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Energy resources and mid-continental (stable continental region) earthquakes over India: association with mantle plume-affected regions

U. Raval[1] and K. Veeraswamy[2,*]

[1]Plot No. 75, St. No. 11, Suryanagar, Uppal, Hyderabad 500 039, India
[2]CSIR-National Geophysical Research Institute, Uppal Road, Hyderabad 500 007, India

In the context of the Indian lithosphere, it is observed that locations of midplate earthquakes and hydrocarbon energy resources have striking correlation with the zones of influence (or corridors) of mantle plumes and their traces. The two mantle plumes (Kerguelen and Reunion) of the Ceno–Mesozoic period have given rise to the large igneous provinces, viz. the Rajmahal Traps on the eastern and Deccan traps on the western sides of the Indian sub-continent; two more mantle plumes (Marion and Crozet) are also believed to have affected India's continental margin. These plumes rise from different mantle depths, strike the base of the lithosphere and transfer the thermo-magmatic flux upwards, which in turn cause tectonic deformation/ movement, and also affect changes in the geophysical/ geological characteristics of the overlying lithosphere due to magmatic underplating, metasomatism and metamorphism, and thermal cooking and also enhancement of productivity of the basins due to heat and nutrient inputs from the mantle plumes coming up from the mantle. In this context, location of the stable continental region/mid-continental earthquakes and hydrocarbon/energy resources of India falling over the zone of influence of mantle plumes is significant and can be gainfully utilized in zeroing on their occurrence.

Keywords: Cratons, hydrocarbon deposits, mid-continental earthquakes, mantle plume and trace, mobile belts.

EARTH science is most directly connected with basic necessities of the human civilization; for example, natural resources and disaster management. In the Indian context, (i) energy crunch due to ever-increasing need, and (ii) disastrous mid-continental (or unexpected stable continental region, SCR) earthquakes, have motivated multi-pronged studies to understand/explore the possible locations of the occurrences of these two factors[1–3]. The present study examines these issues in light of the concept of mantle plumes (or hotspots) and their traces (or plume path) over the lithosphere and analyses if there exists any correlation with the above two factors[4,5].

Mantle plumes and Indian lithosphere: A long geological history exists with regard to effects of mantle plumes over the Indian lithosphere. So far, consequences of

*For correspondence. (e-mail: kv.swamy@gmail.com)

3.3 Ga, 2.5 Ga, 1.1 Ga, 0.75 Ga (ref. 6), 117 Ma (ref. 7), 65.5 Ma (refs 8–10) events have been recognized geologically, geochemically and petrologically (Figure 1). The last two mantle plume events are of the Meso-Cenozoic times, which have given rise to large igneous provinces (LIPs), viz. Rajmahal (~117 Ma) and Deccan (~65.5 Ma) traps. It has been argued that in addition to surface geological manifestations, there are deep-seated effects of plume, which are evidenced as geophysical anomalies and tectonic consequences[11]. The geophysical anomalies recorded over the plume-affected zones corroborate the plume–lithosphere interaction[4,11]. In addition, presence of two more plumes, namely Marion and Crozet[9], helps in the understanding of (i) break-up of Madagascar[12] from greater India, and (ii) 85°E ridge and Afanasy Nikitin seamount in the Bay of Bengal. The possible location of these plumes (and path of recent plumes) at ~100 Ma has been given by Storey[9]. Since only the Dharwar craton has been studied in detail, effects and timings of other mantle plumes that might be associated with the Bastar, Singhbhum and Bundelkhand cratons and their associated mobile belts need to be studied further. In general, the cratons are deep-rooted, cold, highly resistive

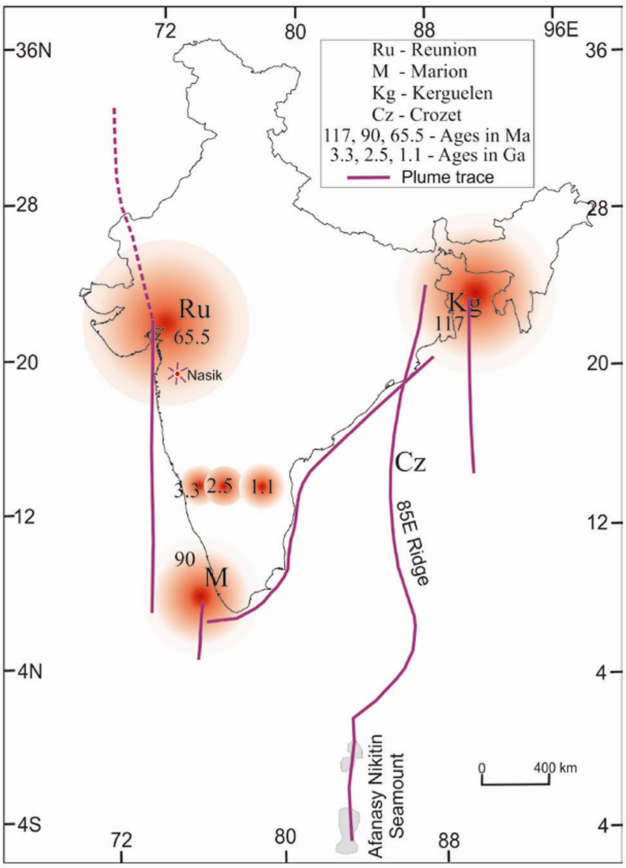

Figure 1. Mantle plumes influenced the overlying Indian continental lithosphere approximately at 3300, 2500, 1100, 117 (ref. 7), 90 (ref. 12) and 65.5 (refs 4 and 10) Ma. The radial distribution of dykes evidenced at Nasik has been considered as a major focus of Deccan Trap outburst.

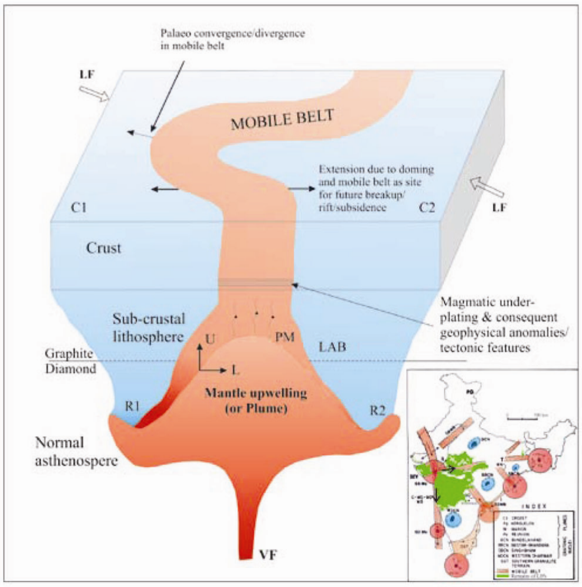

Figure 2. Differences in thermomagmatic responses of cratons (C1, C2) and mobile belts to the asthenospheric upwelling (e.g. Mantle Plume). Inset shows the mobile belt network over the Indian subcontinent[4]. Blue areas, red strips and red circles sequentially indicate cratons, mobile belts and mantle plumes. LAB, Lithoasthenosphere boundary; LF, Lateral force; PM, Partial melts; R1, R2, Cratonic roots; VF, Vertical force.

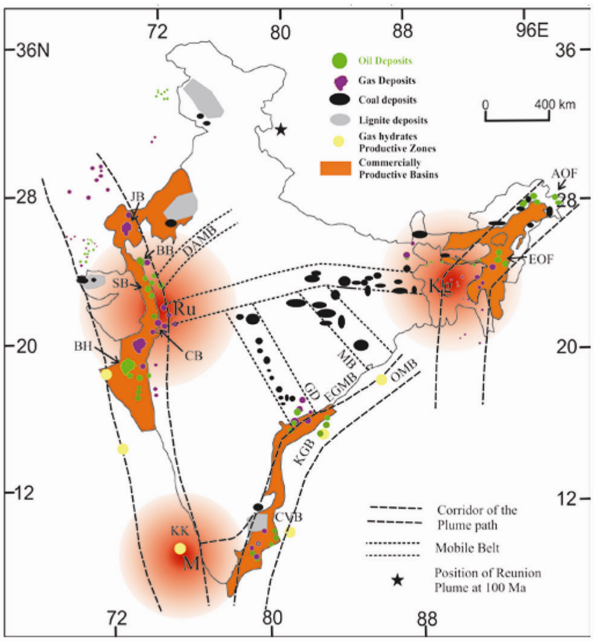

Figure 3. Distribution of oil, gas, coal, lignite and gas hydrate occurrences over the Indian subcontinent and adjoining regions[3,14–16]. Spatial correlation between the plume influenced areas and energy occurrences is evident. Thin dashed lines show the boundaries of mobile belts and thick dashed lines indicate the zone of influence of mantle plumes. Red colour circular areas correspond to the zones influenced by mantle plumes in the past 120 Ma. AOF, Assam Oceanic Front; BB, Barmer Basin; BH, Bombay High; CB, Cambay Basin; CVB, Cauvery Basin; DAMB, Delhi Aravalli mobile belt; EOF, Eastern Oceanic Front; GD, Godavari; JB, Jaisalmer Basin; Kg, Kerguelen; KGB, Krishna Godavari Basin; KK, Kerala Konkan Basin; M, Marion, MB, Mahanadi Basin; OMB, Offshore Mahanadi Basin; Ru, Reunion and SB, Sanchor Basin.

Table 1. Various formations where oil and gas occurrences are found in different basins[3] falling along the Reunion mantle plume trace (also see Figure 4)

Source		Age	m.y.
Jaisalmer	Bandah limestones	Mid- to Upper Eocene	42–55
	Sanu	Paleocene	55–65
	Goru	Cretaceous	65–144
	Pariwar	Cretaceous	65–144
	Jaisalmer	Mid-Jurassic	165–185
Barmer-Sanchor	Tharad formations	Eocene	38–55
	Lathi formation	Lower Jurassic	145–163
Cambay	Tarapur formation	Lower Oligocene to Upper Eocene	30–40
	Kalol formation	Upper and Middle Eocene	40–50
	Kadi formation	Lower Eocene	50–55
	Unawa formation	Upper Paleocene	55–58

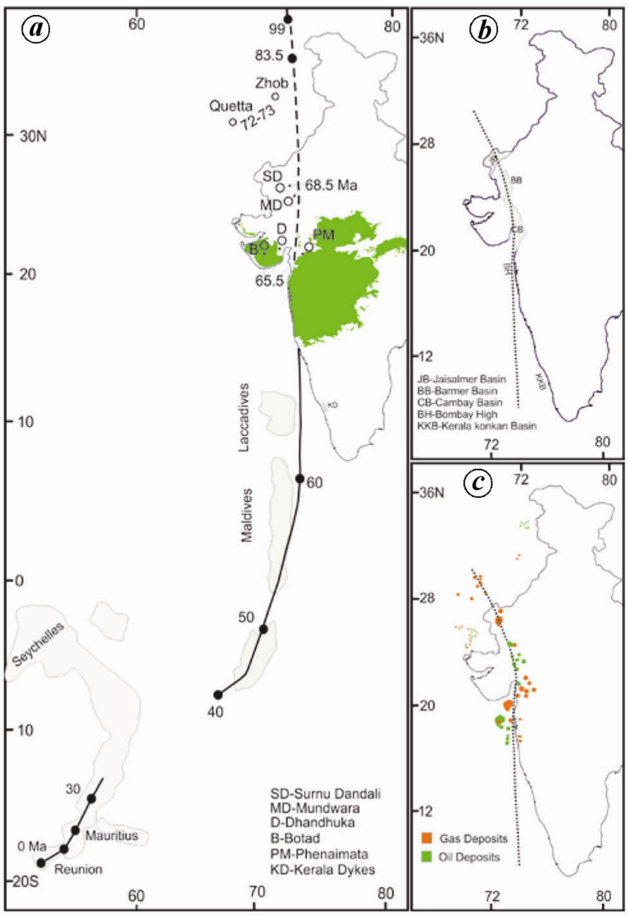

Figure 4. ***a***, Available Ar–Ar ages[34], ***b***, Various sedimentary basins, and ***c***, Oil and gas deposits[3] falling along the Reunion plume trace.

and rigid, while the mobile belts are thin, hot and less resistive. As is well known, the mantle plumes contain exceptionally hot material and rise from different depths in the mantle[13]. During their upward journey from the deep mantle, they strike the base of the lithosphere and transfer thermomagmatic flux (TMF) into the overlying crust–lithosphere regime (Figure 2). It is the last process which appears to significantly modify the geological and geophysical characteristics of the uppermost layers due to thermal input, magmatism, underplating, metamorphism and metasomatism[10]. Such a transfer of matter and thermal energy from the plume to the overlying lithosphere, clearly plays a critical role in tectonic deformation/movement and cooking and enrichment of hydrocarbons in sedimentary basins.

Energy resources and mantle plumes: Figure 3 depicts the zones of influence and corridor affected, since Cretaceous, by mantle plumes over the Indian lithosphere along with the spatial distribution of the occurrences of oil, gas, lignite, coal and gas hydrates[3,14–16]. It is clear that there is an exceptionally strong correlation between the plume-affected zones and location of the hydrocarbon resources. The reason for this could be the cooking of sediments[17] due to significant thermal inputs from the mantle plumes. The amount of heat input will depend on the (pre-, syn- or post outburst) phase of the mantle plume and distance from plume path/outburst region. The mantle plume also provides the nutrients to the sediments[10,18]. It might be possible that these factors get maximized in and around the major oil fields like ‘Bombay High’.

The strong correlation between plume activity and hydrocarbon energy reservoirs as evidenced in Figure 3, can probably be gainfully utilized for more focused exploration. For this purpose reconstruction of exact trace of mantle plume on the overlying lithosphere is needed and effect of the anti-clockwise rotation of the Indian plate also has to be kept in view. In this context, it can be seen that the west coast, Cambay, Sanchor, Barmer and Jaisalmer basins (and also many oil and gas fields within Pakistan) line up quite close to the plume path (Figure 3).

The corridor of the Reunion mantle plume trace (path) has been constrained on the basis of: (i) available Ar–Ar ages (Figure 4 *a*), (ii) sedimentary basins falling along its path (Table 1 and Figure 4 *b*), and (iii) oil and gas deposits (Figure 4 *c*). The corridor of the plume trace is further corroborated by geophysical evidences, viz. (a) an exceptionally high Bouguer gravity anomaly on the northwestern part of the Indian continental lithosphere[4], and (b) nearly

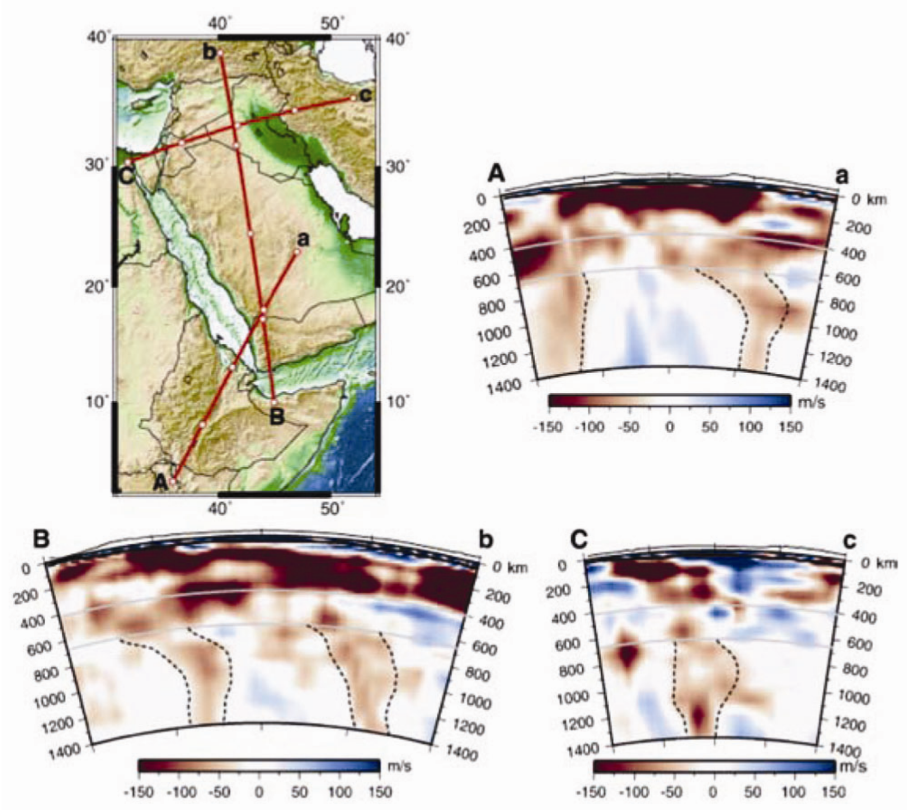

Figure 5. Tomographic vertical cross section maps inferred from S-velocity data for Ethiopia and southern Arabia[23]. Low velocity anomalies that are lying between near vertical dashed lines represent mantle plumes.

Table 2. Some of the major oil producing regions[32] and associated mantle plumes[33]

Major oil producing regions	Associated mantle plume
Middle East	Afar, Tibesti, Jabel Marra
United States	Yellowstone, Baja, Bermuda
Canada	Azores, New England
Venezuela	Fernando
Mexico	Cape Verde
Brazil	Tristan
Nigeria/Angola	Ascension/St. Helena
Norway	Iceland
Algeria	Hogger, Tibesti
Western India (Cambay, Bombay High, etc.)	Reunion
Eastern India (Assam, etc.), Bangladesh	Kerguelen

overlapping and deep-seated (at ~90–110 km depth), low-velocity anomaly[19] caused by the residual thermal anomaly along the plume path. With regard to hydrocarbon resources, recently, attention has been drawn to shale gas (which is the trapped natural gas in the shale environment)[20]. It is interesting to note that the major occurrences of this prospect also fall on the plume trace-affected corridors (see figures 3–6 in Sain *et al.*[20]). The presence of alkaline rocks along the plume trace and their decreasing Ar–Ar ages as one moves from north to south provides definitive constraints on the plume path (Figure 4 *a*).

Similarly, on the eastern side of India, Assam, Bengal basin, Bangladesh deposits could be correlated with the Kerguelen mantle plume. From this point of view, study of influence and consequences due to Marion and Crozet hotspots (mantle plumes) needs to be carried out. Delineation of the path of the Marion and Crozet (figure 4 of Storey[9]) plumes could help in understanding the hydrocarbon resources and the gas hydrate occurrences in the Krishna–Godavari, Mahanadi and Cauvery basins. It seems plausible that development of different hydrocarbon resources (like gas, oil, coal, lignite, etc.) may depend upon the nature/characteristics of the overlying sediments and the amount of thermal input from the mantle plume. In case of the Indian sub-continent, zone of influence of the plumes, their traces and associated mobile belts therefore need more detailed studies.

If channelling of thermo-magmatic flux of the mantle plume to large distances along the mobile belts (inset, Figure 2) is considered[10,21], then depending upon the nature and grade of sediments and available degree of heating, one may try to decipher the promising zones and sequencing of gas, oil, coal, lignite, etc. Existence of triple junction, especially near river deltas, could be quite important as shown in figure 3 of ref. 36. In this context

Table 3. Mid continental seismicity and overlapping plume influenced (uplift/rift) zones of the Indian subcontinent

Location	Year	Magnitude	Latitude	Longitude	Uplift/rift
Reunion plume					
Kutch	1819	7.5	24.25	69.3	Nagar-Parkar
Mount Abu	1848	6.0	24.76	72.54	Aravalli range
Son-Valley	1927	6.5	24	82	Mahadeo Hills
Satpura	1938	6.3	21.53	75.83	Satpura range
Anjar	1956	6.1	23.3	70	Kutch mainland
Koyna	1967	6.3	17.54	73.84	Western Ghats
Bhadrachalam	1969	5.7	17.9	80.6	Godavari
Broach	1970	5.7	21.68	73.2	Cambay
Bhatsa	1983	4.9	19.56	73.38	Western Ghats
Latur	1993	6.4	18.1	76.5	Balaghat range
Jabalpur	1997	5.8	23	80	Vindhyan range
Bhuj	2001	7.7	23.43	70.23	Wagad
Kerguelen plume					
Shillong	1897	8.7	25.6	91	Garo Hills/Meghalaya plateau
Marion plume					
Bellary	1843	5.7	15	77	Deccan/Karnataka plateau border
Coimbatore	1900	6.0+	10.8	76.8	Nilgiri Hills

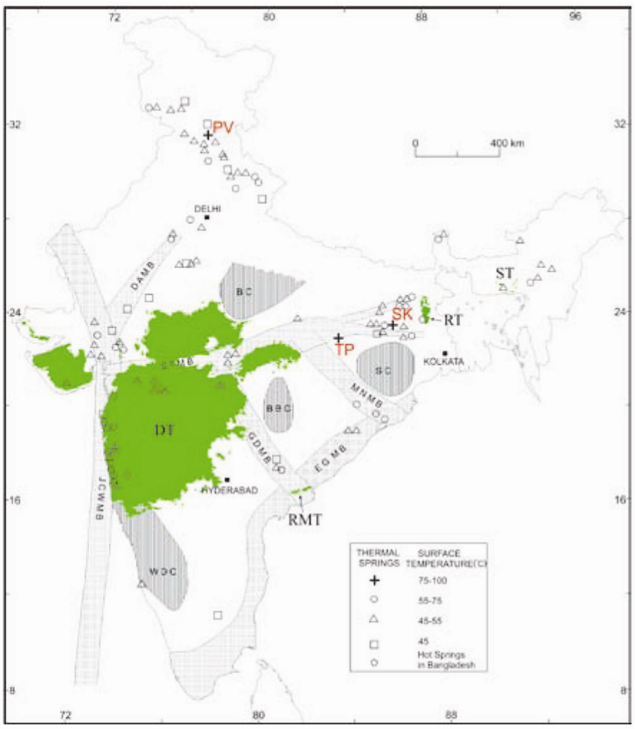

Figure 6. Distribution of hot springs[35,36] over the Indian subcontinent. They are confined either to plume affected areas and/or mobile belt zones. BBC, Bastar Bhandara Craton; BC, Bundelkhand Craton; DAMB, Delhi Aravalli Mobile Belt; EDC, Eastern Dharwar Craton; EGMB, Easternghats Mobile Belt; GDMB, Godavari Mobile Belt; MNMB, Mahanadi Mobile Belt; PV, Puga Valley; RT, Rajmahal Traps; RMT, Rajahmundry Traps; SC, Singbhum Craton; SK, Surajkund; ST, Sylhet Traps; STMB, Satpura Mobile Belt; TP, Tatapani and WDC, Western Dharwar Craton.

it is pertinent to note that Burke has also correlated certain potential energy zones near the western margin of Africa formed due to influence of mantle plumes[22]. In the development of large resources of Arabia, hotspots seem to have played a vital role, because the path of Arabia during the past ~100 Ma could have passed over major hotspots and mantle plumes as shown in figure 5 of ref. 23.

Similar correlation between areas of hydrocarbon occurrence and mantle plumes is also noticed on the global scale (Table 2). Since occurrence of energy resources is being discussed, we examine the occurrence of geothermal springs. Figure 6 depicts the potential thermal energy spots and also thermal springs. From this and Figure 3, it is clear that these fall within the zone of influence of mantle plume, the plume path corridor and the mobile belts affected by plume–lithosphere interaction. The giant and major gas and oil fields of Pakistan also fall on the northwestern part of the Reunion plume trace over the Sulaiman–Kirthar regions of the south-central Indus basin[14].

Mid-continental SCR earthquakes: Figure 7 depicts the major ($M > 6$) earthquakes reported over past two centuries over SCR of India[1,24,25]. Two major observations that need to be emphasized here are: (1) these SCR earthquakes fall in plume-induced basaltic (trap) region, viz. Deccan, Rajmahal and Sylhet, and (2) they appear particularly confined to the mobile belts/rift zones falling within the zone of influence of mantle plumes (Figure 7). It is argued that even the 'stable' region needs to be considered as made up of rigid cratonic part and relatively mobile/palaeo-mobile belts[26] that generally represent palaeo-convergence boundaries. For example, the Central India Tectonic Zone (CITZ) has been considered as a palaeosuture between the Bundelkhand and Dharwar cratons[27].

It may be further noted that most of the major mid-continental (or SCR) earthquakes (Figure 7) have occurred in the palaeo mobile parts of the stable continent[26]. The reason could be that the mobile belts are far more vulnerable to tectonic movements like slip/deformation compared to the rigid cratonic parts. Now, when a mantle plume interacts with the overlying lithosphere, doming, uplift and/or rifting takes place. In case of uplifts, fluids do move along the boundary faults of uplifts, thus facilitating slip. Therefore, many SCR earthquakes could be correlated with uplifts, as shown in Table 3. Thus, one of the main causes in the Indian context seems to be the mantle plume activity. Figure 7 also gives the zones of influence of Kerguelen and Reunion plume outbursts and the corridors along which the Indian lithosphere has passed over these hotspots. Table 3 summarizes these events such as Koyna, Latur (Killari), Anjar, Bhuj, Bhatsa, Broach, Khandwa, Jabalpur and Satpura earthquakes. Quetta and Muzaffarabad may also fall in this category.

On the eastern side also, the Shillong plateau and Kopili lineament fall within the zones of influence and LIP due to Kerguelen plume. It is noted that due to its significant distance from the major tectonic belts of the Himalaya, the Shillong earthquake may not qualify purely under the great Himalayan earthquakes. Since there are additional forces due to the compressional boundary of the Himalaya to the north and convergence with the Burmese plate to the east, obviously the net forcing is likely to be complex. By combining the plume path, zone of influence of mantle plume and mobile belts lying within it, much of the mid-continental (or SCR) seismicity of the India could be deciphered. The observed seismicity all along the Eastern ghats mobile belt[28] also follows the path of Marion mantle plume[9]. Association with mantle plume, corroborated further by the occurrence of alkaline plugs appears to correlate with higher degree of seismicity (e.g. Bhuj, Shillong, Eastern margin, etc.).

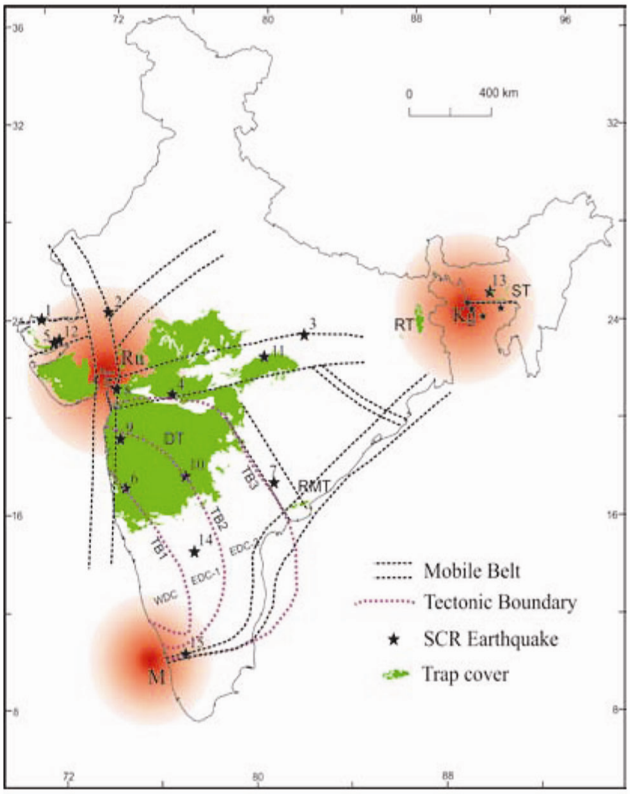

Figure 7. Major stable continental/Mid-continental region earthquakes ($M \geq 6$) over the Indian sub-continent for the past 200 years (based on IMD, 2011) superimposed on plume effected areas. 1, Kutch, 1819; 2, Mount Abu, 1848; 3, Son-Valley, 1927; 4, Satpura, 1938; 5, Anjar, 1956; 6, Koyna, 1967; 7, Bhadrachalam, 1969; 8, Broach, 1970; 9, Bhatsa, 1983; 10, Latur, 1993; 11, Jabalpur, 1997; 12, Bhuj, 2001; 13, Shillong, 1897; 14, Bellary, 1843; 15, Coimbatore, 1900. Green patches over the western and eastern parts correspond to Deccan, Rajmahal and Sylhet traps. TB1, TB2 and TB3 represent the tectonic boundaries between WDC, EDC-1 and EDC-2 (ref. 37). The NE seismicity has been adopted from Kayal[38]. (http://www.imd.gov.in/section/seismo/static/seismicity_map.pdf).

Intraplate Coimbatore earthquake (Figure 7) in the southernmost part of the Indian continental lithosphere also corroborates the suggestion brought out here. For example, (i) it lies in the Marion plume influenced area as evidenced by the 90 Ma Agali-Anaikatti mafic dyke[29]; (ii) the Palghat–Cauvery corridor tectonically resembles a mobile belt due to convergence of Dharwar craton on the north and Southern Granulite Terrain towards south, and (iii) the location of this earthquake is close to the southern boundary of the Nilgiri uplift.

It is pertinent to note that the continental part of the Indian lithosphere collided with the Eurasian plate first at the NW corner at ~57.5 Ma. This impact would cause a major change in the momentum of Indian lithosphere because the Indian plate velocity has reduced at ~55 Ma from $V_1 \cong 16$–19 cm/yr to $V_2 \cong 4.5$–5.5 cm/yr. The stress

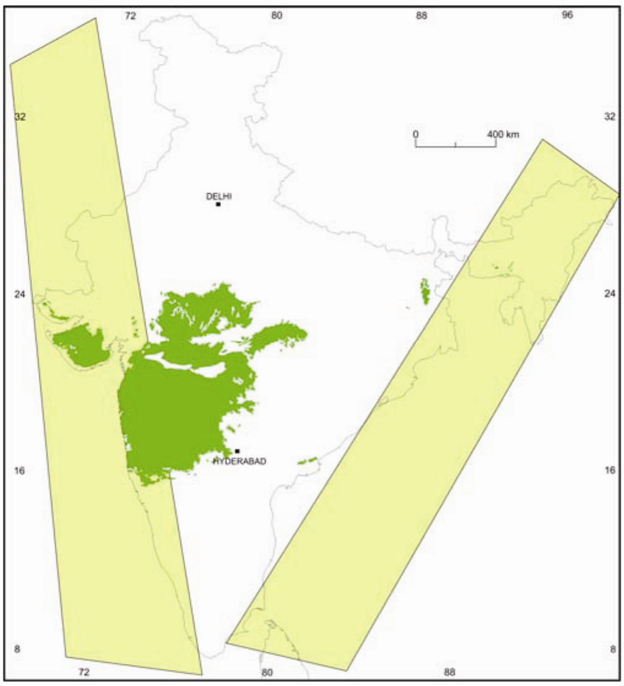

Figure 8. Corridors on either side of the Indian sub-continent represent the plume-affected areas overlapping with hydrocarbon occurrence zones.

generated due to the resulting change in momentum $M_{IL}[V_{1(16–19)} – V_{2(4.5–5.5)}]$ of the Indian plate would significantly affect the western part of India, where M_{IL} is the mass of the Indian lithosphere. The influence of this impact on the western side of the Delhi–Aravalli belt (Pakistan, Western Rajasthan, Kutch and Cambay regions), and NW corner could be quite high and needs to be kept in view while studying earthquakes in this region (Kutch, Mount Abu, Anjar, etc.).

Since the paths of the Reunion and Kerguelen mantle plumes appear to be close to the NW, western, NE and eastern margins (Figure 8), where plate boundary forces (like collision, subduction and strike–slip processes) are active, seismicity there would be most likely of mixed-mode type. For example, the Cambay trend extending along the Jaisalmer/Quetta line represents the plume trace and if rotation of the Indian plate is taken into consideration, the trace would seem to pass through Baluchistan, NW Pakistan, southern Tibet/Himalaya. This corridor appears to have large seismicity due to the combined effects of the plate and plume tectonics.

The present study revealed a significant correlation between zones of influence of mantle plume, and corridor of plume path with (i) hydrocarbon and other energy resources, and (ii) mid-continental seismicity (or stable continental region – SCR) over the Indian region; population of major earthquakes, especially over the trap-covered regions, like Deccan and Rajmahal strongly corroborates the influence of the mantle plume. Recently, Chu *et al.*[30] have also reported that the 2011, *Mw* 5.6 Virginia earthquake of North America seems to fall over a mantle plume trace (during ~50–100 Ma). This track coincides with a seismic anomaly (reduced *P*-wave velocity and high attenuation). Its signature runs from Missouri to Virginia and passes through the New Madrid zone. Since Bhuj and Kutch earthquakes also fall over the trace of the Reunion plume and the western margin – the similarity between the New Madrid zone and Kutch seismicity becomes more striking.

Obviously, both these observations need to be gainfully utilized in the search of (i) potential zones of major earthquake activity in the Indian sub-continent and (ii) promising areas for the hydrocarbon resources. As this study so far has dealt with the 2D mobile belts and corridors, for occurrence of energy resources and earthquakes, it would be appropriate to progress from 2D to 3D zonation by deciphering critical lateral heterogeneities along these 2D corridors, which may help in zeroing of potential zones. For example, this suggestion is exemplified by the 3D anomalies seen along the eastern margin, which broadly represents the 2D path of the Marion plume. Now this path is being cut along the eastern margin by Mahanadi, Krishna–Godavari and Cauvery basins forming some kind of a triple junctions which can be considered as 3D zonation and as surmised above, all these places exhibit significant hydrocarbon occurrences. Similarly, the Cambay basin is also cut across by ridges (figure 11 of ref. 31) forming 3D anomalies. Further, the correlation seen here in case of India, needs to be examined if it holds good globally. It may be noted that this study directly relates with two of the major applications of earth science, viz. energy exploration and disaster management.

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Distribution of major and trace elements of a sediment core from the eastern Arabian Sea and its environmental significance

K. V. Sruthi[1,2], P. J. Kurian[1,]* and P. R. Rajani[1,3]

[1]National Centre for Antarctic and Ocean Research, Headland Sada, Goa 403 804, India
[2]Present address: Korea Institute of Geoscience and Mineral Resources, Daejeon, 305-350, South Korea
[3]Present address: Geological Survey of India, Vasudha Bhavan, Kumaraswamy Layout, Bangalore 560 078, India

A sediment core recovered from the southeastern Arabian Sea off the Indian subcontinent was analysed to understand the distribution of major (Fe, K, Mg, Al, Ca and Sr) and trace elements (Mn, Ni, Cu and Co) as well as their environmental significance. According to the results, variation of Fe, K, Mg and Al during early Holocene period is reflective of the strengthened southwest monsoon and resulting fluvial input of terrigenous materials to the study region. The concentration profile of Ca, Sr and total organic carbon during late Holocene reveals increased productivity and coastal upwelling during recent periods. The profile of redox-sensitive metals indicates the role of terrigenous sources in the variation of these elements apart from the scavenging-releasing effects of Fe–Mn-oxides/hydroxides as well as decrease in oxygen level in sediment–water interface from early Holocene to late Holocene period. The study suggests that two factors are predominantly responsible for observed geochemical variations – terrigenous and biological contribution.

Keywords: Fluvial input, Holocene, major and trace element chemistry, upwelling,

GEOCHEMICAL study of marine sediments provides important insights on the role of environmental processes in controlling sediment distribution, fluctuations in biological productivity, redox state of bottom water, tectonic activity and wind strength[1–7]. The understandings about the distribution of sedimentological, geochemical and magnetic proxies such as clay minerals, elements and magnetic records from sediments are useful tools in the assessment of status of environmental conditions[8–12]. Once elements are discharged into the water, they rapidly become associated with particulates and are incorporated in bottom sediments[13,14]. The elements associated with sediments are, however, not sheltered permanently. Under changing environmental conditions, they may be released to the water column by various processes of remobilization. Also in the marine aquatic systems, sediments may be both a carrier and a possible source of

*For correspondence. (e-mail: john@ncaor.gov.in)