NsPsKs), the average productivity over the period was a little high (2,922 kg/ha) in case of NsPsKs in comparison to that of NPK100 (2,909 kg/ha). However, the average rate of increase in the last phase of experimentation was much higher for NsPsKs and resulted in the highest expected productivity at the last point of time (2,913 kg/ha). For FYM1 treatment, the rate of increase in productivity was a little higher and was followed by a very low increase till the last time point. As far as the average productivity over the entire period of experimentation is concerned, NsPsKs ranked first, followed by NPK100. Thus, in the medium black soil of Junagadh under the intensive cropping system, NsPsKs treatment was found to be better as compared to rest of the treatments in wheat crop.

For wheat crop, the recommended dose is NP100. While comparing the dose with the treatment which proved to be superior in this study, it could be noticed that supplementary potash to the already existing recommended dose resulted in higher productivity for wheat in the intensive cropping system (groundnut–wheat–sorghum) at Junagadh. This clearly suggested either the presence of main effect of potash or the presence of the interactions where potash was involved, or both.

Similar observations were made by Singh and Nambiar[4] in their study on crop productivity under intensive use of chemical fertilizer in long term experiments. Acharya *et al.*[5] had also reported that omission of potash decreased the crop yield.

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Characteristics of the 1997 Jabalpur earthquake and their bearing on its mechanism

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The occurrence of a moderate earthquake near Jabalpur is an example of stable continental region (SCR) seismicity at lower crustal depths. This event is spatially associated with the Narmada–Son lineament, a continental scale structure where at least five earthquakes of $M \geq 5.4$ have occurred during this century. In comparison to other moderate earthquakes in the Indian peninsular shield, the 1997 event has several peculiarities, including a relatively deeper hypocentre, lower level of aftershock activity and shorter recurrence period. In this paper, we describe certain characteristics of this event and propose a conceptual model to explain its mechanism.

AN earthquake of magnitude M_W 5.8 occurred near Jabalpur, central India on 22 May 1997, emphasizing the point that many parts of the peninsular shield have potential for moderate earthquakes. Unlike the 1993 Killari earthquake, this one did not occur as a total surprise because the Jabalpur region has experienced previous seismicity. Its epicentre was located in the ENE–WSW trending Narmada-Son lineament, a major fault zone in the Indian shield. A Precambrian rift that has subsequently been reactivated several times, this fault zone (hereafter referred to as the Narmada rift) has been the location of moderate earthquakes (i.e. $M \geq 5.0$) as well as many of smaller magnitude in the past. The Son Valley (1927, *M* 6.5); Satpura (1938, *M* 6.3); Balaghat (1957, *M* 5.5) and Broach (1970, *M* 5.4) earthquakes are the larger events associated with the rift (Figures 1 and 2).

A look at the spatial distribution of moderate earthquakes in peninsular India immediately suggests a relatively higher level of seismicity associated with the Narmada rift (Figures 1 and 2). Despite the large dimensions and higher level of seismicity associated with it, our understanding of the seismogenic character of this continental structure remains rudimentary. Since most previous events in this region occurred before the development of modern instruments, reliable focal parameters are not available, except for the Broach earthquake. The Jabalpur earthquake was well recorded and its focal parameters estimated using data from 12 digital broad-band stations operated by the India Meteorological Department (IMD). Focal parameters have also been computed by the Harvard University (HRV) and the US Geological Survey (USGS) based on data from global stations (Table 1). With well-constrained data on epicentral parameters, focal mechanism and aftershock activity, we can better explain the earthquake and its relation to the Narmada rift. In this paper we present some characteristics of the Jabalpur earthquake and discuss their bearing on its mechanism.

The most striking difference about the Jabalpur earthquake compared to other moderate events in the Indian shield is its deep focus. The initial estimates indicated a

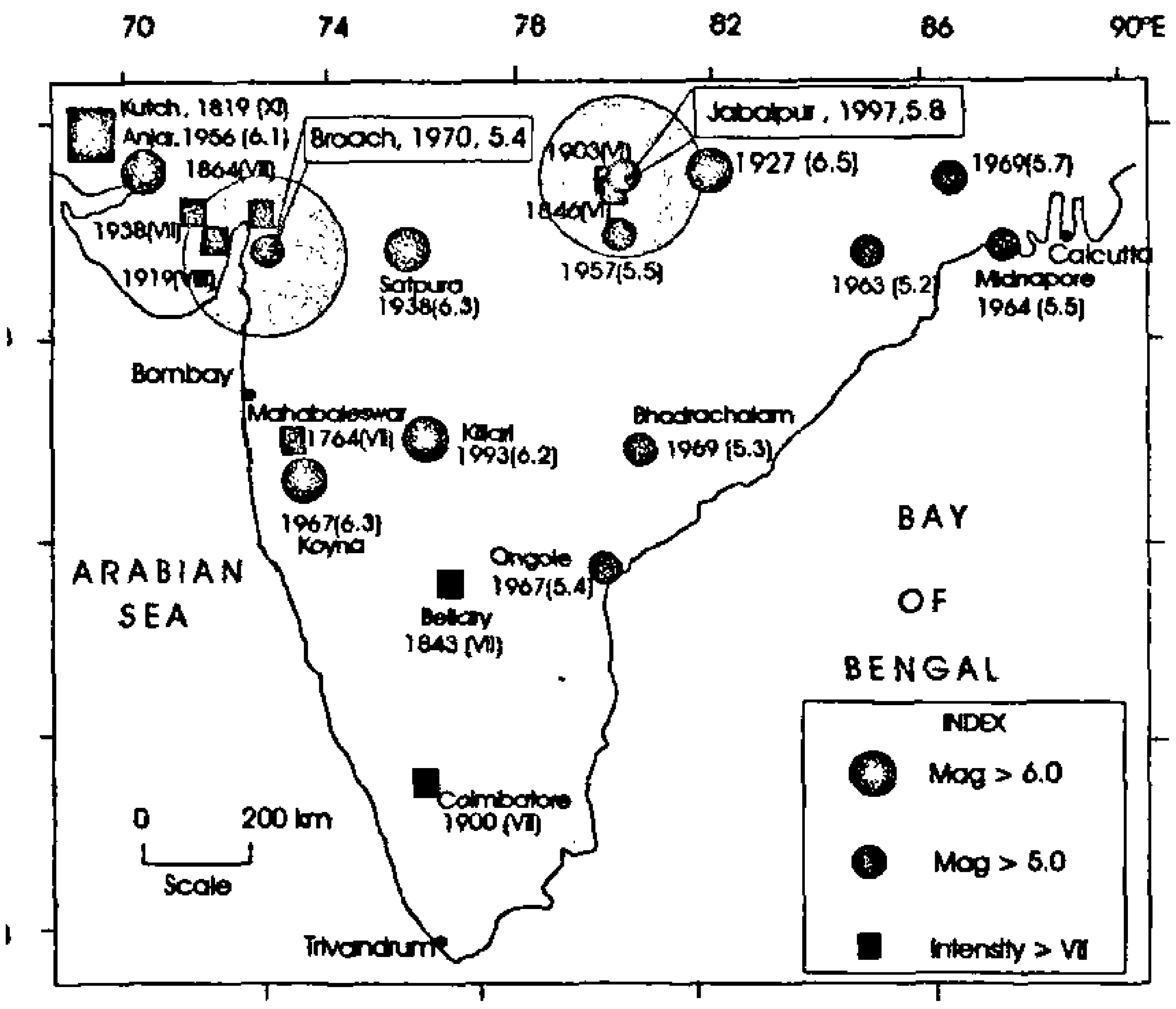

Figure 1. Distribution of earthquakes $M > 5$ in the Indian peninsular shield. Shaded circles denote 150 km radius around Jabalpur and Broach. Events of intensity ≥ VII (MM scale) in the vicinity of other moderate earthquakes are shown.

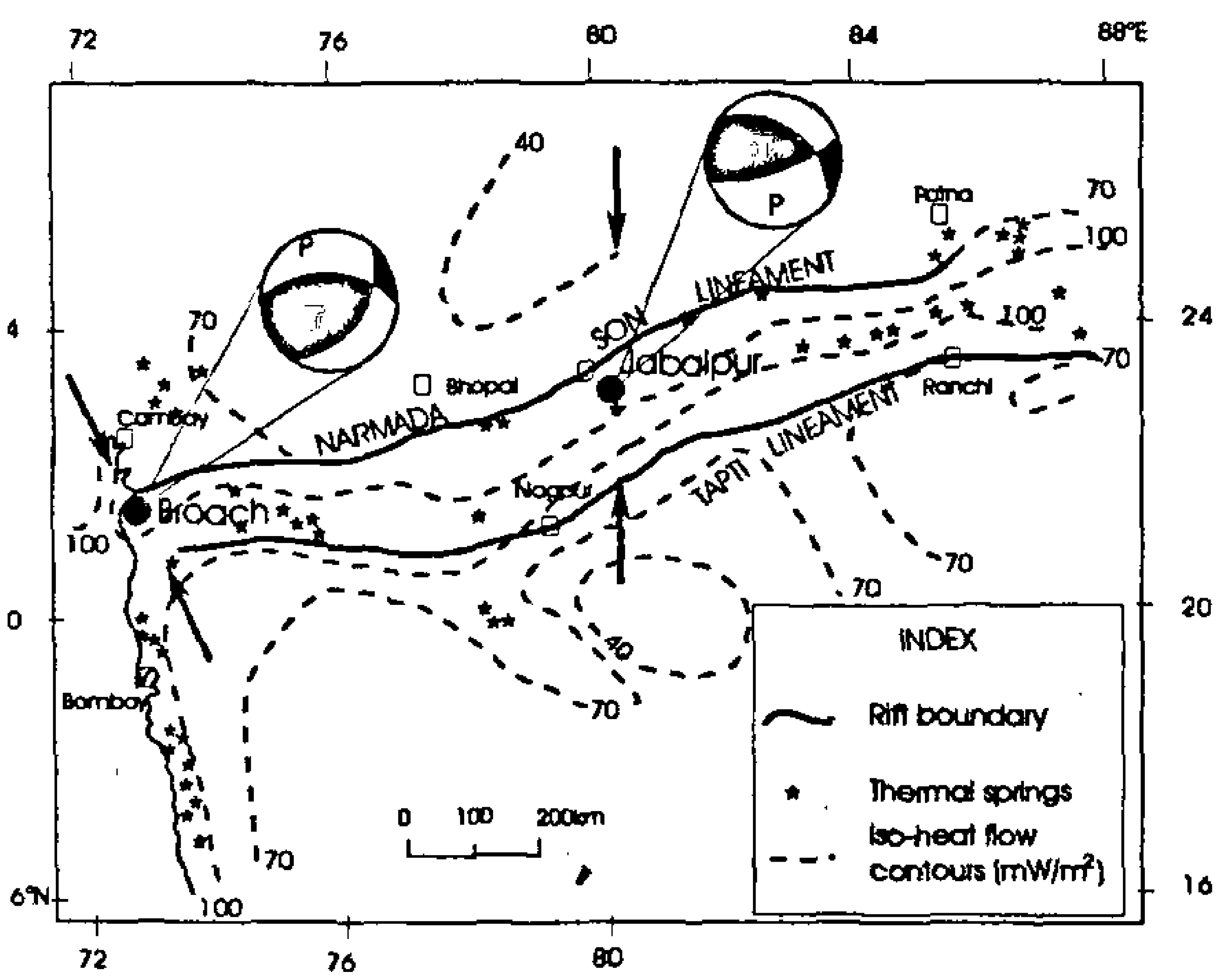

Figure 2. Narmada–Son lineament showing major earthquakes, thermal springs and heat values. Orientation of P-axes and focal mechanism of Broach and Jabalpur earthquakes are also shown. Original sketch by Ravi Sanker[18].

focal depth of 32 to 35 km (Table 1). Later analyses of waveforms (pP, sP) recorded at teleseismic distances have indicated a focal depth of 36 ± 4 km[1]. This depth makes it one of the deepest earthquakes to have occurred in the continental shield regions; it also exceeds the maximum seismogenic depth of 25 km estimated for old cratons[2,3]. Focal depth of the 1938 Satpura earthquake is also reported to be ~ 40 km, based on instrumentally-recorded data[4]. Focal depths of other well-documented earthquakes of $M > 5.0$ in the Indian shield indicate an average seismogenic depth of ~ 10 km (Table 2) which is comparable to the seismogenic depth reported for most other continental regions[2]. In comparison, the Jabalpur earthquake is significantly deeper. If the focal depth of 40 km for the Satpura earthquake is acceptable (obviously with a margin of error), it appears that earthquake nucleation in the lower crust is not uncommon in the Narmada rift.

Table 1. Epicentral parameters of the 21 May 1997 Jabalpur earthquake

Origin time	Latitude °N	Longitude °E	Depth (km)	Magnitude	Source
22:51:28.97	23.17	80.02	32.0	5.7	USGS
22:51:28.70	23.04	80.28	33.0	5.8	HRV
22:51:30.80	23.07	60.06	35.0	5.6	IMD

Table 2. Parameters of selected earthquakes from peninsular India

Date	Location	Magnitude	Depth	Ref.
10 December 1967	Koyna	6.3	4.5 ± 1.5	ISC*
13 April 1969	Bhadrachalam	5.7	10 ± 3	Chung[29]
23 March 1970	Broach	5.4	11 ± 3	Chung[29]
29 September 1993	Killari	6.2	5.0	HRV**
22 May 1997	Jabalpur	5.8	32.0	HRV**

*International Seismological Centre, 1964–1993.
**Harvard University centroid moment tensor solution.

The second notable aspect of the Jabalpur earthquake is its limited aftershock activity compared to other moderate events in the Indian shield. Operation of portable seismic stations in the area started only three days after the main shock and many smaller events that immediately followed may not have been recorded. However, the digital seismic stations at Bilaspur and Bhopal operated by IMD, within a distance of 300 km from Jabalpur are capable of recording events of magnitude ≥ 1.5. In addition, IMD operated a few local stations which recorded nineteen aftershocks during 22 May to 15 July. Five out of these events were of magnitude ≥ 3.0. Seismic stations installed by the National Geophysical Research Institute (NGRI) recorded eleven aftershocks from 25 May to 4 June, which included eight events of magnitude < 3.0 and three events of magnitude > 3.0 (ref. 5). A review of the aftershock activity until 15 July based on the above data indicates substantially lower level of activity associated with the Jabalpur earthquake. This is anomalous, compared to other moderate events in the Indian shield.

The Bhadrachalam and Killari earthquakes provide striking contrasts to the Jabalpur event in terms of their abundant aftershock activity. The former, associated with the Godavari rift, was followed by significant aftershock activity. More than sixty-five aftershocks were recorded at the Gauribidanur array station within a period of 15 days of the main shock[6]; three of them were of $M > 4.1$, and 12 were of $M > 3.1$ (ref. 7). The Killari earthquake was also followed by hundreds of aftershocks out of which 187 were located[8]. A large number of these aftershocks occurred during the first few days after the main event. The Koyna earthquake of 1967 was also associated with a long aftershock sequence[9]. Since the Koyna earthquake is considered to be induced by the reservoir, a comparison may not be appropriate.

In comparison, the Broach earthquake, which occurred in the western extremity of the Narmada rift was followed by fewer aftershocks, analogous to the Jabalpur earthquake. Only six aftershocks of $M \geq 3.2$ were reported for this event[10]. We admit that the picture of the aftershock activity may not be accurate because of the poor instrumentation at the time of the earthquake. Besides, no portable network was installed to monitor the aftershock activity. However, the available data from distant stations (the nearest being at Colaba at a distance of 270 km) and the felt reports do not indicate much aftershock activity.

A third notable feature about the Jabalpur event is its association with a structure that has a well-defined geomorphic expression. Although such associations have been observed for many other moderate earthquakes from the Indian shield, global studies indicate that earthquakes in stable continental regions may occur in regions with subtle or no clear expression of faulting[11]. The occurrence of Killari earthquake in a region of poorly defined geomorphic expressions of faulting may be pointed out as a classic example[12]. In contrast, the Jabalpur earthquake occurred in the Narmada rift, a remarkably linear structure with distinctive geomorphic and tectonic expressions. It may also be noted that other parts of this structure have generated moderate earthquakes in the recent past. Tectonically well-defined structures, capable of generating earthquakes over shorter intervals are rare in stable shield regions. Narmada rift may be considered as a good example of a pronounced tectonic feature with notable seismogenic potential.

The fourth and perhaps the most significant point is that the Jabalpur earthquake occurred in a region where moderate magnitude historic events have occurred. Two historical earthquakes (1846, 1903) of intensity VI are reported from this region. This region has also witnessed two other earthquakes during 1927 (M 6.5) and 1957 (M 5.5). It is important to note that three of these events are located within the radius of 150 km (the average width of the rift) of Jabalpur and the fourth occurred just outside (Figure 1).

The magnitude estimates of the historic events in the Jabalpur region have to be considered with caution. For example, the magnitude of the 1938 Satpura earthquake is reported as 5.5 by Mukherjee[4], and as 6.3 by Gutenberg and Richter[13]. From the descriptions provided by these authors, this event appears to be of moderate magnitude, but 6.3 may be an upper estimate. The magnitude estimate for the 1927 event may not be exact either, but from the descriptions, this event also appears to be of moderate magnitude. Thus, with some margin of errors in the magnitude estimate, it is surmised that moderate earthquakes have occurred in the Jabalpur region in 1927, 1957 and 1997, i.e. at an interval of 35 ± 5 years. No other region in the Indian shield has generated moderate earthquakes over such short intervals of time. Considering the rift as a whole, the interval between moderate events seems to be still shorter. Earthquakes of $M \geq 5.4$ have occurred in the Narmada rift during 1919, 1927, 1938, 1957, 1970 and 1997. Intervals between these events are 8, 11, 19, 13 and 27 years. Thus, the mean interval between moderate events in the region works out to be 16 ± 6 years.

From the above discussion, it can be seen that while most other moderate earthquakes in the Indian peninsular shield have occurred in regions with little or no background seismicity, the Narmada rift has been showing a higher level of activity. This pattern is in sharp contrast to the earthquake cycle at Killari where the previous event of similar size is believed to have occurred thousands of years ago[12]. Interestingly, the historic data base[14] indicates that the Broach region in the western extremity of the Narmada rift has also been the site of historic earthquakes of intensity ≥ VII within a distance of 150 km. However, compared to the Jabalpur region, these earthquakes are fewer in number and smaller in magnitude (Figure 2). None of the other sites, with the exception of Koyna, has experienced nearby earthquakes of intensity VII or larger during the historic past (Figure1).

The Narmada rift is a well-defined tectonic feature that cuts across the Indian peninsula in a ENE–WSW direction. Kaila *et al.*[15] defined the Narmada–Son lineament as a narrow 'horst crustal block' bordered by deep faults extending to the Moho. Considered as the junction of the Bundelkhand block in the north and peninsular block in the south, this intracratonic rift is believed to have originated during middle to late Archaean[16]. Subsequent tectonic events including the Deccan Trap volcanism (60–40 Ma) have led to its reactivation and evolution as a persistent zone of weakness.

Seismically, the Narmada rift is quite active. At least 30 earthquakes of $M > 3.0$ have occurred in this region since historic times. Two earthquakes of $M \geq 6.3$ and three earthquakes of $M \geq 5.5$ have occurred here during the last seventy years[14,17]. Focal mechanisms are available only for the Broach and Jabalpur events and they suggest fault planes oriented NE to ENE and NW to EW (Figures 2 and 3). The ENE-orientation of the Narmada rift is an indication that faulting could occur along this plane. Field evidences are also in support of the in-

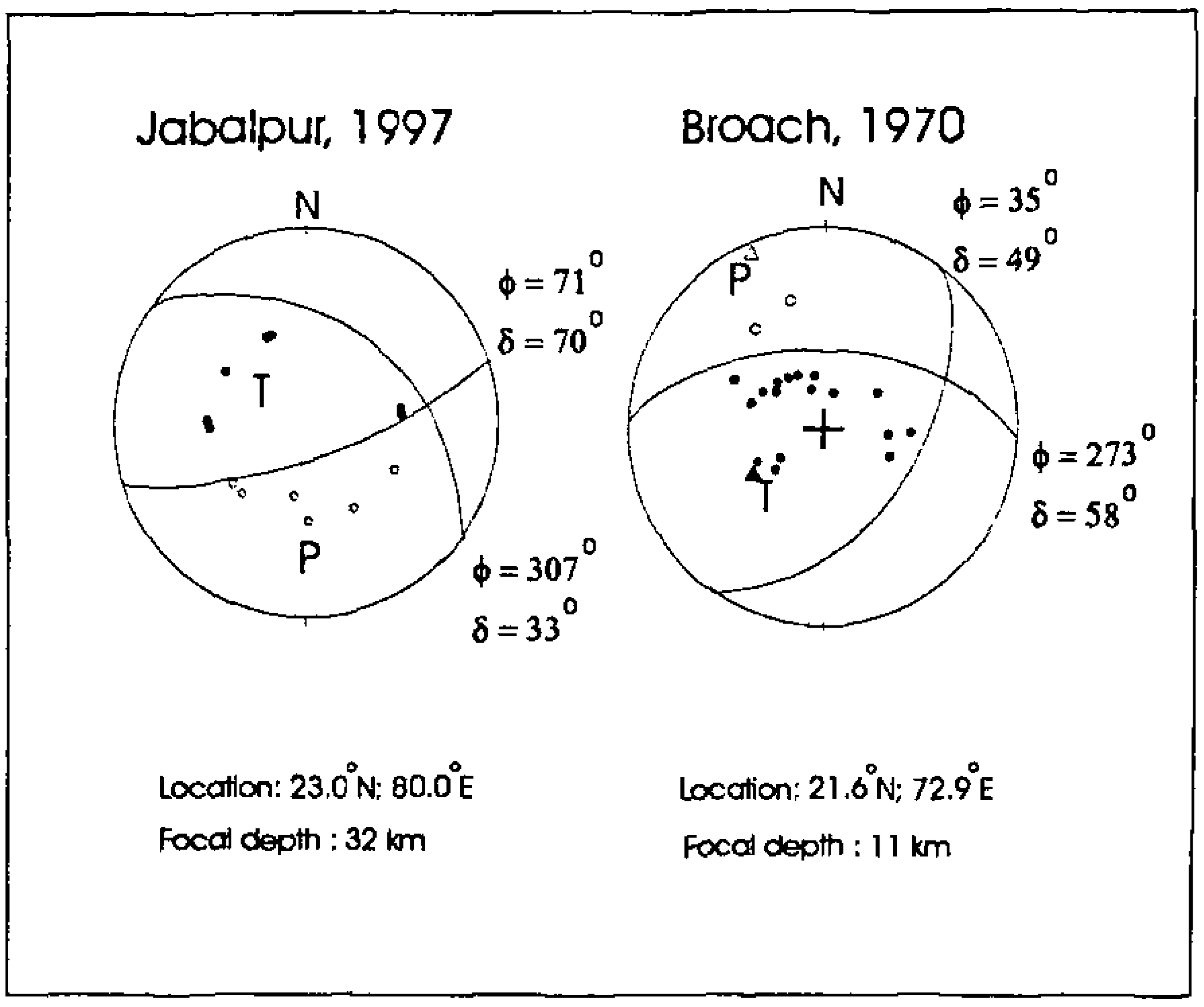

Figure 3. Source parameters of 1997 Jabalpur (IMD) and 1970 Broach[29] earthquakes.

volvement of ENE-oriented fault in the Broach and Jabalpur earthquakes. For example, the fissures that opened during the Broach earthquake were generally oriented in ENE–WSW direction[14]. Prominent ground cracks associated with the Jabalpur earthquake were also oriented in the ENE–WSW direction[5]. Thus, the geological and seismological data point to the reactivation of original faults that are parallel to the Narmada rift.

The most striking feature about the Narmada rift is its anomalous thermal structure expressed by the numerous hot springs and high heat flow within its boundaries. Contours of high heat flow (>100 mW/m^2) follow the axis of the ridge, dropping to about 40 mW/m^2 on either sides of the rift (Figure 2). Even with possible errors in the heat flow measurements, this drastic change is significant. Ravi Sankar[18] argued that an extensive thermal anomaly of this size can be supported only by an active source. Since this region has not been the site of recent magmatic activity, he attributed the increased heat flow to still uncooled plutonic bodies. Based on the thermal structure and seismic velocities, he suggested the presence of an anomalous body at the crust–mantle boundary. Existence of high density material beneath the Narmada rift has also been indicated by independent analyses of gravity and seismic reflection data[19,20]. A recent interpretation of the DSS profile that traverses Jabalpur also suggests presence of high-density material at shallow depths[21]. This high density body with deeper roots suggests that its origin is related to the rifting process. Therefore, it seems plausible that a magmatic body that intruded during the last rifting phase still remains as a 'fossil mantle plume' at crustal depths (Figure 4).

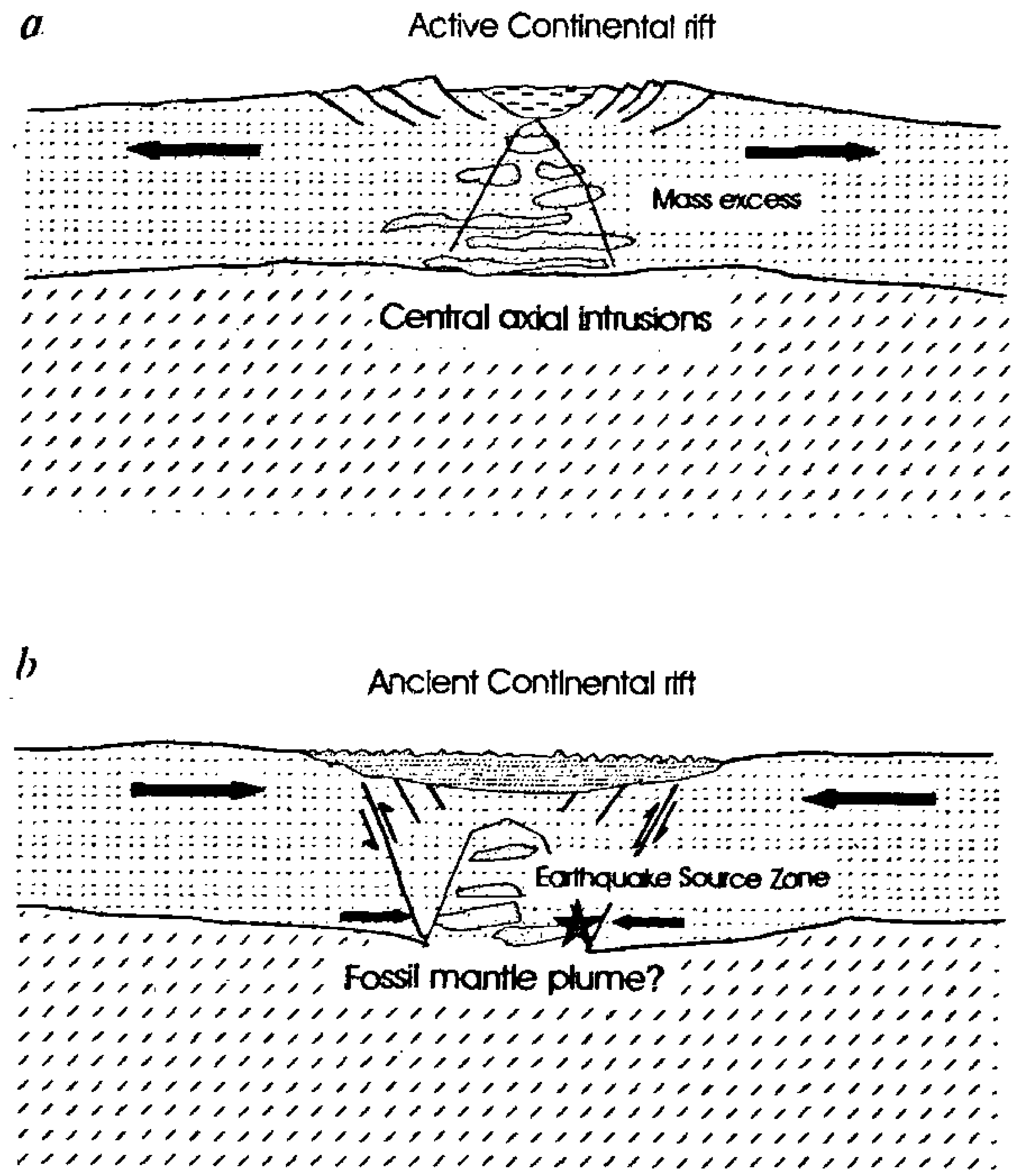

Figure 4. Schematic diagram showing development of active continental rift and later retrogression[27]. Star denotes nucleation of earthquakes at lower crustal depth. Note the stress reversals indicated by solid arrows. Smaller arrows indicate horizontal deviatoric stresses supporting the excess mass.

Existence of frozen mafic intrusions, referred to as 'rift pillows', is commonly observed in many ancient rifts[22]. Zoback and Richardson[23] suggested that seismicity associated with many continental rift basins may be related to buried rift pillows. The frozen excess mass, according to them, is supported by the strength of the cooled lithosphere, requiring additional compressive stresses perpendicular to the rift axis. Stress modification due to rift pillows is suggested to be the mechanism in Amazonas rift (South America) where two moderate earthquakes have occurred at depths of 23 and 45 km. The assumption of a rift pillow beneath the Narmada rift and the model developed by Zoback and Richardson form the basis for the proposed mechanism of the Jabalpur earthquake.

Among the various theories proposed to explain mid-continent seismicity, reactivation of preexisting zones of weakness[24], stress concentration model[25] and strain localization[26] are most widely considered. The zones of weakness model proposes that contemporary earthquake activity is caused by the reactivation of ancient faults and other weak boundaries within the crystalline crust which are presently subjected to appropriately-oriented regional stress field. Earthquakes occur where local deviatoric stress (difference between maximum and minimum principal stresses) exceeds the threshold for brittle failure. The stress concentration theory works on the premise that local variations in the strength of the lithosphere or unsupported mass variations will perturb the ambient stress regime sufficiently so as to trigger earthquakes. Strain localization model proposes that sites of large intraplate earthquakes are controlled by zones of localized strain in the lower crust which concentrate stresses in the upper crust.

It may be realized that no single hypothesis can fully account for the occurrence of intraplate seismicity and their characteristics in different regions. It is also to be noted that the models mentioned above have been based mainly on the earthquake processes in the brittle upper crust and they may not adequately explain the deeper events. Certain elements of these models, in combination with site-specific characteristics may explain them at some locations. We consider the reactivation and stress concentration models to explain the mechanism of the Jabalpur earthquake.

Let us consider the reactivation hypothesis. The ENE–WSW-oriented boundary faults of the Narmada rift provide preexisting zones of weakness that can be reactivated in the present stress field. Originally formed by extension and normal faulting, plate driving forces are likely to have reversed the stresses in many paleorifts[27]. Reversal of stresses in ancient rifts is shown schematically in Figure 4. Although there is an inversion of stresses, the preexisting faults continue to remain weak and the reactivation can still occur. The mean orientation of S_{Hmax} (maximum horizontal compressive stress) in the Indian shield is roughly N23°E; in the Narmada rift it is reported to be nearly N–S (ref. 28). Focal mechanisms of both Broach and Jabalpur earthquakes indicate reverse faulting on nearly ENE striking fault planes. The P-axes of these events are oriented 335.9°N and 181°N respectively, indicating response to compression perpendicular to the axis of the rift (Figure 2). A mechanism involving inversion of stresses and failure along the ENE fault has been suggested also for the Broach earthquake[29]. Thus, it appears that both these earthquakes have occurred by the reactivation of a major preexisting fault zone.

A major limitation of the reactivation hypothesis is that it does not explain the relatively shorter recurrence intervals, particularly in the mid-continent regions which are characterized by uniform stress and lower strain rate[30]. Observations using Global Positioning System (GPS) studies indicate that the Indian shield has been associated with low strain[31]. Most faults in peninsular India have either remained aseismic during the recorded history or they have been reactivated only once during the historic or recent times. Prehistoric seismicity data are sparse from the Indian shield. Among the various earthquake sites in the shield, detailed paleoseismological investigations have been conducted only at Killari[12]. The observations at this site indicate recurrence interval of the order of tens of thousands of years for moderate earthquakes, which is in agreement with the low strain rate. The recurrence rate of moderate earthquakes in the Narmada rift appears to be anomalous in this regard and it appears that some additional forces are required to explain the increased level of seismicity associated with the Narmada rift.

We considered the possible effect of a buried rift pillow on the stress field, following the models by Zoback and Richardson[23]. At this point we have not quantified the effect of this body on the stress field, but hypothesize that if a rift pillow exists beneath the Narmada rift, it must be supported by additional stresses. The maximum principal stresses in the Indian shield are horizontal and nearly perpendicular to the Narmada rift. Results of modelling by Zoback and Richardson[23] suggest that the deviatoric stresses that support excess mass occur perpendicular to the rift. In the case of Narmada, this is roughly north–south, same as the direction of regional S_{Hmax}. Thus, the net effect of a buried mass is to amplify the horizontal compression (Figure 4). It may be noted that the additional stresses are developed at lower crustal depths, where the body is situated.

If excess mass exists at lower crustal depths in the Narmada rift, does it act as a 'stress concentrator'? The stress localization model proposes that crustal inhomogeneities with contrasting mechanical properties may arrest stresses, leading to differential stresses. A high velocity body has been inferred between 23°N and 23.5°N latitude, close to Jabalpur[21]. Origin of the earthquake very close to Jabalpur and at a depth of 36 ± 4 km makes it reasonable to assume that the excess mass at lower crustal depths played a role in its mechanism. It is likely that the excess mass acted as a stress concentrator and also as a source of additional compressive stresses. We believe that the buried rift pillow favours both these processes, leading to earthquakes in its close proximity.

Recurrence of earthquakes over short interval requires a mechanism for faster stress buildup. Localization of stresses and generation of horizontal deviatoric stresses due to the excess mass favour faster stress buildup, in a zone of weakness. We believe that the existence of these deep boundary faults, together with a buried mass close to the crust–mantle boundary are responsible for the faster stress buildup and therefore the shorter recurrence interval in the Narmada rift.

The lower crustal focal depth, which is unusual for mid-continent regions, is intrinsic in this model. If the nucleation of earthquakes is related to the stress perturbation caused by a high density body at lower crustal depths, the focal depth of 36 ± 4 km is not difficult to explain. It is likely that the earthquake nucleated very close to the crust mantle boundary, where the mantle plume is frozen. Occurrence of the 1938 Satpura earthquake at comparable depths suggests that Narmada rift has demonstrated the potential for deep crustal earthquakes in the past.

As discussed earlier, the limited aftershock activity is another peculiarity of the Jabalpur event. Page[32] noted that strong earthquakes vary widely in their production of aftershocks, particularly as a function of the focal depth of the main shock. Thus, shallower events produce significantly larger number of aftershocks compared to deeper events. We believe that the aftershock productivity is also related to the nature of the source zone. The shallow crustal regions are heterogeneous in terms of structural, petrological and mineralogical properties as well as frictional characteristics. Due to these inherent heterogeneities, fault structures in the shallow crust are complicated, compared to their deeper extensions. Consequently, earthquakes that nucleate at shallow depths lead to adjustments in a heterogeneous volume and generate longer aftershock sequences in comparison to the deeper events.

We relate the limited shorter aftershock activity of the Jabalpur earthquake to its deep crustal source. In contrast, the intense aftershock activity at a depth of 2–5 km following the Killari earthquake[8] may be considered an example of reactivation on a shallow crustal fault originating in more heterogeneous source zone. The Broach earthquake originated at a depth of 11 km, but the available data suggests a low-level aftershock activity. We do not have sufficient data on the aftershock activity for other earthquakes in the Narmada rift, but the patterns suggested by the Broach and Jabalpur events indicate lower aftershock activity associated with this structure.

Our synthesis identifies certain unique characteristics of the Jabalpur earthquake which have bearing on its mechanism. Most importantly, the depth at which it nucleated is rather unusual for cratonic regions. Further, it was associated with limited aftershock activity, unlike most other moderate earthquakes in peninsular India. We believe that these two are interrelated and they reflect the unique seismogenic character of the Narmada rift.

Existing models on the mechanism of intraplate seismicity have been developed for earthquakes originating in the shallow brittle crust. Globally, only a few earthquakes have occurred close to the crust–mantle boundary. In the case of Jabalpur earthquake, we favour a combination of the reactivation and stress localization models. Amplification of horizontal compressive stresses due to the effect of a rift pillow is an active element in this model. If the failure threshold depends only on plate driving forces, the reactivation interval may be much longer, but the stress modifications due to the rift pillow are superimposed on the regional stress field. The net effect is to accelerate the stress buildup, reducing the interseismic intervals. At this point, this is only a suggestion, which needs to be quantified. We plan to extend this study to other deep crustal earthquakes to develop more quantitative models.

Narmada rift is the only active structure in the Indian shield where at least five earthquakes of magnitude ≥ 5.5 have occurred during this century. While earthquakes have recurred in some parts of this structure, there are segments that have not broken in the historic or recent past. Going by the past experience, moderate earthquakes can be expected anywhere along this structure. The seismic hazard associated with this structure needs to be reexamined in view of the short period recurrence of moderate earthquakes.

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