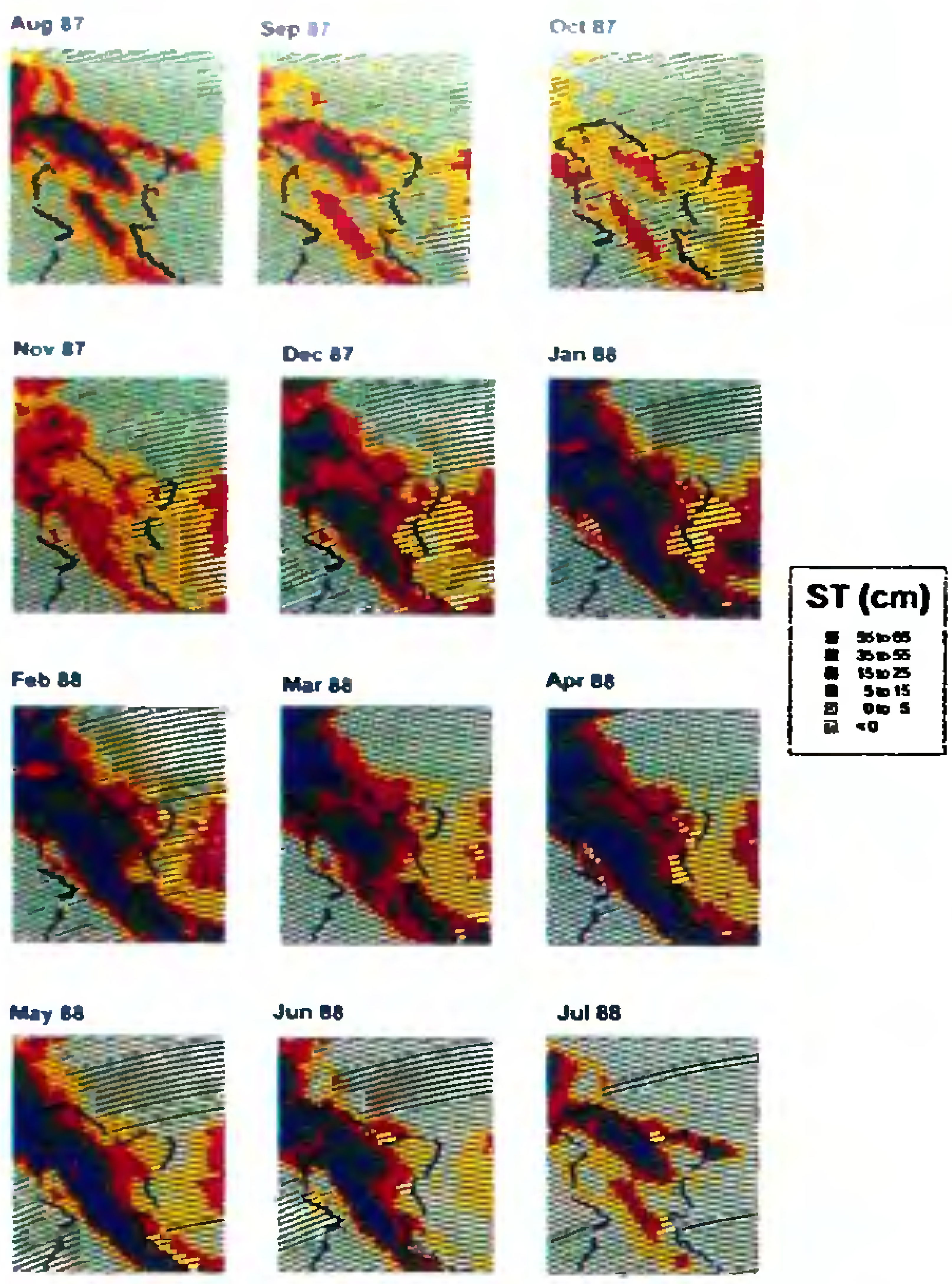


Figure 4. Time series snow thickness.

radius. The estimated snow thickness seen in Figure 4 shows a one-to-one relation with the brightness temperature observed at 85 GHz (Figure 2 *a*). From Figure 4 it is seen that the maximum area in India is covered by snow thickness (> 5 cm) during December 1987–April 1988. The present results show the potentiality of microwave remote sensing data in characterization of snow-covered region. The ground truth information is not available to the authors, such information will be of great help to validate the present result.

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# Single station moment tensor inversion for focal mechanisms of Indian intra-plate earthquakes

**N. Purnachandra Rao**

National Geophysical Research Instiitute, Uppal Road, Hyderabad 500 007, India

**Single station moment tensor inversion of the nearest broadband station data can be effectively used to obtain fairly accurate focal mechanism solutions for small to moderate earthquakes, as demonstrated for the 21 May 1997 Jabalpur earthquake (Mw 5.8). The method is also applied to study the 3 February 1999 Godavari valley earthquake (Mw 3.6) using broadband data of the Geoscope station, Hyderabad. A pure strike-slip solution is obtained with strike 326°, dip 88° and rake 2°. The active tectonics of the Godavari graben is studied using this result in conjunction with the mechanism of the 13 April 1969 Bhadrachalam earthquake (Mw 5.7), which also occurred in the same region. The fault planes of the two earthquakes are correlated with lineaments from Landsat images and the possiblility of a block rotation in this region is suggested.**

THE Indian peninsular region is a mosaic of cratonic blocks bordered by paleo-rift valley zones. In the last few decades enhanced seismic activity has been observed even

*For correspondence. (e-mail: postmast@csngri.ren.nic.in)

in the the 'stable' parts of the Indian continental region[1–3]. It is observed, in general, that most intra-plate earthquakes are confined to the paleo-rift zones[4]. In most cases the mechanism of these earthquakes is not independent of the ambient stress field in the adjoining plate boundary zones[5].

The most common explanation for the occurrence of earthquakes in the interiors of the Indian plate has been the reactivation of pre-existing faults under the influence of the ambient stress field due to the India–Eurasia plate collision forces, oriented NS to NNE[6,7]. However, much remains to be understood about the seismotectonics of the plate interiors, mainly due to the nonavailability of sufficient number of focal mechanism solutions. In the recent times there has been a significant improvement in the deployment of broadband seismic stations on the Indian shield. The present situation has enhanced our hopes of studying the source mechanism of the Indian shield earthquakes, which may contribute to the understanding of earthquakes in the continental interiors in general, and the Indian plate interiors, in particular. However, most earthquakes in this region are usually below 4.5 magnitude, and therefore, cannot provide sufficient number of first motion polarities or proper azimuthal coverage. Also, the signal-to-noise ratio of seismic records falls rapidly with increasing source–receiver distance.

Under the present circumstances, moment tensor inversion technique, using data from the nearest broadband station provides the most viable solution. Several workers have suggested that complete source information can be retrieved using data from a single 3-component station[8–14]. The method is mostly useful for earthquakes of low magnitudes, generally below 4.5, in the context of the Indian shield.

With the development of waveform inversion techniques for determination of source parameters, Centroid Moment Tensor (CMT) solutions are being routinely computed using teleseismic body waves and long period surface waves[15]. Subsequently, techniques were developed for regional moment tensor inversion using surface waves[12,16] and body waves[13,17]. Several approaches were introduced, especially for moment tensors of small earthquakes[18–21]. In the present study, we use the method of Kikuchi and Kanamori[22], slightly modified for the study of near-field earthquakes by Kosuga[14]. The Green's functions are computed using the approach of Takeo[23], which uses a combination of the generalized reflection–transmission matrix method[24,25] and the discrete wave number summation method[26].

In this paper we first demonstrate the validity of the single station inversion method, using the 21 May 1997 Jabalpur earthquake, as an example. A moment tensor solution is computed using data from Bilaspur, the nearest broadband station (Figure 1) and compared with the results of multi-station inversion from previous regional and global studies. Next, we undertake a case study of the recent (3 February 1999, Mw 3.6) Godavari valley earthquake through a moment tensor inversion of data from the Hyderabad Geoscope station. Using this result, the active tectonics of the Godavari valley region is studied in conjunction with that of the 13 April 1969 Bhadrachalam earthquake, which also occurred in this region.

The 21 May 1997 Jabalpur earthquake occurred on the ENE-WSW trending Narmada-Son rift valley zone in Central India[27,28]. The depth of this earthquake at 35 km (ref. 29) is rather unusual for a shield region. A thrust type focal mechanism was obtained with the preferred fault plane oriented N80°E with a dip of 66°. This solution has been interpreted in terms of reactivation of a pre-existing deep-seated fault in the Narmada paleo-rift valley zone (Figure 1)[29–32].

The broadband station nearest to the Jabalpur earthquake is at Bilaspur, located at a distance of 237 km from the epicenter and operated by the India Meteorological Department (IMD), New Delhi. The 3-component waveform data are first corrected for possible trends and instrument response, low pass filtered up to 0.1 Hz, resampled at 1 Hz and integrated to obtain the displacement seismograms. The crustal model of Rao *et al.*[33] for the Indian shield region is used for computation of the synthetic seismograms. The inversion yields a thrust mechanism with strike 70°, dip 73°, rake 84° and a moment magnitude of 5.7. An excellent match is seen between the observed and synthetic seismograms (Figure 2) and the solution is found to be stable although data from only one station are used. The obtained solution also matches very well with those computed by previous workers and agencies using teleseismic data[32] and

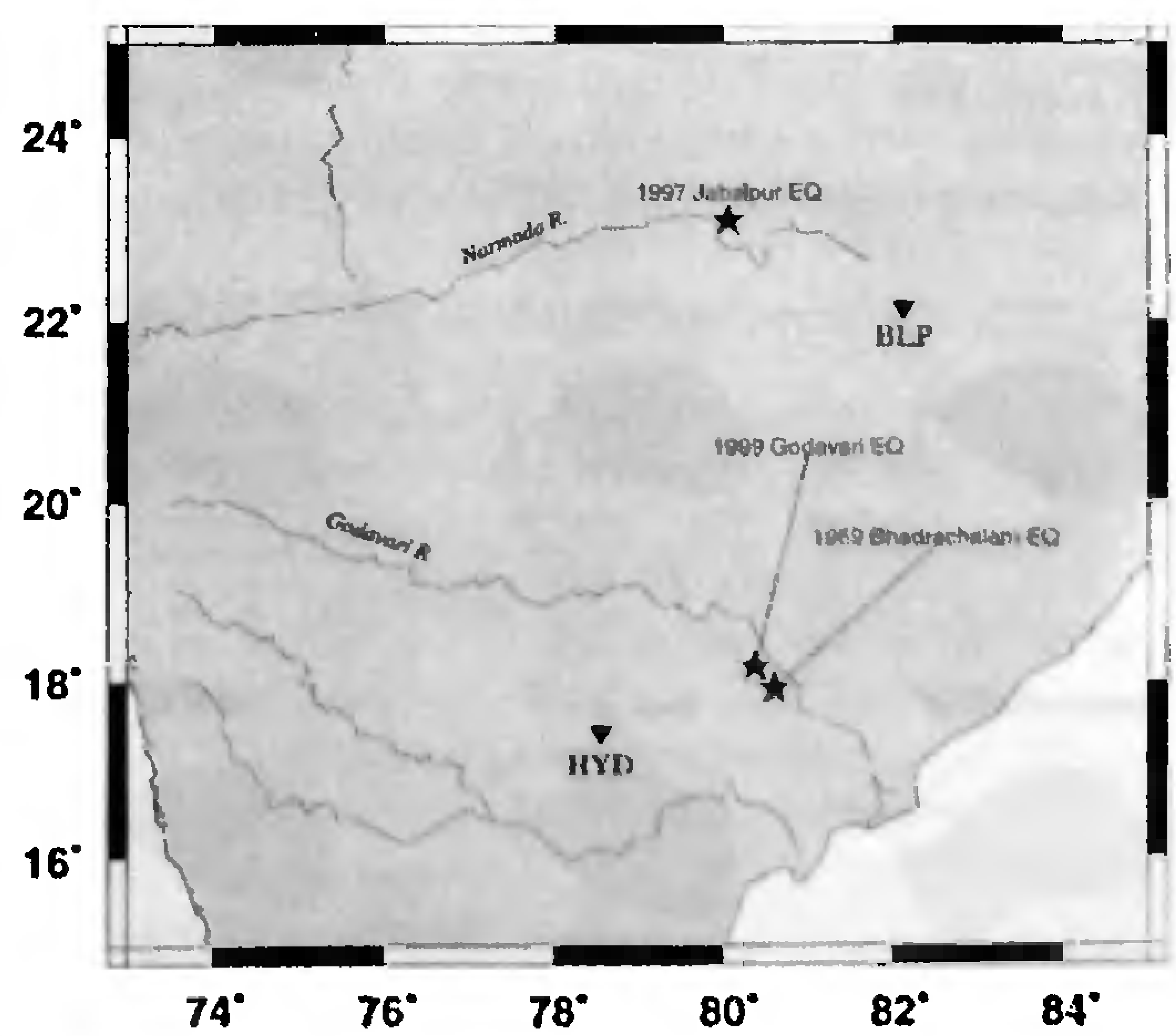


**Figure 1.** Indian peninsular shield region indicating the earthquakes of 21 May 1997 (Jabalpur), 13 April 1969 (Bhadrachalam) and 3 February 1999 (Godavari), and the broadband stations Bilaspur (BLP) and Hyderabad (HYD) used in this study.

regional network data[29,33,34], indicating the potential of the single station inversion method.

On 3 February 1999, at about 23 h 09 min (Universal Time) an earthquake of magnitude 3.6 was reported in the Godavari valley region of Andhra Pradesh. The earthquake was located at 18.15°N, 80.36°E, at a depth of 18 km by the IMD. This lies in the south-eastern part of the Godavari Main basin region, 38 km NW of the Bhadrachalam earthquake of 13 April 1969. The earthquake was reportedly felt in several places like Khammam, Warangal, Kothagudem, Bhadrachalam, Dummugudem, Charla, Venkatapuram, Boorgampadu, Ashwapuram and Manuguru. No damage was caused, probably due to the low magnitude. It is interesting to note that a greater effect was felt in Khammam although it is farther from the epicenter than, for instance, Bhadrachalam. This could be due to the greater transmissibility of seismic waves across the rift valley, and through the Indian shield, rather than along the rift, through the Gondwana sediments. The high transmissibility of the Indian shield was discussed previously by Narain and Gupta[35] and Gupta *et al.*[36].

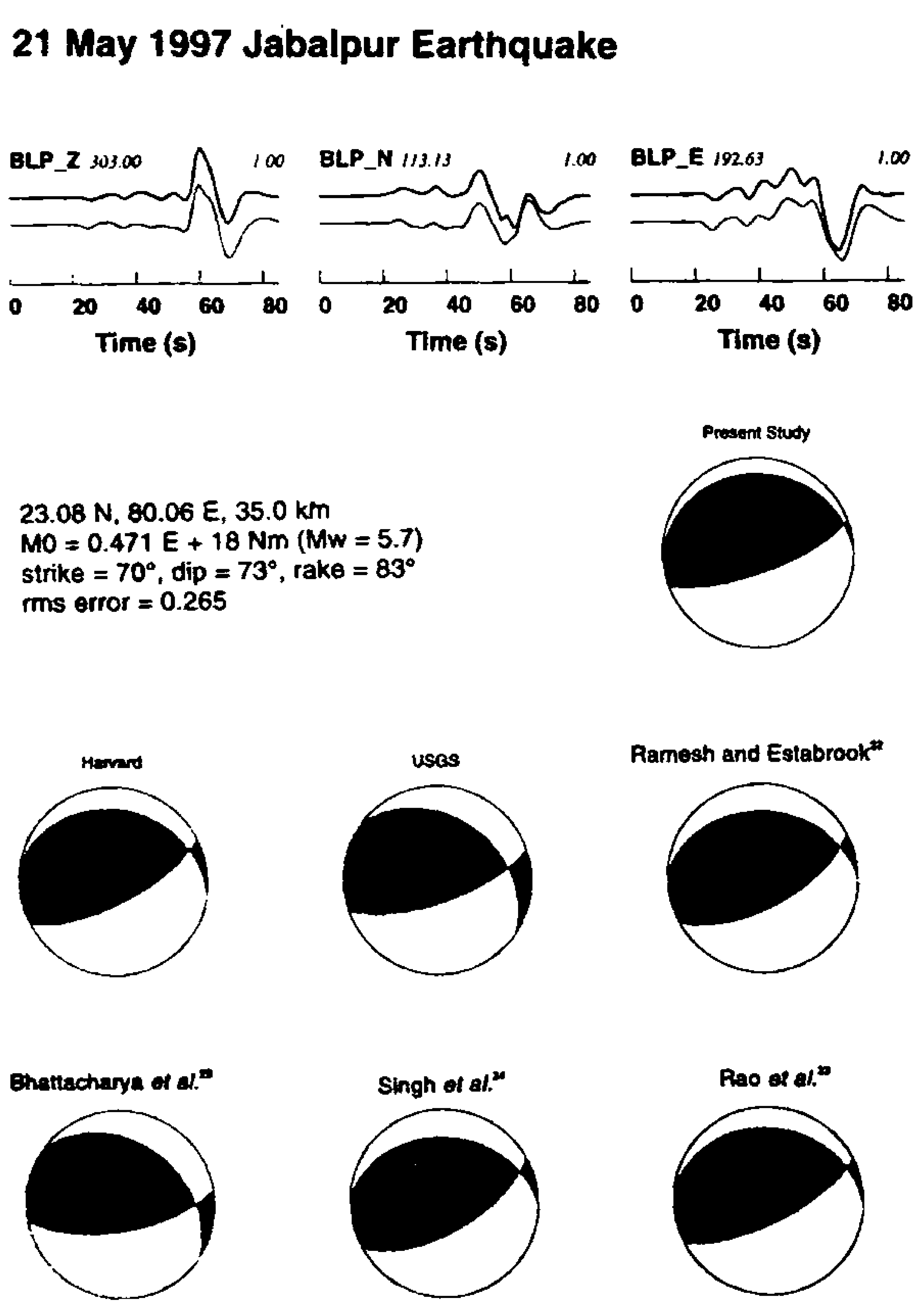


**Figure 2.** Observed (thick) and synthetic (thin) seismograms of the 21 May 1997 Jabalpur earthquake observed at the Bilaspur broadband station. The focal mechanism solution and the result of inversion are shown along with the previous results of multi-station inversion for comparison.

The Godavari rift valley is a NW-SE trending linear belt of Gondwana basin, about 350 km long and 40 km wide, adjoining the Dharwar craton in the south-west and the Bhandara craton in the north-east. It is characterized by a history of rifting, sedimentation and block adjustments including uplift and subsidence, since the Archean times[37,38]. The major stages of the basin evolution include Archean and Proterozoic sedimentation (Pakhal super group) followed by deposition of the upper Paleozoic Gondwana sediments along a distinctly fault-controlled rift valley zone[39]. The northern portion of the Godavari valley, the main basin, is connected to the southern segment by a narrow link, which homes the tri-junction of the Dharwar craton, Bhandara craton and the Eastern Ghats belt. From the Landsat images of the Godavari valley region 110 lineaments ranging from 10 to 200 km have been inferred[40]. The lineaments, mostly of the Archean period, form two distinct sets: a NW-SE trend predominantly found in the main basin with a transition to the NE-SW trend in the south-eastern part, in the vicinity of the Mailaram high. Some of these lineaments could be active faults as indicated by the presence of seismicity. Detailed gravity and magnetic surveys in the Godavari basin have provided anomalies delineating subsurface structures typical of a rift valley system[41–43]. In general, the NW-SE trending lineaments/faults in the rift valley have been delineated. Also, the deep-seated fault separating the Godavari and Chintalpudi basins, and the one NW of Bhadrachalam, along the Mailaram high, trending NE-SW are delineated.

Seismic activity along the boundaries of cratons and rift valleys of the Indian shield has been indicated by historical earthquake data[3,44]. Minor seismic activity has been observed, corresponding to the complex fault systems of the Godavari graben[2,36]. The most significant earthquake in this region has been the Mw 5.7 Bhadrachalam earthquake of 13 April 1969 (refs 1, 36, 45, 46). Focal mechanism studies broadly indicate a strike slip solution with the NE-SW trending plane considered to be the actual fault plane, based on isoseismal trends[1,47]. The most reliable solution, obtained by inversion of teleseismic broadband waveforms[46], has a strike of 245°, dip 72° and rake – 2°, and a *P* axis trend of N20°E. This is in fairly good agreement with the local stress field, presumably due to the India–Eurasia plate collision forces, and has been attributed to reactivation of a pre-existing fault in the paleo-rift zone[6,46]. This apart, very little is known about the seismotectonics of the Godavari rift valley, possibly due to the small number and low magnitudes of earthquakes recorded. In fact, there exists only one focal mechanism solution, corresponding to the 1969 Bhadrachalam earthquake, for the entire region till date. It is, therefore, important to obtain more solutions for earthquakes of this region in order to understand the present tectonic scenario.

The nearest broadband station on the Indian shield which recorded the 3 February 1999 Godavari valley earthquake is the 3-component Geoscope station at Hyderabad, about 200 km from the epicenter. The velocity seismograms of this event (Figure 3) are first corrected for possible trends and instrument response, low pass filtered up to 0.2 Hz, resampled at 2 Hz and integrated to obtain the displacement seismograms. The crustal model of Rao *et al.*[33] is used for computation of the synthetic seismograms. In view of the long period range used, the P and S waves are almost suppressed and the waveform matching is mostly for the surface wave portion. Unfortunately, the vertical component has some low frequency background noise, which gets amplified in the displacement waveforms. The displacement waveform data are inverted to obtain the moment tensor solution that best fits the observed and synthetic seismograms.

Figure 4 shows the observed and synthetic seismograms for the vertical, N-S and E-W component records. A fairly good match is seen mostly for the surface waves portion. The focal mechanism solution obtained is given by strike 326°, dip 88° and rake 2°, and a moment magnitude (Mw) of 3.6. Figure 5 shows a plot of the focal mechanism along with that of the 1969 Bhadrachalam earthquake, superposed with the lineament map of the Godavari basin. It can be seen that the Bhadrachalam earthquake is located close to the Mailaram high, amidst the NE-SW trending set of lineaments, and also has a fault plane with the same orientation. The Godavari earthquake falls in the middle of the basin within the NW-SE trending set of lineaments and also has one of its focal planes oriented in the same direction. In general, the focal plane orientations of the two solutions are very similar. However, the inferred fault planes for these two earthquakes are almost perpendicular. Also, the *P* axis orientations of the two solutions are almost perpendicular to each other, making it difficult to interpret in terms of a uniform stress field in this region.

The NE-SW oriented focal plane, chosen as the plane of faulting of the Bhadrachalam earthquake, is also in agreement with the mapped isoseismal trends[1,47]. In view of the NE-SW trending surface lineaments in this region and also the N-S to NNE-SSW oriented principal stress field direction on the Indian shield[5], it is reasonable to assume reactivation of one of the NE-SW oriented preexisting faults in a left-lateral strike-slip motion. However, a similar interpretation does not hold for the 1999 Godavari earthquake, with the inferred plane oriented NW-SE and the *P* axis azimuth almost perpendicular to the ambient stress field direction. Hence, in view of the differences in geological settings, local trends of the lineaments as well as the *P* axis azimuths, it appears that the two earthquakes are distinct although they occurred in a close vicinity, separated by only about 38 km. One possible way of explaining the mechanism of the 1999 earthquake with respect to the 1969 earthquake is by invoking a clockwise block rotation in this region. Such a block would be adjoined by the NW-SE and the NE-SW oriented planes corresponding to the left-lateral strike-slip fault planes of the two earthquakes respectively

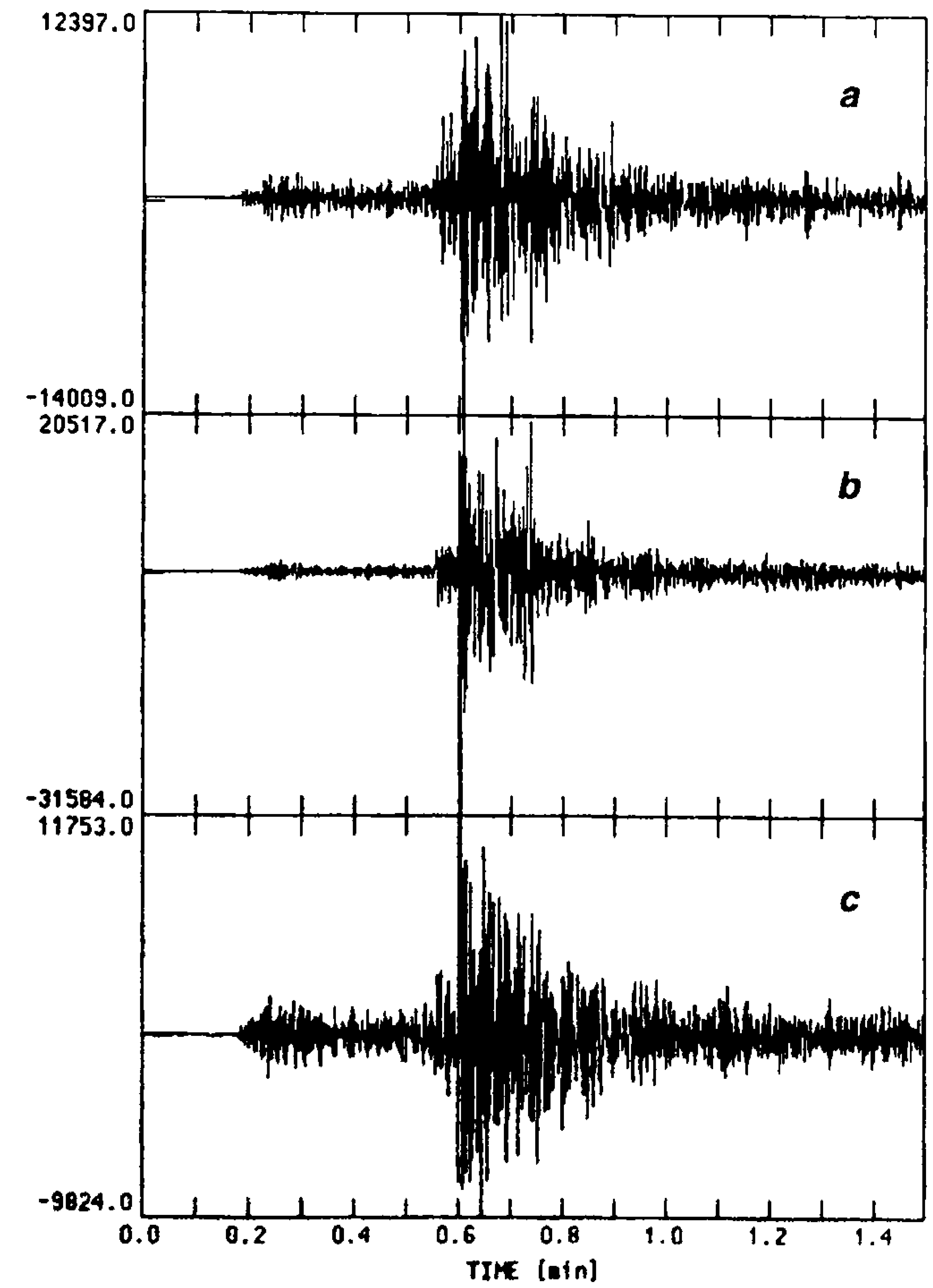


**Figure 3.** **Broadband (velocity) seismograms of the 3 February 1999 Godavari valley earthquake recorded by the Geoscope station, Hyderabad.** ***a*****, vertical;** ***b*****, NS; and** ***c*****, EW components.**

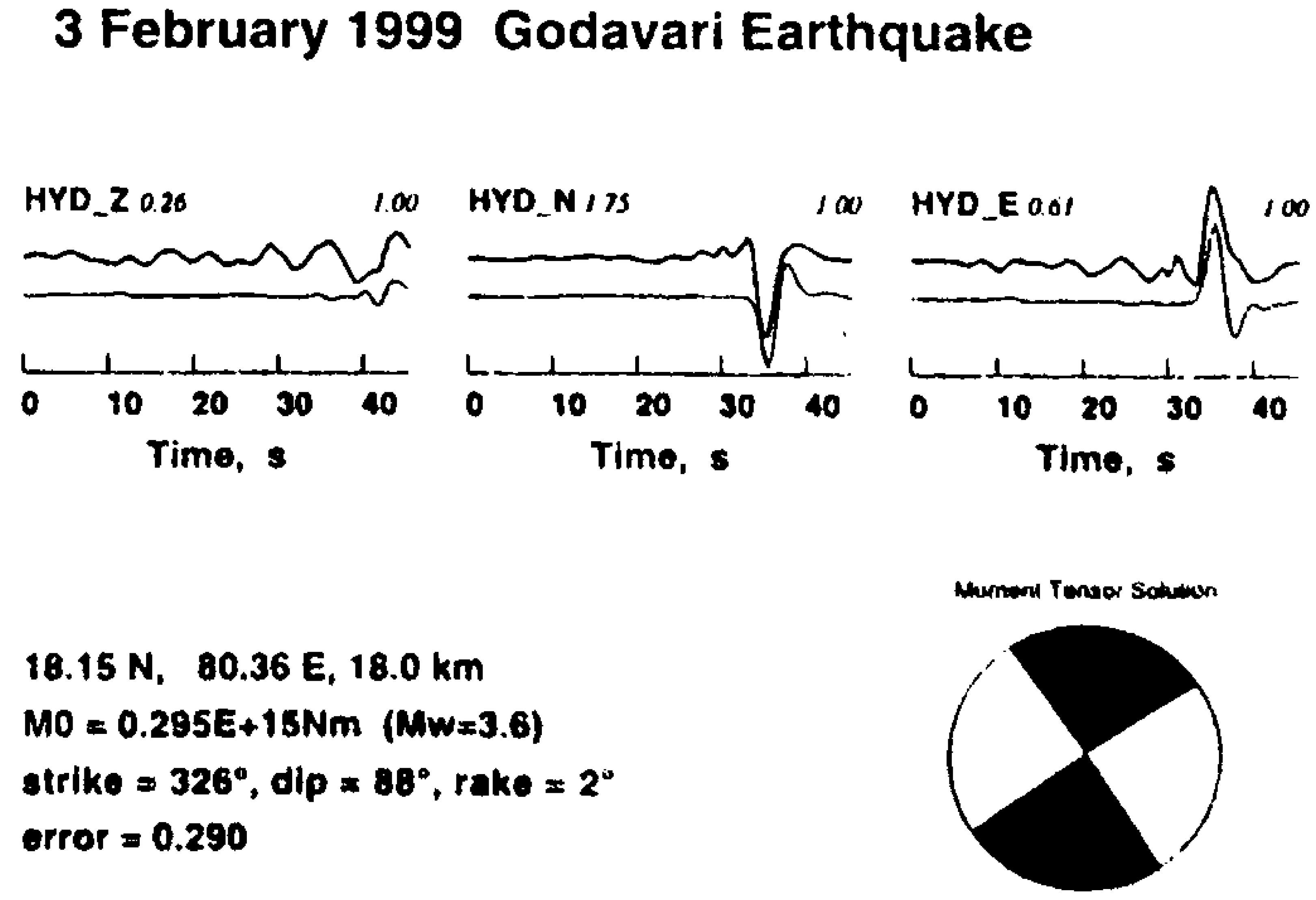


**Figure 4.** Observed (thick) and synthetic (thin) seismograms of the 3 February 1999 Godavari valley earthquake observed at the Hyderabad Geoscope station. The results of single station moment tensor inversion including the focal mechanism solution are shown

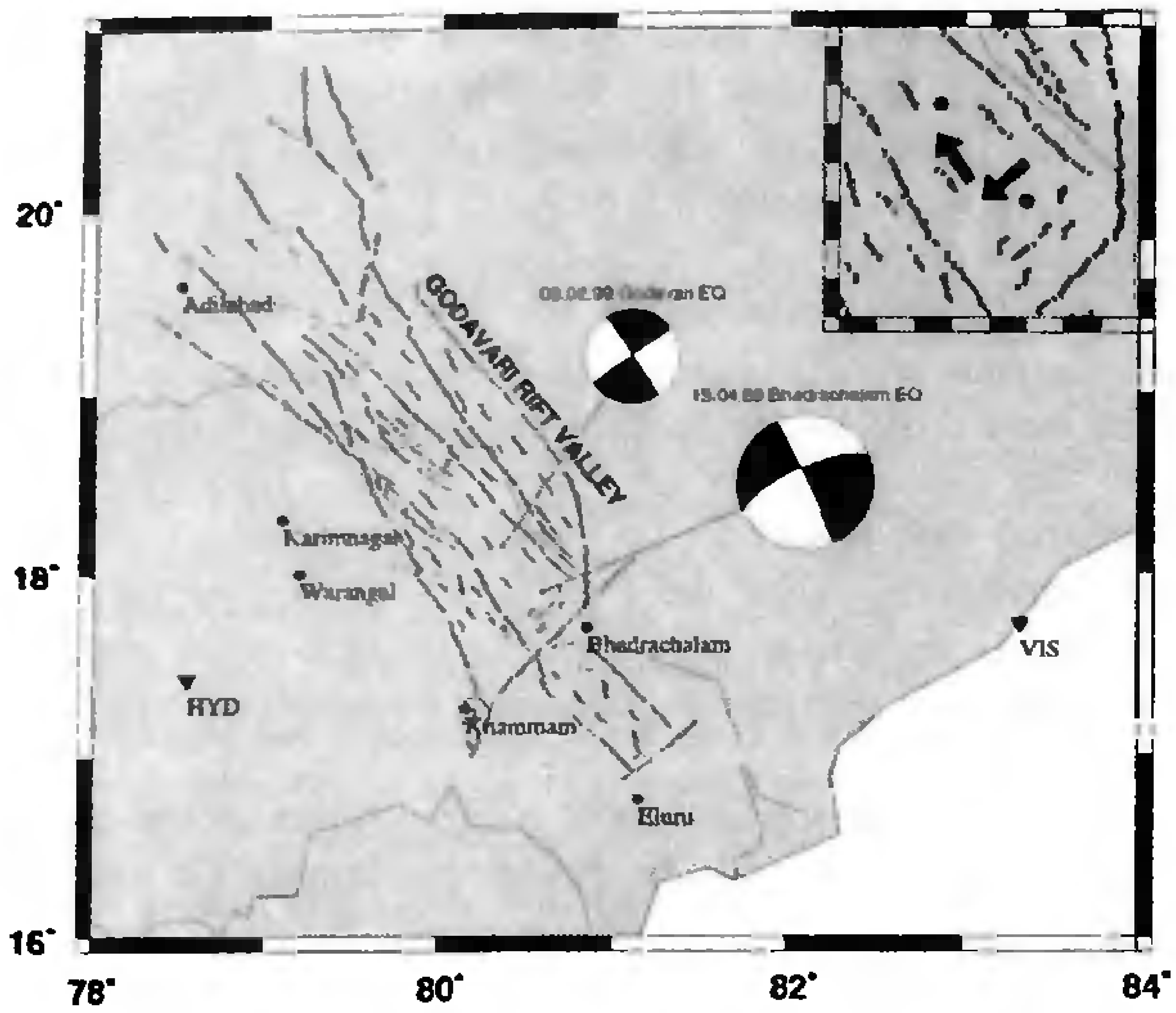


**Figure 5.** Focal mechanism solutions of the 1999 Godavari earthquake (present study) and the 1969 Bhadrachalam earthquake (from Chung[46]) superposed with the lineament map of the Godavari basin (from Rao *et al.*[39]). A close-up view (inset) indicating the inferred directions of slip along the fault planes of the two earthquakes, correlated with the observed lineaments.

and perhaps, the Godavari river in the north (Figure 5) and would account for the otherwise incongruent sense of slips on the two planes. The possibility of such a block rotation in a strike slip environment has been discussed previously[48–52]. However, at present the existing seismological data are too sparse to confirm this interpretation. Other effects of local origin, like stress relaxation or transfer could also give rise to seemingly distinct mechanisms on adjoining faults.

It can be seen from this study that a single station inversion itself can provide a sufficiently good focal mechanism solution. There is no doubt that the usage of data from more stations, preferably with a good azimuthal coverage, gives a better accuracy of the solution. However, the contribution of the nearest station is always maximum, and often sufficient to get at least a first order solution. Moreover, small earthquakes are generally not recorded at more than one station, and the only option for obtaining a solution is to exploit the whole waveforms of the three components of the single station.

The goodness of the solution from a single station inversion normally depends on parameters like the size of the earthquake, the distance between the source and the receiver, the frequency band of observation and the accuracy of the crustal model used. In the case of the Jabalpur earthquake, it appears that all these parameters were ideal, giving rise to an excellent solution. In the case of the Godavari earthquake, the magnitude has been on the lower side, but the accuracy of the crustal model has enabled the computation of synthetics quite accurately. Also, the very broadband feature of the Geoscope station, Hyderabad, which goes down to almost 300 s, compared to 125 s for the Bilaspur station used in the case of the Jabalpur earthquake, has ensured a good signal even after low-pass filtering and integration of the velocity seismograms, and has enabled a stable inversion.

In conclusion, single station moment tensor inversion approach using 3-component seismograms from the nearest broadband station can provide fairly accurate solutions for small to moderate earthquakes of the Indian region. The fault planes of the 1999 Godavari earthquake and the 1969 Bhadrachalam earthquake are inferred as NW-SE and NE-SW, respectively, by correlating with the Landsat images. In spite of the close proximity, the two earthquakes appear to be distinct in terms of the geological settings, local trends of surface lineaments and the inferred $P$ axis orientations. The possibility of clockwise rotation of a paleo-rift block in the south-eastern part of the Godavari basin is suggested.


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