Complex seismic signatures and narrow azimuthal study of Hindukush earthquakes

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Abstract. About eighty earthquakes, exclusively from the Hindukush region, which were recorded at Gauribidanur seismic array (GBA) have been used in the present study. Short period *P*-wave recordings upto 36 seconds were processed using adaptive cross-correlation filtering technique. The main objective of this exercise was to examine the signal complexities and seismic ray direction anomalies of these earthquakes which have identical epicentral distances and a narrow azimuthal range from GBA but different focal depths from 10 to 240 km. Slowness anomalies of the order of 1.4 sec/deg and azimuthal anomalies upto 6° have been found in this case. These deviations have been attributed to the upper mantle region between source and the receiver. Analysis of the data reveals that most of the events occurring at shallower depths had complex signatures as compared to the deeper events. The structure near the source region, complicated source functions and scattering confined to the crust-upper mantle near source are mainly responsible for complexity of the observed signals as the transmission path of the ray tubes from turning point to the recording stations is practically the same.

Keywords. Signal complexities; slowness anomalies; azimuthal anomalies; Hindukush earthquakes.

1. Introduction

Several investigations have been carried out regarding the seismotectonics and analysis of the Hindukush earthquakes during the last decade (Nowroozi 1972; Engdahl 1974; and Chatelain *et al* 1979). In the present paper, we report the observations on the seismic ray direction anomalies and complex signatures of over 80 Hindukush earthquakes recorded at Gauribidanur seismic array (GBA) in southern India. Epicentres are shown in figure 1. The configuration of the GBA is also illustrated in the inset in the upper right of this diagram. The array consists of two *L*-shaped arms (called blue and red lines) each containing ten short-period (1 sec) vertical seismometers spaced at an interval of 2.5 km. The vaults are set over Archaean rocks with unweathered gneisses lying within two metres of surface over most of the regions. The output of each instrument is carried by a telemetry system to a central recording laboratory where it is recorded as a separate channel of a 24-channel FM magnetic tape.

The earthquake data used in this analysis have similar epicentral distances and a narrow azimuthal range but varying focal depths from 10-240 km. Short period *P*-wave recordings up to 36 seconds of these events were processed using adaptive cross-correlation filtering technique (Mereu and Ram 1975). The

Figure 1. Configuration of Gauribidanur Seismic array (GBA) and epicentral location of the earthquakes used. Dotted portion indicates the sampled region of the upper mantle where the seismic rays have got their deepest penetration.

meaningful measurements of slowness and apparent azimuths of the first arrivals were selected and the weighted mean of these quantities was taken. A detailed procedure of the analysis of additional data was given by Ram and Mereu (1977). Local structural correction was not applied in the slowness data as this correction is not significant at least from this direction. Many studies have revealed that GBA is situated, in general, on a relatively homogeneous structures (Corbishley 1970b; Ram and Mereu 1977; Berteussen *et al* 1977).

2. Observations on seismic ray direction anomalies and complex signatures of earthquakes

Seismic ray direction anomalies as obtained from the present analysis are shown in the form of an array diagram (figure 2). Each vector line segment represents an observation which starts (tail) at the slowness value determined from the *P*-tables of a standard earth model and the great circle azimuth as obtained from the NOAA listings and ends (head) at the observed slowness and azimuth values. It is clear from the array diagram that anomalies do not show any systematic mislocation for all the events. However, both the slowness and azimuthal anomalies can be classified into two separate groups showing positive as well as negative bias. The azimuthal anomalies show an almost consistent positive

Figure 2. Seismic ray direction anomalies of the first arrivals of Hindukush earthquakes recorded at GBA, illustrated in the form of an "array diagram". Each vector line segment represents an observation which starts (tail) at the slowness value determined from the JB earth model and great circle azimuth as obtained from the NOAA listings, and ends (head) at the observed slowness and azimuth values.

bias towards the north. It indicates that most of the ray tubes have deviated northward during their transmission path in reaching GBA. Slowness anomalies can be grouped into two systematic patterns. One shows a highly positive bias above 10 sec/deg of absolute slowness value and the other shows a moderately negative bias below this absolute value. There are more rapid variations in the positive slowness anomalies than negative bias. The source of anomalous slowness and azimuth observations may be attributed in the following three areas;

- (i) Hypocentres located in a slab probably sinking into mantle (source region)
- (ii) Beneath the recording sites at GBA, and
- (iii) The turning point of the rays in the upper mantle underlying the Indian subcontinent (dotted portion of figure 1).

Brown (1973) mentioned that lateral heterogeneity in P -velocity will affect azimuth more and slowness less when the ray segment is closer to horizontal, which implies that slowness anomaly reflects rather deeper causes than indicated by azimuthal anomaly. However, Nojonen (1974) considered that horizontal velocity closer to the array than to the source seemed to be the probable cause

for slowness deviations. These conclusions suggest that, at least, slowness anomaly reflects almost negligible cause from source region. There may be some additional effects on the anomaly vector but the source region cannot be responsible for such large mislocations of azimuth. Unsystematic mislocations at an array from the same source region also suggest that source effects are not pronounced. Davies and Sheppard (1972), using data from LASA, also concluded that the main source of slowness anomalies observed are in the mantle. Capon (1973), using a quantitative technique, concluded that in the case of a typical seismic ray direction anomaly, the major part is generated in the crust and the mantle beneath the array.

A sloping crust-mantle interface or the Moho-discontinuity and variations in the thickness of crust underneath the recording stations will influence the observed slowness and azimuthal values. Niazi (1966) considered the effect of a dipping *M*-discontinuity or a simple plane dipping interface to account for the slowness and azimuthal anomalies. The effect of such an interface will introduce approximately sinusoidal variations in the azimuth and slowness anomalies as a function of great circle azimuth. Such sinusoidal variations of anomalies as a function of great circle azimuth were not found in the case of GBA (Ram and Mereu 1977). Berteussen *et al* (1977) have found that GBA appears to be sited on homogeneous structures. They found that 75% of the observations at GBA could be explained in a satisfactory manner if a dipping plane coincident with Moho was introduced with a dip 6° and striking $N 13^\circ E$ as compared to a dip of about 4° and striking $N 50^\circ E$ as postulated by Arora *et al* (1970). In an earlier study by Ram (1976), it was found that relative time residuals have very little dependence on azimuth and distance, thus indicating that the main source of these residual variations observed is probably localized beneath the array. However, our results indicate both positive as well as negative slowness anomalies in narrow azimuthal range thus rejecting the plea, being caused due to a dipping plane beneath the recording stations. Thus, the structural anomalies in the vicinity of the source region and in the crust beneath the array do not seem to be the probable cause to produce slowness and azimuthal anomalies of the magnitude observed. Slowness anomaly as a function of ray direction is in itself inadmissible because all ray tubes to the array must traverse the same section of the crust (narrow azimuthal range) and thus suffer the same deflection (Noponen 1974).

We will now examine the region where rays are bottoming. In this zone, the rays almost become horizontal and thus the velocity gradients will have maximum effect on the ray parameter and the direction. The base of the ray is important in spherically symmetric models because of the large percentage of the ray path located in this region. Unsystematic deviations for the rays which are travelling almost the same source structure and crustal structure beneath the array suggest that probably the upper mantle which the waves have propagated, especially where the rays bottom, is responsible for a significant portion of the azimuthal and slowness anomalies. However, the multipathing of seismic energy and scattering due to heterogeneities present in the upper mantle are partially responsible to some extent. Thus, the slowness and azimuthal anomalies reflect their cause as lateral inhomogeneities present in the upper mantle. In the present case, mislocations are characterized by higher slowness deviations (for positive bias) for

Figure 3. Variation of slowness with epicentral distance. JB standard curve is also shown.

Figure 4. Variation of signal complexities with focal depth as shown by the beam traces (SRB). Time-averaged product (TAP) trace is also shown which illustrates the coherency of the signals. Epicentral distances and azimuths are identical at GBA.

epicentral distances less than 23° and lower slowness deviations for greater epicentral distances as shown in figure 3. The slowness pattern shows an abrupt change just before 23° (corresponding depth of about 625 km) suggesting that the velocity gradients are much more pronounced around this depth as compared to

the shallower depth. A three-layer model in the depth range 400-700 km has been postulated by Ram and Yadav (1981) to explain these anomalies. They have also examined the seismic ray direction anomalies as a function of focal depth for this region.

A search of individual array traces of Hindukush earthquakes indicated that most of the events occurring at shallower depths had complicated signatures as compared to deep focus events. The beam and TAP (time averaged product formed over a window length of 0.75 sec) traces for fourteen earthquakes are shown in figure 4. The peculiarity of these events is that their epicentral distances and azimuths are practically the same but having different focal depths. In other words, the transmission path, especially between the turning points of the ray tubes and the receiver (GBA) is identical. Thus, these events have their focii in an inclined columnar structure in the source region and any complexity in the signals is mainly attributed to the near source heterogeneities.

3. Discussion and conclusion

Ram and Mereu (1977) investigated the lateral variations in the upper mantle structure around India after analysing over 300 earthquakes recorded at GBA and distributed from 0°-360° azimuth range. The variation in slowness and azimuthal anomalies was attributed to the transition zones present between 400-700 km depth range. However, no distinct evidence for sinusoidal variation of these anomalies was obtained by them. The earthquake data used in this analysis are within a narrow azimuthal range thus avoiding the effect of source and structure beneath the recording sites. It is interesting to note that events with identical epicentral distances show sufficient contrast in the slowness and azimuthal anomalies in spite of the identical sources and recording stations. This clearly reflects the cause of such anomalies at the turning point of ray tubes, thus confirming again the presence of transition zones and lateral variations in the upper mantle structure. A velocity model for the Hindukush region was derived by Ram and Mereu (1977) using travel time and slowness data. The events from other source regions including Iran and Pakistan were also included in this model.

The problem of complexity of seismic signals has been examined by a number of scientists. Thirlaway (1963) and Carpenter (1964) suggested that complexity in signal might result from reverberations of the *P* and *S* signals in the crustal layers near the source region with conversion of some of the *S* wave energy into *P* waves. Douglas *et al* (1973) have re-examined the complexity problem for *P* signals in the context of discrimination between nuclear explosions and earthquakes. They suggested that absorption of energy and the multipathing are responsible for complexity of signals up to some extent. Thus, we conclude that the structure near the source region, complicated source function, and the scattering confined to the crust and upper mantle near the source are mainly responsible for the complex signatures of the Hindukush events as the transmission zone of seismic ray tubes from turning point to the recording stations is practically the same. Some of the ambiguities encountered in the interpretation of the data can be minimised after introducing the effect of scattering and attenu-

ation in the analysis of seismic waves. It is proposed to compute spectral estimates of atleast fourteen events shown in figure 4 and their results would appear elsewhere.

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