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Magnetotelluric investigations over geothermal provinces of India: an overview

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Abstract: Magnetotelluric (MT) and audio-magnetotelluric (AMT) studies are sensitive to the geothermal fluids filling the faults and/or fracture zones of the geothermal system. In India, MT/AMT studies have been carried out in NW Himalayas, central, eastern, and western India. In other areas, detailed MT/AMT studies need to be expedited. This review paper presents the art of geothermal exploration in India by using MT/AMT techniques and identifies potential zones that can be exploited for power generation and direct application. Reservoir characteristics, carbon emissions reduction methods, and levelised cost factor are also discussed.

Key words: Geothermal zones, magnetotellurics, conductivity anomaly

1. Introduction

Geothermal system is a natural heat transfer within the Earth's crust where heat is transported from a heat source to the surface. Based on the type of the heat source, a geothermal system has been classified into volcanic or nonvolcanic geothermal system (Hochstein and Sudarman, 2008; Moeck, 2014; Allen et al., 2006). Heat source for (a) volcanic geothermal system is a shallow intrusion associated with an active or recent volcano. Hot steam emitting from a vent around volcano has a surface temperature of ≥100 °C and (b) in nonvolcanic geothermal regions, heat source is associated with the geothermal gradient in sedimentary rocks, deep water circulation, or old granitic intrusion. These regions are associated with low to moderate surface heat flow.

The electrical and electromagnetic geophysical methods are conventionally used in geothermal exploration since the low resistivity zones are related to the fluid circulation. Resistivity parameters that characterize geothermal zones are permeability, porosity, salinity, temperature, and hydrothermal alteration. Presence of fluids (especially hot water) and fractured zones are characterized by low resistivity. The resultant low-resistivity anomalies are the main target for the exploration of geothermal zones by using audio magnetotelluric (AMT)/magnetotelluric (MT) methods (Simpson and Bahr, 2005: Zhang et al., 2015).

Over 340 thermal springs have been identified in India (Shanker, 1991; Chandrasekharam, 2000) and occurrence of these springs have been classified into four different groups (Das et al., 2022) (a) Orogenic belts, (b) areas of deep seated faults and lineaments, (c) rifts and grabens of Gondwana basin, and (d) deep sedimentary basin. The orogenic belt is related to the subduction process in Himalayan region (Becker et al., 2008; Rai et al., 2015). Most of the geothermal zones are situated between the Indus Suture Zone (ISZ), Main Central Thrust (MCT) and the Central Himalayan Axis (Krishnaswamy and Shanker, 1982; Sharma, 2010; Craig et al., 2013). The most important source of high heat flow in this belt has been attributed to the assemblage of high internal radiogenic heat and thermal relaxation subsequent thickening of the Indian crust due to subduction process (Chandrasekharam and Bundschuh, 2008; Searle et al., 2009). To the south of ISZ, Puga-Chumathang area and Nubra valley are characterized by boiling springs, geysers and hydrothermal deposits (Chandrasekharam, 2000; Tiwari et al., 2016). In central Himalaya, most of the thermal springs occur along the river valley and are located in Beas, Parbati, Satluj, and Spiti valley with a temperature range of 34–97 °C. One of the hottest springs is Manikaran with surface temperature of 97 °C and has been studied extensively for electric power generation (Chandrasekharam et al., 2005) (Figure 1). A small number of lukewarm thermal springs (Kalakote, Tattapani, Kurah and Mahogala area) are found in the foothills of the Himalayas and have a temperature range of 42–53 °C (Thussu, 2002). In NE India, thermal springs

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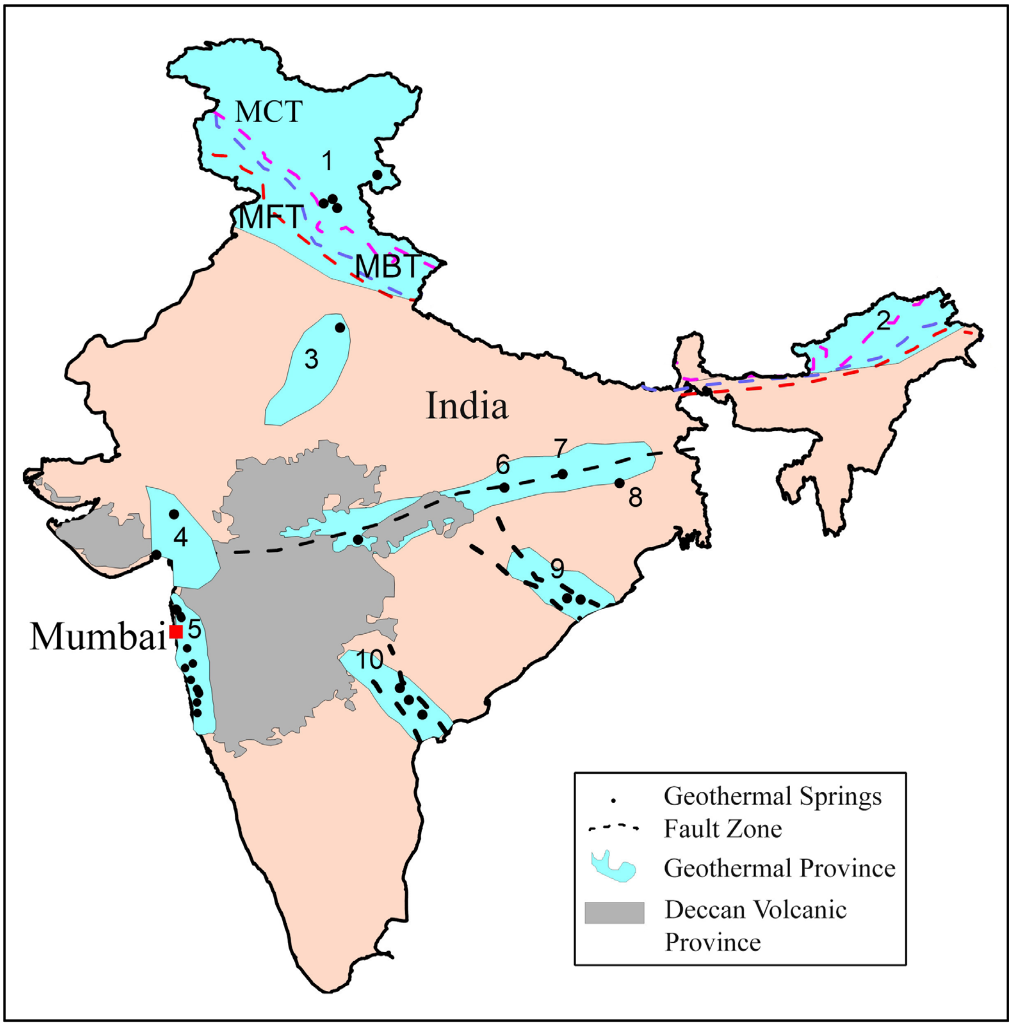

Figure 1. The figure shows the different geothermal zones over the India subcontinent (modified after Chandrasekharam et al., 2005). The numbers represent different geothermal provinces present across the different geological terrains of the Indian subcontinent: 1. NW Himalayas; 2. NE Himalayas; 3. Sohane geothermal zone; 4. Cambay basin; 5. Konkan basin; 6. Tattapani geothermal zone; 7. Surajkhand geothermal zone; 8. Bakreswar Geothermal zone; 9. Mahanadi graben and 10. Godavari graben.

are found in Sikkim, Meghalaya, and Arunachal Pradesh that form an integral part of orogenic belt (related to Indo-Burma subduction process). The surface temperature of Sikkim springs (Yumthang, Yumesamdong, Borong, Polot, and Rishi) range from 38 to 59 °C with moderate discharge of water (Bhatia, 2014).

Thermal springs linked with deep-seated fault/lineaments are located at Son-Narmada-Tapti lineament zone, West Coast of India, Sohna area, and Aravalli horst. Son-Narmada-Tapti lineament consists of 46 geothermal zones, out of which Tattapani thermal spring is well known with a surface temperature of about 98 °C (Navada et al., 1995). At Tattapani, geothermal activity is very intense with several hot spots and water pools and is located at the junction where the Satupura and the Mahanadi mobile belts meet the ENE-WSW trending SONATA lineament zone (Das et al., 2022).

Several hot springs are located along the west coast of India and grouped under West coast geothermal province (Chandrasekharam, 2000) comes under deep-seated fault/lineament category. These hot springs are stretch from Kokaner of Maharashtra state in the north, to Irde of Karnataka state in the south (Bhatia, 2014). Most of these hot springs (low to intermediate enthalpy) emerge all along the West coast fault (WCF), a major tectonic feature that runs parallel to the coast for a length of about

500–600 km (Chandrasekharam, 1985). Geochemical studies denote that these hot water springs are of meteoritic origin that emerges from basement rock (Chatterjee et al., 2016).

Bakreswar in west Bengal and Tantloi in Jarkhand are the geothermal springs in eastern part of India. It is believed that heat is generated due to the presence of radioactive elements in the crust (Chaudhuri et al., 2010). High surface heat flow at these geothermal springs has been explained by a mantle upliftment or mafic intrusion (Singh et al., 2015).

The thermal waters coming out from Sohna geothermal field (near Delhi) is ascribed to the deep flow of groundwater in a tectonic depression created by the down-faulting of a central block lying between two anticlinal ridges belonging to the Delhi mobile belt (Pandey and Negi, 1995) that is associated with the Himalayan orogenic movement (Gupta, 2009).

Thermal springs along the eastern margin of the Aravalli horst mainly consist of Archean to recent lithological units and are characterized by NE-SW trending faults related with the cyclic and dynamic movement of the blocks (Sinha Roy et al., 1998; Minissale et al., 2003). The fault systems provide conduits for deep circulating geothermal waters. The surface temperature of the geothermal waters ranges between 31 and 50 °C (Minissale et al., 2003; Bisht et al., 2011).

Thermal springs associated with Godavari and Mahanadi valleys come under the category of rifts and grabens of Gondwana basins. Rifting along NW-SE intracontinental mobile belts led to the formation of Godavari and Mahanadi basins (Biswas, 1999). As there is no evidence of igneous activity in these grabens, heat flow from these regions are attributed to radiogenic heat generation and moderate thermal conductivity of the silicic rocks (Roy and Rao, 2000).

The Cambay rift basin in western part of India consists of geothermal springs that emerge along faults in the deep sedimentary basin that overlies Deccan lava flows. High heat flow is observed in the northern part and moderate heat flow in the southern part. High heat flow is due to claystone and shale in the sedimentary formations (Roy and Rao, 2000 and Ganguli et al., 2018). In addition, shallow igneous intrusions due to plume-lithosphere interactions also play a key role in high heat flow of the Cambay basin (Gupta, 1981; Danda et al., 2020).

In recent years, many papers have been published about the use of electromagnetic methods for exploration of geothermal zones (Pellerin et al., 1996; Meju 2002; Spichak and Manzella, 2009). In this review paper, we shall present the results of MT application to geothermal zones in Indian region to bring out its application potential in different complex lithological and structural environments.

2. Examples of MT Application for geothermal zones in India

MT is a passive geophysical method that uses normal time variations of the Earth's magnetic (Hx, Hy, and Hz) and electric fields (Ex and Ey) to investigate the electrical resistivity of the subsurface. These transient variations have their origin in electric currents in and beyond ionosphere resulting from complex interactions of radiations and plasma flux from the sun with the Earth's magnetosphere ionosphere. The spectra of these variations cover periods ranging from 10^{-4} to 10^{5} s. In broad band MT, data were recorded from 10^{-3} to 10^{3} s, whereas in AMT, data were recorded between 10^{-4} and 10 s. Depending on the depth of the target of the magnetotelluric survey and the local bulk electrical resistivity of the Earth, the magnetotelluric sounding period varies from 10^{-4} to 10^{3} s. In geothermal exploration, MT method is used for detecting earth layers with different resistivity or conductivity of various rock materials and fluids below the Earth's surface. The MT time series data were processed by using robust reference cascade decimation technique (Jones and Jodicke, 1984; Jones et al., 1989). Analysis of MT data is carried out in frequency domain and computations of cross-spectra/power spectra are carried out between (B_x and E_y) and (B_y and E_x) for different frequencies to determine impedance tensors (Z_{xx}, Z_{xy}, Z_{yx}, and Z_{yy}). Apparent resistivity (ρ_{xx}, ρ_{xy}, ρ_{yx}, and ρ_{yy}) and phases ($Ø_{xx}$, $Ø_{xy}$, $Ø_{yx}$, and $Ø_{yy}$) are estimated for different frequencies from these impedance tensors. Observed MT responses are distorted due to cultural and geological noise. These affects are minimized through tensor decomposition analyses and regional strike determination (Groom and Bailey 1989, 1991; McNeice and Jones 2001; Caldwell et al. 2004; Moorkamp 2007). Once the strike direction is determined, the data is rotated accordingly and assigned XY component to TE mode (E-polarization) and YX component to TM mode (B-polarization). Afterwards static shift effect should be corrected either using transient electromagnetic data (e.g., Sternberg, Pellerin and Hohmann, 1990; Sternberg et al. 1988) or it is solved as a parameter during 2D inversion (Ogawa and Uchida 1996). The decomposed and static shift corrected responses of TE and TM mode data were inverted by using several open-source pieces of software (e.g., Rodi and Mackie, 2001; Candansayar, 2008; Özyıldırım et al. 2017). Thus, the subsurface resistivity models obtained for different geothermal zones are discussed below. In the last 10 years, MT data are collected on the gridded area and they are mostly interpreted by using 3D inversion software. There is also freely available 3D inversion software for MT data inversion (e.g. Siripunvaraporn et al. 2005; Kelbert et al. 2014). However, in the current review, we will only discuss MT results.

2.1. Puga geothermal zone

Puga lies in the south-eastern part of Ladakh and forms a part of the Himalayan geothermal belt. This zone shows evidence of geothermal activity in the form of hot springs, mud pools, sulphur, and borax deposits (Azeez and Harinarayana, 2007; Gupta, 2009). The Puga Valley (extending in east-west direction (approximately 15 km) and width of about 1 km) is a part of the central tectonic belt characterized by the volcanic sedimentary formations surrounded by well-known faults (Kiagor Tso Fault (KTF), Harinarayana et al., 2006). These faults act as a conduit for transportation of the hot water from deeper levels (Jha and Puppala, 2017).

As a part of alternative energy resources, Puga geothermal zone was identified as one of the promising geothermal fields in NW Himalayas by hotspot committee appointed by the Government of India in 1966. Magnetotelluric (MT) studies have been carried out in 2001 across Puga geothermal zone to accesses the geothermal potential of the area (Harinarayana et al., 2006; Abdul Azeez and Harinarayana, 2007). 2D modelling of the MT data brings out a shallow conductivity zone (10–30 Ωm) at a depth of about 400 m (Figure 2a) coinciding with the area of geothermal manifestation and a deep seated conductivity anomaly (5 Ωm) at a depth of about 2–10 km. This shallow conductivity zone coincides with the high temperature related to reservoir 278–283 °C as estimated by Na-K/Na-K-Ca geothermometer and borehole data drilled up to 400 m at the western end of Puga geothermal zone denotes a temperature of about 127 °C. Thus, projected temperature for reservoir at a depth of about 2 km is 260 °C (Shanker et al., 1991). This low resistivity zone may indicate the presence of fluids, partial melts or a combination (Unsworth et al., 2005) as suggested by MT/LMT profiles carried out by Gokarn et al. (2002) and Arora et al. (2007) across NW Himalayas. A prominent intracrustal low velocity zone has been identified within the depth range of approximately 15–40 km across Indo-suture zone from teleseismic studies and has been attributed to the presence of fluids/partial melts (Hazirika et al., 2014). Thus, correlation between LVZ and low resistivity have been attributed to partial melts generated due to decompression melting of the rocks (Tso-Morari gneiss, De Sigoyer et al., 1997; Guillot et al., 1997) and release of volatile fluids (Sen et al., 2013) due to ongoing subduction processes. Thus, fluid phase associated with the rock melts could be the source of geothermal activity in Puga valley (Harinarayana et al., 2006; Abdul Azeez and Harinarayana, 2007). The shallow conductivity anomaly (Figure 2a) could be related to the accumulation fluids (Figure 2b) that may have upward migration through basement faults/fracture zones and its extent is shown in Figure 2c.

2.2. Tatapani geothermal zone

Tatapani geothermal zone is located along the Son-Narmada lineament in central India. Thermal manifestations in Tatapani consists of hot springs (52–97 °C) in marshy ground, and hydro thermally altered clay zones covering an area of about 0.1 km^2 (Ravishanker, 1988). The eastern part of the area consists of gneisses, granites, schists, phillites of the Chotanagpur complex, western and northwestern part consists of shales sand stones and coal bearing Gondwana sediments towards south. MT data sets were acquired in 1998 (Harinarayana et al., 2000) and 2015 (Figure 3a, Patro et al., 2015). 3D inversion carried out for these data sets brings out upper crustal conductor that rises to 1 km and is related to the observed anomalous thermal conditions of the area (Figure 3b; Patro, 2017). These results are supported by borehole thermal logs that denotes high abnormal temperature from Tattapani geothermal zone (GSI, 1987).

2.3. Surajkhand geothermal zone

Bakreswar and Surajkhand along with other geothermal springs occur in Chotanagpur Gneissic Complex (CGC) that is composed of calc-silicate, amphibolite, gabbro, pegmatite, and dolerite (Singh et al., 2015). This Gneissic complex has undergone different tectonic movements from Precambrain (Sarkar, 1982) to Cenozoic period (Shanker, 1991). Deep circulations of meteoric waters along the fracture zones and ongoing tectonic movements have resulted in various geothermal springs in CGC (Deb and Mukherjee, 1969).

Most of the hot springs in Surajkhand occurs along E-W fault and its reservoir temperature varies from 160 to 190 °C (Singh et al., 2015). Rao et al. (2014) carried out MT studies across Surajkhand geothermal zone (Figure 4a). Their results bring out two different conductivity anomaly associated with geothermal zone (a) mid-crustal conductivity anomaly related to partial melts and the associated fluids (Figure 4b) and (b) a shallow vertical feature (fault/fracture zone) that connects the deep seated conductivity anomaly and provides a pathway for upward propagation of fluids.

2.4. Bakreswar geothermal zone (BGP)

AMT studies carried out by Sinharay et al. (2010) across Bakreswar geothermal province (BGP) suggests that the source region is located towards west of BGP and brings out a low resistivity zone at a depth of about 3 km of large horizontal extent (>2 km) (as shown in Figure 5b) and attribute the same to the meteoric fluids. These fluids are gushed up to surface through faults/fracture zones.

Later, Tripathi et al. (2019) carried out a detailed AMT survey in western part of BGP to determine the source region. 3D modelling brings out various conductivity anomalies extending from shallow to deeper depths (Figure 5c) that are surrounded by resistivity blocks. These

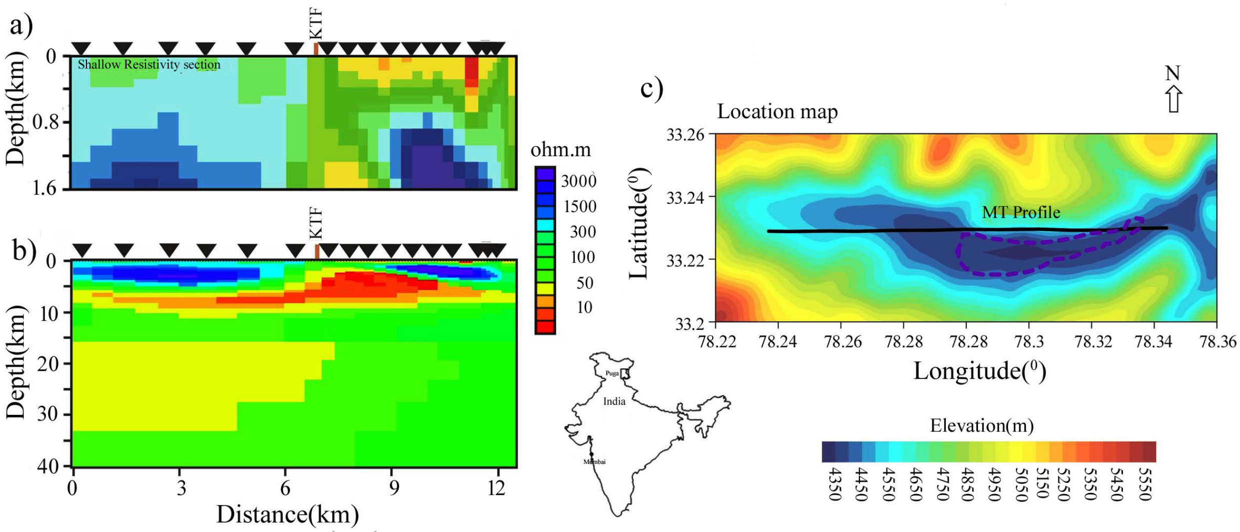

Figure 2. (a) 2D geoelectric structure across Puga geothermal zone (shallow) and (b) deeper section (modified after Harinarayana et al., 2006; Abdul Azeez and Harinarayana, 2007). (c) MT profile across Puga geothermal (shown as dashed line) zone superimposed on topography map.

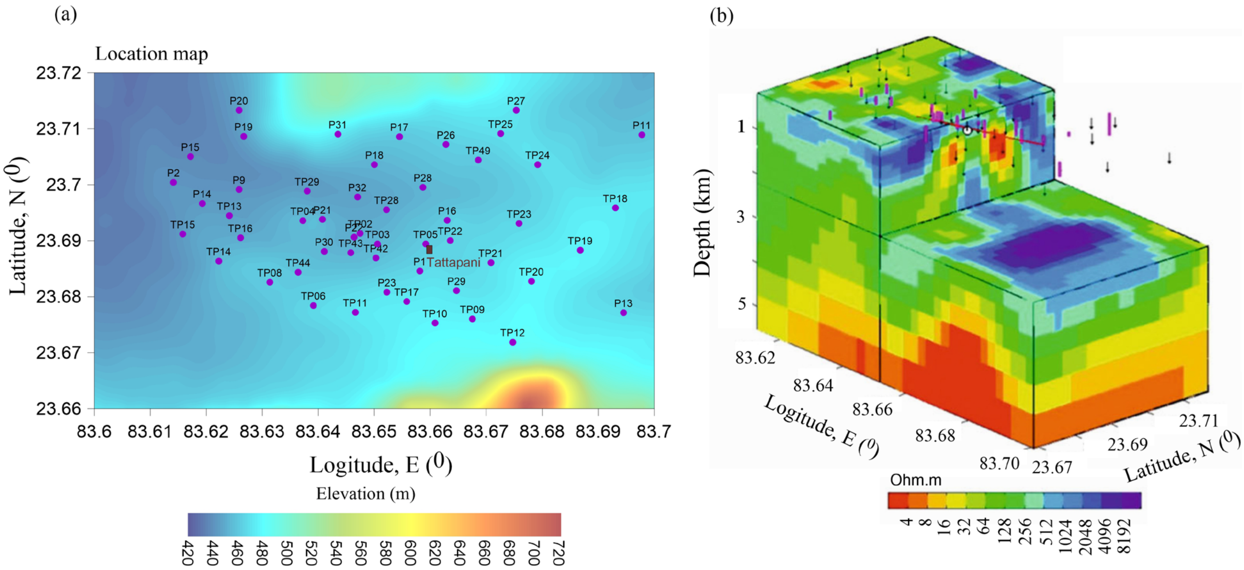

Figure 3. (a) MT stations covered across the Tatapani geothermal zone. (b) 3D modelling brings out different conductivity anomalies located at a depth of about 1–2 km (modified after Patro, 2017).

resistive blocks act as an impermeable bed and regulate the geothermal fluids flowing through the fault zone.

2.5. Cambay basin

Major hot springs in Cambay basin are Unai (55 °C), Dholera (45 °C), Tulsi Shyam (60°C), Tuwa (63 °C), and Barbara (43.5 °C) (Sarlokar, 2018). AMT/MT studies have been carried out in Dholera, Chabsar, and Unai. These results are discussed below

(a) Chabsar hot spring: Chabsar geothermal spring is located 50 km SW of Ahmedabad. Resistivity structure obtained from 24 MT sites (Mohan et al., 2017) shows the presence of a conductive zone at a depth of about 1 km within the traps and connected to west Cambay fault which extends to 2–2.5 km (Figure 6b) and acts as a conduit for heat transfer from deeper level to shallow level. Conductivity anomaly is interpreted in terms of fluids which may have heat source at deeper levels. Detailed heat flow, geochemical and 3D MT survey will be useful in bringing out the characteristics of the source region.

(b) Dholera hot spring: Dholera geothermal springs are located along the western marginal fault of Cambay

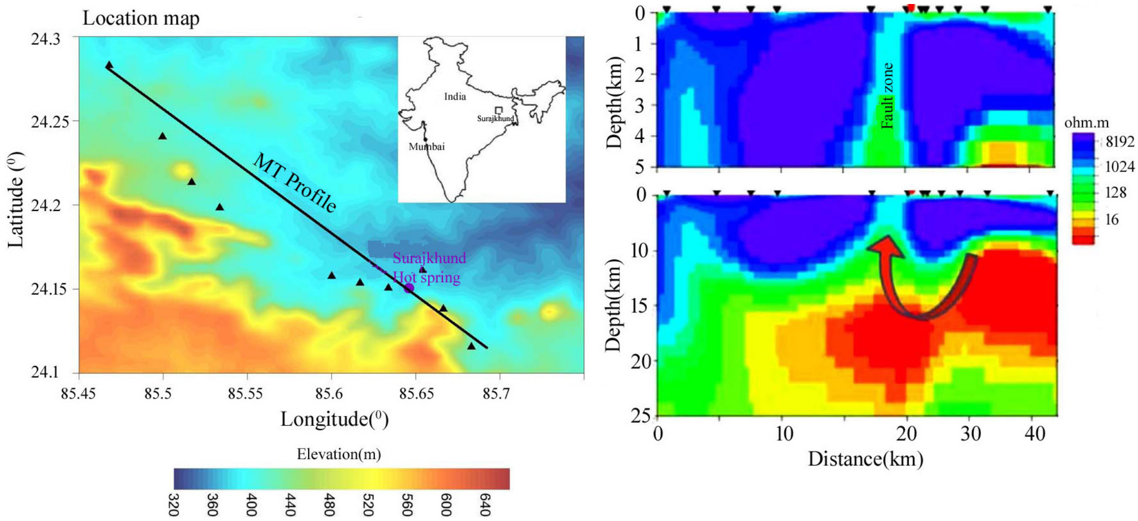

Figure 4. (a) MT profile across Surajkhand geothermal zone and its surrounding regions. (b) Fault zone through which hot fluids are emitted and source region is located a depth of about 5–12 km (modified after Rao et al., 2014).

basin and Saurashtra Peninsula (Sharma, 2013). Primary results by Aghil et al. (2014) denote the presence of shallow conductivity at a depth of about 200–300 m and attributed the same to the presence of fluids. Later, Mohan et al. (2019) carried out a detailed MT survey towards south of Dholera hot springs and brought out a fractured zone (Figure 6d) that may act as exchange of heat source from a deeper source to hot springs. MT results correlate with borehole results suggesting that the thickness of sedimentary basin is about 0.35–0.8 km and Deccan trap is about 1–1.5 km (Mohan et al., 2019).

(c) Unai hot spring: Unai hot spring is located in southern part of Cambay basin and AMT/MT survey was carried out by PBG Geophysical Exploration Ltd., Poland (on behalf of School of Petroleum Technology, Pandit Deendayal Petroleum University, Gandhinagar, Gujarat, India, Sahajpal et al., 2015). This study brings out two different conductivity anomalies: (1) shallow conductivity anomaly up to a depth of about 1500 m related to geothermal fluids embodied in a resistivity block; (2) deep seated conductivity anomaly in terms of magmatic fluids. Both shallow and deep seated conductivity bodies are connected through faults and fluids ascending upward through faults give rise to the hot spring (Sahajpal et al., 2015; Sircar et al., 2015). Geochemical sampling of thermal spring water denotes low level of carbonate and bi-carbonate component in water samples. It also suggests that source of water is deep seated under the trapean flows (Sahajpal et al., 2015)

2.6. Konkan region

Most of the hot springs in the Konkan region are located between the West coast fault (WCF) and the Western Ghats. These thermal springs extend from Koknere in the north to Rajapur in the south and comes under the heat flow zone of III (70-100 mW/m^2) as recorded in borehole data (Shanker, 1988; Chandrasekharam, 2000). High heat flow has been attributed to advective heat transport by upwelling thermal water and possible heat source is the radiogenic heat generated by young granite as well as mafic magma intrusion into the crust as dykes, sills, and magma pockets (Goyal et al., 1998; Karmalkar et al., 2008; Duraiswami and Shaikh, 2013).

Audio magnetotelluric studies have been carried out in Aravali, Tural, and Rajawadi thermal springs (Figure 7a; western part of Maharashtra) for understanding the geoelectrical structure and possible source region of the thermal springs. Major lineaments in Aravali-Tural-Rajawadi regions correlates with aero-magnetic and gravity anomalies and are attributed to basement discontinuities that are trending in north–south, northwest–southeast and northeast–southwest directions (Arora et al., 2018; Low et al., 2020).

Geoelectrical structure shows high conductivity anomaly at shallow depth that coincides with geothermal spring and may represent fracture/fault zone through which hot water gushes up. Another interesting feature is the presence of magmatic intrusive bodies (S1 & S2) beneath the Tural and Rajawadi. This intrusive body (S1 & S2) as shown in Figure 7b acts as a source rock for the above geothermal zones and is related to Deccan volcanism. Thus, hot water temperature recorded at Tural and Rajawadi (60–70 °C) hot springs are higher than Aravalli (42 °C, Reddy et al., 2013). Thus, shallow resistive intrusive magmatic body could be a source rock for additional heat generation at Tural and Rajawadi geothermal zones (Deshmukh et al., 2022).

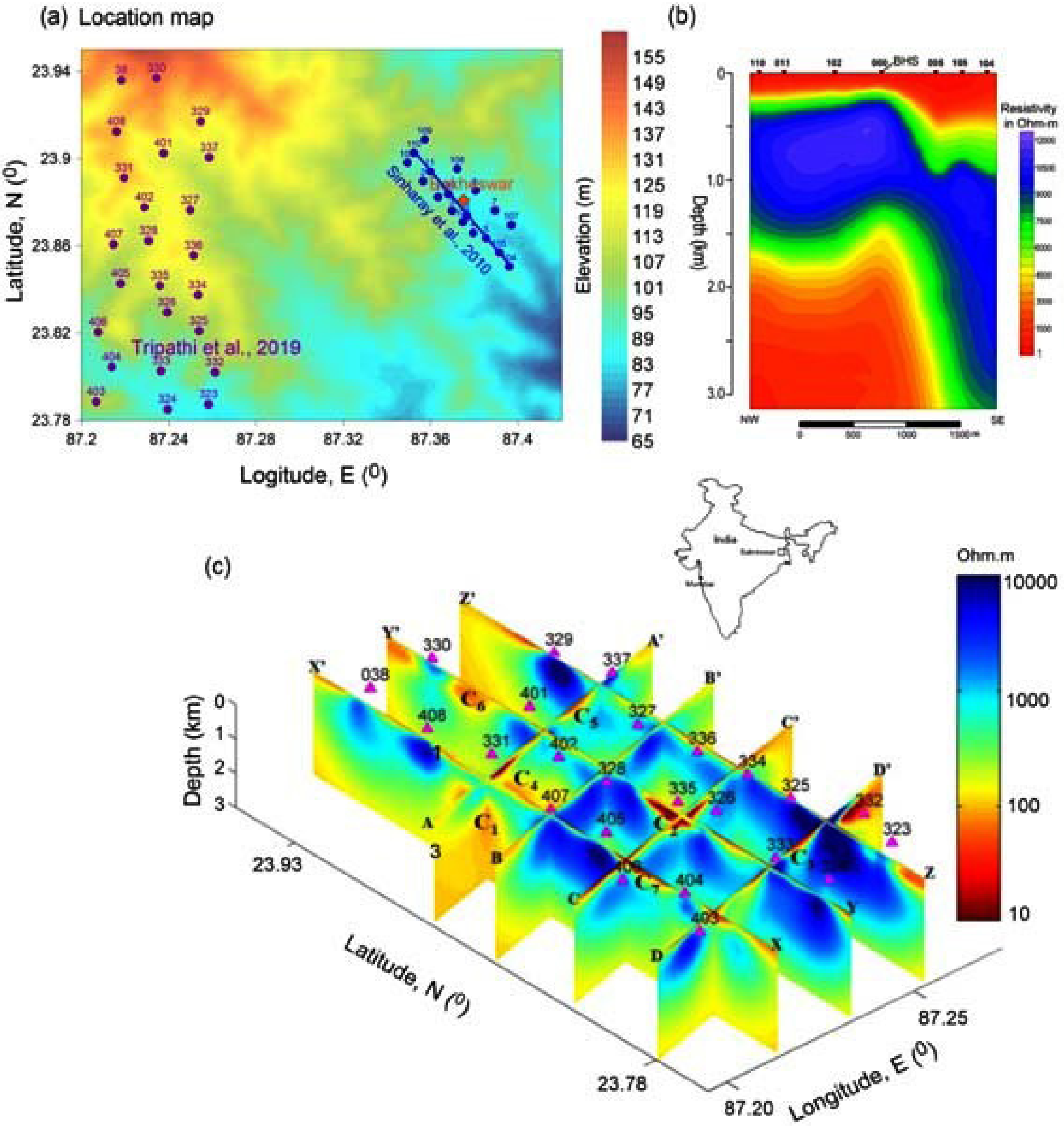

Figure 5. (a) Topography map of Bakreswar geothermal zone and its surrounding regions. MT stations across the Bakreswar geothermal zone, Blue circles denote stations covered zone by Sinharay et al. (2010) and Magenta circles by Tripathi et al. (2019). (b) 2D geoelectric model across the Bakreswar geothermal zone (modified after Sinharay et al., 2010). (c) The longitudinal and latitudinal section represents the 3D MT model of Bakreswar geothermal region (modified after Tripathy et al., 2019).

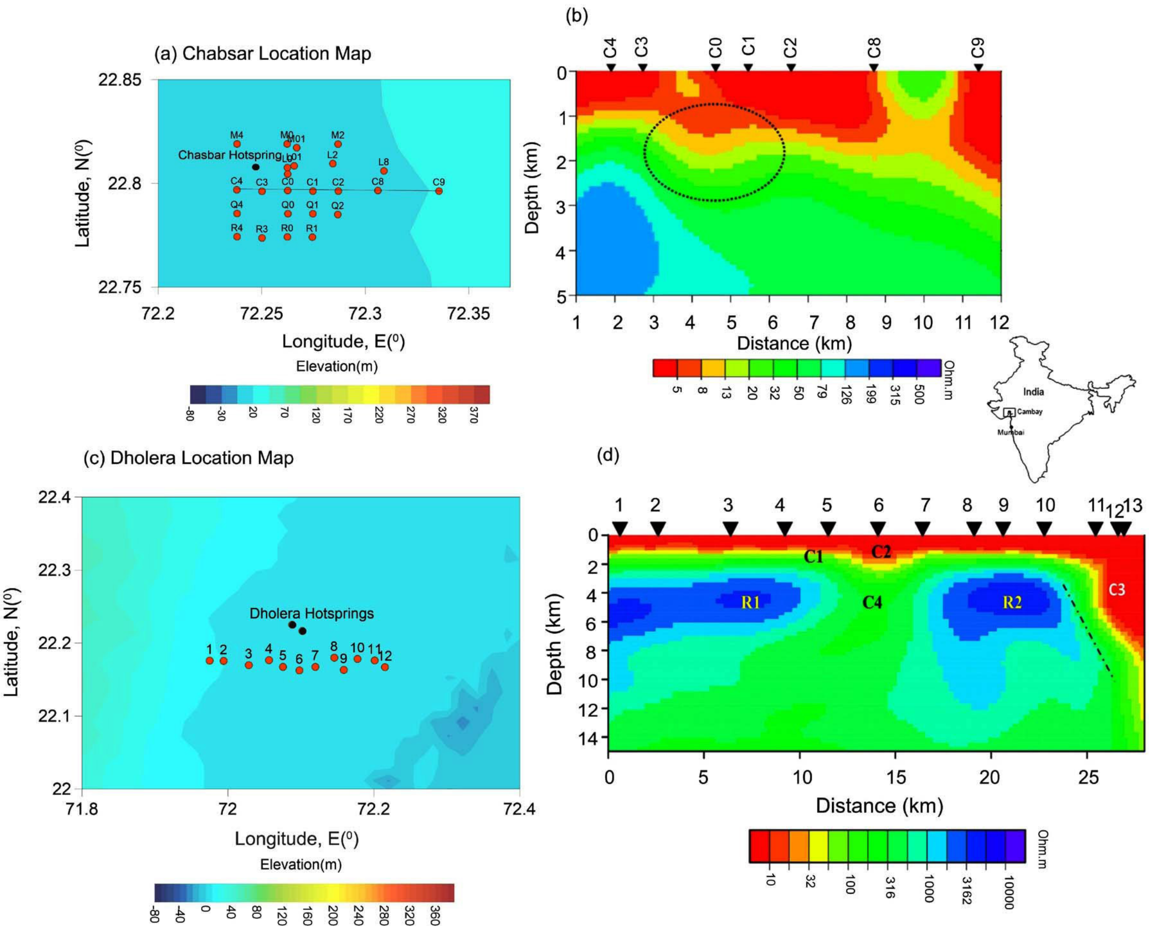

Figure 6. Topography map of Dholera geothermal zone with MT stations. (b) Geoelectric structure brings out anomalous feature towards west of C0 (modified after Mohan et al., 2017). (c) Location map of Chabsar geothermal zone showing MT stations. (d) Conductivity anomaly in between two resistivity blocks acts as a source for Dholera hot spring (modified after Mohan et al., 2019).

3. Discussion

Different conceptual models for various regions were discussed by Moeck (2014). As shown by him, fluid flow regions are reflected as a low resistivity zones. As suggested by Das et al. (2022), geothermal regions in India exist in four different regions. The mechanism of emplacement of high conductivity anomalies (as inferred from MT studies) differ in these regions. In Puga valley, high conductivity anomaly in the depth range of 5–10 km could be attributed to the fluid phase generated by rocks melts due to subduction process. Geothermal zones related to rift valleys are located at Godavari basin, Mahanadi graben, and Cambay basin. In Cambay basin, the presence of shallow conductivity zone is linked to the geothermal fluids along the fault/fracture zone that acts as a conduit for heat transfer from deeper depths to shallow levels. Deep seated conductivity anomaly is attributed to magmatic fluids related to Deccan plume activity. In deep seated fault zones like Tattapani, Surajkhand, Bakreswar, and west coast of India geothermal zones, shallow conductivity anomalies are related to the deep circulation of meteoric waters along fracture zones.

It is apparent from the MT/AMT investigation carried out in various geothermal provinces of India that the granites are the main hosts for geothermal fluids and the circulating fluids are heated by natural radioactive heat generated by these granites. The major tectonic fabric penetrating the granites is the main loci channelizing the fluids from deeper horizon to the surface. The depth of fluid circulation, as evident from the geophysical studies, lies in between 2 and 3 km. Thus, the Indian geothermal provinces are entirely different from other geothermal provinces associated with subduction tectonics and volcanic terrains. The geothermal plays here in India, like other regions (Saudi Arabia), are the high radiogenic granites. The granites of the geothermal provinces from

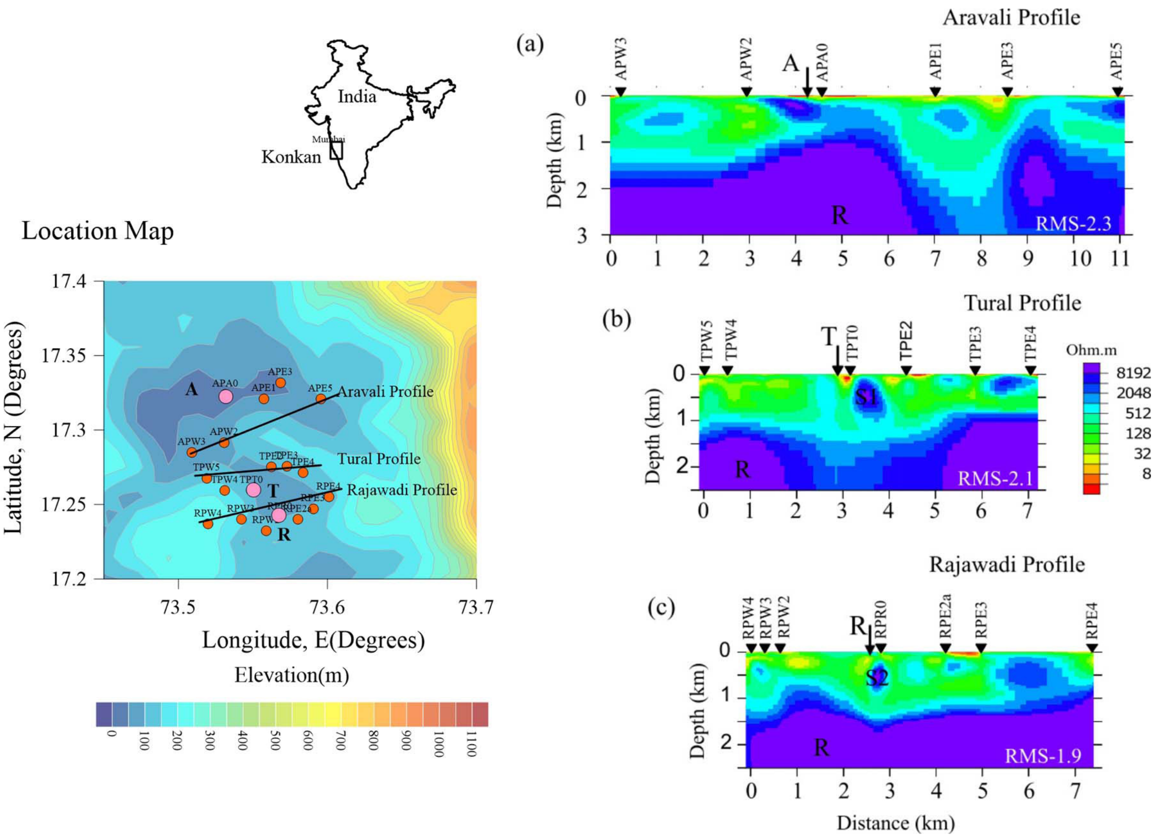

Figure 7. (a) Map shows the topography map of Konkan geothermal province and its surrounding regions. Red circles represent the AMT stations covered across the Aravali, Tural, and Rajawadi geothermal zones and 3 profiles across geothermal zones are shown. (b) 2D geoelectric structure along the AMT profiles across the Aravali (APA0), Tural (TPT0), and Rajawadi (RPR0) geothermal zones (Desmukh et al., 2022).

the Himalayas, west coast, Godavari rift and central Narmada-Son lineament (SONATA) and other regions of India, have high uranium, thorium and potassium content. The radiogenic heat generated by these rocks vary from 5 to 41.68 to μW/m^3 (global average: 5 μW/m^3) while the heat flow over these regions vary from 71 to 180 mW/m^2 (Alam et al., 2004; Chandrasekharam and Antu, 1995; Chandrasekharam and Chandrasekhar, 2009, 2010; Chandrasekharam et al., 2014, 2021; Hemant et al., 2014; Singh et al., 2014a,b, 2015, 2018, 2020 a,b, 2022; Singh et al., 2015; Minissale et al., 2000, 2003; Trupti et al., 2018). In addition, high fluoride content in the thermal waters (1 to 24 ppm; Minissale et al., 2000, 2003; Trupti et al., 2016; Chandrasekharam and Varun, 2020) and high ^{4}He (1% to 8%; Chaudhuri et al., 2015; Singh et al., 2022) in the thermal waters further support circulation of the waters in granites in all the above provinces. Thus, the geophysical, geological, and geochemical investigations carried out over all the geothermal provinces of India indicate that all the geothermal systems in these provinces represent a natural enhanced geothermal systems (EGS) or deep petrothermal systems, supported by the heat generated by the radiogenic granites in addition to the natural heat flow from the mantle. The advantage in these provinces is that a system of fractures, representing natural heat exchanger, exists with a scope of expanding the fracture systems and increasing the circulation volume and rate of the fluids. Since the regions receive sufficient recharge from the annual monsoon that varies from 1000 to 5000 mm per year, and snow melt in the Himalayan regions, there is always continuous recharge to the geothermal reservoir. The cumulative outcrop area of the radiogenic granites in India is about 150,000 km^2 (Chandrasekharam and Chandrasekhar, 2008; Chandrasekhar and Chandrasekharam, 2008). Such granites are potential sources for generating electricity. EGS systems are well established now and are being commercialized. After the successful completion of the Soultz project with a pilot power plant with installed capacity of 3 MWe, the EGS project in Incheim, Germany with an installed capacity of 4.8 MWe and with thermal capacity of 10 MWt is now in operation. Several such projects are in operation in the world. The latest EGS project that is nearing completion is that in UK. The United Downs Deep Geothermal Power Project (UDDGP) will be commissioned shortly with an installed capacity of 3 MWe and 30 MWt (Chandrasekheram et al., 2022). The UDDGP project uses the latest technology of harnessing heat from radiogenic granites circulating fluids through a shear in the Cornwall granite (Chandrasekharam et al., 2022). The power generation capacity of the Indian granites, with such high heat production and heat flow values, have been assessed and reported in several publications cited above. One cubic kilometre of such radiogenic granites can generate 79×10^6 kWh of electricity (Somerville et al., 1994). This assessment was made based on the Cooper Basin EGS project in Australia (Somerville et al., 1994). Therefore, 1000 km^3 of Ladakh granites from the Himalayan Geothermal Belt, at about 3 km depth, for example, is capable of generating about 62×10^{12} kWh of power (Chandrasekharam and Chandrasekhar, 2008). Thus, the radiogenic granites of India, with an outcrop area of 150,000 km^2 have the potential to generate 3.133 BTU (British Thermal Unit; equivalent to 7×10^{22} kWh). One percent of this potential, if exploited, will wipe out the 1000×10^9 kWh of power deficit of the country. Exploiting energy from these rocks will pave the way for sustainable development, driving the country towards net zero emissions (NZE) scenario recommended by the International Energy Agency (IEA, 2021). Besides electricity, geothermal heat can be utilized for dehydration of agricultural produce. Dehydrated agricultural products have a high export potential supporting the economic structure of the country as well as the rural population that depend on the agricultural income (Chandrasekharam, 2001).

4. Conclusion

In India, MT/AMT studies have been carried out in NW Himalayas, central and western India. Further, detailed MT/AMT studies need to be expedited. MT data obtained in 3D grid pattern will be helpful in bringing out the valuable information about the extent of geothermal zone as seen in Tattapani and Bakreswar geothermal zones.

The MT/AMT investigations over the geothermal provinces of India, extending from the Himalayas to the Godavari rift, reviewed in this paper reveal granites as the main geothermal reservoir, hosting the geothermal fluids. This demonstrates that the geothermal systems in India represent natural EGS, with high radiogenic granites as the main heat source. While geophysical data suggest granite hosted geothermal systems, the geochemical signature too corroborates with the geophysical studies. Thus, the geothermal fluids from all the provinces record high crustal helium, boron isotope signature and high fluoride concentration. The oil and gas industries are seriously contemplating on expanding their activity to explore and exploit this vast unexplored energy source. The technology to harness heat from granites is now mature and like India, several countries have accumulated a large subsurface data base using the technology described above. EGS can be established anywhere and with the currently developed drilling technology, the unit cost of electricity is now comparable to the cost of energy generated by fossil fuels. Energy from granites is clean and can support sustainable development, making countries food-, water-, and energy-independent. Besides energy, the global GHG emissions can be reduced drastically thus controlling the global climate change. India has a great opportunity to follow clean energy pathway in the future.

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