GEOPHYSICAL RESEARCH LETTERS, VOL. 21, NO. 15, PAGES 1635-1638, JULY 15, 1994

Seismic azimuthal anisotropy beneath the Pakistan Himalayas

Eric A. Sandvol, James F. Ni and Thomas M. Hearn

Department of Physics, New Mexico State University, Las Cruces, New Mexico

Steve Roecker

Department of Earth and Environmental Sciences, Rensselaer Polytechnic Institute, Troy, New York

Abstract. Teleseismic S, SKS and SKKS data, collected from a temporary broadband array across the Himalayan front in Pakistan, are analyzed for shear-wave splitting parameters. The SKS and SKKS phases have ray paths originating from both the South Pacific and Colombia which have azimuths approximately 40° apart with respect to the Pakistan array. If significant seismic azimuthal anisotropy is present we should observe splitting associated with one of these ray paths. No evidence was seen for any shear-wave splitting beneath any of the stations in the array. Teleseismic S waves were also used in order to provide better azimuthal coverage for the shear-wave splitting measurements. We were able to correct for any source-side anisotropy when needed. No receiver-side splitting was observed in any of the S wave data. The lack of shear-wave splitting beneath the Pakistan array indicates that there is no appreciable large-scale azimuthal anisotropy beneath this part of the Himalayas. Therefore, if there is any significant strain in the upper mantle beneath this area, it must either be vertically oriented, or, if horizontal, vertically vary in such a way that the integrated effect on S wave splitting is null.

Introduction

Measurements of shear wave anisotropy allow some insight into the nature of strain in the upper mantle, principally because such anisotropy appears to result from the lattice preferred orientation of olivine aggregates caused by this strain [e.g. Nicolas and Christensen 1987, Ribe 1992]. In order to measure the seismic azimuthal anisotropy beneath the Pakistan Himalayas we have attempted to identify shear-wave splitting from a variety of phases, including S, SKS, and SKKS recorded from a portable broadband array located between the Lesser and Higher Himalayas in Pakistan (Figure 1). These phases split into fast and slow shear-waves due to the integrated effect of azimuthal anisotropy in the upper mantle. Measurements of shear-wave splitting from data collected by this array may elucidate the strain field and thus the deformation in the upper mantle beneath the western termination of the Himalayan collision zone.

The Himalayas are a result of continental collision between the Asian and Indian plates over the last 60 Ma. The geology of the western Himalayan syntaxis is quite complex, the main structural trend of the western Himalayas extends northwest-southeast and contrasts sharply with the nearly east-west trending foreland structures of the Hazara Arc (Figure 1)[e.g. Ni et al., 1991]. This paradox in structural trends in this part of the Himalayas led Seeber and Armbruster [1979] to suggest that the shallow features of the Pakistan Himalayas are detached and rotated into the present east-west direction. Velocity structures from local earthquakes [Ni et al., 1991] and teleseismic earthquakes [Menke, 1977] both suggest that the Indian lithosphere dips 4° - 6° towards northeast, but the subcrustal structure is not yet known. It has been suggested by many authors that the uplift of the western Himalayas occurred during recent geological times, especially in the Nanga Parbat-Haramosh region located just north-northeast of the western Himalayan Syntaxis [Ni et. al., 1991]. There is little doubt that the force driving this uplift must reside in the mantle and is produced by the density differences between cold and hot mantle material. What is in doubt is how and where these forces are exerted.

Copyright 1994 by the American Geophysical Union.

Paper number 94GL01386
0094-8534/94/94GL-01861$03.00

Data and Methods

The western Himalayan seismic experiment deployed an 11 station array in the Lesser and Higher Himalayas (Figure 1 and Table 1), where 9 of the stations had broadband

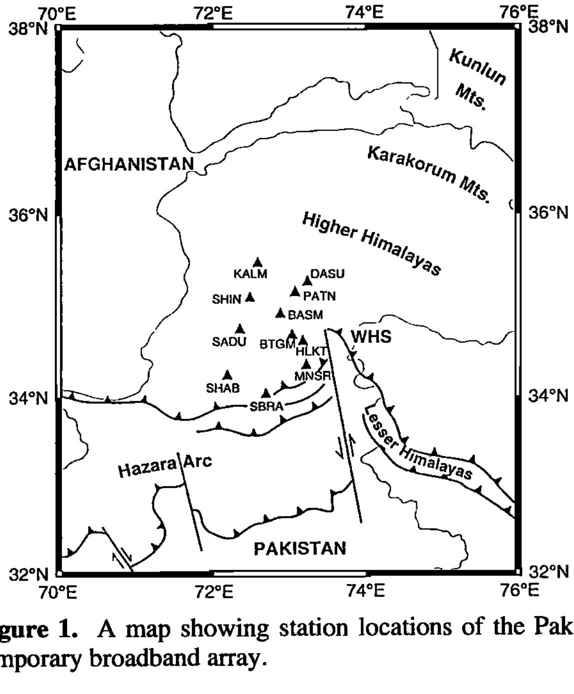

Figure 1. A map showing station locations of the Pakistan temporary broadband array.

Table 1. Stations in the Pakistan Broadband Array.

Station	Latitude	Longitude	Elevation
SBRA	34.029	72.628	415
SHIN	35.082	72.474	1463
SHAB	34.230	72.172	366
PATN	35.143	73.065	1106
DASU	35.262	73.217	1220
BASM	34.900	72.866	762
HLKT	34.605	73.160	1675
SADU	34.732	72.336	1005
BTGM	34.673	73.024	1067
MNSR	34.342	73.206	1115
KALM	35.485	72.569	2255

STS-2 Streckeisen seismometers. Each of the broadband stations had two data streams, one for recording teleseismic events (10 sps) and one for recording local and regional earthquakes (50 sps). We used data exclusively from the teleseismic data stream in this study (Table 2). SKS and SKKS records were only used at distances from 85° or greater. We used only those teleseismic S waves originating from 65° to 85° from the Pakistan array, thereby avoiding any distortions of the shear-wave particle motions [e. g. Nuttli, 1961; Kennett, 1991].

The method used to resolve the shear-wave splitting parameters for S waves involves searching throughout all of the shear-wave splitting parameter space for the fast-slow coordinate system which comes closest to having a singular time domain covariance matrix of the particle motion in the horizontal plane [e.g. Silver and Chan, 1991; Savage and Silver, 1993]. For the SKS and SKKS waves, this method reduces to minimizing the energy in the transverse component because these phases are radially polarized.

Errors associated with shear-wave splitting parameters are estimated using both a bootstrap technique [Sandvol and Hearn, 1994] and the method of Silver and Chan [1991]. Silver and Chan's method uses the f-test to determine whether or not the shear-wave splitting parameters are significantly different from those of an isotropic model. The bootstrap technique involves the randomization of the noise contained in each of the shear-wave waveforms. The randomized noise is then combined with the original waveform to calculate one hundred independent shear-wave splitting inversion solutions. From the distribution of these solutions we compute two standard deviations for the fast direction and lag time. The bootstrap error analysis allows us to distinguish among data with no apparent splitting, data with splitting, and noisy data [Sandvol and Hearn, 1994].

Since all teleseismic S waves used in this study originated from shallow events, we need to determine the source-side azimuthal seismic anisotropy. This task is accomplished using S waves recorded at permanent broadband stations. For example, we determine the shear-wave splitting parameters beneath station AAK from SKS and SKKS phases. We then remove the azimuthal seismic anisotropy beneath station AAK and solve for the source-side shear-wave splitting parameters. Once we have obtained the source-side shear-wave splitting parameters we can eliminate the source-side splitting in the S waves which originated from the same source and were recorded at various stations in the Pakistan array. This technique also was employed successfully by a number of other researchers in their search for azimuthal seismic anisotropy [e.g. Vinnik and Kind, 1993, Fischer and Yang, 1994].

Results and Conclusions

S waves from eight events and SKS and SKKS waveforms from ten events collected from the Pakistan array were analyzed. None of these data showed any significant splitting beneath the Pakistan Himalayas. Figure 2 is an example of SKS waves recorded at five stations along with corresponding particle motions. Energy is primarily present in the radial component while there is little energy in the transverse component. The particle motion of the SKS waves is linear indicating that there is either no azimuthal anisotropy, or the polarization of the SKS phase was either perpendicular or parallel to the fast direction. The majority of the SKS data recorded were polarized along an east-west direction. An SKS wave from the Colombia foreshock (1992-291) has a back-azimuth 319°, approximately 50° from the east-west orientation. These SKS waves also showed little evidence of

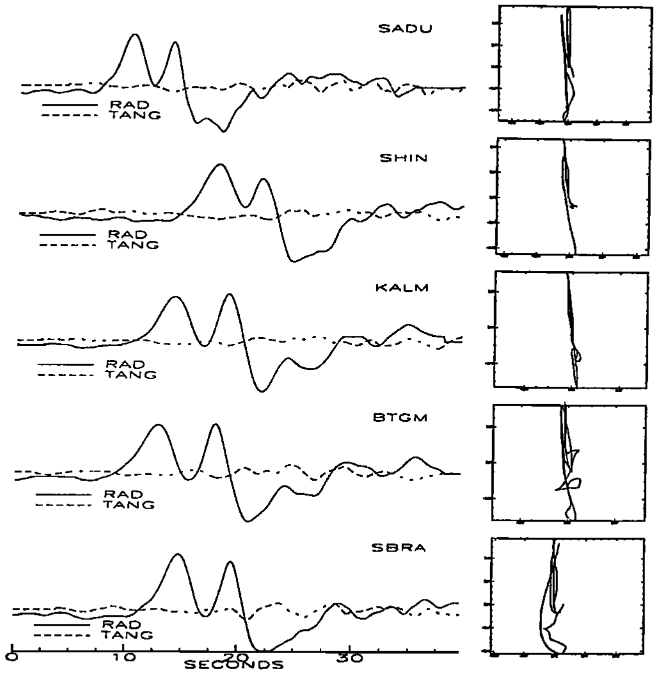

Figure 2. An SKS phase originating from an event in Vanuatu (1992-285) recorded at five of the nine broadband stations in the Pakistan array. The vertical axis of the particle motion corresponds to the energy in the radial component and the horizontal axis corresponds to the transverse component. The lack of energy in the transverse component is a strong indicator that this shear-wave is not split.

Table 2. Events used for Shear-Wave splitting Analysis.

Day	Seconds	Depth	Latitude	Longitude	Delta	Azimuth	mb
			Teleseismic S Waves				
274	53400.3	33	51.26	-178.07	74.52	37.97	6.2
275	50236.7	33	51.10	-117.98	74.66	38.07	6.0
292	130853.5	109	-6.29	130.22	67.77	114.92	5.7
295	121115.3	32	-6.90	144.17	78.93	106.31	5.8
305	143426.7	33	-2.39	141.22	73.89	104.44	5.8
315	95813.3	55	51.47	-177.61	74.63	37.61	5.7
316	212614.1	33	51.18	-179.24	73.97	38.48	5.7
322	64639.7	33	-5.81	130.56	67.71	114.29	5.7
			Teleseismic SKS and SKKS Waves				
285	192429.2	157	-19.28	168.91	105.50	102.82	6.4
289	223707.1	33	-14.45	166.63	101.07	99.89	6.1
291	83239.9	10	6.87	-76.82	129.56	319.65	6.2
292	151159.3	10	7.12	-76.89	129.38	319.90	6.6
296	90424.9	33	-30.00	-177.28	121.63	116.46	6.0
298	82304.3	41	-29.44	-177.38	121.31	105.91	5.8
309	181317.2	33	-14.16	167.49	101.60	99.17	6.0
317	222858.4	368	-22.35	-178.08	117.53	99.02	5.9

All events occurred in year 1992.

splitting at all stations. The SKKS phase (the longer ray path) from the Colombian main shock (1992-291) recorded at Patan (PATN) and Mansehra (MNSR) with a back-azimuth of 138° also showed no splitting.

The lack of azimuthal coverage from SKS and SKKS phases led us to investigate splitting from teleseismic S waves. We analyzed S waves from 10 shallow events located in the South Pacific and Aleutians. Figure 3 shows an example of S waves from the 1992-292 New Guinea event. We were able to correct for any source-side contribution of azimuthal anisotropy through the method discussed earlier. The S wave particle motion is approximately linear, again indicating no significant amount of splitting is present. The S waves from the Aleutian events were all polarized along a north-south azimuth and yielded results consistent with our SKS analysis. Polarization

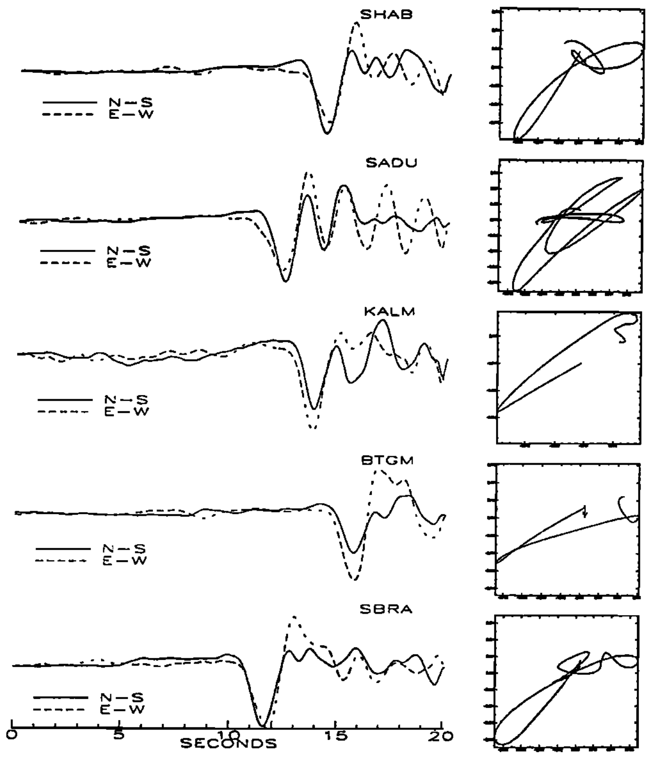

Figure 3. Five horizontal seismograms containing a teleseismic shear wave originating from an event in New Guinea (1992- 292). The vertical axis of the particle motion plots is the north-south amplitude and the horizontal axes is the east-west amplitude. The mean polarization of these waveforms is 55°. All five seismograms have a roughly linear particle motion even though we have not corrected for any source-side shear-wave splitting. Grid search inversions of these waveforms indicate that none of these shear-waves are split.

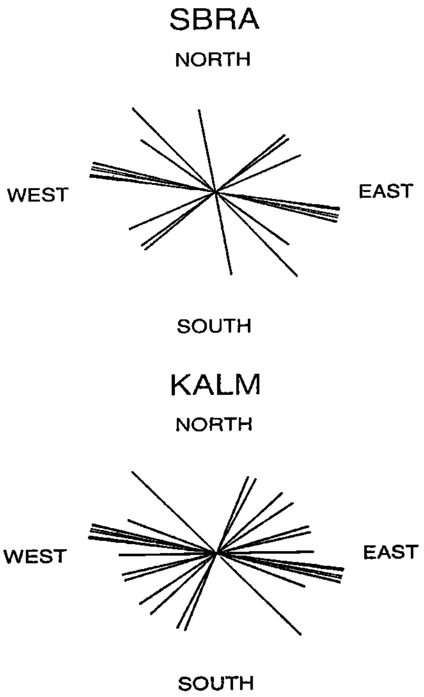

Figure 4. A windrose diagram illustrating the polarizations from the shear-waves analyzed at stations SBRA (southern-most station) and KALM (northern-most station). The azimuthal coverage for both of these stations rules out the possibility that the lack of splitting observations is due to the shear-waves being polarized either perpendicular or parallel to the fast direction.

directions for S, SKS, and SKKS phases are plotted on wind rose diagram for stations at Sobra City (SBRA) and Kalam (KALM) (Figure 4). The angular coverage is sufficiently large to rule out any azimuthal anisotropy beneath the Pakistan Himalayas.

The lack of shear-wave splitting beneath the Pakistan Himalayas is an unusual result from our seismic work in the Himalayas. For convergent plate margins, global studies of azimuthal seismic anisotropy show that the fast direction of azimuthal anisotropy usually aligns nearly parallel to the plate boundary [Vinnik et al., 1992]. In western Tien Shan, it was found that the fast directions of the split shear-waves were parallel to the mountain belt [Makeyeva et al., 1992]. A similar result might have been expected in the Pakistan Himalayas, namely approximately east-west oriented fast directions of azimuthal anisotropy. The lack of any detectable anisotropy means that if there is any significant strain in the upper mantle, it must either be vertically oriented, or, if horizontal, vary with depth in such a manner that the net effect on shear wave splitting is null. We note that geophyciscal observations [e.g. Molnar et al., 1993] suggest that the coldest part of the mantle underlies the western Himalayan syntaxis and the Karakorum and the Kunlun Mountains, and therefore a predominately vertical strain field resulting from localized downwelling is not unlikely for this region.

Acknowledgments. We thank John Armbruster, Arthur Chen, Tom Fairbanks and Scott Phillips for helping us to collect data. The Pakistanis from the Pakistan Water and Power Development Authority also participated in field work. We want to thank Martha Savage and an anonymous reviewer for their constructive comments. U.S. Funding was provided by a grant from USAID Grant # COM-5600-G-00-0019-00.

References

Fischer, K., and X. Yang, Anisotropy in Kuril-Kamchatka subduction zone structure, *Geophys Res. Lett.*, 21, 5-8, 1994.

Kennett, B. L. N., The removal of free surface interactions from three-component seismograms, *Geophys. J. Int.*, *104*, 153-163, 1991.

Makeyeva, L.I., L.P Vinnik, and S.W. Roecker, Shear-wave splitting and small-scale convection in the continental upper mantle, *Nature, 358*, 144-147, 1992

Menke, W.H., Lateral inhomogeneities in P velocity under the Tarbela array of the lesser Himalayas of Pakistan, Bull. Seismol. Soc. Am., 67, 725-734, 1977.

Molnar, P., P. England, and J. Martinod, Mantle dynamics, uplift of the Tibetan Plateau, and the Indian Ocean, *Review of Geophysics*, 31, 357-396, 1993.

Ni, J., O. Ibenbrahim, O., and S. Roecker, Three dimensional velocity and hypocenters of Earthquakes beneath the Hazara Arc, Pakistan: Geometry of the Underthrusting Indian Plate, *J. Geophys. Res.*, 96, 19865-19877, 1991.

Nicolas, A. and N.I. Christensen, Formation of anisotropy in upper mantle peridotites-A review, in *Composition, Structure and Dynamics of the Lithosphere-Asthenosphere System*, Geodyn. Ser., Vol. 16, edited by K. Fuchs, and C, Froidevaux, AGU, Washington D. C., 111-123, 1987.

Nuttli, O. The effects of the earth's surface on the S-wave particle motion, *Bull. Seismol. Soc. Am., 51*, 237-246, 1961.

Ribe, N.M., On the relationship between seismic anisotropy and finite strain, *J. Geophys Res.*, *97*, 8737-8747, 1992.

Sandvol, E., and T. Hearn, Bootstrapping shear-wave splitting errors, *Bull. Seis. Soc. Amer.*, in press, 1994.

Savage, M.K., and P.G. Silver, Mantle deformation and tectonics: Constraints from seismic anisotropy in western United States, *Phys. Earth Planet. Inter.*, 78, 207-227, 1993.

Seeber, L., and J.G. Armbruster, Seismicity of the Hazara Arc in northern Pakistan: Decollement vs. basement faulting, in *Geodynamics of Pakistan*, edited by Farah, and K.A. DeJong, pp. 131-142, Geological Survey of Pakistan, Quetta, 1979.

Silver, P.G., and W., Chan, Shear-wave splitting and mantle deformation, *J. Geophys Res.*, *96*, 16,429-16,454, 1991.

Vinnik, L.P., and R. Kind, Ellipticity of teleseismic S-particle motion, *Geophys. J. Int.*, *113*, 165-174, 1993.

Vinnik, L.P., L.J. Makeyeva, A. Milev, and A. Yu. Usenko, Global patterns of azimuthal anisotropy and deformations in the continental mantle, *Geophys. J. Int., 111, 433-447*, 1992.

E. Sandvol, Department of Physics, New Mexico State University, Las Cruces, NM 88001-0001. (e-mail: esandvol@atlas.nmsu.edu)

J. Ni, Department of Physics, New Mexico State University, Las Cruces, NM 88001-0001. (e-mail: jni@atlas.nmsu.edu)

T. Hearn, Department of Physics, New Mexico State University, Las Cruces, NM 88001-0001. (e-mail: thearn@atlas.nmsu.edu)

S. Rocker, Department of Earth and Environmental Sciences, Rensselaer Polytechnic Institute, Troy, NY 12180-3590.

(Received February 22 1994; accepted April 25, 1994)