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Predominance of plate motion-related strain in the south Indian shield

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Seismic anisotropy in the lithosphere, manifested by the splitting of shear waves into two orthogonal polarizations directions, is related to the lattice preferred orientation of olivine, which in turn is influenced by the direction of flow in the mantle[1,2]. Such anisotropy inferred beneath Precambrian terrains is interpreted as related to either present day plate motion (mantle flow direction)[3,4] or ancient anisotropy fossilized in Precambrian terrains[5]. We present here data from digital broadband seismographs at Hyderabad and Gauribidanur, which indicate that the azimuth of seismic anisotropy is closely aligned with the present day northward direction of absolute plate motion for India. These results confirm our earlier findings from analogue seismic data elsewhere[3] wherein we infer that shearing of the sublithospheric mantle by the moving plate results in resistive drag by the mantle leading to preferred crystallographic orientation near the base of the plate.

FLOW of the mantle beneath stable continental interiors is best documented by the observation of the phenomenon of shearwave splitting due to mantle anisotropy. Seismic anisotropy may be caused by the preferred orientation of anisotropic materials such as mantle minerals (mainly olivine, orthopyroxene), that tend to become aligned in the flow direction during rock deformation. Thus, the shear history and, therefore, the finite strain involved forge preferential orientations in material giving rise to the observed anisotropic seismic velocities in a particular direction. Laboratory experiments[6], theoretical modelling studies[1,2] and observations on natural anisotropic crystals[7] reveal that the fast polarization direction is parallel to the crystallographic axis [100]. This in turn is found to exhibit the same parallelism with the extension direction for nearly all types of finite strain that encompass the various tectonic processes. Therefore the fast polarization direction, strain-induced lattice deformation and orientation of finite strain principal axes have a definite relationship based on the nature of the tectonic process.

An established tool to study azimuthal anisotropy is to observe shearwave splitting in seismic phases, SKS and SKKS, which propagate through the Earth's core and arrive at the receiver in a near vertical direction. Their polarization is controlled almost exclusively by azimuthal anisotropy underneath the receiver. Being P–S conversions at the core mantle boundary, the SKS and similar seismic phases are radially polarized in an isotropic, spherically symmetric earth. The presence of detectable SKS energy on the transverse component seismograms (T) in addition to the signal in the radial component (R) would therefore signify departure from the above idealized conditions. Ellipticity of the horizontal particle motion in these seismic phases is a prime diagnostic of anisotropy. A clear shift in time of T-component SKS phase with respect to that in the R-component by a quarter period is another important diagnostic of azimuthal anisotropy beneath the receiver.

Most of shearwave splitting data in Precambrian terrains come from north America[6,8] and southern Africa[4]. To these we add our seismic observations from two broadband seismograph stations in the south Indian shield located at Hyderabad (HYB) and Gauribidanur (GBA) (Figure 1) on Precambrian gneisses for few events (Table 1) documenting the phenomenon of shearwave splitting in the region. In passing, we also mention the results from our earlier study[3] (Figure 1) based on the analysis of analogue records. This study, besides contributing in a small way to the scanty data base from Precambrian terrains of the world, should also help go a little further in resolving the question as to whether seismic anisotropy is primarily a fossil feature of lithosphere inherited from the Precambrian or is always closely aligned with the current plate motion direction.

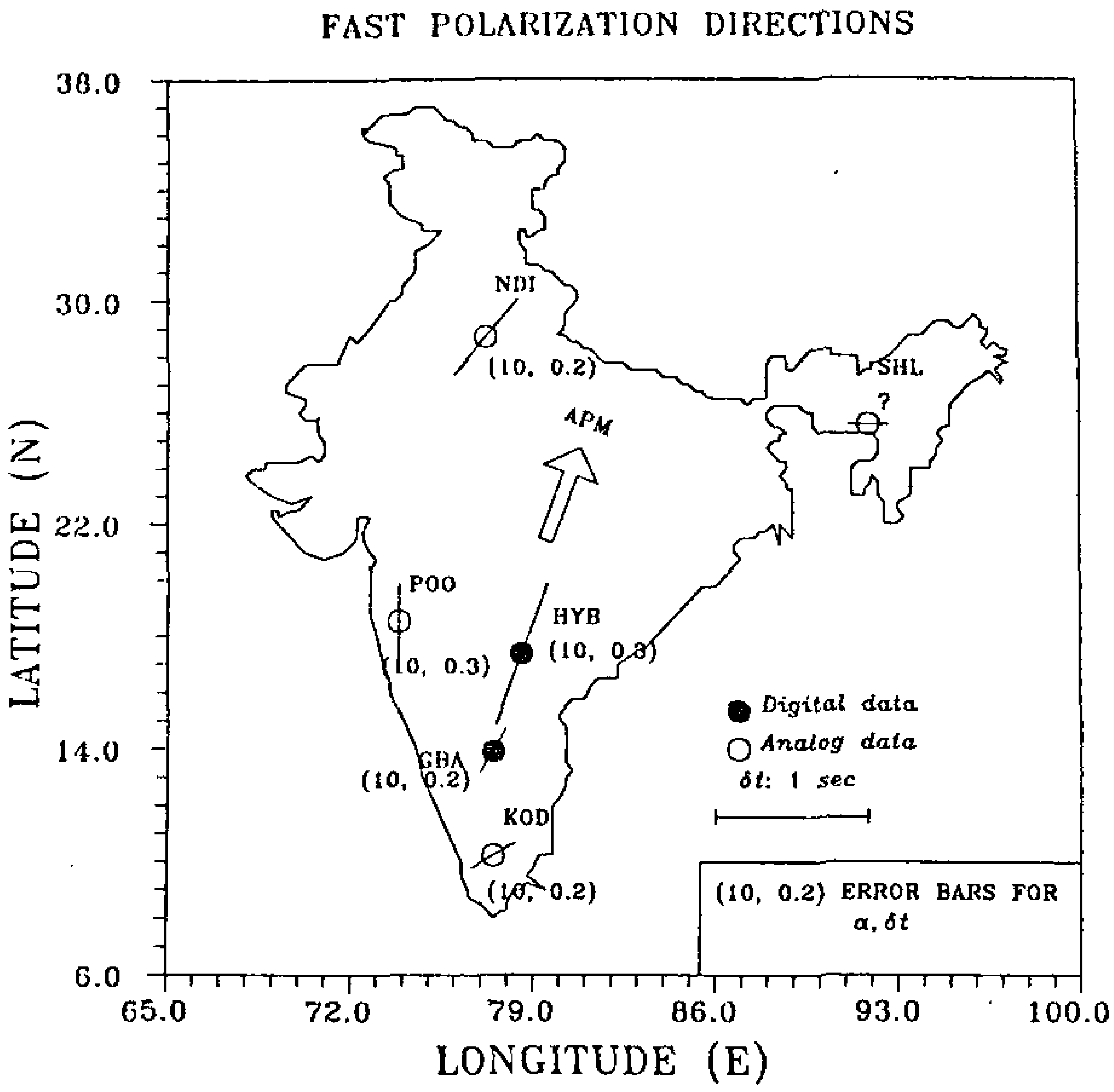


Figure 1. Map of India showing the direction of fast polarization (azimuth) indicated by straight line for analogue (WWSSN) stations and by arrow for digital stations from the present study. Length of the line is proportional to the delay time (δt) observed at each station (see scale bar). The direction of absolute plate motion [adapted from AM1-2(Minster and Jordan[10]) is also suggested by Gripp and Gordon[11] after incorporating the NUVEL-1 global plate motion model] for India is shown by the wider arrow. Note the close alignment between 'α' at stations and the absolute plate motion direction. Quantities given in brackets at each station correspond to errors in α, δt respectively. Filled circles represent digital station data. Open circles indicate analogue station data.

A linearly polarized shearwave on encountering an anisotropic zone splits into two orthogonally polarized shear waves that travel with different velocities. In this study the records of SKS and SKKS phases were inverted to arrive at the direction of fast split wave (α) and the delay time (δt) between the arrivals of the two split waves using the inversion scheme[9], detailed in ref. 3. The optimum pair of $\alpha, \delta t$ values is obtained by minimizing the r.m.s. difference between the observed T component and the theoretical T component corresponding to the observed radial component (R). A penalty function E also called 'energy function' is computed for every event and for the whole set of events together at each of the stations. The energy function E is of the form:

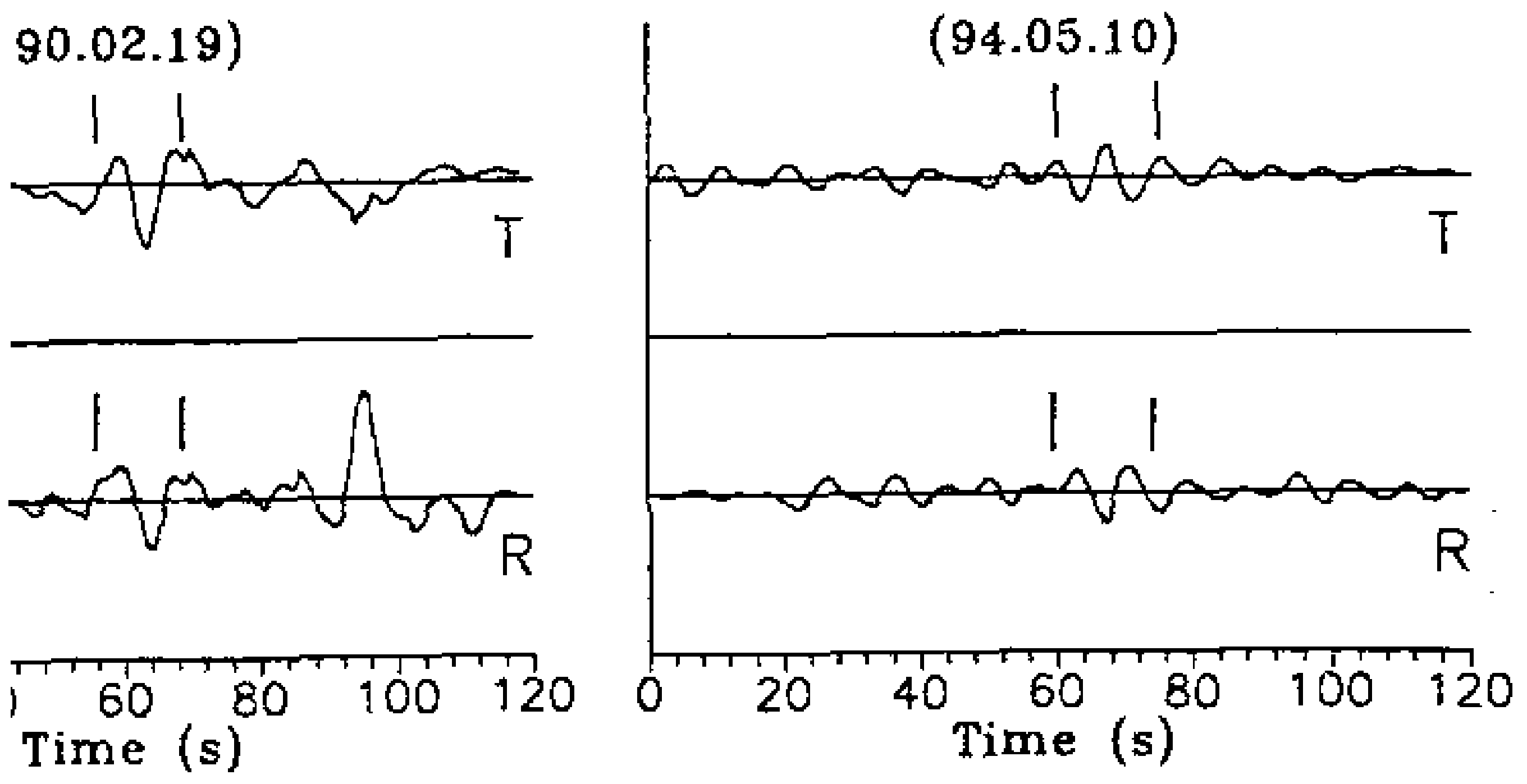
$$E(\alpha, \delta t) = \{1/N \textstyle\sum_{\text{events}} \int [T_0(t) - T(t, \alpha, \delta t)]^2 \, \mathrm{d}t \, / \int R^2(t) \, \mathrm{d}t\}^{1/2},$$

where α is a trial azimuth for the axis of fast velocity measured clockwise from north, δt is a trial delay time, T_0 is the observed transverse (T) component of the seismogram, R is the observed radial component of the seismogram and N is the number of events. That pair of α and δt which gives the minimum of E for all the trial values is designated as the parameter of anisotropy. This pair is arrived at, by conducting a grid search over the values of parameters α and δt between the ranges 0° and 180° in steps of 10° and 0 to 2 s with increments of 0.2 s respectively. Scatter in estimates of parameters for individual events is within $\pm 20°$ for α and ± 0.4 s for δt. The combined processing of all events, however, reduces the r.m.s. scatter to $\pm 10°$ in α and $\pm$ 0.3 s in δt.

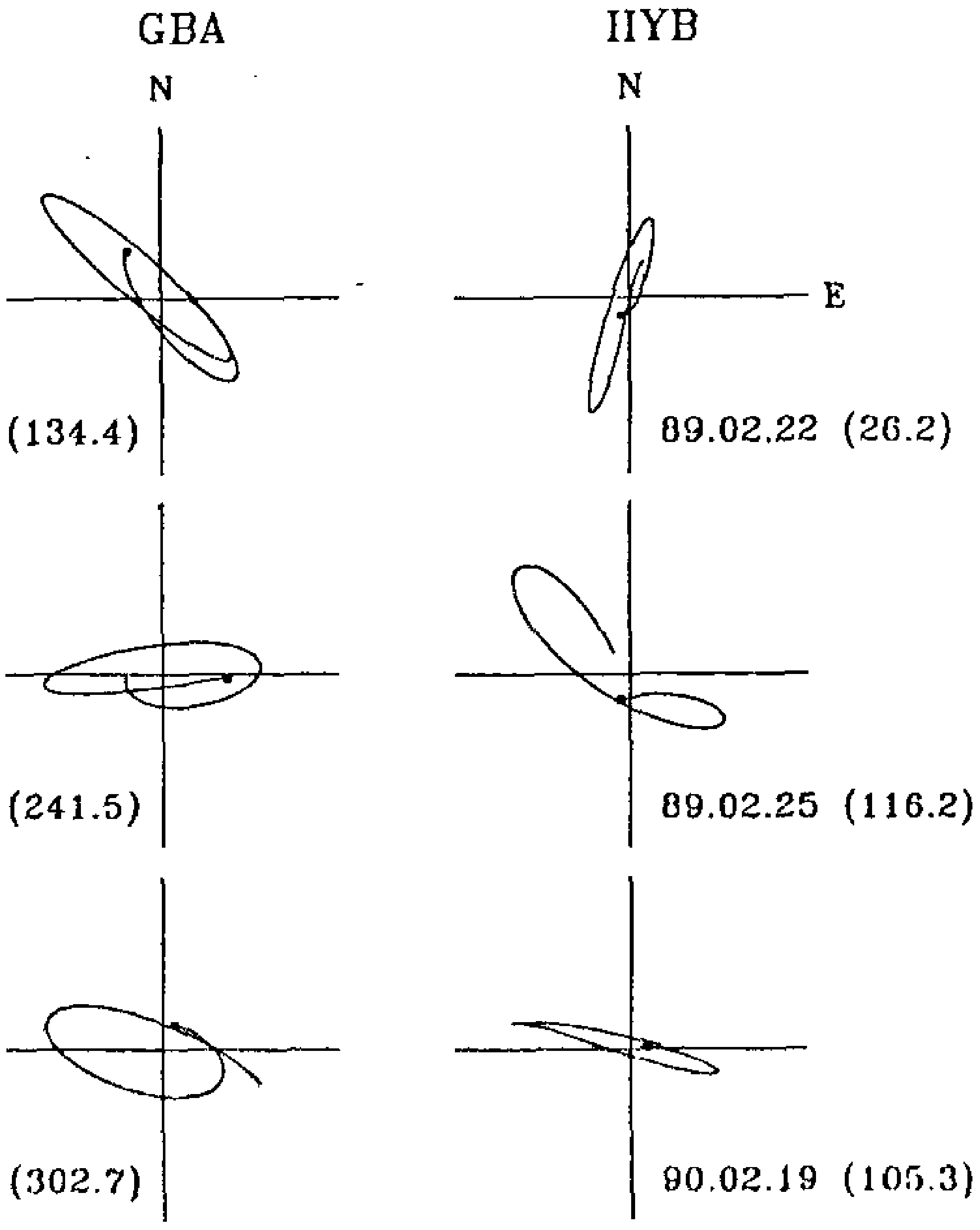
The recorded seismograms at HYB and GBA were individually filtered through frequency bands 0.1–0.25 Hz and 0.067–0.12 Hz and then analysed. An example of the rotated seismograms at HYB and GBA (Figure 2) clearly shows a strong SKS signal in both R and T components with amplitudes much higher than the background noise. The prime diagnostics of anisotropy, ellipticity in horizontal particle motion and quarter period phase shift between T and R components of the SKS and similar phases are clearly demonstrated in Figures 3 and 4 respectively at both HYB and GBA. Combined processing of all the seismograms at each station provides the best estimate of anisotropic parameters α, δt and are indicated by the positions of minima that emerge

Table 1. List of events at stations GBA and HYB used in this study along with their hypocentral parameters

Date (yr mo da)	Origin time (hr mn sec)	Lat (deg)	Long (deg)	Depth (km)	Delta (deg)	Azimuth (deg (N))	phase	Station
89 05 31	05 54 20.5	45.38 S	167.08 E	023	099.3	134.4	SKS	GBA
94 05 10	06 36 28.3	28.50 S	063.09 W	601	140.5	241.5	SKS	GBA
94 05 31	17 41 55.6	07.41 N	072.03 W	01.1	143.2	302.7	SKKS	GBA
89 02 22	10 25 45.6	56.27 N	153.66 W	033	094.5	026.2	SKS	HYB
89 02 25	11 26 34.0	30.02 S	177.91 W	021	109.9	116.2	SKS	HYB
90 02 19	06 48 10.2	15.47 S	166.40 E	012	092.5	105.3	SKKS	HYB



Example of rotated seismograms (*T, R*) at stations HYB
The phase of SKKS/SKS is marked by vertical bars in the
at HYB and GBA respectively.



Particle motions for SKS/SKKS are shown for all event
s study at stations GBA and HYB. Filled square indicates
f particle motion. The date of event is followed by the
parentheses.

to be comparable in α, in the respective penalty function plots (Figure 5 *a*, *b*). The fast polarization directions (α) at HYB and GBA overlap in the NNE direction with δt values 1.5 s and 0.5 s respectively. The average azimuth of fast polarization direction at HYB and GBA is close to the range 20–30° as measured clockwise from north (i.e. NNE) and is at an high angle to any of the known major geologic structural strike directions in the Precambrian gneisses of this region. It is interesting to note that the inferred NNE fast anisotropic direction is closely aligned with the present day absolute plate motion direction of India. Results from our earlier study based on analogue measurements[3] in south Indian shield (Figure 1) also yield the above inferred NNE fast azimuth. Our digital observations in south Indian shield do suggest a close alignment of the fast seismic anisotropic direction with the present day northward mantle flow direction. The analogue result at POO also supports the above observation. However, given the geologic and geochronologic diversity of the Indian shield in general, and the south Indian shield in particular, it would be interesting to identify the locales:

a) with dominance of frozen anisotropy in the lithosphere due to strains associated with tectonic processes of the past (fossil strain model) that are manifested as major strike directions in the geologic fabric of a terrain;
b) and those, where the recently formed anisotropy in the asthenosphere due to strains associated with current mantle flow direction predominate. In such a case the continental mantle deforms in the same way the oceanic mantle does.

There could, however, be areas where both these deformations over-print on each other. Therefore, to enable answer the question whether seismic anisotropy in Precambrian terrains of India is primarily a fossil feature of the lithosphere or is dictated by present-day absolute plate motion direction, data from various geologic terrains of India need to be studied.

The obvious test would be to examine data from all over India where one might expect the geologic fabric ranging from the Archaean to Proterozoic times to vary from place to place manifesting it as continental anisotropy (related to palaeo-tectonic processes). On the other hand, if the present-day plate motion-related strain is the dominant force in forging anisotropy over the Indian shield, the fast polarization directions at all the locations would be near identical and closely aligned with the northward mantle flow direction or at the most vary slowly.

Such a test is likely to fail where the magnitudes of anisotropy from these two causatives are quite significant (perhaps in comparable measure) but in orthogonal directions. However, the eastern Dharwar craton with predominant NNW geologic strike direction and the southern granulite terrain with predominant E–W strike structures (orthogonal to the plate motion direction) offer excellent sites to test the hypotheses. Unfortunately, in the western parts of the country the Deccan trap cover obscures the geologic fabric preventing us from per-

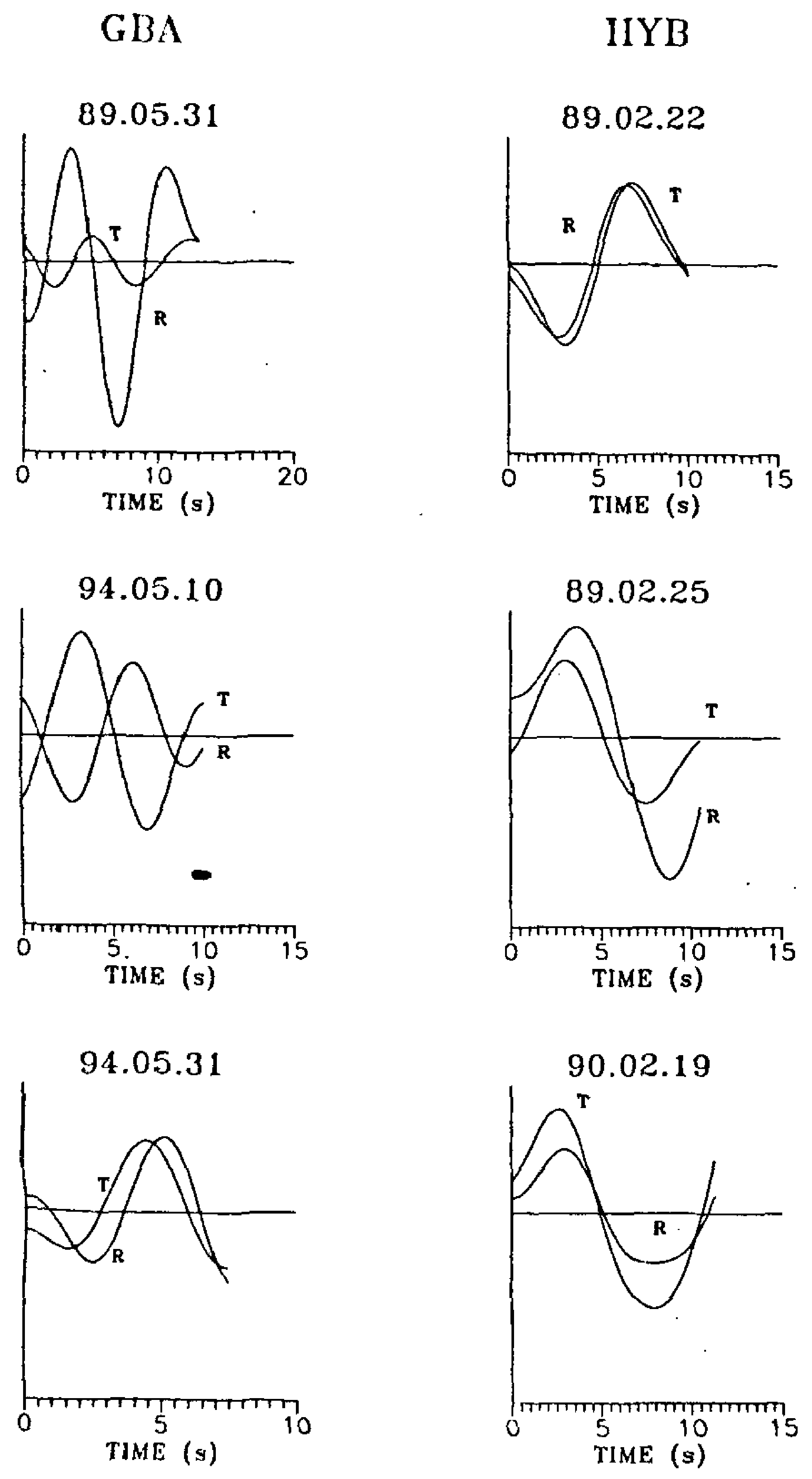


Figure 4. Time window of SKS/SKKS in *R* and *T* component records for all events at GBA and HYB. This time window is also used to calculate the penalty function *E* from which the parameters of anisotropy ($\alpha, \delta t$) are determined. Note the shift in time of the phase in *R* and *T* components.

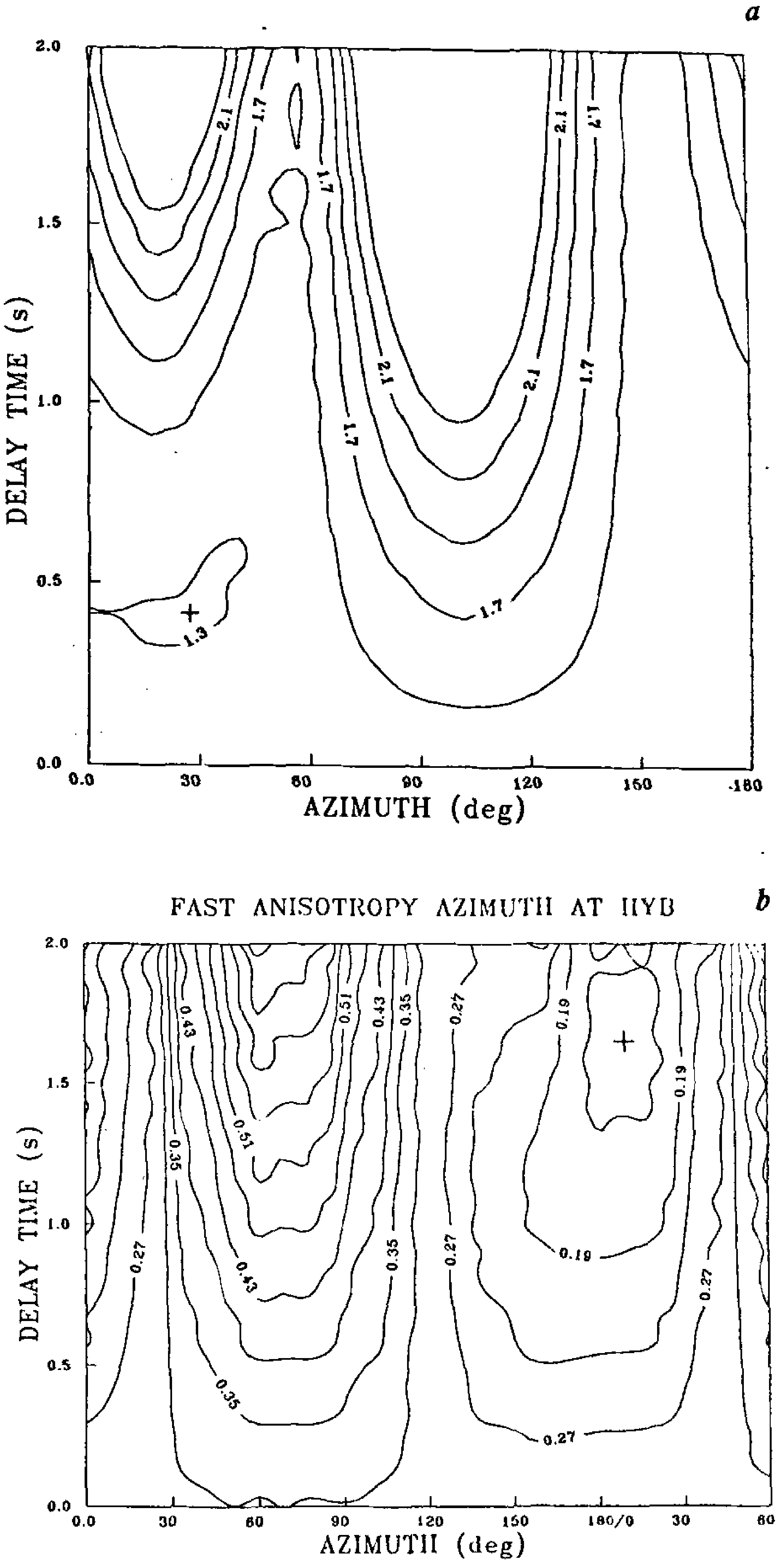


Figure 5 *a* and *b*. *a*, Plot of penalty function *E* (contours) for combined processing of the events (listed in Table 1) at GBA. The position of minimum of *E* is marked by '+'. The optimal values of fast azimuth (α) and delay time (δt) are about 30° and 0.45 s respectively. *b*, Plot of penalty function *E* (contours) for combined processing of the events (listed in Table 1) at HYB. The position of minimum of *E* is marked by '+'. The optimal values of fast azimuth (α) and delay time (δt) are about 20° and 1.6 s respectively.

forming any meaningful hypothesis testing. Therefore, absence of fast polarization directions in NNW and E–W directions in south India but their alignment with NNE plate motion direction would strongly suggest that the present-day mantle flow is the candidate to explain the measured fast anisotropy directions as is the case at present.

This primarily suggests the dominance of strain associated with the absolute plate motion in forging the observed anisotropy closely aligned to its NNE direction in the entire south Indian shield in preference to any fossil strain inherited from Precambrian. Such an alignment between the fast direction of anisotropy and present-day plate motion direction is argued to be a result of the resistive drag by the mantle at the base of a moving plate in similar Precambrian terrains of north America and southern Africa[4,8]. It is shown that due to resistive drag forces at the base of the plate, the deformation assumes the form of a progressive simple shear aligning the [100] axis (longest strain axis) of olivine in the direction of current plate motion[2].

With regard to the difference in magnitudes of delay times at HYB and GBA, as mentioned earlier, both the deformations, i.e. contribution from continental rocks by way of 'frozen anisotropy' and that associated with the present-day plate motion strain (absolute plate motion related strain), could be at high angles cancelling each other resulting in a smaller time delay at station GBA but not so at HYB. It is important to remember that GBA is in very close proximity to a major structural boundary striking NNW, the Closepet granite, a postulated suture between the eastern and western Dharwar cratons of Archaean age. The strike of this boundary is roughly NNW which is at a reasonably high angle to the NNE absolute plate motion direction. Such a disposition, as is the case now, could possibly lead to presence of anisotropy in the lithosphere (fossil model, NNW) and the asthenosphere (absolute plate motion related strain, NNE) to be different resulting in smaller delay times as observed at GBA.

It should, however, prove rewarding to conduct measurements at close spaced stations at an average spacing of about 50 km in the south Indian shield and other Precambrian terrains of the world before discarding the fossil strain hypothesis in preference to a more mobilistic interpretation of anisotropic observations. It should also be remembered that the present observations in south Indian shield need to be confirmed by a larger digital data base before vindicating either of the hypothesis.

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