, from which a fast direction and time-shift could be computed. The uncertainty is difficult to evaluate. It is at least 10° for the direction and 0.2 s for the time-shift. We also observed about 30 quasi-linearly polarized shear waves. This happens when the polarization of the incident S wave is close to the fast or slow axis of the anisotropic zone, or, of course, if no anisotropy is present. Therefore, we also report on linear particle motions, because the directions they have should be consistent with the fast directions deduced from split particle motions at the same stations.

Results

Figure 3 shows a split S wave from event 21 observed at station KIP (Kipapa). A semi-

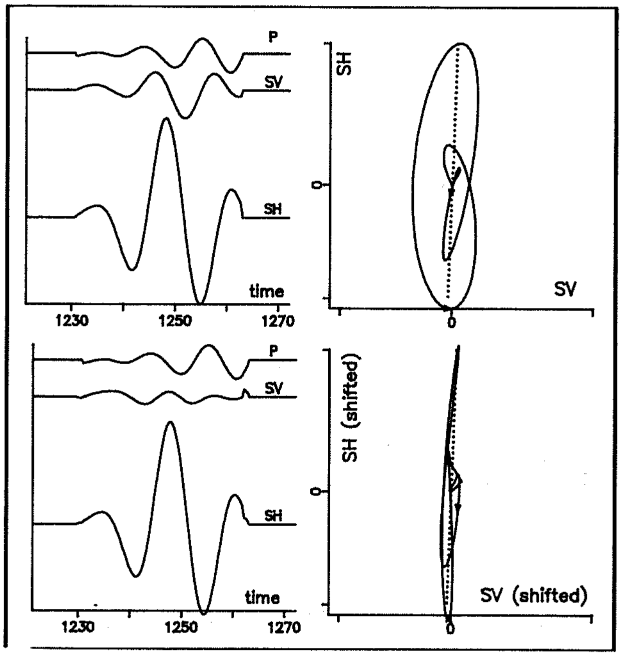

Fig. 3. *Top*: Observed S-phase at KIP from earthquake # 21. The back azimuth is 269° and the epicentral distance 73°. The data have been low-pass filtered. The particle motion (right) is not linear, and very similar to the synthetic of Figure 1. *Bottom* : reconstructed S-pulse when the anisotropy deduced from the splitting is removed. The dotted line is the theoretical polarization computed from the earthquake's focal mechanism.

elliptical particle motion is observed in the S-plane, very similar to the synthetic in Figure 1. The cross-correlation method gives a time-shift of 1.0 second for a rotation angle of 45°. This gives a N45 fast direction at KIP. When the effect of anisotropy is removed, the reconstructed pulse is almost linearly polarized, and in very good agreement with the polarization computed from the earthquake's focal mechanism. Table 2 summarizes our observations of split or unsplit shear waves at the 9 stations.

The fast directions obtained for the 4 stations on the American continent are given in Figure 4. Beneath Westford (WFM), 2 solid bars define a roughly E-W fast direction, with time-shifts between 0.8 and 1.2 seconds. Three arrivals with linear polarizations are close to the inferred fast direction and the one pointing N-S is equally compatible if one assumes that it coincides with the slow direction. One solid bar is in contradiction with this direction and is not interpreted. One interpretation of that anisotropy is a strong preferential orientation of at least 100 km of the lithosphere beneath that North-American margin. The direction can be linked to the present-day plate motion, or be fossil anisotropy from the time of the opening of the North Atlantic Ocean. For Santa Cruz (SCZ), we observe a NW-SE fast direction, with a splitting of about 0.8 sec. The anisotropy could be due to a broad shear zone beneath the San Andreas fault. The Heredia station (HDC2), in Costa Rica, has a fast direction nearly perpendicular to the subduction trench. Subduction induced flow beneath the continent is a very efficient process for developping preferential orientation of olivine crystals (Ribe, 1989). Fast directions perpendicular to the trench have been obtained by Ando (1984) for other stations in South-America. The Cayenne station (CAY) lies on the Brazilian shield. No splitting was observed at that station. Linear particle motions were obtained for five directions, which scan a complete quadrant, i.e. all possible directions. This indicates that if anisotropy is present, it is probably below our resolution limit (0.4 s).

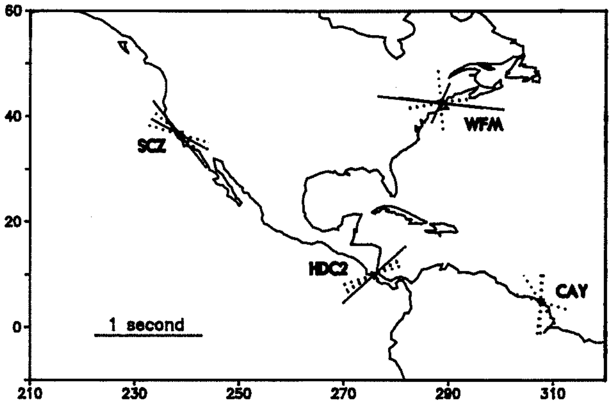

Fig. 4. Fast directions and time-difference between the fast and slow directions, at 4 Geoscope stations on the American continent. The magnitude of the time-shifts is given by the length of the solid bars according to the scale drawn for one second. The dotted lines are the polarization directions for which no splitting is observed.

TABLE 2. Summary of the observations at 9 stations

4	WFM	SKS	83°	L	2	KIP	SKS	77°	L
3	WFM	SKS	97°	0.8 s	2	KIP	SKKS	177°	L
19	WFM	SKS	83°	L	21	KIP	S	44°	1.0 s
5	WFM	S	175°	L	1	KIP	ScS	26°	1.4 s
20	WFM	S	25°	0.4 s	4	KIP	ScS	113°	L
23	WFM	S	80°	L					
14	WFM	ScS	96°	1.2 s	7	RER	sSKS	88°	L
					11	RER	S	131°	1.2 s
20	SCZ	SKS	131°	L					
21	SCZ	SKS	106°	L	6	PPT	ScS	51°	1.2 s
20	SCZ	S	141°	0.8 s					
18	SCZ	S	118°	0.6 s	12	INU	SKKS	86°	L
					20	INU	SKKS	74°	L
22	HDC2	SKS	72°	L	20	INU	sSKKS	74°	L
22	HDC2	S	57°	L	16	INU	SKKS	62°	L
23	HDC2	S	61°	L	10	INU	S	96°	1.2 s
23	HDC2	ScS	48°	0.8 s	13	INU	S	60°	0.6 s
					15	INU	ScS	146°	0.6 s
24	CAY	SKKS	6°	L					
21	CAY	SKKS	0°	L	9	SSB	SK(K)S	61°	L
8	CAY	SKKS	147°	L	17	SSB	SKS	60°	L
20	CAY	ScS	106°	L	17	SSB	SKKS	60°	L
9	CAY	ScS	107°	L	11	SSB	SK(K)S	60°	L

The number refers to the earthquakes in Table 1. The initials define the station; the analyzed phase is indicated. For the split waves, we give the azimuth of the fast direction with respect to North, followed by the time-shift in seconds. For the unsplit waves, flagged with L, the listed direction is the azimuth of the polarization.

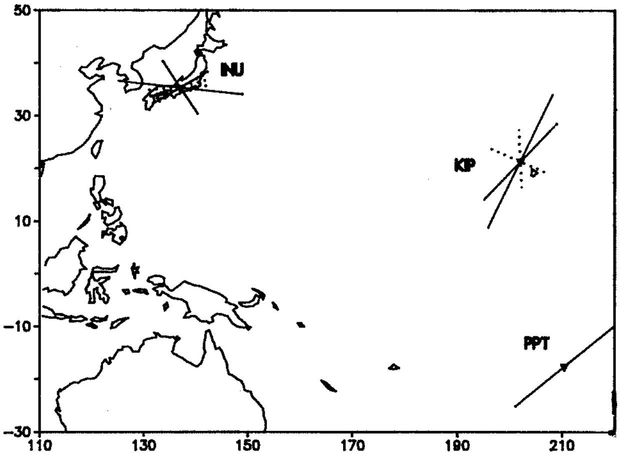

Fig. 5. Same as Figure 4 at 3 stations in the Pacific Ocean.

No splitting was observed at the Saint-Sauveur station (SSB) in France. Clear linear particle motions were obtained for SKS phases. However, all the observations correspond to the same N60 polarization. Anisotropy could be present, if its fast (or slow) velocity is close to that direction. In a recent analysis, Vinnik and Farra (personnal communication, 1988) report strong anisotropy at that station with a N140 fast direction.

Figure 5 shows our results for 3 stations in the Pacific Ocean. Large anisotropies are found both at Papete (PPT) and Kipapa (KIP). While P_n studies have demonstrated that the fast direction is usually aligned with the spreading direction in the oceans (Morris et al., 1969), our results indicate a fast direction that is nearly orthogonal to the present or fossil spreading direction. The same is true for the station in La Réunion (RER), not represented (see Table 2). This could indicate that the mantle beneath oceanic islands is quite different from "normal" oceanic mantle. We hypothetize that hot-spot related flow has strongly reorganized the base of the lithosphere and the mantle beneath it. The last station for which reliable splitting was observed is the Inuyama station (INU) in Japan. However, the fast directions we find from different records are clearly incompatible. One interpretation is that at least two anisotropic regions, with different fast directions, are crossed by the waves. Indeed, one could expect strong anisotropy induced by the subduction of both the Pacific and Philippine plates. Synthetic seismograms built with two superposed anisotropic regions show that the cross-correlation method then yields fast directions, which, in general, have nothing to do with any of the true fast directions. It should be possible to use these synthetics to better constrain the fast directions present beneath INU.

Conclusions

Anisotropy that implies strong mineral alignment over at least 100 km of the mantle has been found beneath 7 stations of the Geoscope network. The fast direction and time-shift have been retrieved from the analysis of shear-wave splitting. The fast direction beneath the oceanic island stations are almost perpendicular to the spreading direction, in contrast with what is found for "normal" oceans. The results presented in this paper were obtained using data recorded during less than 2 years. A more complete and precise analysis should be possible as more data become available.

Acknowledgements. We wish to thank the staff of the Geoscope network, and in particular A. Pyrolley. We are grateful to B. Romanowicz, A. Souriau, A. Deschamps, H. Lyon-Caen, P. Bernard, L. Vinnik and V. Farra. This work was supported by INSU-CNRS/IST "Geoscope". ENS Paris-Géologie Contribution # 64.

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(Received January 23, 1989;
revised March 20, 1989;
accepted March 21, 1989.)