Neotectonic fault movement and intraplate seismicity in the central Indian shield: A review and reappraisal

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The central Indian shield area is characterized by earthquakes with dominantly oblique-reverse movements on pre-existing faults along paleo-rift zones. These earthquakes, occurring hundreds of kilometers away from the plate boundary, are considered as Stable Continental Region (SCR) earthquakes. In this contribution, we have attempted to analyze the nature of intraplate earthquakes of the central Indian shield with special reference to the Son-Narmada-Tapti (SONATA) zone which is known as a paleo-rift with Precambrian ancestry and a proven geological history of repeated tectonic rejuvenation throughout the Phanerozoic. The cause of the neotectonic fault movements, the paleo-seismic records and the seismic history of the SONATA zone are discussed in detail. Geological, geophysical and heat flow measurement data suggest stress concentration in the SONATA zone in response to the far-field plate boundary forces arising out of the Indo–Tibetan plate collision in the north (Himalayas), which causes intraplate earthquakes in this tectonically stable region. A review of the present state of knowledge on the tectonically active areas in the central Indian cratonic area is presented here. We have also attempted to give an appraisal of the tectonic reactivation of pre-existing rift-related faults under the neotectonic stress field, using new data from our analogue experimental work.

Keywords: Neotectonics, Heat flow, Fault reactivation, SCR earthquakes, Central Indian shield

INTRODUCTION

Earthquakes very commonly occur in plate boundary domains like oceanic spreading centers (e.g., the Mid-Atlantic Ridge), subduction zones (e.g., the circum-Pacific ‘Ring of Fire’), and continental collision orogens (e.g., the Himalayas). Subduction zone earthquakes are often very large in magnitude and release a significant amount of seismic energy. For example, the 1960 Chile earthquake (Mw 9.5), the largest earthquake recorded so far, released about 25% of the total seismic moment released globally between 1904 and 1986 (Scholz, 1990). It has been shown that about 85% of the seismic moment release occurs through earthquakes at the subduction zones, and overall, the shallow-focus plate boundary earthquakes are responsible for 95% of the moment release worldwide (Scholz, 1990). In contrast, earthquakes occurring within the plate interiors release less seismic energy and are much less frequent. Therefore, intraplate earthquakes have generally got relatively less attention from the geologists/seismologists. However, intraplate earthquakes can be very detrimental to the society, as they often strike in densely populated areas of the continents, and are mostly unexpected and catch people unaware and unprepared for the disaster. Some well-known examples are the 1811–12 Charleston earthquakes in New Mexico, USA, the 1819 Rann of Kachh earthquake, India, the 1976 Tangshan earthquake, China, the 1988 Tennant Creek earthquake, Australia, and the 1993 Killari earthquake, India, among others. All these earthquakes occurred within the so-called ‘Stable Continental Region’ (SCR), hundreds of kilometers away from the plate boundaries. The causative factor of these SCR earthquakes has mostly been ascribed to the reactivation of old faults/weak zones within the apparently ‘stable cratonic domain’ (Johnston and Kanter, 1990). The major problem with the SCR earthquakes is that strain builds up very slowly in these cratonic domains, and therefore the fault movements recur after a very long period of time. Due to such large recurrence intervals, the seismic history of the terrain remains obscure as the instrumental records of seis-

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micity exist only for the last 100 years, and the historical accounts of earthquakes are available at best for the last 1000 years. The geological study of exhumed old fault zones within the continental interiors is the best possible method to assess the seismic history and potential of the cratonic domains.

Within the peninsular shield of India, traditionally considered as a stable continental region, at least 11 earthquakes of significant magnitude \((M > 5)\) have occurred since the 18th century (Rao, 2000). Seismic events recorded at Mahabaleshwar (1764), Kutch (1819), Coimbatore (1900), Son valley (1927), Satpura (1938), Koyna (1967), Broach (1970), Killari/Latur (1993), Jabbalpur (1997), and Bhuj (2001) are some of the prominent SCR earthquakes of India (Fig. 1). Among these, a number of events, viz. Son valley, Satpura, Broach, and Jabbalpur occurred within (or very close to) the E–W trending Narmada–Son geofracture, better known as the Son–Narmada–Tapti (SONATA) lineament zone. The Kutch and Bhuj earthquakes occurred within the E–W trending Kutch rift zone, sub-parallel to the Narmada–Son geofracture (Fig. 1). The SONATA zone is the most prominent geomorphic feature of the central Indian shield, principally defined by the Satpura Mountains, flanked by the Narmada–Son river valley in the north and Tapti–Purna river valley in the south. It has been shown by several workers that the ridges and the valleys of this zone are all fault-bounded, and some of the faults are showing clear signs of neotectonic activity which manifests in hot springs, and intermittent earthquakes in this zone (Ravishanker, 1987; Roy and Devarajan, 2003; Bhattacharjee et al., 2016). In the present contribution, we shall attempt to summarize the geological and geophysical structure of the SONATA zone and the neotectonic character of the bounding faults. In the above context, we shall examine the possible causal relationship between the intraplate seismicity of the SONATA zone and the far-field plate boundary forces arising out of the Indo–Tibetan plate collision. For the sake of brevity, we

![Figure 1](image-url)

**Figure 1.** Distribution of recent and historical earthquake epicenters in the Indian Peninsula showing the major paleo-rift zones along with the Precambrian cratonic fragments and mobile belts (modified after Gowd et al., 1996; Rao 2000).
shall refrain from discussing the other major intraplate earthquakes that have occurred within the southern Indian peninsular region, in the Pranhita-Godavari rift and in the western continental margin area of India.

**GEOLOGICAL SETTING OF THE CENTRAL INDIAN SHIELD**

The peninsular shield of India is constituted of two major cratonic fragments – the North Indian Block (NIB) comprising the Bundelkhand–Marwar craton and the South Indian Block (SIB) comprising the combined Dharwar–Bastar–Singhbhum cratons. The NIB and SIB were stitched together along an E–W trending Proterozoic mobile belt called the Central Indian Tectonic Zone (CITZ) (Fig. 2a) through multiple events of crustal collision and accretion (Roy and Prasad, 2003; Chattopadhyay et al., 2017). The CITZ comprises three major supracrustal fold belts, viz. Mahakoshal, Betul, and Sausar belts from north to south, set within a vast country of unclassified gneiss–migmatite–granite laced with linear granulite belts (Fig. 2b). A number of major faults/shear zones traverse the CITZ along its length, viz. Son–Narmada North Fault (SNNF), Son–Narmada South Fault (SNSF), Gavilgarh–Tan Shear/Fault zone (GTSZ/GFZ), and Central Indian Shear/suture (CIS) which also define the boundaries of the major litho–tectonic domains within the CITZ (Fig. 2b). The SNNF, SNSF, and GTSZ define the Son–Narmada–Tapti (SONATA) lineament zone mentioned earlier (compare Fig. 1 with Fig. 2b). All the major earthquakes of the central Indian shield have taken place within the SONATA zone, with only a few major events (e.g., the 1967 Koyna and the 1993 Killari earthquakes) recorded from the cratonic part outside the CITZ. We shall, therefore, limit our discussion on the seismic events of the SONATA zone only, with a brief discussion on the other events to maintain the geological context.

**Geological character of the SONATA zone**

The Son–Narmada lineament is a fundamental weak zone within the Central Indian craton. West (1962) first pointed out that the Meso–Neoproterozoic Vindhyan rocks are restricted to the north of this lineament, while the Gondwana Supergroup (Permian to Cretaceous) occurs only in the south of this line, suggesting repeated movement on the bounding faults at different periods since the early Proterozoic. The SONATA zone, also known as the Narmada–Son geofracture, is believed to be dominated by a Cretaceous-age rifting which produced a large scale horst-and-graben structure. The high mountains of Satpura range supposedly represent the horst, flanked by two grabens – the Narmada graben in the north and the Tapti–Purna graben in the south which host thick piles of Quaternary sediments (Ravishanker, 1987, 1995) (Fig. 3). To the north of the Narmada valley stands the high mountain ranges of the ‘Vindhyas’, constituted of the Meso–Neoproterozoic Vindhyan sedimentary sequence. The boundary of the Narmada graben and the Vindhyan Mountains is defined by the SNNF, while the southern margin of the graben against the Satpura Mountain range is roughly demarcated by the SNSF. The Gavilgarh–Tan shear/fault (GTSZ/GFZ), locally known as Satpura Foothill Fault (SFF), Salbardi Fault or Ellichpur Fault, demarcates the southern margin of the Satpura ‘horst’ against the Tapti graben (or half-graben) (Ravishanker, 1987). The horst-and-graben model of the SONATA zone (Fig. 3) essentially means that all these faults (SNNF, SNSF, and GTSZ) are normal faults with downthrows of hundreds of meters, at least in the post–Cretaceous period. Several workers have later questioned the horst-and-graben model and have argued that the SNSF and GTSZ are, in fact, reverse faults which suggest that the Satpura block is a compressional ‘pop-up’ structure (e.g. Acharya and Roy, 2000; Sheth, 2018).

The SNNF possibly originated as a transcurrent ductile shear zone, which reactivated as a normal fault during the Paleoproterozoic and controlled the deposition of the volcano–sedimentary litho-package of the Mahakoshal Group. There is no reported evidence of reactivation of SNNF after the Mesoproterozoic (Roy and Devarajan, 2003). The SNSF marks the southern boundary of the Mahakoshal belt. The earliest deformation of SNSF is characterized by sinistral–reverse, oblique–slip ductile shearing, and extensive mylonite formation in the Paleoproterozoic (Roy and Devarajan, 2000). Subsequently, the shear zone underwent brittle reactivation as a normal fault during the Lower Permian and was further affected by compressional reactivation during the Paleogene and Quaternary (Roy and Devarajan, 2003). The GTSZ/GFZ juxtaposes cross–bedded Gondwana sandstone of Permian to early Cretaceous age against the younger (Late Cretaceous–Paleocene) Deccan Trap basalt flows lying to its south. In the northern block, the Gondwana rocks are overlain by Late Cretaceous Lameta beds and the Deccan Trap flows successively. Further east, in the Kanhan River valley, GTSZ is exposed as a spectacular ductile shear zone (Fig. 2b) with evidence of repeated strike–slip movements in the Neoproterozoic and Cambro–Ordovician time (Chattopadhyay et al., 2008). Roy and Devarajan (2003) have argued that GTSZ/GFZ possibly reactivated as a normal fault in the Permian and controlled the sedimentation of Gondwana Supergroup in the Satpura basin up to the early Cretaceous period. Bhattacharjee et al.
(2016) have demonstrated post-Cretaceous upliftment of the Satpura block along an E-W striking, steep northerly dipping reverse fault (Gavilgarh Fault Zone, i.e., the western part of GTSZ). Through Optically Stimulated Luminescence (OSL) dating of terrace sediments from the N-S flowing rivers, they have suggested four major reverse fault movements in the Quaternary (~ 65–80, ~ 50, ~ 30–40, and ~ 14 ka), amounting to a total recorded fault slip of about 15–20 m. A significant amount of reverse slip (~ 600 m) during Paleogene, involving only the Late Cretaceous–Paleocene GTSZ dukedown, has been observed. These observations support the hypothesis of Neogene collision and exhumation in the GTSZ. The suggested tectonic event appears to be a critical stage in the formation of the modern geomorphology of the Satpura block, characterized by steep scarps and limestone escarps with some evidence of karstification.
taceous–Paleocene Deccan Trap basalt flows, was suggested by these authors. Sheth (2018) has argued that GTSZ (or SFF) is a north-dipping reverse fault, and the southern scarp of the Satpura Mountains, earlier considered as an expression of a south-dipping normal fault defining the Satpura Horst structure, is actually a denuded fault-line scarp. Copley et al. (2014) observed step-like displacement of alluvial fans along the Tapti North Fault (TNF), another major fault within the Satpura block, and argued that the fault slipped in reverse sense with a minimum displacement of 15 m in the Quaternary (~10–15 ka) and could have generated an earthquake of Mw 7.6–8.4 magnitude. All these works emphasize that the SONATA faults have undergone reverse-slip movement in the Paleogene and Quaternary.

Geophysical and geothermal character of the SONATA zone

The crustal structure of the SONATA zone has been well characterized by Deep Seismic Sounding studies (Kaila and Krishna, 1992). The DSS profiles created along six different N–S transects across the lineament (Fig. 4a) clearly brought out the faulted structure of the crust and the varying depth of the crustal-mantle boundary (MOHO). Especially the two central profiles (i.e., Ujjain-Mahan and Khajuria Kalan-Pulgaon transects shown in Fig. 4a) show the major faults (SNSF and GTSZ) bounding the Satpura Ridge, the Narmada valley, and the Tapti-Purna valley (Fig. 4b). These faults are interpreted as steep-dipping faults reaching up to the crust-mantle boundary. It is interesting to note that in all the DSS profiles, the SNSF is shown as southerly dipping and the GTSZ as northerly dipping fault, which contradicts the earlier geological interpretation of the horst-and-graben structure (e.g., Ravishanker, 1987). The MOHO depth was interpreted to vary from 38–45 km along the DSS profiles. This is much higher than the average thickness of the Indian crust (35 km). Acharyya and Roy (2000) suggested that the crustal thickening in the SONATA zone...
may have taken place through the underplating of mantle-derived high-density material below the crust during the Neoarchean–Paleoproterozoic time, and a much later phase of magmatic underplating in Cretaceous–Paleocene, related to the Deccan Trap volcanism. Another remarkable feature of the SONATA zone is the high Bouguer gravity anomaly along the Satpura mountain (−25 mGal) compared to the surrounding area (−40 to −60 mGal) (Murthy et al., 1990). Such anomalously high gravity also suggests the presence of high-density material at depth below the SONATA zone, especially under the Narmada valley between the SNNF and SNSF.

High heat flow values (100–180 mW/m²), almost double the global average heat flow in the continents (≈ 60 mW/m²), are observed along the axial zone of the SONATA lineament, mainly concentrated along the southern margin of the Satpura mountain and along its northern boundary near Tattapani–Jhor geothermal belt (Fig. 5). Several hot springs are found in the SONATA zone, which are usually linearly aligned along the lengths of the major fault zones and/or lithological contacts and these correlate well with the epicentral locations of historical earthquakes in central India (Acharyya and Roy, 2000) (Fig. 5). Ravishanker (1995) suggested that such anomalous heat flow could be related to active tectonics of the Paleogene–Quaternary period due to the movement on deep faults perturbing the MOHO.

**NEOTECTONIC MOVEMENT AND SEISMICITY OF THE MAJOR FAULTS**

The neotectonic regime of an area usually comprises the tectonic activity related to the present-day plate boundary configurations, plate motions, and the associated stress fields (Stewart and Hancock, 1994). In this context, the neotectonic activity of the Indian craton includes tectonic movements that have taken place since the docking of the Indian plate with the Tibetan (Eurasian) plate during the...
Upper Eocene. We have already mentioned that the major faults of the SONATA zone (e.g., SNNF, SNSF, and GTSZ) are fundamental weak zones within the Indian crust and have a long history of tectonic activities from Paleoproterozoic to Paleogene and Quaternary. The recent seismic events within the SONATA zone are mostly related to the neotectonic movements along some of these faults (Roy and Devarajan 2003), as are detailed below.

The Central Indian shield area has experienced at least six major earthquakes in the last 100 years, viz. Son valley (1927), Satpura (1938), Koyna (1967), Broach (1970), Killari (1993), and Jabalpur (1997) events, which have been instrumentally recorded (Fig. 1). Of these, the Koyna and Killari events occurred outside the SONATA zone, in areas covered by thick Deccan Trap lava flows where the pre-existing faults are not well-demarcated, and there is hardly any record of historical earthquake activity. The 1967 Koyna earthquake ($M_w \approx 6.7$) has been interpreted as a reservoir-triggered earthquake related to the filling of a major dam (Koyna/Shivajisagar reservoir) since 1961–62 (Gupta, 2002). The earthquake, which killed 200 people, had a hypocentral depth of 8–12 km and was attributed to the reactivation of an NNE–SSW striking, steep westerly dipping fault (Talwani, 1997). The Koyna reservoir area has since been seismically active with hundreds of low magnitude earthquakes recorded over the years. Gahalaut et al. (2004) have argued that fault interaction and stress transfer from one fault to another within a close network of pre-existing faults could be a reason for sustaining a high level of seismicity for a long period. The rupture zone of the 1993 Killari (or Latur) earthquake ($M_w \approx 6.3$) was studied by deep trenching (Rajendran et al., 1996), which suggested that the earthquake was caused by a low-angle (~15° dip) southwesterly dipping reverse fault. A number of older thrust planes were identified in the trench walls suggesting repeated reactivation of an older thrust zone by contractional deformation prior to the recorded history of earthquakes.

Within the SONATA zone, the most devastating earthquake occurred in May 1997 near Jabalpur ($M_w \approx 5.8$) that caused a huge loss of life and property. It was caused by a sinistral oblique-reverse slip of about 37 cm which represents a major reactivation event of the SNSF (Bhattacharya et al., 1997). The Jabalpur earthquake had a large depth of focus ($36 \pm 4$ km), very limited aftershock activity, and most importantly, it occurred in an area where moderate earthquakes are well known in the recorded history. Another interesting feature of the Jabalpur earthquake is that it occurred in a region of high heat flow (about 100 mW/m²). In view of the absence of any recent magmatic activity in this area, the high heat flow was attributed to the existence of high-density magmatic material (e.g., mafic magmatic body emplaced during rifting) near the crust–mantle boundary between SNNF and SNSF, which is supported by DSS studies (Rajendran and Rajendran, 1998, and references therein).

Among the other major earthquakes recorded within the SONATA zone, the 1927 Son valley (or Umaria) earthquake of magnitude 6.5 had epicenter very close to the SNSF (Chandra, 1977). The 1938 Satpara earthquake ($M \approx 6.3$) was felt in most parts of the central and western India. The epicenter was located within the Satpara Mountains, north of the Tapti river valley, and the hypocentral depth was calculated as 40 km, with N–S elongated isoseismal contours (Mukherjee, 1942). The Balaghat earthquake of 1957 ($M \approx 5.5$) occurred near the southern margin of the Sausar belt and is attributed to a reactivation of the CIS. At the western end of the SONATA zone, the Broach earthquake ($M \approx 5.4$) occurred in March 1970 and caused heavy damage to the town of Broach, Gujarat. Fault plane solutions indicate a causative fault with ENE–E–W orientation and a shallow focal depth of 11 km (Chung, 1993). Extensive liquefaction of soft sediments on the banks of the Narmada River was reported.

From the detailed map of earthquake epicenters in the central part of the SONATA zone, it is clear that the Satpara–Narmada–Tapti belt is seismically very active (Fig. 5). From the seismological study of the major earthquakes described above, it is clear that the SNSF has been neotectonically reactivated a number of times and has given rise to major earthquakes, although the absolute ages of all the neotectonic fault movements of SNSF are not yet available. The SNNF, on the other hand, does not show any unambiguous evidence of neotectonic reactivation from the available geological or geophysical studies (Acharyya and Roy, 2000). Although no major historical earthquake has been directly attributed to the movements on GTSZ (or GFZ), geological studies have proven multiple phases of reactivation of GTSZ, including at least four episodes of fault movement in the Quaternary (Bhattacharjee et al., 2016), as already mentioned in Section 2.1. Similarly, Tapti North Fault shows evidence of reverse fault slip in the Quaternary (~ 10–15 ka), which might have generated a significant pre-historic earthquake ($M_w \approx 7.6–8.4$) (Copley et al., 2014).

**PALEO-SEISMIC RECORDS FROM THE SONATA ZONE**

As SCR earthquakes are very infrequent, most of the older earthquakes do not have any seismological record, and paleo-seismological study is the only source of information about the intensity of ground shaking, rough estimate of magnitude, approximate location of the epicenter, na-
ture of the causative fault movement, among others (Tut- 
tle, 2001). Soil liquefaction features like sand dyke and 
sill, sand blow, and the sand volcano can develop in an 
earthquake of magnitude 5.0 but become quite common 
sediment features in the Quaternary sediments along the 
bank of the Narmada River in the west of the Jabalpur town. 
Clastic dykes of sandy and silty material were found in-
truding thinly laminated sand, silt, and clay of Hirdupur 
Formation (upper Pleistocene). Soft sediment deformation 
structures like ball- and pillow structure, and small scale 
brittle faults in the Quaternary sediments were also report-
ed from the same stratigraphic horizon farther west. These 
structures were correlated with paleoseismic activity, due 
to their location near the SNSF, and restriction of the 
structures in only one layer, under and overlain by unde-
formed sediments. However, a detailed study of the paleo-
earthquakes from these features has not been carried out.

Another set of paleoseismic records comes from the 
hard, crystalline basement rocks of the Gavilgarh-Tan 
Shear Zone (GTSZ) in the form of distinct layers of pseu-
dotachylyte. Pseudotachylyte is a dark-colored aphanitic 
rock that forms by friction-induced heating and local 
melting of the country rock during seismic slip (≥1 m.s \(^{-1}\)) along a fault (Rice, 2006). However, purely 
crush-origin pseudotachylytes are also described from na-
ture (Lin, 1996). In the sheared granitic basement rocks 
exposed in the eastern part of the GTSZ in the Kanhan 
River bed, Chattopadhyay et al. (2008) found two distinct 
sets of pseudotachylyte layers, viz. mylonitized pseudota-
chyltye (Pt-M) and cataclasite-originated pseudotachyltye 
(Pt-C). Both the Pt-M and Pt-C layers are generally con-
cordant to the mylonitic foliation of the host granitic 
rocks, but thin veins emanating from these layers cross-
cut the host rock foliation at high angles (Figs. 6a and 6b). 
The Pt-M layers have an oblique foliation defined by 
elongate relict fragments of quartz and neo-crystallized 
chlorite grains, suggesting post-emplacement shearing 
(Fig. 6c), while the Pt-C layers contain angular fragments 
of quartz/feldspar and mica with no evidence of any fur-
ther metamorphic/deformation overprint (Fig. 6d). This 
also indicates that Pt-C veins are younger to Pt-M veins 
and formed at a shallower depth during exhumation of the 
shear zone. While the host mylonite shows unequivocal 
evidence of amphibolite facies (T ≳ 500 °C) sinistral-
sense wrench-type shearing, the Pt-M microstructures in-
dicate post-emplacement dextral shearing in the green-
schist facies conditions (T ≳ 300–400 °C). The Pt-C layer 
shows brittle deformation at sub-greenschist facies condi-
tion (< 500 °C) (Chattopadhyay et al., 2008). Through 
the detailed mapping of the Pt-C vein network and the 
associated brittle fractures, Chattopadhyay et al. (2014a) 
suggested that these Pt-C veins were formed in a paleo-
earthquake of moderate size (Mw ≈ 5.7). \(^{40}\)Ar/\(^{39}\)Ar dating 
of the pseudotachylites of GTSZ suggested an age of 
> 672 Ma for the Pt-M and ~ 459 Ma for the Pt-C (Chat-
topadhyay et al., 2014b). The geological history of the 
pseudotachylites thus clearly suggests that two major 
seismogenic fault reactivation movements occurred in the 
GTSZ in the Neoproterozoic and in the Ordovician. 
A few outcrops in the western part of GTSZ (GFZ) near 
Salbardi show fluidized gouge layers, but their timing and 
their relationship with the GFZ movement are uncertain.

**FAR-FIELD STRESS AND INTRAPLATE 
DEFORMATION IN CENTRAL INDIA**

As described in the preceding sections, most of the SCR 
earthquakes recorded within the central Indian shield are 
found to be associated with reactivation of pre-existing 
faults. The seismological data of the earthquakes, wherever 
available, generally show reverse fault-slip with minor 
strike-slip components on roughly E-W or ENE- 
WSW striking fault planes, e.g., Broach (1970), Killari 
(1993), and Jabalpur (1997) events. The seismological 
study of the 1997 Jabalpur earthquake indicates that the 
principal compressive stress (P-axis or \(\sigma_1\)) on the fault 
plane (SNSF) is oriented in an NNE-SSW direction 
(Acharya and Roy, 2000). Earlier, Gowd et al. (1992) 
found the mean orientation of \(S_{H(MAX)}\) as N23°E in the 
mid-crustal stress province (shield area) of the Indian sub-
continent, using orientations derived from borehole break-
outs, hydraulic fracture stress measurements and fault 
plane solutions of known earthquakes. The nature of seis-
mic fault reactivation and orientation of \(\sigma_1\) or \(S_{H(MAX)}\) sug-
gest that the intraplate deformation and earthquakes of the 
Indian peninsular shield are likely caused by the compres-
sive plate boundary stresses generated by the Indo-Tibet-
an plate collision in the Himalayan region.

**Amplification of stresses in paleo-rift zones with high heat flow**

Gowd et al. (1996) have evaluated the average global
Figure 5. (a) Heat flow map of the SONATA zone, also showing the positions of hot springs and recent earthquake epicenters (modified after Ravishanker, 1995; Acharyya and Roy, 2000; Bhattacharjee et al., 2016).
stress field from hydrofracture data and suggested that $S_{\text{HMAX}}$ increases with depth with a gradient of 29 MPa/km and $S_{\text{HMIN}}$ varies with a gradient of 13.5 MPa/km. From the compiled dataset of earthquake locations in the Indian shield, they have shown that 80% of the earthquakes of the Indian peninsula have occurred in linear belts with high heat flow (e.g., the SONATA belt, the West coast belt, and the Godavari graben). From the calculated value of ridge-push forces from the Indian Ocean spreading centers and the isostatically compensated load of the Tibetan plateau uplift, the average gradient of $S_{\text{HMAX}}$ in the high heat flow linear belts (e.g., the SONATA zone) was found to be 55 MPa/km which is two times the global average of 29 MPa/km (Gowd et al., 1996). Based on these calculations, these authors suggested that stress amplification in the zones of high heat flow could have facilitated reactivation of faults, especially in the E-W trending paleo-rift zones like the SONATA belt in response to the far-field plate boundary forces. Focal mechanism study of the 1970 Broach earthquake and the 1997 Jabalpur earthquake show dominant thrust faulting (with sub-ordinate strike-slip component) as the mode of fault reactivation. Structural inversion of the rift zones under the action of compressive far-field stresses is, therefore, the most likely cause of the neotectonic movement and seismicity in the SONATA zone.

Inversion of SONATA rift zone under compression: experimental study

It is often reported that the disrupted basement of a rift basin acts as a mechanical discontinuity leading to stress concentration which can localize the development and the position of subsequent thrusts during tectonic inversion of the stretched crust (e.g., Gillierst et al., 1987; Butler et al., 2006). Earlier normal faults may reactivate either entirely or partially as a thrust fault, or the younger thrust may cut the older normal fault and carry a sliver of the footwall rock as ‘cut-off’. To address this issue of the kinematics of possible reverse reactivation of the SONATA zone, we have carried out a few sandbox experiments on the compressional inversion of an extensional rift basin as described below.

Experimental set-up, material, and methods. The modeling apparatus consisted of a glass box of dimensions $50 \times 40 \times 15$ cm$^3$, in which a layered sand-pack of 1.5 cm thickness was deformed. The glass box had three fixed walls and one moving wall (indenter) which was attached to a motor-driven piston moving at a constant speed of 1 mm/min in all the experiments. Dry quartz-rich sand with an average density of 1.6 gm cm$^{-3}$ (average grain size 0.5 mm) was used as modeling material to simulate the brittle crustal rocks in laboratory conditions. Two ‘L’ shaped stiff but thin steel plates were placed facing each other with the basal arms touching each other (Fig. 7ai). A layered sand model of $50 \times 40 \times 15$ cm$^3$ was built by sieving alternate layers of non-colored and red-colored sand over the plane formed by the base of the indenters (Fig. 7ai). The sand was colored with a non-reactive vegetable dye which did not change its mechanical property. Therefore, the layers were only passive markers and did not impart any mechanical anisotropy to the model. One of the L-shaped plates (the right-hand side plate in Fig. 7a) was pulled away slowly with a constant speed (1 mm/min). This resulted in the stretching of the sand model, exactly over the increasing gap between the indenter bases, which created a rift basin bounded by normal faults in the sand layer (Figs. 7aii, 7bi, and 7bii). Later, the basin was filled by sieving alternate layers of non-colored and black-colored sand, simulating younger sedimentation over a rifted basement (Figs. 7aiii and 7biii). Subsequently, the same L-shaped indenter was pushed back slowly (at a speed of 1 mm/min) toward its initial position, inducing tectonic inversion of the system (Figs. 7aiv and 7biv).

Model scaling. For any geologically relevant experiment using analog model material, the model should be scaled to their natural counterparts, according to the scaling laws (Hubbert, 1937; Ramberg, 1981). The sand models had an approximate length scaling ratio of $10^{-6}$ (i.e., 1 cm in the model represented 10 km in nature) which should be approximately equal to the stress ratio of the model and the natural system. In such mechanical analog models, the stress ratio is represented by the ratio of cohesion in analog model material (sand) and that of the natural rocks, when the angle of internal friction (e.g., $\varphi = 25-35^\circ$) for the two materials is kept same (Davy and Cobbold, 1988). Common upper crustal rocks (e.g., shale, sandstone, limestone, etc.) have cohesive strengths in the range of 5-10 MPa, and the angle of internal fric-
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tion is around 27–32° (Schön, 2011). Thus, to maintain the stress ratio of $10^{-6}$, the model material should have the cohesion of about 5–10 Pascal (i.e., very weak or negligible cohesion). The conditions are broadly satisfied by dry sand ($\phi \approx 31^\circ$, cohesion negligible). The sand models were therefore broadly scaled to nature, and the experimental structures are directly comparable to natural rifts and compressional fold-and-thrust belts.

**Experimental results and interpretation.** The experiments show that in the initial (extensional) phase, a rift basin developed in the sand model by two major normal faults dipping towards each other and bounding the rift basin (Fig. 7bii), just above the velocity discontinuity imparted by the edge of the moving plate below. It simulated the stretching of a Precambrian basement (e.g., the central Indian cratonic basement), including older sedimentary rocks. Refilling of the rift basin with dry sand simulated a rift graben (Satpura basin) filled by the younger (e.g., Gondwana Supergroup) sediments in the Paleozoic. When the model was shortened by reversing the movement of the L-shaped plate, stress concentrated directly at the base of the paleo-rift and led to its structural inversion by reverse (thrust) faulting (Fig. 7biv). It is interesting to note that in one side of the rift (right-hand side in Fig. 7biv), a new thrust cut the footwall of the rift bounding normal fault (Fig. 7bv), and uplifted the older sedimentary rocks of the basement as a sliver (i.e., footwall cut-off). On the left side of the rift, the major basin bounding thrust reactivated the rift margin along a plane joining all the tips of the small scale normal faults of the rift (Fig. 7biv) which was basically a fault line scarp, defined by the contact between the pre-rift rocks (white-and red-layered sand) and the post-rift sediments (white-and black layered sand). This suggests that during tectonic inversion, thrusts may follow contacts between different lithological units, likely having different strengths. The inverted rift seen in the final stage of the experiment (Figs. 7aiv and 7bv) represents a structural ‘pop-up’ flanked by inward dipping reverse faults and many smaller reverse faults inside the pop-up structure. This structure closely resembles the interpreted tectonic structure of the SONATA zone (Fig. 8). The south-dipping SNSF and the north-dipping GFZ (GTSZ) define the limits of the central pop-up, i.e., the Satpura Mountain which is an inverted Gondwana basin. The reverse faulting occurred mostly in the post-Cretaceous (Paleogene) period, affecting the Deccan Trap cover, and also in the Quaternary as discussed earlier by several authors (Copley et al., 2014; Bhattacharjee et al., 2014).

**Figure 7.** Sandbox experiments on the inversion of a rift system. (a) sketches and (b) photographs of the experimental model. The rift opens under extension by the movement of one basal plate to the right and closes by the reversal of the movement of the basal plate. See the text for details.
The two basins flanking the Satpura Mountains in the north and in the south are occupied by the Narmada and the Tapti–Purna river systems, respectively. This inverted structure of the Satpura is also corroborated by the DSS profiles where SNSF and GTS are shown as dipping southward and northward, respectively (Fig. 4b), and also by the reverse movement on GTS and SNSF found by geological evidence and earthquake focal mechanism as discussed earlier in this paper.

**DISCUSSION**

From the distribution of earthquake epicenters in the Indian shield (Fig. 1) it is clear that most of the historical and recent earthquakes have occurred in the linear belts with high heat flow (>80 mW/m^2), which are also characterized by the presence of pre-existing faults usually related to the paleo-rifts. Zoback et al. (2002) have argued that the lithosphere in a stable cratonic area is in a state of failure equilibrium, and small stress perturbations can produce significant changes in the rate of deformation - by about three orders of magnitude. Similarly, the presence of anomalous upper mantle structure (e.g., ‘rift pillow’ of high-density magmatic rocks) can lead to a local stress concentration and enhanced seismicity at depth. Zoback et al. (2002) also showed that high heat flow in a region induces higher temperature in the lower crust and upper mantle which deforms at a higher strain rate (in the order of 10^{-15}s^{-1} or higher) compared to the colder parts of the craton, where maximum strain rate does not exceed < 10^{-17}s^{-1}. As the ductile part of the lithosphere is mechanically coupled with the uppermost brittle crust, enhanced deformation of the lower crust-upper mantle in the high heat flow belts will concentrate neotectonic fault movement and seismicity in these zones. Microearthquake studies in the Pandhana area (near the epicenter of 1938 Satpura earthquake) in 1994–1995 have indicated a swarm–like activity, concentrated in the depth range of ~ 500 meters to about 7 km (Gaonkar and Srirama, 2003). These results indicate that the majority of the earthquake activity in the SONATA zone is caused by the upper crustal fault movement.

Vita–Finzi (2004) proposed that the linear belts of seismic fault movements in the Indian shield area can be explained by large (400–800 km) wavelength buckle folding of the Indian lithosphere in response to the ridge-push forces emanating from the Indian Oceanic spreading centers and the collisional forces in the Himalayas. They argued that buckling of the lithosphere can induce reverse faulting at depth and can explain the earthquake distribution along the E–W trending linear seismic belts in the Indian craton. However, buckling and upwarp of the Indian plate should also manifest in shallow level normal faulting and associated seismicity in the linear belts, which are not detected in the geophysical studies.

Geodetic GPS survey over the period 1995-2007 (using 29 continuous GPS stations and 41 survey–grade GPS stations) have suggested that the Indian peninsula is experiencing an average shortening rate of 0.3 ± 0.05 nanostrain.year^{-1}, which is largely accommodated by a crustal shortening of 2 ± 1 mm year^{-1} across the SONATA zone (Banerjee et al., 2008). This work clearly shows that the collisional plate boundary stress is causing active contractional deformation of the SONATA zone.

In our experiments described above, we have shown that a velocity discontinuity created by a basal plate can induce rifting in the central part of the model and upon inversion of the stress system (from extension to compression) and can close the rift by reverse faulting, which partly reactivate the earlier normal faults, and partly cut across them. This structural inversion of a paleo-rift also creates a positive topography (‘pop–up’ structure) at the center which resembles the Satpura mountain block, flanked by neotectonic reverse faults (Fig. 8). This model explains the present tectonic situation observed in the SONATA zone quite well. The velocity discontinuity created by the rigid plate simulates a weak zone in the load–bearing upper mantle. Our argument is that the up-
per mantle below the SONATA zone which has a Precambrian ancestry and shows record of repeated later fault movements (in Paleozoic, Mesozoic, Paleogene, and Quaternary) is mechanically weak as all the bounding faults (e.g., SNNF, SNSF, and GTSZ) are steep, mantle-reaching faults according to the DSS profiles (Fig. 4). Therefore, during the shortening due to the compressive plate boundary forces, the far-field stresses are concentrated at the crust–mantle interface, and inversion of the paleo-rift takes place by reverse faulting, often reactivating the earlier normal faults. This can explain the deep-focus (~ 40 km focal depth) earthquakes with a reverse-oblique fault slip, as suggested for the Satpura (1938) and Jabalpur (1997) earthquakes within the SONATA zone. Stress concentration due to the presence of anomalous, high-density magmatic rocks (rift pillow) at the crust–mantle interface has been suggested for the Jabalpur earthquake (Rajendran and Rajendran, 1998). The high heat flow along the SONATA belt is also likely to cause enhanced deformation of the weak upper mantle, and induce stress perturbation at the crust–mantle boundary (e.g., Zoback et al., 2002), resulting in selective tectonic inversion of the ancient rift zone in the upper crust in comparison to the deformation of the surrounding craton. The intraplate deformation of the central Indian shield is, therefore, most likely controlled by the far-field N–S compressive stress system induced by the ridge push from the Indian Ocean spreading center and buttressing of the Indian plate below the Tibetan (Eurasian) plate in the Himalayan collision zone.

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