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# ORIGIN OF GEOTHERMAL WATERS ALONG THE EAST COAST OF INDIA

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## ABSTRACT

New sources of alternative energy are continuously being searched for and exploited to meet the increasing demand of energy. Geothermal energy has been given a high importance being one of the cleanest and reliable renewable energy resources. The management and sustenance of geothermal power plants depend largely on the availability of geothermal water, its origin, as well as on the mixing/cooling processes that take place during the ascent of the geothermal water. In this study an attempt is made to determine the origin of geothermal waters occurring in the eastern part of India. For this purpose, the springs located in the Indian states of West Bengal, Jharkhand and Odisha are considered. The isotopic data for thermal springs of West Bengal and Jharkhand are from earlier studies, while for the thermal springs of Odisha, 40 water samples including thermal water, groundwater, river water, cold springs and precipitation events, were collected for this study and analysed for hydrogen and oxygen isotopes. The thermal springs of West Bengal and Jharkhand have high salinity, however, through isotopic signature it is established that the thermal water is of meteoric origin and the high salinity has been attributed mainly to prolonged rock-water interaction. The isotopic signature of the non-thermal waters at West Bengal and Jharkhand is characterized by negative shifts from the Global Meteoric Water Line (GMWL) that could indicate a fraction of recycled moisture in the local precipitation. The thermal waters from the areas show a similar isotopic signature. Oxygen and hydrogen isotopic ratios demonstrate that the thermal water of Odisha is of local meteoric origin. Some of the groundwater samples show substantial evaporation but the absence of a significant oxygen shift and relatively low TDS values indicate a limited rock-water interaction. Six of eight thermal springs are located along the northern and southern boundaries of the Mahanadi graben. Their position along the graben boundary helps the surface water percolate to greater depths at a faster rate without providing sufficient time for rock-water interaction. Isotopic composition of the two precipitation events measured from the Odisha region fits the Local Meteoric Water Line (LMWL) well, defined from the GNIP station at Sagar, indicating that the line may also be used as LMWL for the Odisha region. However, some of the thermal waters follow the GMWL demonstrating that more precipitation samples from the Odisha region are needed to describe the Odisha local precipitation line in detail.

# 1. INTRODUCTION

Geothermal energy is one of the energy resources that is, clean, sustainable and it is the most reliable base load type of renewable energy (Glassley, 2014). Unlike solar, wind and hydropower energies, it does not fluctuate due to seasonal changes. The on and off-grid usage of geothermal energy has been demonstrated globally, where in addition to power generation, it is effectively being utilized for direct applications such as space heating, bathing and swimming, agricultural drying, greenhouse cultivation, aquaculture and road and pathways heating etc. (Tester et al., 2006; Mahesh, 2013). The utilization of geothermal energy based on the temperature of the geothermal fluid has been depicted in a chart format, known as the Lindal chart (Lindal, 1973). The chart provides an instant overview of the utilization of geothermal fluid for various purposes. According to the Lindal chart, high enthalpy (temperature > 200°C at 1 km depth) energy sources can be used directly for electricity generation, while moderate to low enthalpy (temperature <200°C) resources can be utilized for drying agricultural and fishery products, house heating/cooling and also for various touristic purposes. The reservoirs trapping the geothermal energy occur in a number of geological settings with varying reservoir temperatures and depth (Glassley, 2010). An eco-friendly extraction of energy from a geothermal reservoir causes less $CO_2$ emissions per unit of electricity than fossil fuels. It is envisaged that a widespread utilization of geothermal energy can also provide a viable solution to mitigate the problem of climate change by significantly reducing greenhouse gas emissions (IPCC, 2008). The advantages associated with geothermal energy are driving the global community to explore new geothermal resources and maximize the utilization of already existing resources in a sustainable manner. Countries like the U.S.A, Philippines, Indonesia, Mexico, Italy, Iceland, Turkey, Kenya, Japan, New Zealand etc. are meeting a significant portion of their energy needs by geothermal energy (World Energy Council, 2016).

According to a recent International Energy Agency (IEA, 2018) report, the per-capita $CO_2$ emission for India is 1.7 ton/year. With ever increasing energy demand for its growth, India is presently experiencing two big challenges: i) meeting its energy demand and ii) cut $CO_2$ emissions. However, it is very clear that with conventional energy resources both challenges cannot be addressed simultaneously. The dilemma can only be solved by developing new alternative energy resources. It has recently been realized that in addition to solar and wind energy, India has a high potential for geothermal energy and in recent years efforts have been put into harnessing the geothermal resources. In this regard, a detailed survey involving various geophysical and geochemical techniques has been conducted across the country (Thussu, 2002). Potential geothermal areas have been demarcated and a national policy has been drafted to exploit these geothermal fields (Ministry of New and Renewable Energy, 2018). It has been proposed to establish a few pilot power plants to ascertain the feasibility and possible issues associated with their utilization, before setting up full capacity power plants. For setting up a geothermal power plant, the depth of the heat source (i.e. reservoir depth) and its temperature are considered as the most important factors. Once the plant is established, the sustenance of the power plant largely depends on the origin and chemistry of the geothermal fluids. Literature archives show that several attempts have been made to determine the temperature and depth of geothermal reservoirs in India, however, limited attempts have been made to determine the origin of the thermal water (Krishnaswamy 1975; Chandrasekharam and Chandrasekhar, 2010a, b; Shanker et al., 1991; Singh et al., 2014). The aim of the present study is to fill this gap by studying the origin of the geothermal fluids of the thermal springs located in eastern India by stable water isotope research.

# 2. BACKGROUND

## 2.1 Introduction of Indian geothermal systems

India has nearly 400 thermal springs that are distributed in various geothermal provinces across the country (Zimik et al., 2017). Ten geothermal provinces have been identified based on their tectonic history, tectonic structure, heat flow values and geothermal gradients. These are the Himalayan

Geothermal Province, Naga Lushai Geothermal Province, Andaman-Nicobar Islands Province, West Coast Geothermal Province, Cambay Graben Geothermal Province, Aravalli Province, Son-Narmada-Tapti (SONATA) Geothermal Province, Godavari Geothermal Province, Mahanadi Geothermal Province and South Indian Cratonic Province (Thussu 2002; Shanker et al., 1991; Chandrasekharam and Chandrasekhar 2010a). The location of important thermal springs, geothermal provinces, average heat flow values and the geothermal gradients are given in Figure 1.

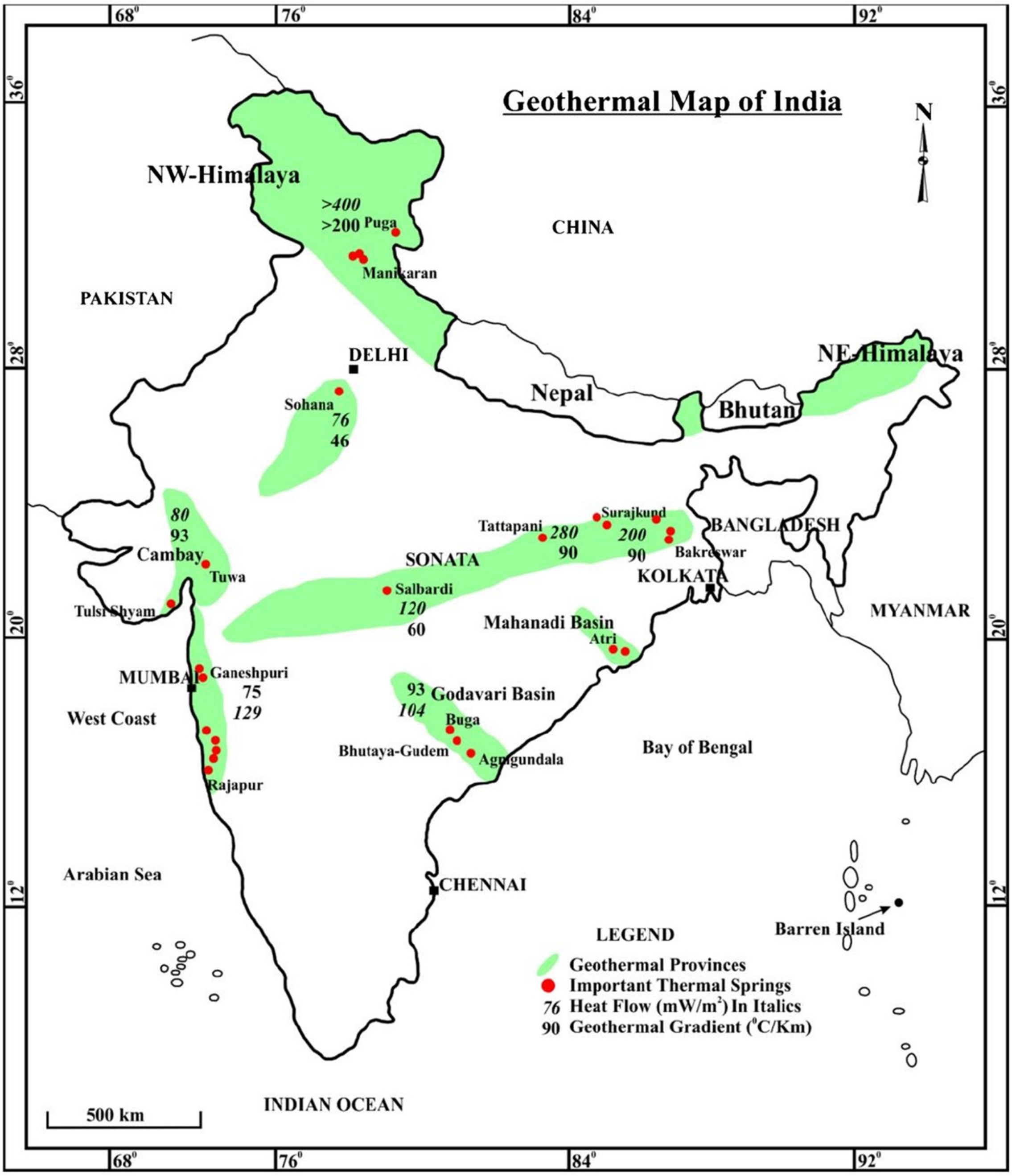


FIGURE 1: Geothermal provinces of India (after Singh et al., 2016)

### 2.1.1 Himalaya geothermal province

The tectonic activity caused by the collision of the Indian plate with the Eurasian plate, makes this province a potential geothermal resource (Figure 2). The higher heat flow values observed in this province (>100 mW/m$^2$) are the result of subduction and shallow crustal melting processes. Chemical geothermometers show that the reservoir temperature ranges between 150 and 200°C.

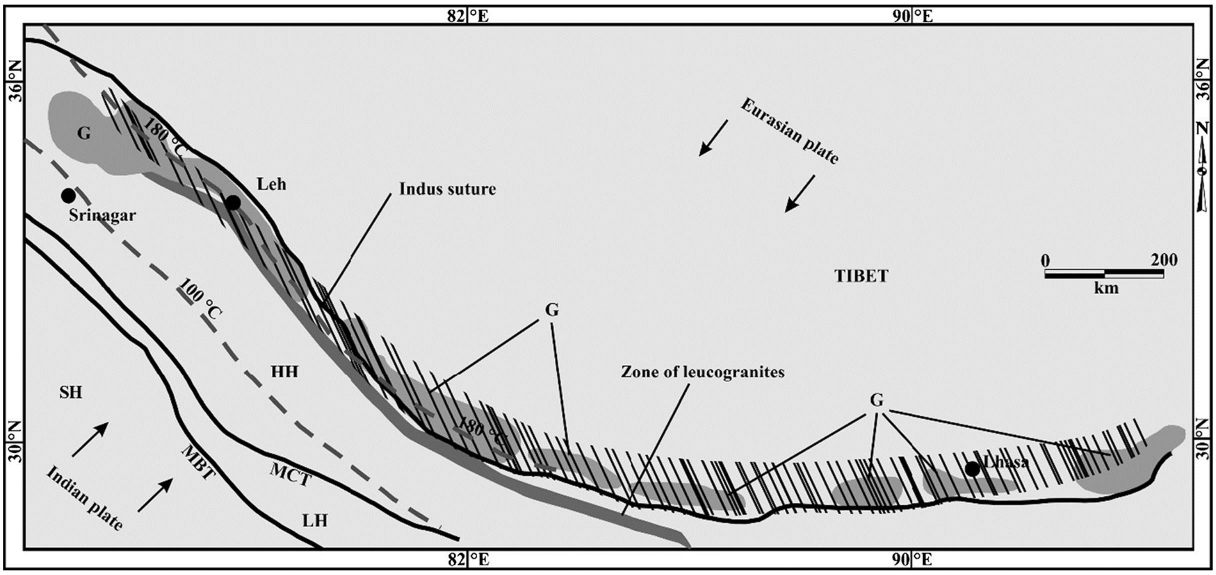


FIGURE 2: Tectonic features of the Himalayan province (Singh et al., 2016)

### 2.1.2 Sohana geothermal province

Sohana geothermal province is located about 24 km south of the city of Gurgaon in the state of Haryana. The thermal water emerges to the surface through numerous thermal springs and with temperature range between 28 and 47°C. The water attains heat mainly due to the deep circulation of groundwater in a tectonic depression, which is developed by the down-faulting of a central block lying between two anticlinal ridges belonging to the Delhi mobile belt (Mondal, 2018). The estimated geothermal gradient is 41±10°C/km with a heat flow of 10 ±25mW/$m^2$ (Negi et al., 1987). Boreholes drilled in the area recorded a maximum temperature of 55°C at a depth of 547m.

### 2.1.3 West coast geothermal province

This geothermal province is located along the west coast of India. Eighteen geothermal springs are reported in this province with surface temperatures range between 47 and 72°C. The origin of these thermal springs is traced to waters penetrating the 65 m.y. old Deccan Flood Basalt (DFB). Gravity surveys clearly show a thinning of the lithosphere along the province and also a shallowing of the 1250°C isotherm at 20 km depth (Negi et al., 1992). The higher thermal regime at a shallow depth results in a high heat flow of 75-129 mW/$m^2$. The reported geothermal gradient from a borehole survey is about 57°C/km. The reservoir temperature estimated using gas and cation geothermometers ranges between 120 and 150°C. A conceptual model explaining the groundwater flow is shown in Figure 3.

### 2.1.4 Gujarat-Rajasthan geothermal province

Gujarat Geothermal Province has around 22 geothermal springs which are located in the Cambay basin. Cambay basin is an elongated rift basin (north-south direction) bounded by two deep seated north-south oriented faults along the eastern and western edge of the basin (Valdiya, 2016). The basin has been formed due to the movement of the Indian plate in a northward direction and its anticlockwise rotation during the late cretaceous period. The structure and lithology of the Cambay basin is shown in Figure 4. The surface temperature of the thermal springs ranges between 35 and 93°C and the highest surface temperature has been reported near the Godhara granitic intrusion (955 Ma) (Gopalan et al., 1979). However, the eastern part of this province consists of Archean to recent lithological units. In this part, several NE-SW trending faults developed due to the cyclic and dynamic movement of the blocks. The fault systems provide conduits for deep circulating geothermal waters. The surface temperature of the geothermal waters ranges between 31 and 50°C, and the estimated reservoir temperatures vary from 120

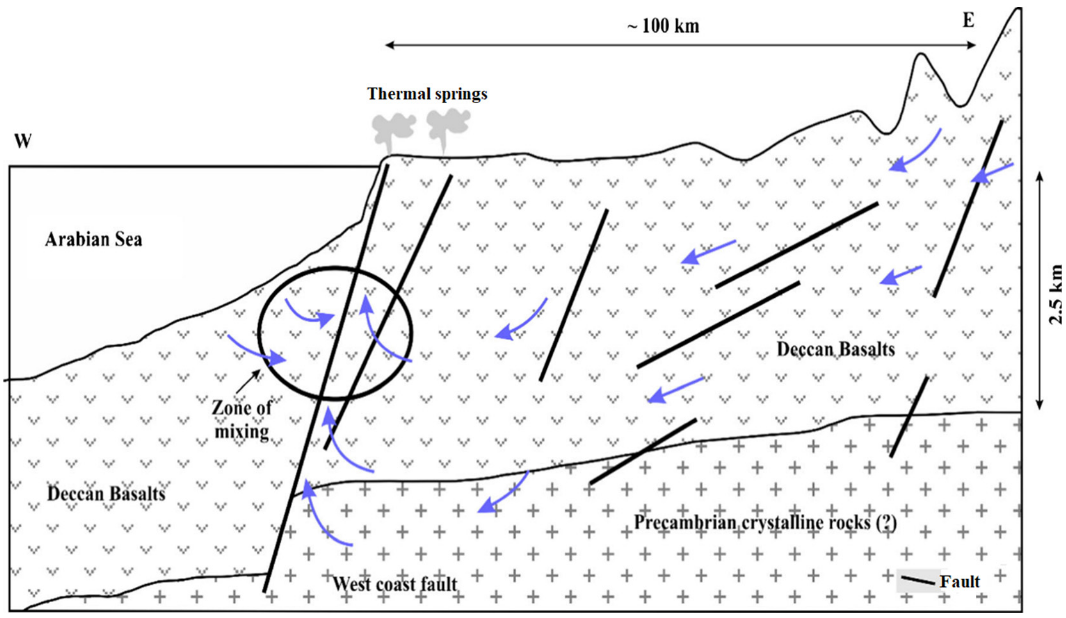


FIGURE 3: Geothermal fluid circulation along the west coast of India (Singh et al., 2016)

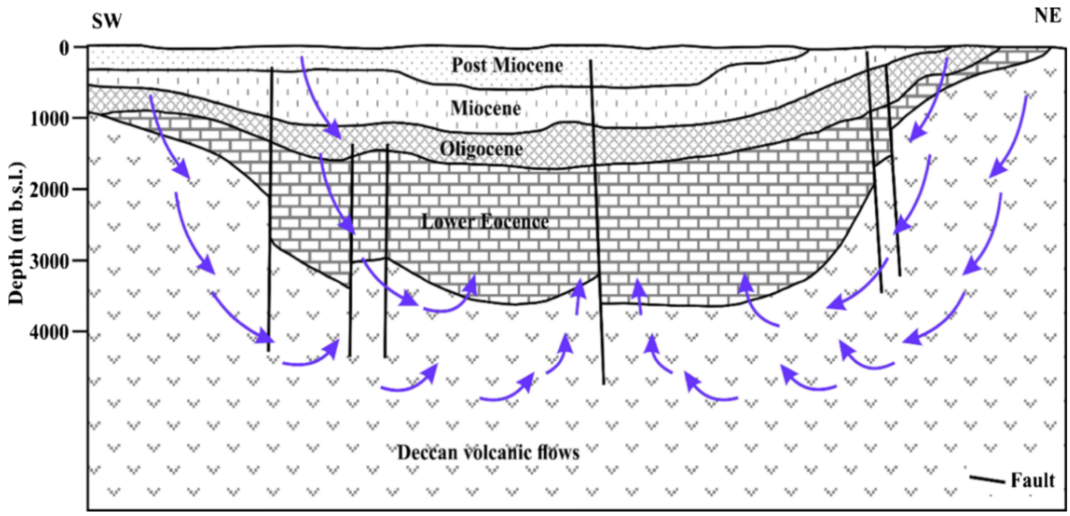


FIGURE 4: Structure and lithology of the Cambay geothermal field (Singh et al., 2016)

to 150°C (Pitale et al., 1987). The maximum recorded heat flow value recorded in the area is 205 $mW/m^2$.

### 2.1.5 Godavari geothermal province

Godavari Geothermal Province lies in the tectonically active zone associated with a NW-SE- oriented graben structure in SE India. The reported surface temperature of the geothermal springs in this province ranges from 30 to 62°C. The area has a temperature gradient of about 45°C/km and heat flow values of 104 $mW/m^2$ (Pandey and Negi, 1995).

### 2.1.6 Mahanadi geothermal province

Several geothermal springs are reported in this province located in eastern India. At a few places are single hot spring while at other places multiple openings have been reported (Kundu et al., 2002, Zimik et al., 2017). There are places where hot springs and cold springs occur close to each other. This indicates a complicated fracture pattern having a different orientation on a very small scale. Since the study area falls in the Mahanadi geothermal province a more detailed account of this province regarding geology, structural features etc. is given subsequently in Section 3, under the heading Geology and Hydrogeology of the East Indian geothermal areas.

### 2.1.7 SONATA geothermal province

SONATA geothermal province in central India is associated with the Son-Narmada-Tapti (SONATA) rift system which was formed during the early stages of the development of Indian plate when two proto-continents interacted. Later, it got reactivated when the Indian plate collided with the Eurasian plate. Deep reflection seismic profiles across the SONATA province suggest that the fault system reaches down to the mantle depth (Singh et al., 2016). The Tattapani field is the main hot spring area of this province and is related to the Balarampur fault system. A schematic cross section showing the geology and structure of the Tattapani geothermal system is given in Figure 5.

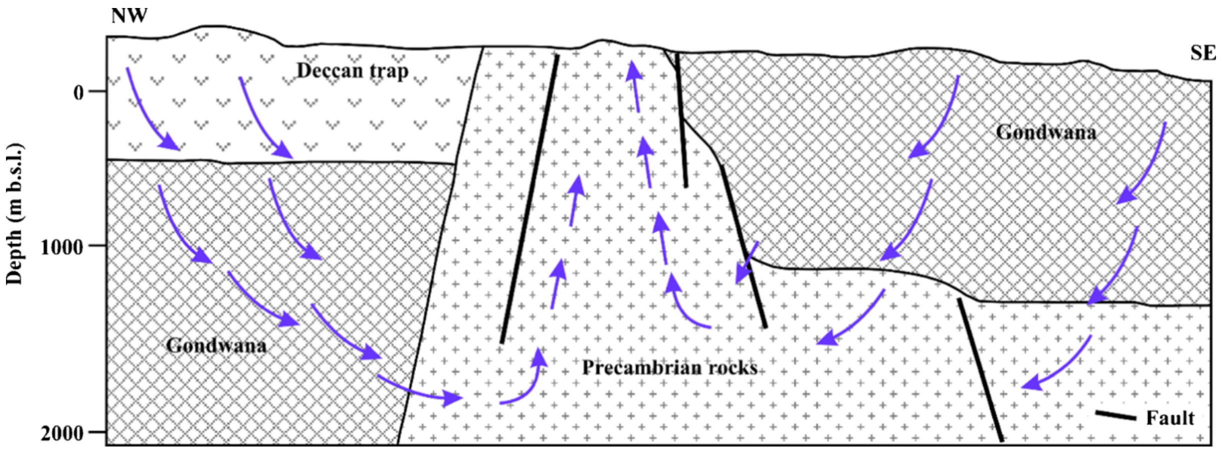


FIGURE 5: Geology and structure of the Tattapani geothermal field (Singh et al., 2016)

The Gondwana sediment provides insulation over granitic intrusives occurring at a depth around 2 km. The geothermal gradient of the area is 60°C/km. The surface temperatures of the geothermal waters range from 30 to 93°C. Geochemical geothermometers indicate that the reservoir temperature at Tattapani geothermal field ranges between 205 and 217°C at a depth of around 3 km (Singh et al., 2016). The presence of high helium content in the geothermal water suggests that radioactive decay is mainly responsible for the high temperature gradients at the SONATA geothermal province. The Precambrian rocks are enriched in radioactive minerals. The shallow occurrence of granitic intrusions below the Gondwana cap rock makes SONATA one of the best candidates for enhanced geothermal systems in the country.

Based on the detailed studies described above, the following geothermal sites have been identified as the most promising geothermal sites; Tattapani in Chhattisgarh (SONATA Geothermal Province), Puga and Chumathang in Jammu & Kashmir (Himalaya Geothermal Province), Cambay Graben in Gujarat (Gujarat-Rajasthan Geothermal Province), Manikaran in Himachal Pradesh (Himalaya Geothermal Province), and Surajkund in Jharkhand (Mahanadi Geothermal Province). However, other geothermal sites are getting evaluated further and the present work is a part of that evaluation.

## 2.2 The concept of isotopic studies

All the constituents present in geothermal waters can be classified into two categories, (i) non-conservative constituents, and (ii) conservative constituents. Non-conservative constitutes are those constituents whose concentrations can be modified as a function of processes such as rock water interaction, temperature etc. The concentrations of these constituents are primarily used to estimate the reservoir temperature. However, on the other hand the concentrations of conservative constituents (also called non-reactive constituents) do not vary because of temperature or time. These constituents are generally used to trace the origin of geothermal waters. Isotopes of hydrogen, oxygen, carbon, strontium etc. can be used as conservative constituents. Hydrogen has two stable isotopes, ${}_1^1H$ and ${}_1^2H$ (or D for deuterium), while oxygen has three stable isotopes, ${}_8^{16}O$, ${}_8^{17}O$ and ${}_8^{18}O$. The abundance of ${}_8^{16}O$, ${}_8^{17}O$ and ${}_8^{18}O$ is 99.76%, 0.04% and 0.20%, respectively. Due to the negligible amount of ${}_8^{17}O$, it is generally not considered and thus only ${}_8^{16}O$ and ${}_8^{18}O$ are used for oxygen water isotope studies.

Generally, the abundance of stable isotopes is very small and thus it is difficult to measure their concentration precisely and accurately. For this reason, in most of the isotopic studies ratios are used and are represented as the ratios of heavy isotope/lighter isotope relative to an international standard. In the present study, the $H^{2/}H^1$ and $^{18}O^{/16}O$ ratios are considered. These ratios act as excellent natural tracers for determining various physicochemical processes in geothermal systems, such as the origin of thermal fluids, mixing of shallow groundwater with thermal water, steam separation and rock-water interaction (Panichi and Gonfiantini, 1977; Barbier et al., 1983). The results are generally reported in the usual δ notation which gives the measure of the deviation of isotopic ratios of the samples from the international standard V-SMOW (Vienna-Standard Mean Ocean Water) in per mil (‰) units. The δ notation for isotopic deviation is given by the equation:

$$\delta = \left(\frac{R\ sample}{R\ (V-SMOW)} - 1\right) * 1000 \tag{1}$$

where R is $^{18}O/^{16}O$ ($\delta^{18}O$) or D/H ratio (δD).

According to the above definition, δ values for ocean water are close to 0‰. Because the lighter water molecule evaporates more easily than the heavier water molecules the water vapour is more depleted in the heavy isotopes than the water body. Clouds formed by the condensation of evaporated water are therefore depleted in heavier isotopes. Further, during the condensation process, it is the heavier isotopes that come into the liquid phase (i.e. rain droplets) first. For this reason, the first rain event has more heavy isotopes than the cloud itself. During a subsequent rain event, the rain water becomes more and more depleted in heavier isotopes. Further, the isotopic ratios are affected by various factors such as the altitude, distance from equator, and inland distance from the evaporation source to the precipitation site. Measurements of precipitation across the globe showed that $\delta$D values are empirically related to the $\delta^{18}$O values according to the following equation (Craig, 1961):

$$\delta D = 8 \cdot \delta^{18}O + 10 \tag{2}$$

This equation defines the global meteoric water line (GMWL) (Figure 6). Stable isotope values in unaltered groundwater are also expected to satisfy this equation. However, in a few cases local corrections are required and LMWLs have been defined. Kumar et al (2010) defined a LMWL using isotopic data from 272 precipitation samples from different parts of India:

$$\delta D = 7.93\ (\pm 0.06) \cdot \delta^{18}O + 9.94\ (\pm 0.51)\ (r2 = 0.98) \tag{3}$$

From the equations above the LMWL is almost identical to the GMWL. As India is a very large country with significant variation in isotopic composition in precipitation from north to south and east to west, several LMWLs have been defined. The two local water lines defined for the eastern part of India used as reference lines in the present study are also shown in Figure 6. These are:

$$\delta D = 4.2 \cdot \delta^{18}O - 5.0 \tag{4}$$

defined by Kumar et al. (2011) for non-thermal West Bengal and Jharkhand waters and

$$\delta D = 7.9\ (\pm 0{,}29).\ \delta^{18}O + 8.23(\pm 1{,}81) \tag{5}$$

based on 14 precipitation samples from the GNIP station at Sagar (Kumar et al., 2010).

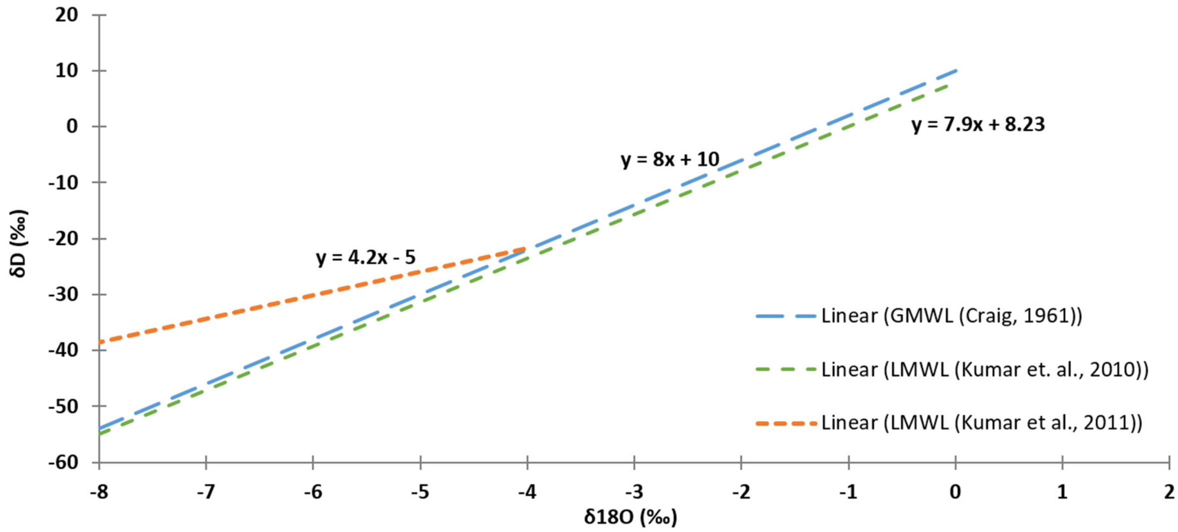


FIGURE 6: $\delta$D- $\delta$O$^{18}$ plot showing the Global Meteoric Water Line (GWML) and the Local Meteoric Water Lines (LMWL, Craig, 1961; Kumar et al., 2010; Kumar et al., 2011)

The linear relationship between $\delta^{18}$O and $\delta$D reflects kinetic and equilibrium processes. A second order parameter, deuterium excess (d-excess), defined as d = $\delta$D - 8$\delta^{18}$O by Dansgaard (1964) highlights the isotopic variability driven by kinetic fractionation and reflects deviation from the GMWL. The d-excess is useful both for studying moisture source origin and evaporation.

As demonstrated in Figure 7 surface evaporation or surface heating leads to enrichment of both the $\delta^{18}$O and $\delta$D ratios. In addition to surface processes, there are few subsurface processes that also can play an important role in modifying the $\delta^{18}$O and $\delta$D ratios of groundwater. Rock water interaction process at > ~100°C causes the enrichment of $\delta^{18}$O compared to $\delta$D. This leads to a positive shift of $\delta^{18}$O (Figure 7). Though it is very rare to have a $\delta^{18}$O shift to the left of the GMWL it can happen and is referred as a –ve shift. As shown in Figure 7 the –ve shift indicates interaction of sea water or formation water with the surrounding rocks at very low temperature, which leads to the depletion $\delta^{18}$O and insignificant changes in $\delta$D values (Nicholson, 1993). Ocean water is the primary source of global precipitation. During the formation of vapours from ocean water, lighter isotopes preferentially go into the vapour phase. The fractionation thus causes the rainwater to remain lighter than the ocean water and the places of accumulation of rainwater (i.e dams, ponds etc.) are always depleted in heavier isotopes as compared to the source of the vapour (i.e. ocean water). The evaporation from these already depleted water bodies (i.e dams, ponds etc.) causes further fractionation and gives rise to more depleted vapours. Thus, the recycled moisture is lighter than the primary moisture and the rain formed from this recycled moisture falls on the left of the global meteoric water line.

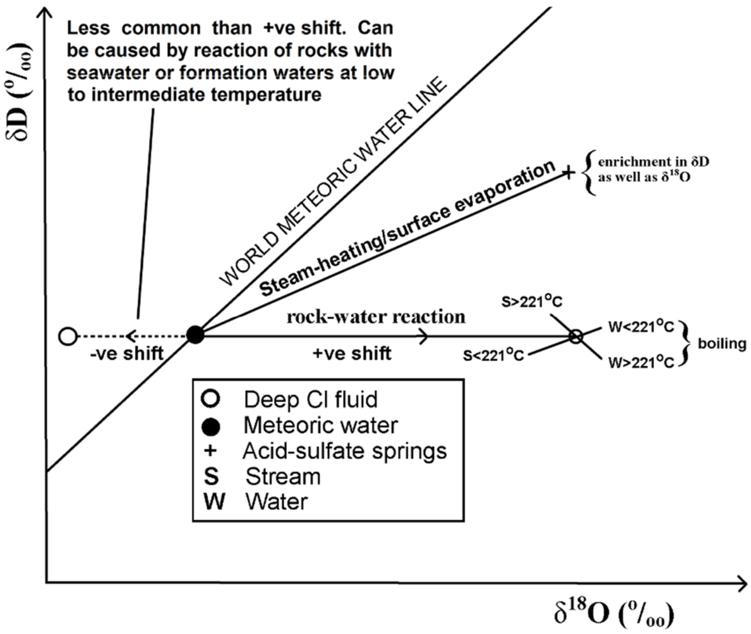


FIGURE 7: Stable isotope signatures of meteoric water and associated active processes within geothermal reservoirs (Nicholson, 1993)

Isotopic studies conducted on geothermal water across the globe indicate that most of the high temperature fields lie in the +ve shift zone, which indicates intense rock-water interaction (Truesdell and Hulstons 1980).

### 2.2.1 Isotopic studies of Indian geothermal waters

Few studies have been conducted to determine the origin of thermal water located in different parts of India. Interestingly, the studies from the western, eastern, northern and central part of India show different results in terms of origin of thermal water and their interaction with the reservoir rocks (Giggenbach, 1981). The west coast geothermal belt (includes the west coast geothermal province and Gujarat-Rajasthan geothermal province) has around 60 geothermal springs (Dowgiallo, 1977; Sarolkar, 2005). The isotopic analysis of these thermal waters involves O, H, C, S, B, and Sr (Chandrasekharam et al., 1989; Muthuraman and Mathur, 1981). The results of these studies indicate that the thermal waters are not fed by recently recharged rain water, as they have depleted deuterium content in comparison to present day precipitation. The tritium values also confirm their non-modern meteoric origin. Further, the significant $\delta^{18}$O shift observed in these waters indicates a long-term rock water interaction. The $Sr^{87}/Sr^{86}$ ratio indicates that these thermal waters have been circulated deep into the basement granitic rocks and picked up the Sr from Archean granites (Reddy et al., 2013; Chatterjee et al., 2017). Similar studies have been made on a few selected geothermal springs in the eastern part of India (Sharma et al., 2010; Nagar et al., 1996; Kumar et al. 2011; Majumdar et al., 2005). The isotopic composition of oxygen indicates that insignificant rock-water interaction has occurred (Majumdar et al., 2005). However, there were indications of mixing of thermal waters with the non-thermal waters (Kumar et al., 2011). Studies conducted on thermal water samples collected from the northern (Puga and Manikaran geothermal areas) and central (Tattapani geothermal area) parts of India, indicate different results. The thermal springs of the Puga geothermal area show a $\delta^{18}$O shift of 1.5‰. This is mainly attributed to rock-water interaction occurring in the subsurface. The shift may also indicate higher temperature within the deeper zones. In case of the Manikaran geothermal area, it has been inferred that the water is largely of meteoric origin with a possible component of a fossil brine. The presence of any magmatic component has not been detected (Giggenbach et al., 1983, 1992). The investigations in the case of Tattapani geothermal area indicate that the thermal water is meteoric and shows negligible rock-water interaction. Some mixing of hot water with the local cold groundwater has also been found (Navada and Rao, 1991).

## 3. GEOLOGY AND HYDROGEOLOGY OF THE EAST INDIAN GEOTHERMAL AREAS

The east coast geothermal fields include the Bakreshwar thermal springs located in the state of West Bengal, Tantloi thermal springs in the state of Jharkhand and a thermal spring cluster distributed across the state of Odisha. These thermal spring clusters are named after their locations, such as Attri, Magarmuhan, Bankhol, Boden, Tattapani, Tarabalo, Deuljhori and Badaberena.

### 3.1 Bakreswar and Tantloi geothermal areas

The Bakreswar thermal springs (23°52′00″N: 87°25′00″E) lie in the Birbhum district of the Indian state of West Bengal. The average temperature of these springs ranges between 45 and 71ºC. The springs occur in an E-W direction similar to the trend of the Gondwana sedimentary basin in the central part of Chotanagpur Gneissic Complex. Another thermal spring cluster, named Tantloi (24°23′00″N: 87°16′00″E) is located 20 km NW of Bakreswar in the Santhal Parganas district of Jharkhand. The emergence of these springs near the West Bengal-Jharkhand border has been associated with a buried N-S trending fault which intersects the Son-Narbada-Tapti (SONATA) lineament, a mega mid-continent lineament that extends from the Indian state of Gujrat to West Bengal (Figure 8). Studies have further indicated that the presence of fractures associated with a faulting event plays a controlling role in the distribution of geothermal water (Singh et al., 2015).

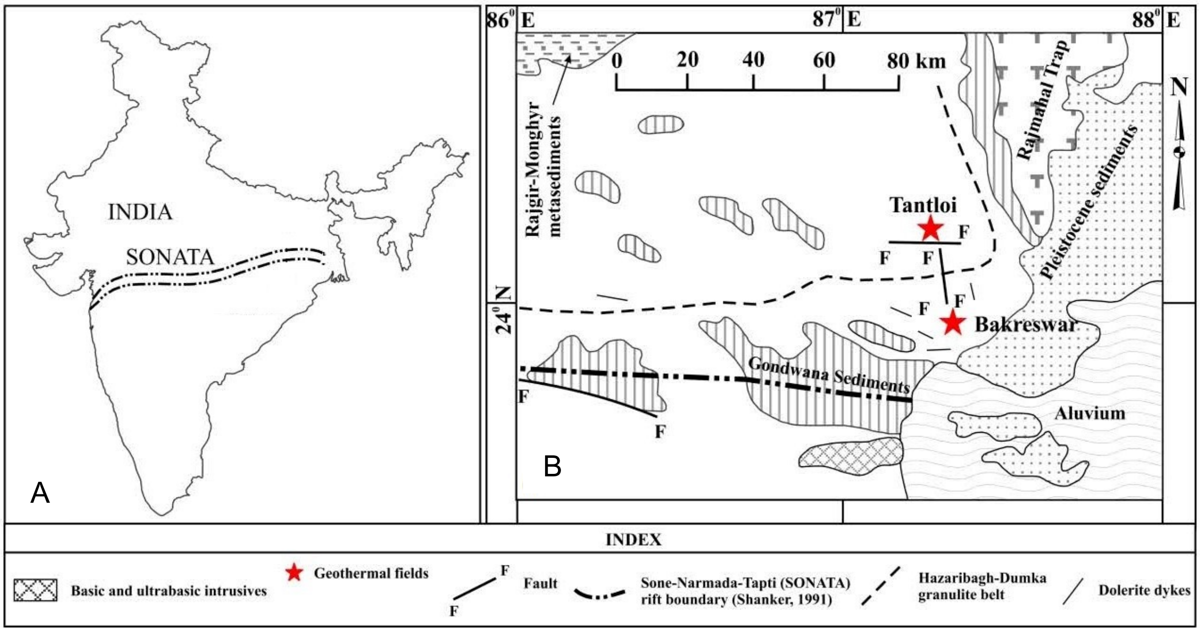


FIGURE 8: A) Map of India showing the SONATA lineament,; B) Regional geological setting and locations of Bakreswar and Tantloi thermal springs (Singh et al., 2015)

### 3.2 Geothermal clusters of the state of Odisha

The state of Odisha, which has an area of about 155,842 km$^2$ lies along the east coast of India within latitudes 17°48' - 22°34' North and longitudes 81°24' - 87°29' East. The state of Odisha has eight thermal springs in the Mahanadi Geothermal Province that are of Archaean/Pre-Cambrian age. At some of the hot springs such as Attri, Magarmuhan, Bankhol, Boden and Tattapani the hot water discharges from a single spot, whereas at Tarabalo, Deuljhori and Badaberena, there are multiple discharge points (Zimik et al., 2017; Kundu et al., 2002). The temperature of the hot spring water collected from these springs ranges from 28°C to 58°C. However, in an earlier study, a maximum temperature of 67ºC was reported from a thermal spring in the Attri area (Singh et al., 1995). A few studies have been done on the genesis of the thermal springs of Odisha (Mahala et al., 2012), and also on the hydrology and geochemistry (Singh et al., 1995; Dash et al., 2013; Zimik et al., 2017). The state of Odisha comprises mostly of Precambrian rocks (73%), Quaternary formations (19%) and minor patches of Tertiary formations (8%) (Chowdhury et al. 2011). All the thermal spring manifestations of Odisha occur in three different geological settings. Thermal springs located at (i) Attri, Tarabalo, Deuljhori and Tattapani lie within the Eastern Ghats Supergroup; (ii) Magarmuhan, Bankhol and Badaberena within the Iron Ore Supergroup (IOSG); and (iii) Boden lies within the Vindhyan Supergroup. The Mahanadi and Godavari rift system divides the Eastern Ghat Belt (EGB) into the northern, central and southern segments, of which the northern and part of the central segments fall within the boundaries of the state of Odisha (Sarkar and Nanda 1998). In the Odisha sector, the EGB is broadly divided into the Khondalite Group, Charnockite Group and Migmatite Group, which from east to west lie in the sequence of the Eastern Khondalite Zone, Central Migmatite Zone, Western Khondalite Zone, Western Charnockite Zone and Westernmost Transition Zone (Ramakrishnan, 1987).

The rock types encountered at the Attri, Tarabalo, Deuljhori and Tattapani thermal springs are mainly laterite, khondalite, charnockite and augen-gneiss (granitic), while those at Magarmuhan and Bankhol are mostly quartzite of IOSG (Mahala et al., 2012). The presence of NW-SE and NE-SW fractures/lineaments at Attri and Tarabalo have been well established (Thussu, 2002). Deuljhori is located close to a NNE-SSW trending shear zone and the thermal springs are located along the banks of the Mahanadi river, which flows along a NW-SE fault in the area. One fracture trending NW-SE to

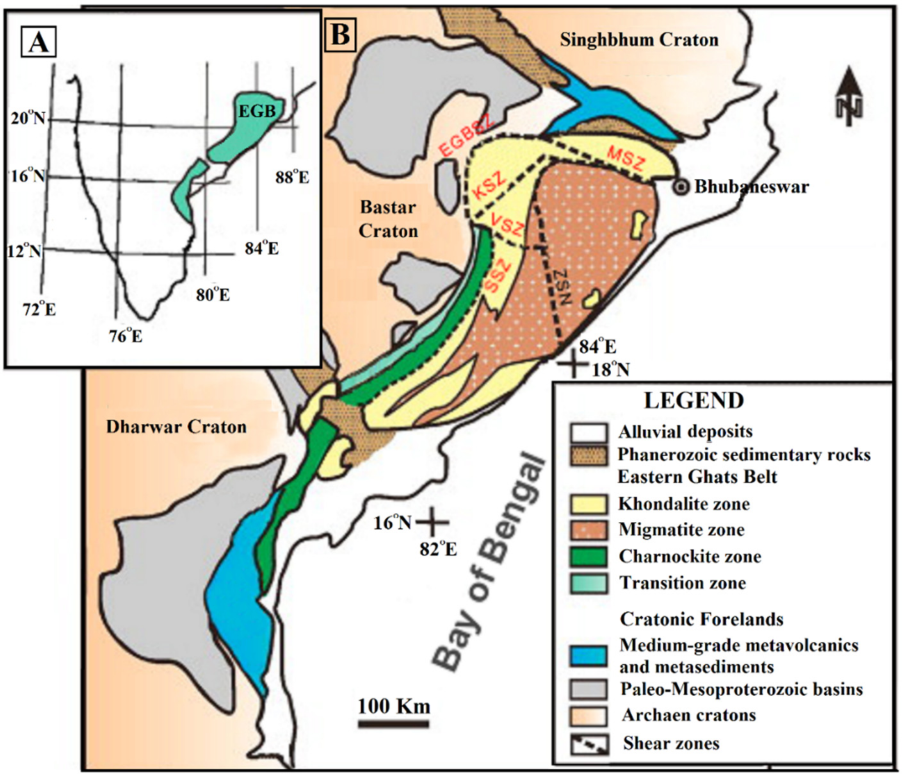


FIGURE 9: Map showing a location of the Eastern Ghat Belt (EGB) in India, litho-tectonics units of the EGB and adjacent cratons. Abbreviations used are MSZ: Mahanadi Shear Zone, VSZ: Vamshadhara Shear Zone, NSZ: Nagavalli Shear Zone, SSZ: Sileru Shear Zone, KSZ: Koraput–Sonepur Shear Zone, and EGBSZ: Eastern Ghats Boundary Shear Zone (Dasgupta et al. 2013)

WNW-ESE runs parallel to the Mahanadi lineament and passes very close to the Deuljhori thermal springs (Thussu, 2002). The geology of the area is shown in Figure 9 and the generalized stratigraphic succession of the study area is given in Table 1.

TABLE 1: Geological succession of Odisha (Chowdhury et al., 2011)

<table>
<tr><th>Age</th><th colspan="2">East India craton and Singhbhum-Gangpur mobile belt</th><th colspan="2">Eastern Ghats belt</th></tr>
<tr><td>Palaeo Proterozoic</td><td colspan="2">Upper Bonai group/Simlipal group/<br>Singhbhum group/Gangpur group/<br>Dhanjori group/Bonai lava/<br>Dangoaposi lava/Dhanjori lava</td><td>Migmatite Group</td><td rowspan="6">EASTERN GHATS SUPERGROUP</td></tr>
<tr><td>Protero-zoic</td><td colspan="2">Granophyre (Mayurbhanj granite)<br>Newer dolerite<br>Gabbro, norite, anorthosite</td><td rowspan="3"></td></tr>
<tr><td rowspan="6">Archaean</td><td colspan="2">Chhotanagpur gneissic complex</td></tr>
<tr><td colspan="2">Ultramafics of Sukinda-Nuasahi<br>Granitic complex</td></tr>
<tr><td>Bonai granitic complex</td><td rowspan="3">IRON ORE SUPERGROUP</td><td>Charnockite Group</td></tr>
<tr><td>Lower Bonai group</td><td>Khondalite Group</td></tr>
<tr><td>Gorumahisani-Badampahar group</td><td colspan="2" rowspan="2"></td></tr>
<tr><td colspan="2">Singhbhum Granite/Nilgiri granite<br>Older metamorphic tonalitic gneiss<br>Older metamorphic group</td></tr>
</table>

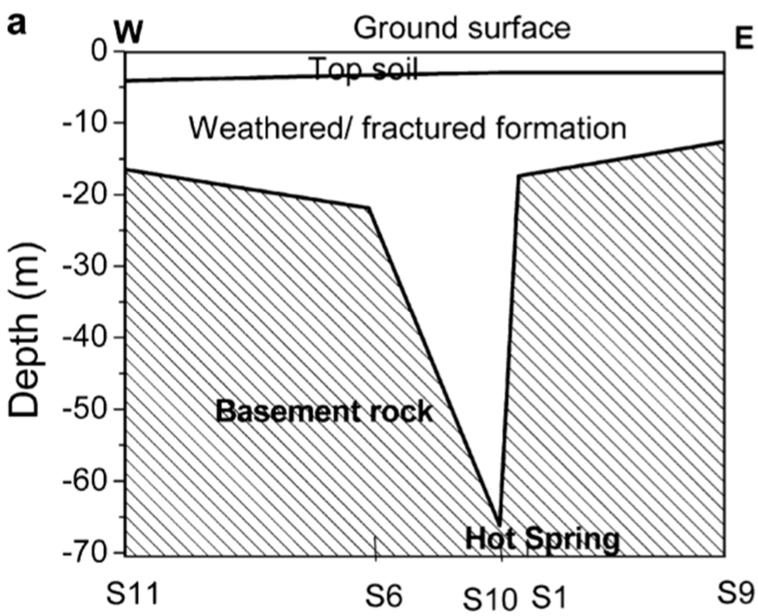


FIGURE 10: Geological section of the Tarabalo geothermal area (Kundu et al., 2002)

A geophysical study carried out in the Tarabalo geothermal area indicates that the occurrence and movement of shallow, non-thermal groundwater takes place mostly in the weathered and fractured rocks, constituting the main aquifer system in the area under water-table conditions (i.e. unconfined) (Kundu et al., 2002). The thickness of the aquifer varies with the topography (Figure 10). The minimum aquifer thickness was found in the high topographic area and it gradually increases towards the hot springs and attains a maximum thickness of about 66 m near the Tarabalo hot spring. Topography, basement configuration and thickness of the weathered and fractured rocks constitute the main factors that control the groundwater system in the area.

### 3. 3 Sample collection and methodology

The area covered in the present study is divided into two parts; (i) the Bakreswar and Tantloi geothermal areas, and (ii) the geothermal areas of the state of Odisha. For the present isotopic research, an earlier study conducted on the Bakreswar and Tantloi areas is considered (Kumar et al., 2011). Kumar et al. (2011) report δD and $\delta^{18}$O data from six thermal springs at Bakreswar and four thermal springs at Tantloi, as well as samples from cold groundwater and surface water. Water samples from hot springs of Odisha were collected for the present study. Additionally, water samples from rivers, cold springs, groundwater and rain events were collected. The locations of the Odisha geothermal springs are shown in Figure 11.

The samples were collected in pre-washed high-density polyethylene (HDPE) bottles. The water samples were filtered in the field with a 0.45μm nylon filter (25 mm diameter) and stored at low temperature in air tight bottles until analysed. Each sampling site was geo-referenced using a Garmin Global Positioning System (GPSMAP-76S) instrument. Various physic-chemical properties including pH, temperature, and conductivity were measured in the field during the collection of the samples. The tube wells were pumped for five minutes to clear the water standing in the tubes before samples were collected.

### 3.4 Analytical techniques

The D/H and oxygen isotope ($^{18}$O/$^{16}$O) ratios of the water samples were determined during the summer 2018, using an Isotope Ratio Mass Spectrometer (IRMS), Delta V Advantage (ThermoFisher) at the water stable isotope laboratory Reykjavik Iceland. The equipment is designed to measure isotopic mass-to-charge ratio of lighter elements that can be transformed into gaseous substances. A gas bench device was used as an inlet system. 200 μL samples were placed in 12 mL vials and flushed with a He gas mixture. For hydrogen isotope measurements, 98% He and 2% $H_2$ was used as the flush gas and for oxygen isotope measurements 99.7% He and 0.3% $CO_2$ was used. For oxygen the reaction time after

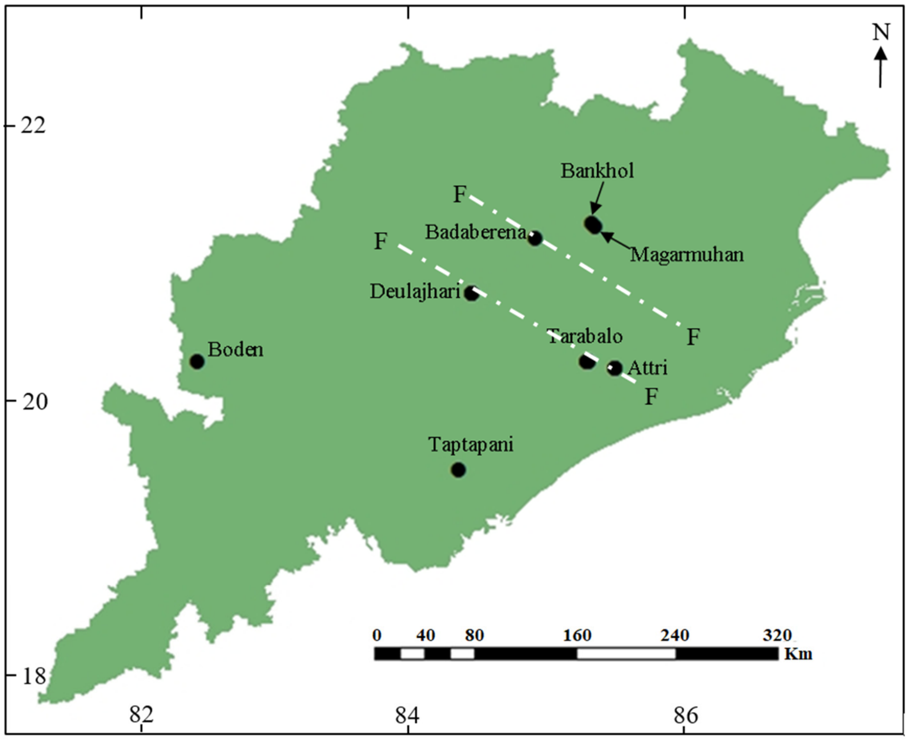


FIGURE 11: Location map indicating sample collection sites. Thermal water, groundwater and river water were collected from locations near to each other, thus could not be shown separately. F---F indicates a fault line

flushing was 24 hours in order for isotopic equilibration between the flush gas and the sample to be attained. Platinum sticks were used as a catalyst for the hydrogen isotope measurements which shortened the equilibration time after flushing to only 6 hours. To avoid the vulnerability of the gas bench device to changes in temperature, a constant room temperature was maintained at 20°C. Helium was used as a carrier gas. The reference gas precision for $\delta^{18}O$ and δD was 0.05 ‰ and 0.6‰, respectively.

## 4. RESULTS

The mean values of the stable isotope analysis from thermal spring water, groundwater and surface waters analysed for this study are presented in Tables 2-5.

TABLE 2**:** Mean δD, $\delta^{18}O$ and d-excess values of thermal spring waters

| Location | Temp. ($^{O}$C) | δD (‰) | $\delta^{18}$O (‰) | d-excess (‰) | Description |
|---|---|---|---|---|---|
| Bakreswar Thermal Water* | 28 | -33.0 | -6.2 | 16.7 | *Thermal springs located in the state of West Bengal and Jharkhand* |
| Tantloi Thermal Water* | 29 | -35.9 | -6.4 | 15.0 | |
| Attri Thermal Water | 53 | -27.6 | -4.6 | 9.2 | *Thermal springs located in the state of Odisha* |
| Badaberena Thermal Water | 39 | -29.2 | -4.7 | 8.5 | |
| Bankhol Thermal Water | 42 | -39.1 | -6.0 | 9.1 | |
| Boden Thermal Water | 28 | -27.0 | -4.3 | 7.5 | |
| Deuljhori Thermal Water | 57 | -20.7 | -3.4 | 6.4 | |
| Magarmuhan Thermal Water | 36 | -21.5 | -2.6 | -1.1 | |
| Tattapani Thermal Water | 41 | -39.3 | -6.2 | 10.5 | |
| Tarabalo Thermal Water | 50 | -26.3 | -4.3 | 8.0 | |

* Isotopic data taken from earlier study by Kumar et al., 2011. Rest of the data shown is generated at the University of Iceland.

TABLE 3: Mean δD, $\delta^{18}$O and d-excess values of groundwater near thermal springs

| **Location** | **δD** (‰) | **$\delta^{18}$O** (‰) | **d-excess** (‰) | **Description** |
|---|---|---|---|---|
| Bakreswar groundwater* | -27.2 | -5.1 | 13.6 | *Groundwater near thermal springs located in the state of West Bengal and Jharkhand* |
| Tantloi groundwater* | -34.7 | -6.8 | 20.0 | |
| Attri groundwater | -29.5 | -4.7 | 8.0 | *Groundwater near thermal spring located in the state of Odisha* |
| Badaberena groundwater | -28.7 | -4.5 | 6.9 | |
| Bankhol groundwater | -25.7 | -3.8 | 4.5 | |
| Boden groundwater | -27.2 | -4.2 | 6.2 | |
| Deuljhori groundwater | -29.1 | -4.4 | 6.3 | |
| Magarmuhan groundwater | -26.8 | -3.9 | 4.1 | |
| Tattapani groundwater | -34.2 | -5.4 | 9.1 | |
| Tarabalo groundwater | -5.5 | 0.5 | -9.2 | |

* Isotopic data taken from earlier study by Kumar et al., 2011. Rest of the data shown is generated at the University of Iceland.

TABLE 4: Mean δD, $\delta^{18}$O and d-excess values of river water near thermal springs

| **Location** | **δD** (‰) | **$\delta^{18}$O** (‰) | **d-excess** (‰) | **Description** |
|---|---|---|---|---|
| Bakreswar river water* | -26.1 | -5.0 | 13.5 | *River water near thermal springs located in the state of West Bengal and Jharkhand* |
| Tantloi river water* | -29.1 | -5.7 | 16.6 | |
| Badaberena river water | -40.8 | -5.8 | 5.9 | *River water near thermal spring located in the state of Odisha* |
| Bankhol river water | -33.1 | -5.0 | 7.0 | |
| Boden river water | -24.0 | -3.7 | 5.6 | |
| Magarmuhan river water | -33.4 | -5.0 | 6.7 | |
| Tattapani river water | -29.3 | -4.6 | 7.7 | |

* Isotopic data taken from earlier study by Kumar et al., 2011. Rest of the data shown is generated at the University of Iceland.

TABLE 5: Mean δD, $\delta^{18}$O and d-excess values of precipitation events near thermal springs

| **Location** | **δD** (‰) | **$\delta^{18}$O** (‰) | **d-excess** (‰) | **Description** |
|---|---|---|---|---|
| Bakreswar* | -- | -- | -- | *Data for precipitation events for the state of West Bengal and Jharkhand not available* |
| Tantloi* | -- | -- | -- | |
| Precipitation Event 1 | 7.43 | -0.15 | 8.63 | *Rainwater near thermal spring located in the state of Odisha* |
| Precipitation Event 2 | 7.16 | -0.08 | 7.80 | |

* Isotopic data taken from earlier study by Kumar et al., 2011. Rest of the data shown is generated at the University of Iceland.

### 4.1 The Bakreswar and Tantloi area

The δD and $\delta^{18}$O values of the Bakreswar thermal springs vary from -37.7 to -25.2 and -7.4 to -4.8 ‰, respectively (Kumar et al., 2011). The d-excess values for these thermal springs also show a wide variation and range between 9.9 and 21.8‰. On the other hand, the Tantloi thermal springs show a slightly less variation in δD, $\delta^{18}$O and d-excess values, which range between -37.7 and -32.8‰, -6.9 and 6.0‰ and 10.9 and 19.2‰, respectively. The mean values are shown in Table 2, whereas Figure 12 shows all the available data. Also shown on Figure 12 are the GMWL (Craig, 1961) and the LMWL defined by Kumar et al. (2011).

Results for the three groundwater samples obtained for the Bakreswar area for δD, $\delta^{18}$O and d-excess values range from -29.3 to 23.8‰, -5.4 to -4.6‰, and 13 to 14‰ respectively, (Kumar et al., 2011) For the Tantloi area, only one groundwater sample is reported (Kumar et al., 2011) with the values of -34,7 ‰, -6,8‰ and 20‰ for δD, $\delta^{18}$O and d-excess, respectively (Table 3). δD, $\delta^{18}$O values of all the water samples from Bakreswar area are shown in Figure 12.

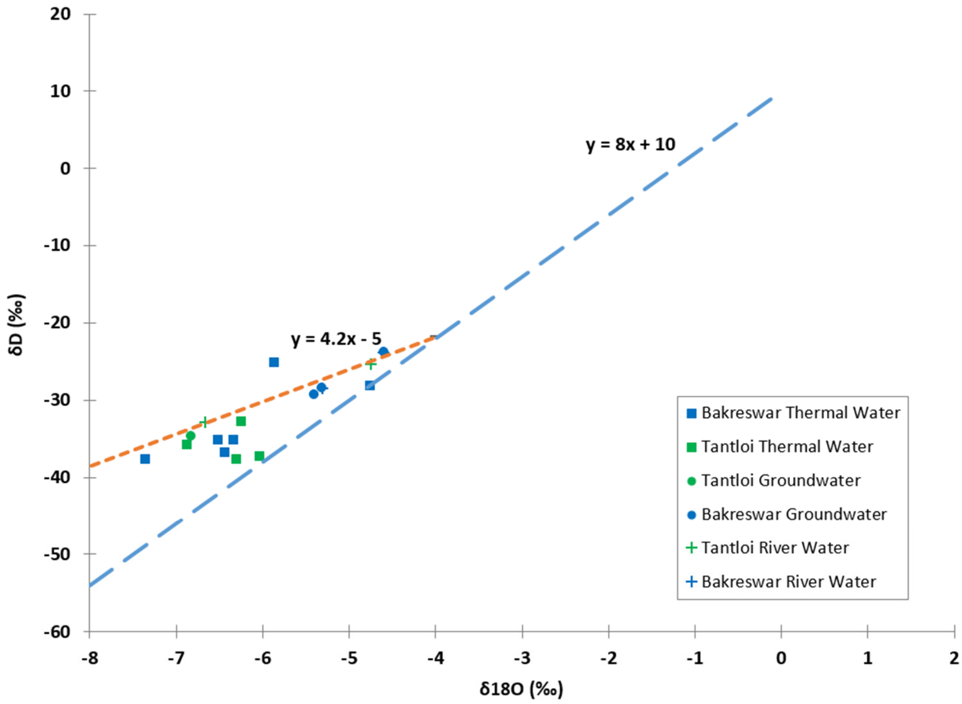


FIGURE 12: Plot showing the position of Bakreswar and Tantloi thermal waters with reference to the GMWL, and LMWL as defined in Figure 6

Two river water samples from Bakreswar and Tantloi were considered. The δD and $\delta^{18}O$ values for the Bakreswar river water range between -28.5 to 23.8‰ and -5.3 to -4.6‰, respectively, with d-excess values ranging between 13 and 14‰. Similarly, for the Tantloi river water the values range between -32.9 and -25.3‰ and -6.7 to -4.8‰ for δD and $\delta^{18}O$, with d-excess values ranging between 12.7 and 20.5‰ (Kumar et. al., 2011). The mean values for the river waters are given in Table 4. The isotopic values of the river samples are plotted on Figure 12.

## 4.2 Odisha

The mean values for the isotopic results for the thermal springs at Odisha are shown in Table 2 and all analyses for the thermal waters are plotted on Figure 13.

The thermal springs at Attri, Badaberana, Tarabolo and Boden show similar values, where the Attri thermal springs δD and $\delta^{18}O$ values range from -28.5 to -26.7‰ and -4.7 to -4.6‰, for δD and $\delta^{18}O$ respectively, and the d-excess values range between 8.7 to 10.0‰. Badaberena thermal springs show similar values ranging from -30.4 to -28.3‰, -4.9 to 4.4 ‰ and 6.7 to 9.9‰, for δD, $\delta^{18}O$ and d-excess, respectively. Boden thermal springs also have values in similar range where δD, $\delta^{18}O$ and d-excess values range from -27 to -26.8‰, -4.28 to -4.32‰ and 7.2 to 7.8‰ respectively and Tarabalo thermal springs also show similar values where δD, $\delta^{18}O$ and d-excess values ranges from -26.6 to -26.0‰, -4.4 to -4.1‰ and 6.5 to 9.1‰, respectively.

Lighter δD and $\delta^{18}O$ values are observed at Bankhol and Tattapani where for the former the range is from -39.2 to -38.9‰, -6.0 to -6.04‰, and 8.8 to 9.1‰ for δD, $\delta^{18}O$ and d excess respectively, and for the latter the δD, $\delta^{18}O$ and d-excess values range from -39.5 to -39.1‰, -6.3 to -6.2‰ and 10.51 to 10.43‰, respectively.

Dulijhari thermal springs show the highest δD values of -21.3 to -20.3‰, $\delta^{18}O$ values range between -3.5 and -3.3‰ and d-excess values from 5.9 to 7.3‰. Magarmuhan thermal waters show the biggest

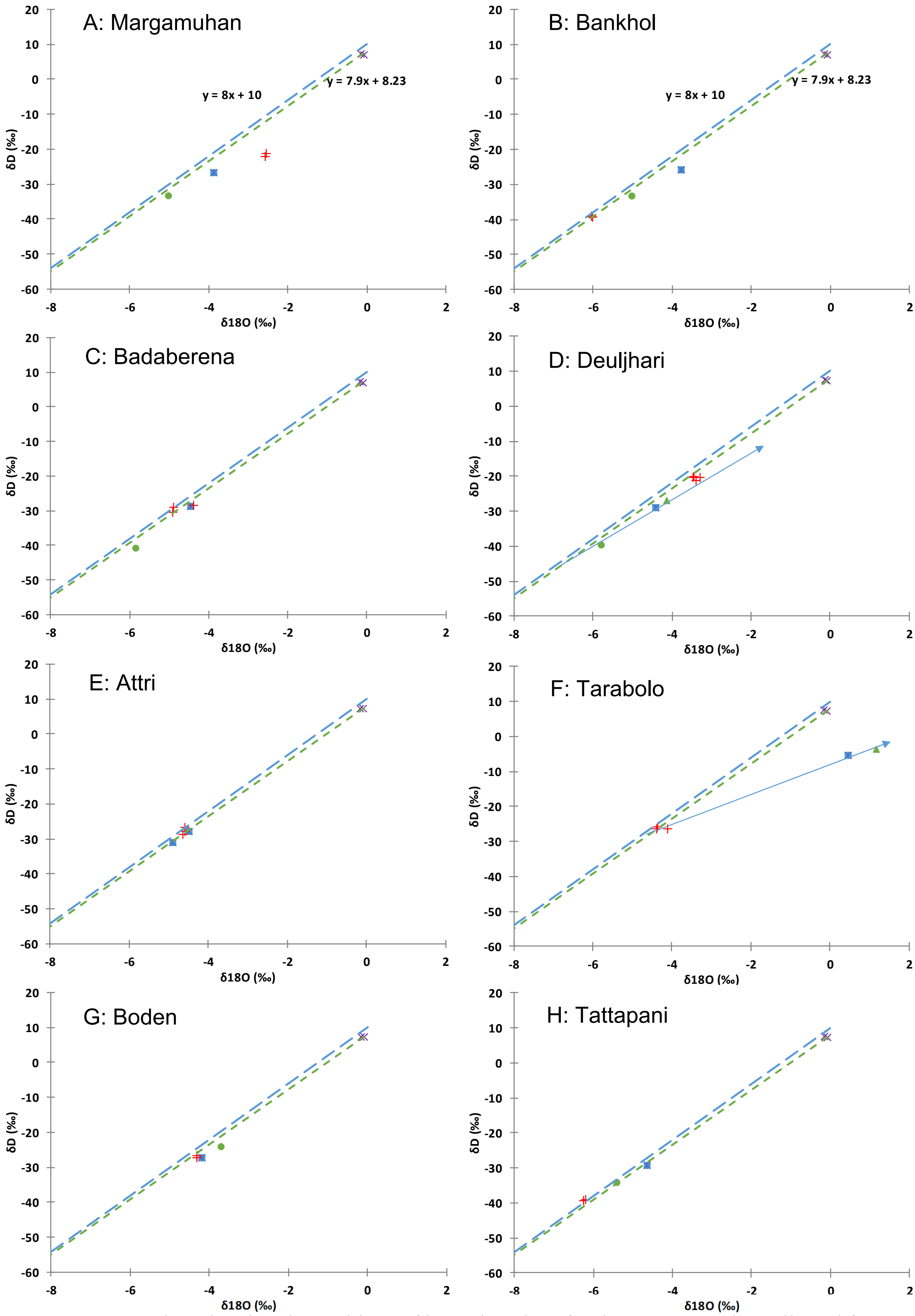


FIGURE 13: Plots showing the positions of isotopic values for the water samples collected from Odisha with reference to the GMWL and LMWL (Craig, 1961; Kumar et al., 2010)

Legends: ✕ Rainwater, ✚ Thermal water, ■ Groundwater, ● River water, ▲ Cold spring water variation from the MWL with δD, $\delta^{18}O$ and d-excess values from -21.9 to 21.2‰, -2.6 to -2.5‰ and -1.2 to -0.9‰, respectively.

Only one sample was collected from the Badaberena, Bankol, Boden, Magarmuhan and Tapatani groundwater in the Odisha area and two samples from the Attri groundwater. Results are shown in Table 3 and Fig. 13. The δD and $\delta^{18}O$ values for the groundwater samples collected from Attri range from -31.1 to -27.8 and -4.9 to -4.5 respectively, with d-excess values ranging between 8.0 and 8.2.

Samples from five rivers were collected for isotopic analyses from the Odisha region (Table 4 and Fig. 13). The river samples range in δD from -24 to -40.8‰, in $\delta^{18}O$ from -3.7 to -5.8‰, with d excess values ranging from 5.6 to 7.7‰.

The samples from the two precipitation events from the state of Odisha were collected on 25.7.2018 and 28.7.2018. These sample were measured for isotopic composition. The δD values ranged from 7.16 to 7.43‰ and $\delta^{18}O$ from -0.08 to -0.15‰, with d-excess values ranging from 7.80 to 8.63‰.

The d-excess values for the Odisha samples are shown on Figure 14 against the respective $\delta^{18}O$ values. The d-excess for the GMWL (10) and the LMWL (8.23) (Kumar et al., 2010) are also shown on the figure.

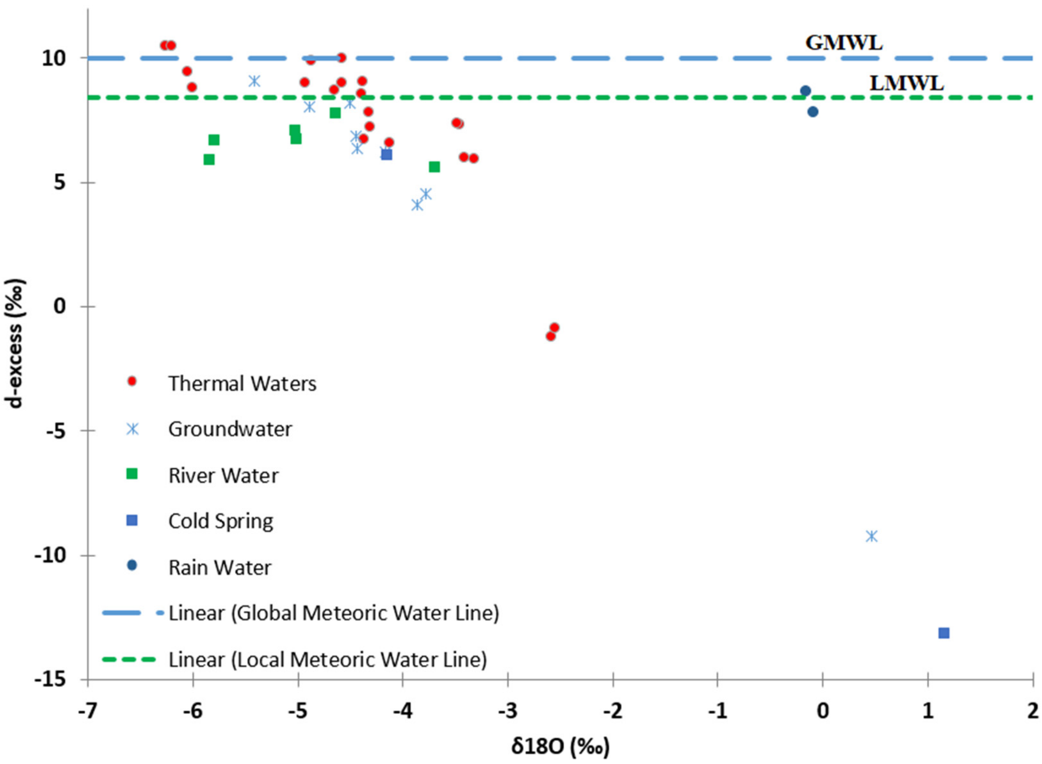


FIGURE 14: d-excess vs $\delta^{18}O$ plot for thermal and non-thermal water samples collected from Odisha

## 5. DISCUSSION

All the isotopic data considered in this study were compared with reference to the GMWL (Craig, 1961), and the LMWLs as defined by Kumar et al. (2010). The rain water samples collected from the state of Odisha fall on the LMWL as defined by Kumar et al. (2010).

### 5.1 Bakreswar and Tantloi geothermal areas

The isotopic characteristics of the Bakreswar and Tantloi thermal waters are shown on Figure 12 in comparison with the LMWL (Kumar et al., 2011) and GMWL (Craig, 1961). Most of the thermal water samples from Bakreswar and Tantloi plot to the left of the global water line and between the global and LMWLs. Two of the samples fall above the LMWL while two of the samples fall on the GMWL. It is not common that water plots left of the GMWL. It is suggested that this can be explained by recycled moisture due to precipitation of locally evaporated and condensed water from the nearby areas. In addition to several small water bodies, the Bakreswar dam is in vicinity of the thermal spring area. Another dam, the Nachan dam is also located within 10 km from the thermal spring area. The evaporation of rain water collected in these reservoirs may produce depleted water vapours as compared to the primary rain/meteoric water produced by evaporation of ocean water. It is also possible that due to prolonged water-rock interaction at low temperatures, the water sample may fall on the left of the GMWL. The wide spread of the thermal waters from the GMWL indicates that a varying percentage of local vapour contributed to the precipitation. Systemically lower $\delta D$ and $\delta^{18}O$ values obtained in the thermal waters as compared to the non-thermal waters (Table 2 & 3) and placement of two thermal water samples on the GMWL further indicates that the thermal water is derived from precipitation. Thus, the genesis of the thermal waters is attributed to meteoric origin. The absence of a substantial oxygen shift in the thermal waters clearly indicates that the possibility of an isotopic exchange with the surrounding rocks/sediments is limited in these springs. Additionally, high helium and radon gas concentrations observed in the thermal waters of Bakreswar and Tantloi springs in earlier studies suggest a helium and radon gas input from great depth. In a few studies conducted in the same area, high chloride and Na + K content has been reported, explained by prolonged rock-water interaction (Singh et al., 2015). Minerals such as mica and apatite present in the granitic host rocks have been suggested as the source of these elements in the geothermal waters (Savage et al., 1987).

### 5.2 Geothermal clusters of the state of Odisha

For the sake of discussion the thermal springs of Odisha are classified into three categories based on their geographical locations and their relationship with the structural features of the area; (i) the thermal springs located on the northern edge of the graben (or northern horst), which includes the thermal springs of Magarmuhan, Bankhol and Badaberena; (ii) the Deuljhori, Tarabalo and Attri thermal springs that are located on the southern edge of the graben (or southern horst); and (iii) the Tattapani and Boden thermal springs that are also located on the southern horst but are far away from the fault zone.

#### 5.2.1 Geothermal areas located on the northern edge of the graben

(a) *Magarmuhan:* The river water (i.e. surface water) is the lightest among all the water samples collected from this area and falls slightly below, but close to the meteoric water line. This indicates limited evaporation of the rainwater during its travel from the catchment area to the river and further during the downstream flow. The increased $\delta D$ and $\delta^{18}O$ values in the groundwater indicate that during the infiltration process, some degree of evaporation has taken place, which leads to the enrichment of heavier isotopes in the groundwater. The degree of evaporation further increases when the heated groundwater comes to the surface in the form of thermal springs at Magarmuhan. There is a general increase in the degree of evaporation from river to groundwater to the thermal waters as shown in Figure 13A.

(b) *Bankhol* is close to Magarmuhan and the river water at Bankhol has almost identical isotopic values as the river water at Magarmuhan (Figure 13B). Their proximity and similar isotopic values indicate that both these rivers either draw water from the same catchment or their catchment areas are very close to each other. Like Magarmuhan, here the river water also falls close to the LMWL which indicates very limited (or almost negligible) evaporation. The groundwater, however, shows some degree of evaporation and becomes relatively heavier. It is interesting to note that the thermal water is lighter than the river water in the area. The thermal water discharge having lighter isotopic composition than the surface water/groundwater is possible under two scenarios; (i) either the geothermal reservoir has such a high temperature that it is mainly producing steam which is condensed during its ascent or (ii) the thermal water has a lighter water source. The reservoir temperature, measured using chemical geothermometry on the Bankhol thermal waters, indicates that the reservoir temperature ranges between 100 and 110°C (unpublished data from a PhD student). At such a low temperature, the production of significantly large vapour fraction is not possible and thus the lower isotopic values assigned to the condensation of steam does not seem convincing. Further, the temperature of the thermal water discharge at Bankhol is 42°C. It is interesting to note that the isotopic characteristics of the Bankhol thermal springs are very similar to the Badaberena river water which flows in the adjoining area (Tables 2 and 3). It is geologically well established that the area is structurally highly disturbed and, in addition to the major faults running in the East-West and North-South directions, there exists several fractures that are oriented in the NE-SW direction (Behera et al., 2004). The striking isotopic similarity between the Bankhol thermal water and Badaberena river water supports the possibility of water from Badaberena river water seeping down through the fault structure and being intercepted by another set of fractures or joints to supply water (at least a significant portion) to the Bankhol thermal springs.

(c) *Badaberena:* The river water at Badaberena is much lighter than the other river waters on the northern edge of the horst (Table 4). The Badaberena river water and the groundwater falls very close to the GMWL/LMWL, indicating a very limited evaporation of rainwater before it becomes part of the surface or groundwater system (Figure 13C). The river water, being in direct contact with the atmosphere, shows slightly higher evaporation as compared to the groundwater, which is reflected in the form of a higher deviation from the GMWL/LMWL. The Badaberena thermal water falls exactly on the GMWL/LMWL. This suggests that the rainwater infiltrates quickly through the fractures without significant evaporation and there is no isotopic exchange between the infiltrating rainwater with the surrounding host rock until it appears again on the surface as thermal discharge.

### 5.2.2 Geothermal areas located on the southern edge of the graben

(a) *Deuljhori:* The river water at Deuljhori is as depleted in heavier isotopes as the Badaberena river water which lies on the northern edge of the graben (Table 4). None of the water samples from the Deuljhori area falls on the meteoric water line (Figure 13D). This indicates that the water samples have undergone some degree of evaporation. The placement of the Deuljhori river water, groundwater, cold spring water and the thermal water on a straight line clearly suggests an increasing degree of evaporation in the same order after the rainwater falls on the surface. The water from the Deuljhori thermal springs is isotopically the heaviest water collected from all the thermal springs spread across the state of Odisha. This may be due to their relatively higher temperature (53-57°C, Table 2) which may lead to a higher depletion of lighter isotopes or enrichment of the heavier isotope in the thermal waters.

(b) *Attri*: The geothermal area is located exactly on the top of the main E-W trending fault (Figure 11). The presence of faults and fractures provides conduits for quick infiltration of the rainwater, thus minimizing the time available for evaporation to take place. The placement of both the thermal and groundwater water samples on the GMWL/LMWL and their similar isotopic signature supports the quick infiltration of rainwater without any significant evaporation (Tables 2 & 3, Figure 13E). Further, the presence of prominent fractures facilitates (i) deeper circulation leading to more heating, and (ii) faster ascent leading to less cooling of the thermal waters. The temperature of the thermal discharge at Attri ranges between 50 and 56°C which is among the highest temperatures reported from the thermal springs in the state of Odisha.

(c) *Tarabalo:* The isotopic characteristics of Tarabalo thermal spring are similar to that of the Attri thermal springs (Table 2, Figure 13F). Such striking isotopic similarities indicate that the thermal springs in both areas are fed by the same water source. The proximity of Tarabalo and Attri and the presence of numerous joints on the southern part of Mahanadi graben makes this possibility more likely (Kumar et al., 2007).

### 5.2.3 Geothermal areas located on the southern edge of the graben but away from the fault zone

(a) *Boden:* The groundwater and the thermal waters of the Boden area fall close to each other and close to the GMWL/LMWL (Figure 13G). This indicates that the groundwater is circulating as thermal water without any appreciable change in its isotopic characteristics. Further, the thermal waters have only 2-3°C higher temperature than the groundwater. This hints to a shallow depth of water circulation. The Boden thermal spring area does not lie in the faulted zone, thus, there are not many fractures in the area. These conditions do not favour the deep and quick circulation of water.

(b) *Tattapani:* Like Boden, the groundwater and the thermal water of the Tattapani area also falls on the GMWL/LMWL though considerably more depleted (Figure 13H). This confirms that the origin of the groundwater and the thermal waters is local precipitation. The river water collected from the Tattapani area, however, shows a slight deviation from the meteoric water line, which reflects the effect of evaporation from the surface water body.

The d-excess values are useful to study evaporation on the original water sources as it becomes increasingly lower with a higher degree of evaporation. It is interesting to note that some of the thermal waters have d-values close to 10 while others show values closer to the LMWL (8.23) and others still lower values suggesting that those samples have undergone evaporation (Figure 14). A similar trend is observed for the groundwater and cold springs. The river water also shows the isotopic signature of a slight evaporation.

## 6. CONCLUSIONS

The study provides a comprehensive understanding of the origin of geothermal waters located along the east coast of India, which includes the Bakreswar thermal springs of West Bengal, Tantloi thermal springs of Jharkhand and eight thermal springs located in the adjoining state of Odisha. Stable isotopic data for Bakreswar and Tantloi was incorporated from Kumar et al. (2011), while isotopic data for the thermal springs of Odisha was generated by analysing thermal water samples. Based on the isotopic data, it is concluded that evaporation from reservoirs and ponds located close to the Bakreswar and Tantloi springs plays an important role in determining the isotopic characteristics of precipitation in the area which in turn affects the surface water, groundwater and thermal waters. Accordingly, the isotopic composition of the Bakreswar and Tantloi thermal waters is controlled by different proportions of recycled moisture. For the thermal water of Odisha, the isotopic signature indicates that the source of the thermal waters is local precipitation, reflected in the Badaberena and Deuljhori river waters. Some springs show mixing with more enriched precipitation e.g. the measured precipitation events. Most of the thermal springs plot on, or close to the LMWL defined by GNIP data at the Sagar station (Kumar et al, 2010). Some evaporation is detected in the Deuljhori thermal springs and considerable evaporation in the Magarmuhan springs. The surface water and the groundwater show different degrees of evaporation. The absence of the +ve oxygen shift clearly indicates insignificant rock-water interaction. The isotopic composition of the two precipitation events measured in Odisha fall on the Sagar meteoric water line (Kumar et al., 2010), indicating that the line may also be used as the LMWL for the Odisha region. However, some of the thermal water fits well with the GMWL (Craig, 1961) demonstrating that more precipitation samples from the Odisha region are needed to describe the Odisha precipitation line in detail.

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