Structure and seismotectonics of Satpura, Central India

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Each intracontinental region of epeirogenic uplifts in Indian shield is a composite of smaller wavelength features of uplift, separated in some areas by sharp lowering tectonic lineaments. Despite the large dimension, considerable uplift and high seismicity associated with the Satpura orogenic belt, its seismoenic character is not well understood. A close look at the spatial distribution of moderate earthquakes in peninsular India, considered as a ‘Stable Continental Region’, reveals a relatively higher level of seismicity associated with the Narmada Son Lineament (NSL). The seismicity pattern of the elevated Pachmarhi plateau (a part of Satpura range) shows the concentration of the seismicity at the boundary of the Satpura Gondwana basin, which is uplifted more than 500 m along its boundary faults. They are predominantly associated with strike-slip or thrust mechanism; consistent with the compressive stresses transmitted from the plate boundary. Besides, the influence of uplifting process that possibly originates through lithosphere–mantle interaction could be a significant contributor; perhaps not uniform in magnitude and direction as the plate tectonic stress. The plateau forming processes and the 3-D character of distensional tectonics that epeirogenic uplift imposes on an otherwise compressive domain are proposed as a mechanism for the present-day seismicity of the region.

Several intracontinental regions of epeirogenic uplifts that endeavour to establish a mass balance arising from both mantle and crustal buoyancy characterize the Indian shield. The major uplifted plateaus in the shield are (i) the NW trending Western Ghats, (ii) the NE trending Eastern Ghats, (iii) the easterly trending Satpura orogenic belt, (iv) the NE trending Aravalli mountain range, and (v) the Shilong plateau that shares the Himalayan tectonic regime. The Son–Narmada–Tapti (SONATA) zone, encompassing the Satpura orogenic belt, is the most conspicuous feature among them. It characterizes a consistent ENE–WSW trending structural feature delimited by faults on either side, giving rise to a graben and horst structure in the region. Despite its large dimension and considerable uplift, lithotectonic evolution of the Satpura orogenic belt and its seismoenic character are still matters of speculation and debate.

Narmada–Son Lineament (NSL) is a mid-continental rift system that divides the Indian shield into two halves. A thick pile of Deccan lava flows covers the western part of the NSL. Other litho associations forming an integral part of the lineament zone include the Late Archaean to Early Proterozoic Mahakoshal group with occasional patches of relict basement granite-gneisses, Vindhyan Supergroup, Gondwana Supergroup, Lameta Group and the Quaternary/Recent alluvium and laterite (Figure 1). The volcano-sedimentary Mahakoshal fold belt presents a lithological sequence evolved in an intracratonic rift, bounded by two major faults, termed as the Narmada North Fault (NNF) and the Narmada South Fault (NSF) trending ENE–WSW (Figure 2). In contrast to the dormant tectonic history of the NNF, the NSF has witnessed protracted reactivation from Precambrian to Phanerozoic. Movement along the NSF resulted in uphorsting of the Mahakoshal belt, thus restricting the northward extension of the Gondwana basin into the Vindhyan province. This condition continued during the Permo-Triassic Gondwana sedimentation of the Satpura and South Rewa basins resulting in the pre-Upper Gondwana depocentres to the immediate south of the NSF. There is geological evidence that the NSF was again partially reactivated during Deccan volcanism in the area. Faulting activity continued in post-trappean times offsetting the Quaternary sediment cover. One such example exhibited by block faulting could be noticed southeast of Jabalpur. This fault could be traced and is sub-vertical having N60°–70°E strike. The controversy, therefore, still exists as to whether NSF is a zone of persistent weakness and tectonism or it is the consequence of a strong plume head that mushroomed beneath the region. In this study the historical seismicity, Deep Seismic Sounding (DSS), and gravity data have been analysed and the results are considered in the light of available geological information of the area to come out with a model, which could satisfy seismo-tectonic features observed in the area.

Seismicity

Seismicity is the manifestation of tectonically weak zones/faults, which might be still active. In order to study the seismicity of the region (20°N to 25°N and 74°E to 83°E), historical earthquake data since 1060 have been considered (Figures 1 and 2). The seismicity map has been prepared from combination of PDE data and historical earthquake data from catalogues5–8. Though the significant earthquakes in Central India are Son valley/Rewa (1927, $M = 6.5$),
Figure 1. Geological map of central India showing the geological boundary of the Satpura Gondwana basin. SB, Satpura basin; SRB, South Rewa basin. Earthquake epicentres (solid circles) and geological map of central India. Source of magnitude of historical earthquakes is listed in ref. 8.

Satpura (1938, $M = 6.3$), Balaghat (1957, $M = 5.5$), Broach (1971, $M = 5.4$) and Jabalpur (1997, $M = 6.0$), focal mechanism solutions are available only for the Broach and Jabalpur earthquakes showing fault planes oriented in NE to ENE and NW to EW$^{9,10}$, respectively. These are indications that faulting could occur along this plane. Field evidences are also in support of the involvement of an ENE-oriented fault in the Broach and the Jabalpur earth-
quakes. Fissures that opened during the Broach earthquake were generally oriented in ENE–WSW direction. Ground cracks associated with the Jabalpur earthquake were also oriented in ENE–WSW direction. Thus, the geological and seismological data show a good correlation of spatial distribution of historical earthquakes with known linear tectonic features of the Son–Narmada–Tapti (SONATA) zone in central India. Further, recurring seismicity points to the reactivation of original faults that are associated with the Narmada rift. Because of the poor distribution of recording stations in the adjoining region, the catalogue is short of full details, especially of lower magnitude earthquakes. However, considering a long duration of seismicity one can draw certain inferences. The trend of spatial distribution of earthquakes in the central India shows three interesting correlations:

(1) Most of the historical earthquakes are confined to geological contacts (Figure 1).

(2) A simple seismicity pattern of this region shows a distinct correlation with the Satpura Gondwana basin margin (Figures 1 and 3), suggesting their proneness to reactivation.

(3) Although NSL is regarded as a major tectonic feature passing through the Deccan trap covered regions, the area between longitudes 75° and 78°E, completely covered with Deccan traps, is conspicuously devoid of seismicity. Several thermal springs along the NSL occurring mostly at the contact of Vindhyan–Deccan traps or Gondwana–Deccan traps outcrops are associated with seismicity. We find a distinct pattern that is related to tectonic setting and earthquake occurrence in the NSL zone (Figures 1 and 2).

Evidence of blind faults derived from deep seismic sounding data

Among all, the most devastating earthquake was the 1997 Jabalpur earthquake. The earthquake was found to be associated with a fault well-indicated by clear shifts in refracted travel times on the Hirapur-Mandla DSS records of SP150 and SP160 (ref. 12). Although Reddy et al.13, Sain et al.14, Tewari et al.15 and more recently Murty et al.16 have modelled and updated their models using different tools, still the fault marked (interpreted by them) is nowhere close to the seismogenic fault discussed by Acharyya et al.17. Because of the recording gap between SP150 and SP160 due to cultural noise in the Jabalpur city, it was not possible to fix the place of the fault on the surface (Figure 4). The Jabalpur earthquake (1997) provided additional data to fix the position of that fault on the surface. The hypocentral cross section of the main shock and aftershocks of the Jabalpur (1997) earthquake along NW–SE line (Figure 5) cutting across the seismogenic zone and aftershock zone show that the seismogenic fault FF′ dips steeply towards SE17. Its fault plane cuts the surface in a seismogenic zone17. It is interesting to note that Srivastava et al.4 and Srivastava and Pattanayak18 have reported a major shift (~150 m) in the stratigraphic height of a lava flow at the western flank of the Nagapahar range south of the Jabalpur on the basis of correlation of various Deccan trap flows in the eastern Deccan volcanic province. They have interpreted it to be due to a NE–SW trending, post-Trappean normal fault in this region. In the light of hypocentral cross section, presence of shift in Deccan trap’s flows and geological evidence of well-developed fault gorges5, the place of basement fault may be reviewed and could be correlated with the seismogenic fault delineated by hypocentral cross section. Similar post-Deccan trap faults have also been reported along the Satpura range. Crookshank19 opined that emplacement of intrusive complex may have resulted in faulting in lava flow. Cox20, however, has attributed it to post-eruptive isostatic adjustments.

Tectonic implications

Much intra-continental deformation within the crust is accommodated by reactivation of pre-existing structures21. Reactivation of pre-existing faults22 and variation of local stress concentration23 are generally considered as causative mechanisms for intraplate seismicity. However, localized zones of high strain rate24 can also explain some of the upper crustal earthquakes. The zone of weakness model proposes that contemporary earthquake activity be caused by the reactivation of ancient faults and other weak boundaries within the crystalline crust, which are presently subjected to apparently ambient regional stress field. Earthquake occurs where local deviatoric stress exceeds the threshold for brittle failures. In fact, structural reactivation, a common feature of deformation in continental crust, is mostly accounted for by the reactivation of existing planes of weakness rather than by creation of new faults. As a result, intraplate seismicity on the continent is commonly concentrated along the ancient fault zones25. With far field compression generated at the plate boundaries, local stress perturbations may also be caused by lateral variations in crustal structure, density, lithological boundary and stress concentration along the edges of structures. The stress concentration theory works on the lithospheric mass variations and perturbs the ambient stress regime to the extent of triggering earthquakes. Stress localization model proposes that sites of large intraplate earthquakes be controlled by the zone of localized strain in the lower crust, which concentrates stresses in the upper crust.

SONATA is a critical example of the current debate. From the observation of the spatial distribution of historical earthquakes in the SONATA zone (Figure 1), it can be seen that the NSL has experienced only diffused occasional earthquakes, whereas the Pachmarhi plateau is surrounded by at least eight historical earthquakes. The
Figure 3. a, Seismicity and elevation image map of the west-central India showing the distribution of historical earthquakes (marked with solid circles) between longitude 74\(^\circ\)E and 83\(^\circ\)E and latitude 19\(^\circ\)N and 25\(^\circ\)N; b, Increased seismicity (marked by red solid circle) can be seen around the elevated Pachmarhi plateau between longitude 77\(^\circ\)E and 80\(^\circ\)E and latitude 21\(^\circ\)N and 23\(^\circ\)N. Geological boundary of the elevated Gondwana basin is marked with white lines and the basin margin fault (after Pande and Tiwari\(^42\)) is marked by black solid lines. Contours of elevation, at an interval of 100 m, are marked by thin solid lines.
earthquakes around the Pachmarhi are aligned with the Satpura Gondwana basin margin faults (Figure 3a, b). These faults controlled the depositional history of the Satpura Gondwana sediments as they are located at geological contacts between Gondwana rocks and Archaean basement on the southern margin and Gondwana/Mahakoshal on the northern margin. A sudden change in elevation of about 500 m of Pachmarhi Gondwana basin above the granite-gneiss basement shows that there has been post-Gondwana epeirogenic uplift in this area. There could be various causes for such an uplift. A possible mechanism of the epeirogenic uplift was discussed by McKenzie\textsuperscript{26} and it was summarized that the intrusion of large thickness of basic magma into the lower part of the continental crust could cause epeirogenic uplift under favourable conditions and could result in pushing the crust upward along the faults. Geochemical and petrological evidence indicate that majority of lower Deccan tholeiites lava evolved in local and multiple magma chambers close to the surface up to a depth of 7 km\textsuperscript{27}. The emplacement of such a thick magmatic body could cause an up warp above this body and also could cause down warp below it to stay at depth. The eruption activity in the Satpura area is considered to be along Satpura axis from south of Khandwa to north of Mandla through Lakhandon\textsuperscript{27} (Figure 1). Hence, the axis of eruption most probably would be along the boundary of this uplift and/or adjoining graben/rift structure. Dykes with ENE–WSW trends intrude the Deccan trap flow profusely along Narmada-Tapti rift and over Gondwana near Betul. Field and geochemical relations and age similarities (67–64 Ma) of many mafic dykes and basal flows indicate their comagmatic nature and establish many rift-oriented mafic dykes as primary feeder.

It may also 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. As mentioned earlier, at least two major earthquakes in Narmada zone are deep focus earthquakes, namely the 1938 Satpura earthquake at a depth of 40 km (M 6.3) and of 1997 May 21 Jabalpur earthquake.
Figure 5.  

(a) Epicentral map of the main shock and aftershocks of 21 May 1997 Jabalpur earthquake. The meizoseismal zone (isoseismal VIII) is shown with dashed line. The fault plane solution (lower hemisphere) of the main shock and aftershocks are illustrated with usual notation (after Acharyya et al.).

(b) Hypocentre section of the main shock (hatched circle) and aftershocks (solid circle) of Jabalpur earthquake, 1997 along A–B in the dip direction of Narmada south fault. The fault F–F’ extends to mantle depths (after Acharyya et al.).

(M = 6.0) at a depth of about 35 km. The occurrence of deep focus earthquakes at lower crustal depths is quite unusual for Indian shield and mid-continental zones and indicates that the causative mechanism is related to crust–mantle interaction. Rao et al. support the idea of weak intrusives in the lower crust that are capable of stress concentration. Rezanov inferred that the most probable composition of weak inclusion in the lower crust is serpentinitized ultramafic rocks formed by dehydration of the mantle-derived rocks. Disposition of these earthquakes along NSL, magmatic intrusion in the middle crust and the possible presence of serpentinitized ultramafic rocks in the lower crust could be a probable cause of stress accumulation in the lower crust.

Correlation of Bouguer anomaly, shallow and deep seismic velocity structure and heat flow anomalies show presence of mafic bodies as shallow as 5–6 km along the Satpura. The low-velocity/low-density lower crust serpentinitized layer at the base of the crust in the given rheological boundary conditions acted as local stress concentrator for the deeper earthquakes of the region. Contrary to this, the elliptical shaped NE–SW trending gravity-high in the western part of the NSL (west of the Godavari graben) was interpreted to be due to the high-velocity/high-density intrusive body at the base of the crust. This implies that the magmatic under plating, which was inferred from Bouguer gravity high axis by Singh and Meissner, is not seismogenic.

In the Satpura Gondwana basin near Pachmarhi, the heat flow data is so disturbed that a large variation in surface heat flow (48–96 mWm$^{-2}$) is observed in a small area of 50 km × 50 km. Gupta inferred that the surface waters percolate through dyke contacts and show a disturbed surface heat flow. Some of the lineaments of the region are also associated with geothermal springs. Regional association of thermal springs with seismicity have also been reported. Presence of thermal springs scattered along well-defined tectonic structures generating earthquakes along Satpura, suggest that the faults associated with such structures are seismically active. Since most of the described faults where springs emerge are seismically active, they must be considered as excellent sites for monitoring seismic activity.

Conclusions

The main conclusions that arise from the re-evaluation of the seismic data can be summarized as follows:

– The Satpura Gondwana basin encompassing Pachmarhi has been upwarped over and above normal Satpura elevations.

– The occurrence of historical earthquakes shows a striking correlation with major faults and contacts between different geological units.

– It has been found that the area has undergone post-Gondwana uplift. The epicentral distribution pattern suggests reactivation of the fault systems, flanking the uplifted Satpura Gondwana block. In other words neo-tectonic activity is still on.


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