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Research paper

Deep scientific drilling results from Koyna and Killari earthquake regions reveal why Indian shield lithosphere is unusual, thin and warm

O.P. Pandey

CSIR-National Geophysical Research Institute, Uppal Road, Hyderabad 500007, India

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ABSTRACT

The nature of crustal and lithospheric mantle evolution of the Archean shields as well as their subsequent deformation due to recent plate motions and sustained intraplate geodynamic activity, has been a subject of considerable interest. In view of this, about three decades ago, a new idea was put forward suggesting that out of all shield terrains, the Indian shield has an extremely thin lithosphere (~100 km, compared to 250–350 km, elsewhere), apart from being warm, non-rigid, sheared and deformed. As expected, it met with scepticism by heat flow and the emerging seismic tomographic study groups, who on the contrary suggested that the Indian shield has a cool crust, besides a coherent and thick lithosphere (as much as 300–400 km) like any other shield. However, recently obtained integrated geological and geophysical findings from deep scientific drillings in 1993 Killari (M_w: 6.3) and 1967 Koyna (M_w: 6.3) earthquake zones, as well as newly acquired geophysical data over other parts of Indian shield terrain, have provided a totally new insight to this debate. Beneath Killari, the basement was found consisting of high density, high velocity mid crustal amphibolite to granulite facies rocks due to exhumation of the deeper crustal layers and sustained granitic upper crustal erosion. Similar type of basement appears to be present in Koyna region too, which is characterized by considerably high upper crustal temperatures. Since, such type of crust is depleted in radiogenic elements, it resulted into lowering of heat flow at the surface, increase in heat flow contribution from the mantle, and upwarping of the lithosphere-asthenosphere boundary. Consequently, the Indian shield lithosphere has become unusually thin and warm. This study highlights the need of an integrated geological, geochemical and geophysical approach in order to accurately determine deep crust-mantle thermal regime in continental areas.

1. Introduction

The earth is known to be an extremely active physical system in comparison to other planets. The nature of its crustal and mantle lithosphere evolution, as well as its subsequent deformation, specially for unique Archean shield like India which differs from other stable areas of the earth (Naqvi et al., 1974; Radhakrishna and Naqvi, 1986; Naqvi and Rogers, 1987; Rogers and Callahan, 1987), has been a subject of considerable interest. Long back, a hint was given that Indian shield could be hotter (Rao and Jessop, 1975; Singh and Negi, 1982). In that light, based on heat flow and geodynamical considerations, two papers simultaneously appeared in mid eighties (Negi et al., 1986, 1987), which were further followed by Pandey and Agrawal (1999). These studies, for the first time, demonstrated in detail unusual character of the Indian shield, compared to other similar shield terrains round the globe. It was advocated that the Indian shield lithosphere is extremely thin (~100 km), hot, highly deformed and non-rigid, compared to 250–350 km in other shields (Chapman and Pollack, 1974, 1977; Pollack and Chapman, 1977; Polet and Anderson, 1995; Artemieva and Mooney, 2001; Priestley and Mckenzie, 2006). This unusual behaviour for Indian shield was consistent with the geodynamic episodes that took place in Indian subcontinent since its breakup from Antarctica 130 Ma ago, which degenerated the Indian lithosphere from its bottom (Pandey and Agrawal, 1999 and references therein) that included super mobility (20 cm/yr) between 80 and 53 Ma, as well as its migration for about 9000 km.

E-mail address: om_pandey@rediffmail.com.
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These new findings were of far reaching consequence to Archean crustal evolution and thus, as expected, met with strong scepticism mainly by seismic tomographic and heat flow researchers, who believed in stability of ancient shield terrains. Thus, a debate started, whether the ancient shield terrains have had stable roots since Archean era or whether the recent plate motions have sheared and deformed them (Vinnik et al., 1992, 1995; Nyblade et al., 1996; Ramesh et al., 1996)? Based on teleseismic P-wave residuals tomographic studies, Iyer et al. (1989) stated that a high velocity anomaly exists in the depth range of 100 to 400 km beneath the Deccan Volcanic Province (DVP) (Fig. 1), thereby implying presence of a coherent, colder and comparatively rigid lithosphere root extending to a depth of about 400 km beneath this region. This study was first of its kind in India, therefore looked upon as a bench mark study. It was followed by a large number of similar studies. For example, Srinagesh et al. (1989) and Ramesh et al. (1990, 1993) proposed presence of a thick high velocity upper mantle between the depths range of 60–80 and 300–400 km, for the south Indian shield also. They argued that the presence of a thick rigid lithosphere would mean that the south Indian upper mantle has remained undeformed since its stabilization, supporting the long held traditional view of stability of Archean terrains. Several studies that further followed, like Rai et al. (1992), Gupta et al. (2003a) and Ravi Kumar and Mohan (2005), also supported such views. However, recent seismic tomographic and receiver function studies do not concur with them, as discussed later.

Heat flow investigators also came out with similar findings. Gupta et al. (1991) and Gupta (1994), based on analysis of available heat flow data, indicated presence of a more than 200 km thick lithosphere beneath Archean Dharwar craton and Deccan volcanic provinces. They also analysed heat flow data from various Precambrian terrains of the world (Gupta, 1993) and expressed that the Indian shield is neither hotter than other Gondwana shield, nor its super mobility affected its thermal characteristics. Similarly, Roy and Rao (2003) also analysed heat flow data over the Dharwar craton and found existence of cold crust (Moho temperatures: 285–410 °C) beneath Dharwar craton. Another study which further followed was by Senthil Kumar et al. (2007), who based on heat flow and heat generation study, found an extremely low Moho heat flow of about 7 mW/m^2 and Moho temperature ~280 °C below southern part of DVP.

In the present work, we use new findings provided by recently carried out deep scientific drilling in Koyna and earlier in Killari seismic zones of the DVP (Gupta et al., 2003b, 2015), together with newly acquired geophysical/geological data over this terrain, for accurately constraining the heat production model. This has enabled us to reliably determine the temperature-depth distribution inside the earth, which is crucial for lithospheric thickness estimation.

2. Changing perceptions and present investigations

Interestingly, such perceptions changed with time due to acquisition of new heat flow and broadband seismic data. For example, in an important study, Ray et al. (2003) carried out detailed heat flow and crustal heat production measurements in the southern Granulite Terrain of south India, referred as SGT in Fig. 1. This study indicated presence of high mantle heat flow (23–32 mW/m^2) and high Moho temperatures (550–660 °C) in the northern block of SGT. Interestingly, the measured heat flow here is quite low at only 36 ± 4 mW/m^2. Similarly, based on recently carried out deep scientific drilling (KBH-1 borehole) in Koyna seismic zone, Gupta et al. (2015) reported presence of quite high temperatures, 130–150 °C at 6 km and 165–225 °C at 10 km depth only, as shown in Fig. 2. This was in total contrast to earlier studies in DVP, where an extremely low Moho temperatures of 280 to 350 °C was reported (Roy and Rao, 1999; Senthil Kumar et al., 2007).

In a same manner, due to large scale acquisition of new seismic data and receiver function studies, many of the tomographic researchers, including those who proposed 300–400 km thick lithosphere as mentioned above, have lowered such estimate

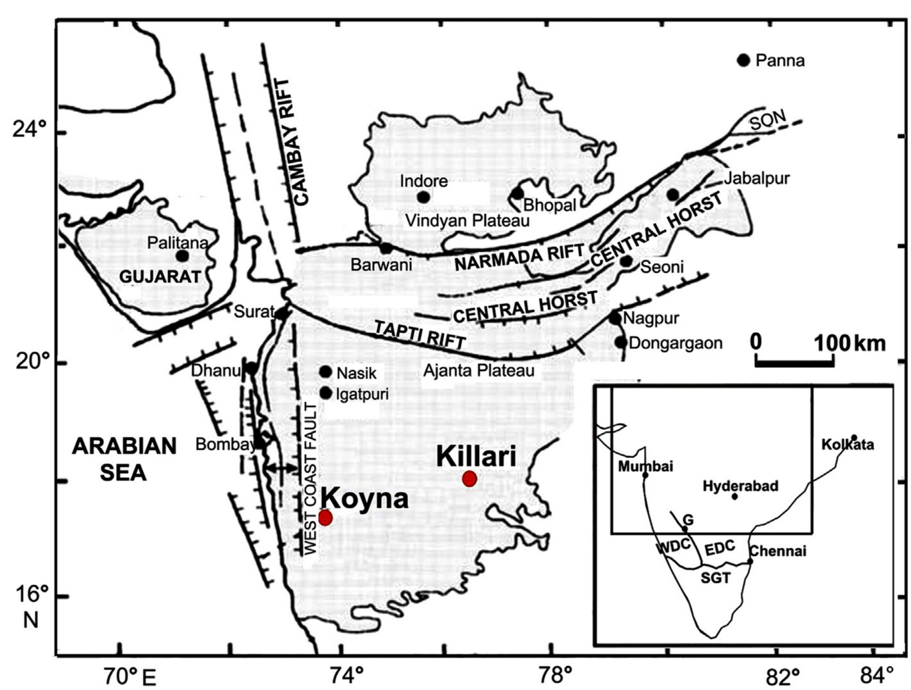

Figure 1. Tectonic map of the part of Peninsular India, showing locations of Killari, Koyna and major rift valleys. Area covered by Deccan volcanics is mildly shaded. SGT in inset refers to Southern Granulite Terrain and "G" to location of the Gadag region in WDC. WDC and EDC are western and eastern parts of the Dharwar craton respectively.