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Isotopic Characteristics of East Indian Geothermal Water

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ABSTRACT

Long term sustenance of a geothermal power plant depends largely on the availability of geothermal water, which in turn is related to its origin. In this study, an attempt has been 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 were considered. New isotopic data ($\delta^{18}O$, δD) for the thermal area of Odisha, including thermal water, groundwater, river water, cold springs, and precipitation events were obtained for this study. Oxygen and hydrogen isotopic ratios demonstrate that the thermal water of Odisha is of local meteoric origin. Some of the thermal water samples show substantial evaporation. The absence of a significant oxygen shift and relatively low TDS values in the thermal water indicate a limited rock-water interaction. Six of the total eight thermal spring areas of Odisha are located along the northern and the southern boundary of the Mahanadi graben. Their position along the graben boundary helps the surface water to 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 well the Local Meteoric Water Line (LMWL) defined from the GNIP station at Sagar, indicating that the line may also be used for the Odisha region. However, some of the thermal water follow the Global Meteoric Water Line (GMWL) demonstrating that more precipitation samples from the Odisha region are needed to describe in detail the Odisha local precipitation line.

The thermal springs of the state of West Bengal and Jharkhand are highly saline, however, their isotopic signatures clearly indicate that the thermal water is of meteoric origin, and higher salinity is attributed to prolonged rock-water interaction. The isotopic signature of the non-thermal waters in these regions show a negative shift from the GMWL indicating that the non-thermal water has a significant fraction of recycled moisture.

1. INTRODUCTION

Geothermal energy is one of the unconventional energy resources that is, clean, sustainable and is the most reliable base load type of energy (Glassley, 2014). Unlike solar, wind and hydropower energies, it does not fluctuate due to seasonal changes. Further, it is also envisaged that the widespread utilization of geothermal energy can provide a viable solution to mitigate the problem of climate change by significantly reducing greenhouse gas emissions (IPCC, 2008). The advantages associated with the geothermal energy are driving the global communities to explore new geothermal resources and maximize the utilization of already existing resources in a sustainable manner. According to the recent International Energy Agency (IEA) report, the per-capita CO_2 emission for India is 1.7 ton/year (IEA, 2018). With ever increasing energy demand for its growth, India presently is experiencing two big challenges: i) meeting its energy demand and ii) cut CO_2 emission. There is no doubt that with conventional energy resources both challenges cannot be addressed simultaneously. This 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 harness the geothermal resources. In this regard, a detailed geological survey involving various geophysical and geochemical techniques have been conducted across the country (Thussu, 2002). Potential geothermal areas have been demarcated and national policy has been drafted to exploit these geothermal fields (Ministry of New and Renewable Energy, Govt. of India). 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 heat source (i.e. reservoir depth) and its temperature are considered as the most important factors. However, once the plant is established, the sustenance of the power plant largely depends on the quantity and chemistry of the geothermal fluids which in-turn depends upon the origin of 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 (Chandrasekharam and Chandrasekhar 2010a, b; Shanker et al., 1991; Singh et al., 2014).

Few studies that have been conducted to determine the origin of thermal water, in the western, eastern, northern and central part of India show different results in terms of the origin of thermal water and their interaction with the reservoir rocks (Giggenbach, 1981). The west coast geothermal belt (includes west coast geothermal province and Gujarat-Rajasthan geothermal province) has around 60 geothermal springs (Dowgiallo, 1977; Sarolkar et al., 2005). The isotopic analysis of these thermal water involves O, H, C, S, B, and Sr (Muthuraman et al., 1981). The results of these studies indicate that the thermal waters are not fed by recently recharged rainwater, as they have depleted deuterium content in comparison to the present-day precipitation. The tritium values also confirm their non-modern meteoric origin. Further, the significant $\delta^{18}O$ shift observed in these water 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 few selected geothermal springs occurring 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 northern (Puga and Manikaran geothermal areas) and central (Tattapani geothermal area) part of India, indicate different results. The thermal springs of the Puga geothermal area show $\delta^{18}O$ shift of 1.5‰. This is mainly attributed to rock-water interaction occurring at the subsurface. The shift may also indicate a higher temperature at the deeper zones. In case of 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). The investigations in case of Tattapani geothermal area indicates 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).

The aim of the present work is to study the origin of geothermal fluids of the thermal springs located in eastern India by stable water isotope research.

2. STUDY AREA

India has nearly 400 thermal springs that are distributed in various geothermal provinces across the country (Zimik et al., 2017). Ten geothermal provinces namely 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 have been identified based on their tectonic history, tectonic structure, heat flow values and geothermal gradients (Thussu 2002; 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.

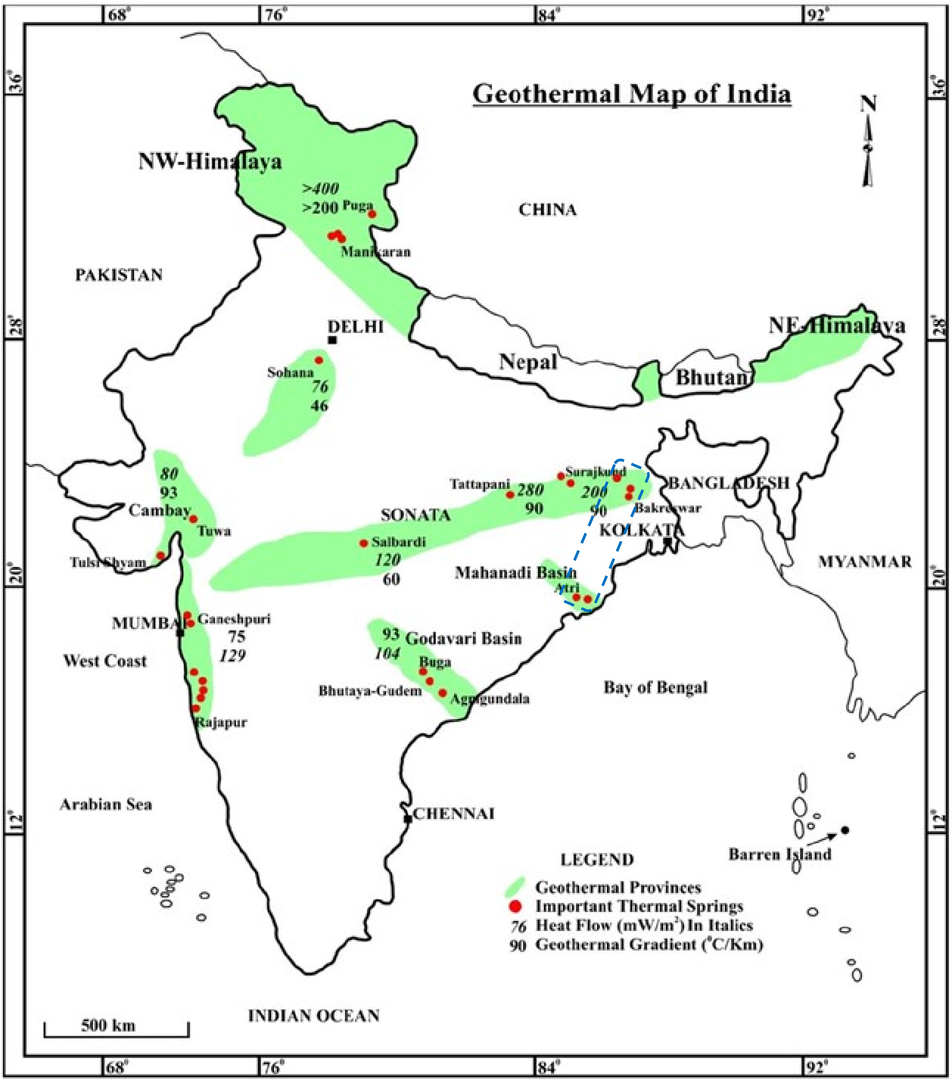

Figure 1: Geothermal provinces of India (Chandrasekharam and Chandrasekhar 2010a)

In the present study, the geothermal areas located along the eastern coast of India have been considered. Their locations are, shown within the blue box on Figure 1. The east coast geothermal areas include 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. The Odisha thermal spring clusters are named after the location of their occurrence as Attri, Magarmuhan, Bankhol, Boden, Taptapani, Tarabalo, Deuljhori and Badaberena (Figure 3).

2.1 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 45-71°C. The springs occur in an E-W direction similar to the trend of Gondwana sedimentary basin in the central part of Chotanagpur Gneissic Complex. Another thermal spring cluster, named as Tantloi (24°23′00″N: 87°16′00″E) is located 20 km NW of Bakreswar in 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 2).

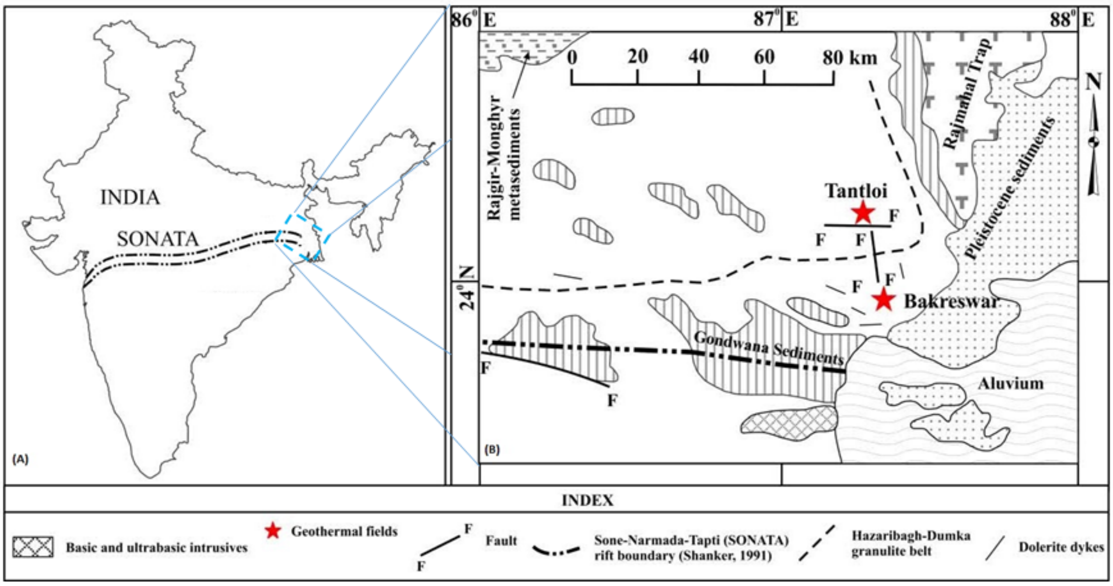

Figure 2: (A) Map of India showing the SONATA lineament, (B) Regional geological setting and location of Bakreswar and Tantloi thermal springs (after Singh et al., 2015).

2.2 Geothermal clusters of the state of Odisha

The state of Odisha, which has an area of about 1,55,842 km^2 lies along the east coast of India within latitudes 17°48' - 22°34' North and longitude 81°24' - 87°29' East. As demonstrated on Figure 3 it has 8 distinct thermal areas which all belong to the Mahanadi Geothermal Province that are of Archaean/Pre-Cambrian age. At some of these thermal areas such as Attri, Magarmuhan, Bankhol, Boden and Taptapani, 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 areas range from 28 - 58ºC. However, in an earlier study, the maximum temperature of 67ºC was reported from a thermal spring in the Attri area (Singh et al., 1995). A few studies done on the hydrology and geochemistry of thermal water indicates that the chemistry of the thermal water does not change seasonally with the on-set and off-set of the summer monsoon (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 Taptapani lies within the Eastern Ghats Supergroup; (ii) Magarmuhan, Bankhol and Badaberena within the Iron Ore Super Group (IOSG); and (iii) Boden lies within the Vindhyan Supergroup. The Mahanadi and Godavari rift system divide the Eastern Ghat Belt (EGB) into the northern, central and the southern segments, of which the northern and part of the central segment fall within the boundaries of the state of Odisha (Sarkar and Nanda 1998). 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 river Mahanadi, which flows along a NW-SE fault in the area. One fracture trending NW-SE to WNW-ESE runs parallel to the Mahanadi lineament and passes very close to the Deuljhori thermal springs (Thussu, 2002).

3. SAMPLE COLLECTION AND METHODOLOGY

The present isotopic study is twofold (i) we present new isotopic data from the geothermal areas of the state of Odisha, where water samples from thermal springs, rivers, cold springs, groundwater and rain events were collected., (ii) we consider an earlier study of the Bakreswar and Tantloi geothermal areas by Kumar et al., (2011), where δD and δ^{18}O data from 6 thermal springs at Bakreswar and 4 thermal springs at Tantloi as well as samples from cold groundwater and surface water are reported.

The samples were collected in pre-washed high-density polyethylene (HDPE) bottles. The water samples were filtered in the field with 0.45µm nylon filter (25 mm diameter) and stored at low temperature in airtight bottles until further analysis. Each sampling site was geo-referenced using a Garmin Global Positioning System (GPSMAP-76S) instrument. Various physico-chemical properties including pH, temperature, and conductivity were measured in the field during the collection of the samples. The tube wells were pumped for 5 minutes to clear the water standing in the tubes before samples were collected.

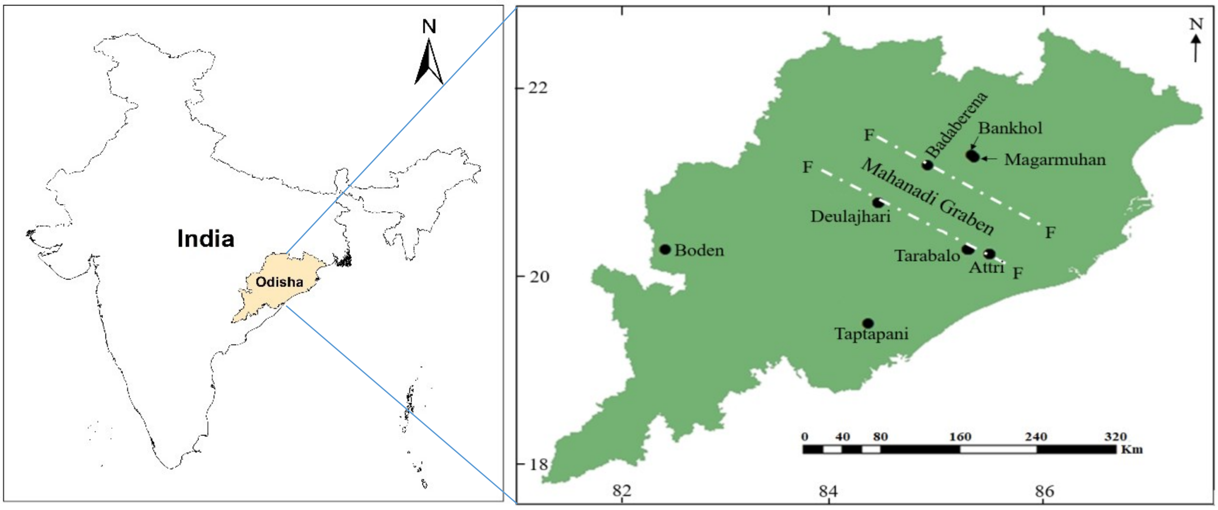

Figure 3: (A) Map of India showing the state of Odisha, (B) Location map indicating sample collection sites. Thermal water, groundwater, and river water were collected from the locations very near to each other, thus could not be shown separately. F---F indicates the fault line.

3.1 Analytical Techniques

In the present study, hydrogen isotope ratio ($^{2}H/^{1}H$) and oxygen isotope ratio ($^{18}O/^{16}O$) of the water samples were determined using Isotope Ratio Mass Spectrometer (IRMS), Delta V Advantage (ThermoFisher) at the Reykjavik water stable isotope laboratory, Iceland during the summer of 2018. The equipment is designed to measure the 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. 200µL samples were placed in 12mL vials and flushed with a He gas mixture. For hydrogen isotope measurements, 98% He and 2% H_2 was used and for oxygen isotope measurement 99.7% He and 0.3% CO_2 was used as the flush gas. For oxygen, the reaction time after 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 AND DISCUSSIONS

4.1 Bakreswar and Tantloi geothermal areas

The isotopic characteristics of the Bakreswar and Tantloi thermal waters are shown in Figure 4 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 GMWL and between the global and local meteoric water lines. Two of the samples fall above the LMWL while two of the samples fall on the global meteoric water line. This can be explained by moisture recycling, which happens due to precipitation of locally evaporated and condensed water from the nearby areas. In addition to several small water bodies, a dam known as the Bakreswar dam is located in the vicinity of the thermal spring area. Another dam known as the Nachan dam is also located within 10 km from the thermal spring area. The evaporation of rainwater collected in these dams may produce depleted water vapor as compared to the primary rain/meteoric water produced by evaporation of the ocean water. The spread of the thermal waters from GMWL indicates that the local vapor contributes to the primary precipitation to a varying degree. Systemically lower δD and $\delta^{18}O$ values obtained in thermal water as compared to the non-thermal waters and placement of two thermal water samples on the GMWL, further indicates that the thermal water is derived from precipitation. Thus, the genesis of thermal water is attributed to meteoric origin. The absence of a substantial oxygen shift in the thermal waters clearly indicates that the possibility of isotopic exchange with the surrounding rocks/sediments is limited in these springs. Additionally, high Helium and Radon gas concentrations observed in the thermal water of Bakreswar and Tantloi springs in earlier studies suggest an inflow of these gasses from great depths. In a few studies conducted in the same area, high chloride and Na+K content have been reported. Prolonged rock-water interaction has been identified as the dominant process for such enrichments (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). This interpretation, however, contradicts with the isotopes that suggest no oxygen shift and thus limited water-rock interaction.

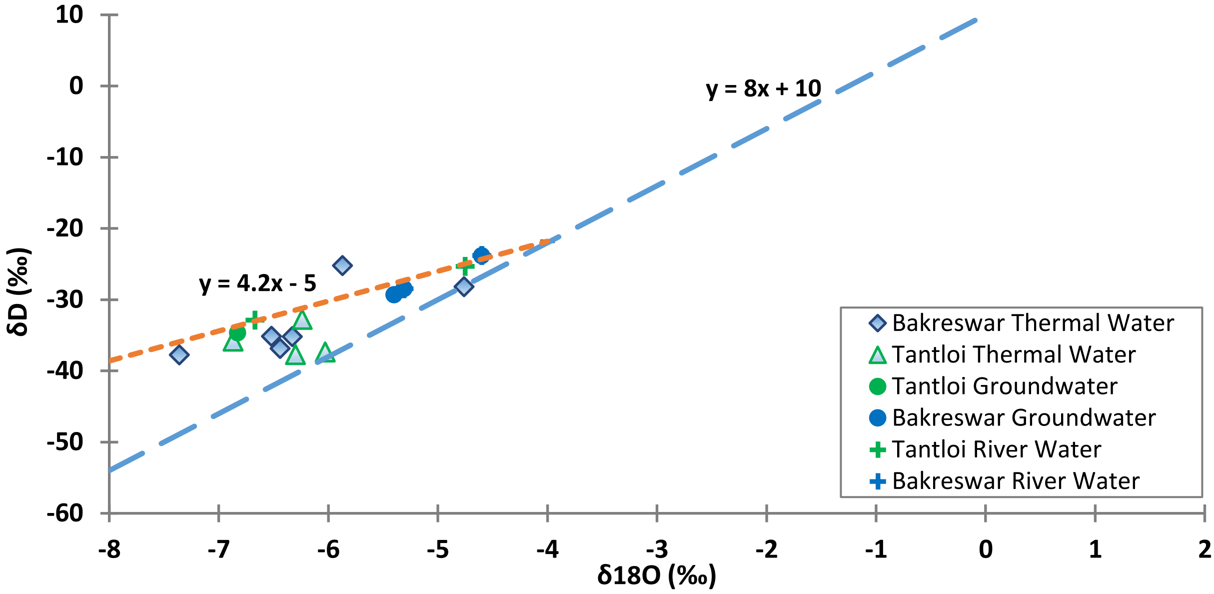

Figure 4: Plot showing the position of Bakreswar and Tantloi thermal waters with reference to GMWL and LMWL as defined by Craig (1961) and Kumar et al. (2011) for West Bengal and Jharkhand waters, respectively.

4.2. Geothermal clusters of the state of Odisha

The rainwater samples for two rain events were collected from a place near to Attri thermal springs which is ~ 50 km from the Bay of Bengal. Due to its proximity to Bay of Bengal and local wind patterns, most of the moisture has been derived from the Bay of Bengal and thus the rainwater samples do not show isotopic depletion and d^{18}O values remain close ~0‰. It must be emphasized however that these precipitation samples reflect only isotopic composition of 2 rain events and may not be representative of the local mean annual precipitation.

The origin of the Mahanadi river is mainly from the rainfall in the catchment area which lies in the state of Chhattisgarh (i.e. central-west India) and partly from the western Odisha. The rainfall in the catchment area is dominantly derived from the water vapors originating from the Arabian sea and a relatively smaller vapor fraction from the Bay of Bengal. The vapors from the Arabian sea have to travel thousands of kilometers before raining in the catchment area, thus becomes highly depleted as compare to the vapors derived from the Bay of Bengal. The same is reflected in the form of significant isotopic depletion in Mahanadi and its tributaries. Studies have found that the Mahanadi river water near Cuttack (~ 100 km inland from the Bay of Bengal) shows d^{18}O values of -6‰ (Lambs et al., 2005). The isotopically depleted rainwater feds the rivers and the groundwater, thus both show isotopically depleted characteristics.

The thermal springs of Odisha are classified into three categories based on their geographical locations and their relationship with structural features of the area, (i) the thermal springs located on the northern edge of the graben (or northern horst), which includes 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 Taptapani and Boden thermal springs that also are located on the southern horst but are far away from the fault zone (Figure 3). The isotopic data for individual springs is shown in Figure 5 with reference to GLWL as defined by Craig (1961) and LMWL as defined by Kumar et al., (2010) for Sagar station.

4.2.1 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 δD and δ^{18}O values in the groundwater indicate that during the infiltration process some degree of evaporation has taken place, which leads to 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 the river to groundwater to the thermal waters as shown in Figure 5A.

(b) Bankhol: Bankhol is very close to Magarmuhan and the river water at Bankhol has almost identical isotopic values as the river water at Magarmuhan (Figure 5B). 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. Similar to Magarmuhan, here also, the river water falls close to LMWL which indicates very limited (or almost negligible) evaporation. The groundwater, however, shows some degree of evaporation and becomes slightly heavier. Interestingly the thermal water is lighter than the river water in the area. 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 gets condensed during its ascent or (ii) the thermal water has a lighter water source. The reservoir temperature applying chemical geothermometry on Bankhol thermal waters indicate that the reservoir temperature ranges between 100-110^{O}C (unpublished data). At such a low temperature, production of significantly large vapor fraction is not possible and thus the lower isotopic values assigned to the condensation of steam do not seem convincing. Further, the temperature of the thermal water discharge

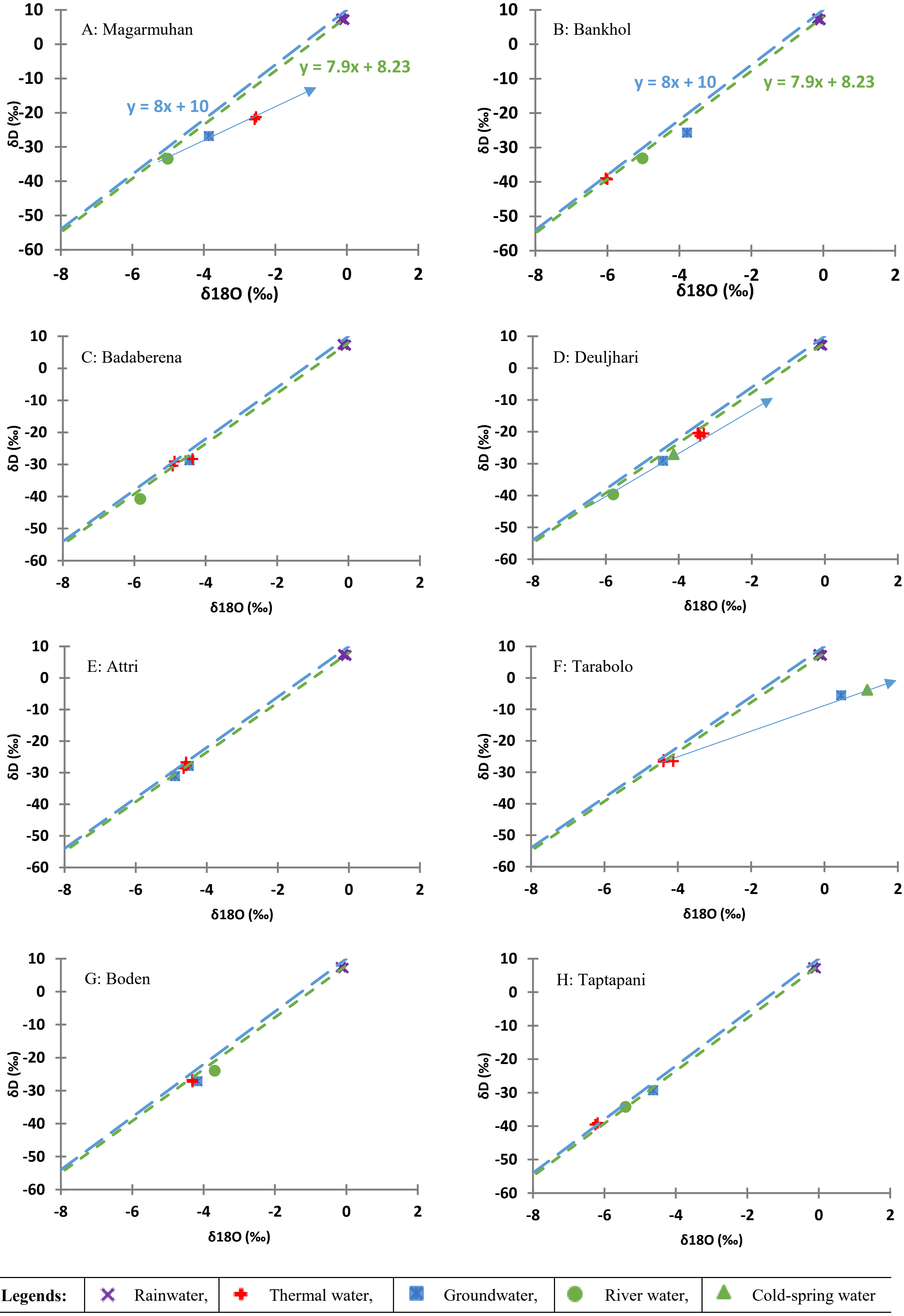

Figure 5 (A-H): Plots showing the position of the thermal water of Odisha with reference to GMWL (Craig, 1961) and LMWL (Kumar el al., 2010).

at Bankhol is 42 ^{O}C. It is interesting to note that the isotopic characteristics of the Bankhol thermal springs are very similar to the Badaberena river water (Figure 5C) which flows in the adjoining area. It is geologically well established that the area is structurally highly disturbed and in addition to the major faults running in East-West and north-south directions, there exists a number of fractures that are oriented in 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 %) 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. The Badaberena river water and the groundwater falls very close to the global/LMWL indicating very limited evaporation of rainwater before it becomes part of the surface or groundwater system (Figure 5C). The river water is in direct contact with the atmosphere show slightly higher evaporation as compared to the groundwater, which is reflected in the form of higher deviation from global/LMWL. The Badaberena thermal water falls exactly on the global/LMWL. This suggests that the rainwater infiltrates quickly through the fractures without significantly being evaporated and also there is no isotopic exchange between the infiltrating rainwater with the surrounding host rock while it appears again on the surface as thermal discharge.

4.2.2 Geothermal areas located on the southern edge of the graben

(a) Deuljhori: The river water at Deuljhori is as depleted as the Badaberena river water which lies on the northern edge of the graben. None of the water samples from Deuljhori area falls on the meteoric water line (Figure 5D). This indicates that the water samples have undergone some degree of evaporation. The placement of Deuljhori river water, groundwater, cold spring water and the thermal water on a straight line clearly suggests increasing degree of evaporation in the same order after the rainwater falls on the earth's surface. The water from Magarmuhan and Deuljhori thermal springs are isotopically the heaviest among the water samples collected from the thermal springs spread across the state of Odisha. This confirms a high degree of evaporation at Deuljhori which is comparable to the Magarmuhan thermal water.

(b) Attri: Attri geothermal area is located exactly on the top of the main E-W trending fault. The presence of faults and fractures provides conduits for quick infiltration of the rainwater, thus minimizes the time available for the evaporation to take place. The placement of both the thermal and groundwater water samples on the global/LMWL and their similar isotopic signature supports quick infiltration of rainwater without any significant evaporation (Figure 5E). Further, the presence of prominent fracture facilitates (i) deeper circulation leading to a higher temperature, and (ii) faster ascent leading to less cooling of the thermal waters. The temperature of the thermal discharge at Attri ranges between 50 to 56^{o}C which is among one of the highest temperature reported from the thermal springs of the state of Odisha.

(c) Tarabalo: The isotopic characteristics of Tarabalo thermal spring are similar to that of the Attri thermal springs (Figure 5F). Such striking isotopic similarities indicate that the thermal springs in both areas are fed by the same water source, supported by the proximity of Tarabalo with Attri and the presence of numerous joints on the southern part of the Mahanadi graben (Kumar et al., 2007). Considerable evaporation is observed in the groundwater, and cold springs (Figure 5F).

4.2.3 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 Boden area fall close to each other and also close to the global/GMWL/LMWL (Figure 5G). This indicates that the groundwater is circulating as the thermal water without any appreciable change in its isotopic characteristics. Further, the thermal water has only 2-3^{o}C higher temperature than the groundwater indicating a very shallow water circulation. The Boden thermal spring area does not lie in the faulted zone, thus, the presence of fractures are quite restricted in the area. These conditions do not favor deep and quick circulation of water.

(b) Tatapani: Similar to Boden, the groundwater and the thermal water of the Taptapani area falls on the GMWL/LMWL though considerably more depleted (Figure 5H). This confirms that the origin of the groundwater and the thermal waters is local precipitation. The river water collected from the Taptapani area, however, shows a slight deviation from the metric water line, which reflects the effect of evaporation from the surface water body.

5. 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. Based on the isotopic data it is concluded that evaporation from dams and ponds located close to the Bakreswar and Tantloi springs play an important role in determining 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 a different proportion of recycled moisture. In the case of the thermal water of Odisha, isotopic signature indicates that the source of the thermal waters is precipitation in the headway of Mahanadi river, as reflected in the Badaberena and Deuljhori river water. Some springs show mixing with more enriched precipitation. Most of the thermal springs plot on or close to the LMWL defined by GNIP data at the Sagar station. 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 +ve oxygen shift clearly indicates insignificant rock-water interaction. Isotopic composition of the two precipitation events measured from Odisha fall on the Sagar meteoric water line indicating that the line may also be used as LMWL for the Odisha region. However, some of the thermal water fits well with GMWL, demonstrating that more precipitation samples from the Odisha region are needed to describe in detail a local Odisha precipitation line.

REFERENCES

Behera L., Sain K., and Reddy P. R.: Evidence of underplating from seismic and gravity studies in the Mahanadi delta of eastern India and its tectonic significance. *Journal of Geophysical Research*, **109**, (2004), B12311, doi:10.1029/2003JB002764,

Chandrasekharam, D., and Chandrasekhar, V.: Energy independence through CDM using geothermal resources: Indian scenario, *Proceedings,* World Geothermal Congress (2010a), 1-5.

Chandrasekharam, D., and Chandrasekhar V.: Geochemistry of thermal springs of Orissa, India, *Geothermal Res. Counc. Trans.,* **34**, (2010b), 665-667.

Chatterjee, S., Sarkar, A., Deodhar, A.S., Biswal, B.P., Jaryal, A., Mohokar, H.V., Sinha, U. K., and Dash, A.: Geochemical and isotope hydrological characterization of geothermal resources at Godavari valley, India, *Environmental Earth Science*, **76**:97 (2017).

Chowdhury, I., Ray, B., and Ali, A.: Geology and mineral resources of Odisha, Geological Survey of India, *Miscellaneous Publication*, **30** (3), (2011).

Craig, H.: Isotopic variations in meteoric waters. *Science*, **133**, (1961), 1702-1703.

Dash, A., Palita, S.K., and Patra, H.K.: Physico-chemical analysis of thermal spring of Atri in the district of Khurda, Odisha, India, *International Journal of Chemical Sciences and Applications*, **4**, 2, (2013), 97-104.

Dowgiallo, J.: Hot springs of the west coast (Konkan) region, Maharashtra, *Unpublished UNDP report*. IND/73/008 UN Project, (1977).

Giggenbach, W.F.: Geothermal mineral equilibria, *Geochim. Cosmochim. Acta*., **45**, (1981), 393-410.

Giggenbach, W.F., Gonfiantini, R., Jangi, B.L., and Truesdell, A.H.: Isotopic and chemical composition of Parbati Valley geothermal discharges, NW-Himalaya, India, *Geothermics*, **12**, (1983), 199-222.

Glassley, W.E.: Geothermal energy: renewable energy and the environment, *Taylor and Francis*, Boca Raton, (2014), pp. 423.

IEA: Global Energy & CO_2 Status Report 2017, (2018) https://www.iea.org/publications/freepublications/publication/GECO2017 .pdf

IPCC: IPCC scoping meeting on Renewable Energy Sources-*Proceedings* (2008) pp.192. https://www.ipcc.ch/pdf/supporting-material /proc-renewables-lubeck.pdf

Kumar, P., Das, N.K., Mallik, C., and Bhandari, R.K.: Stable isotopes study on geothermal waters in eastern India, *Current Science*, **101**, 9, (2011), 1205-1209.

Kumar B, Rai SP, Kumar US, Verma SK et. al. : Isotopic characteristics of Indian precipitation. *Water Resource Research*, **46**, (2010), W12548. https ://doi.org/10.1029/2009W R0085 32

Kundu, N., Panigarahi, M.K., Sharma, S.P., and Tripathy, S.: Delineation of fluoride contaminated groundwater around a hot spring in Nayagarh, Orissa, India using geochemical and resistivity studies; *Environ. Geol.*, **43**, (2002), 228-235.

Lambs, L., Balakrishna, K., Brunet, F., Probst, J. L., : Oxygen and hydrogen isotopic composition of major Indian rivers: a first global assessment; *Hydrol. Process*., **19**, (2005), 3345–3355.

Lindal, B.: Industrial and Other Applications of Geothermal Energy, Except Power Production and District Heating, *UNESCO*, Geothermal Energy, Earth Sciences, **12** (1973).

Mahala, S.C.: Geology, Chemistry and Genesis of Thermal Springs of Odisha, India, *Springer*, (2019).

Majumdar, N., Majumdar, R.K., Mukherjee, A.L., Bhattacharya, S.K., Jani, R.A.: Seasonal variations in the isotopes of oxygen and hydrogen in geothermal waters from Bakreswar and Tantloi, Eastern India: implications for groundwater characterization, *J. Asian Earth Sci*., **25**, (2005), 269–278.

Muthuraman, K., and Mathur, P.K.: Experimental water/rock interaction studies and the thermal waters of the west coast of Maharashtra, India, *J. Geol. Soc. Ind*., **2**, (1981), 69–77.

Nagar, R.K., Vishwanathan, G., Sagar, S., and Sankaranarayanan, A.: Geological, geophysical and geochemical investigations in Bakreswar–Tantloi thermal field, Birbhum and Santhal Parganas districts, West Bengal and Bihar, India, *Proceedings of the Seminar on Geothermal Energy in India* (eds. Pitale, U. L. and Padhi, R. N.), Geological Survey of India Special Publication, **45**, (1996), 349-360.

Navada, S.V., and Rao, S.M.: Isotope studies of some geothermal waters in India, *Isotopenpraxis*, 27, (1991), 153-163.

Ramakrishnan, M.: Stratigraphy, sedimentary environment and evolution of the late Proterozoic Indravati basin, Central India, *Mem. Geol. Soc. India*, **6**, (1987), 139–160.

Reddy, D.V., Nagabhushanam, P., and Ramesh, G.: Turnover time of Tural and Rajwadi hot spring waters, Maharashtra, India. *Curr. Sci*., **104**, (2013), 1419-1424.

Sarkar, A. and Nanda, J.K.: Tectonic segments in the Eastern Ghats Precambrian mobile belt (Abs.), *Proceedings,* Dr. M.S. Krishnan Comm. National Seminar. Calcutta, (1998), 173–174.

Sarolkar, P.B.: Geochemical characters of Hot Springs of West Coast, Maharashtra State, India. *Proceedings,* World Geothermal Congress, (2005), 1-4.

Savage, D., Mark, R.C., Antoni E. Milodowski, I. G.: Hydrothermal alteration of granite by meteoric fluid: an example for the Carnmen ellies granite, United Kingdom. *Contributions to Mineralogy and Petrology*, **96**, (1987), 391–405.Shanker, R., Guha, S.K., Seth, N.N., Mathuraman, K., Pitale, U.L., Jangi, B.L., Prakash, G., Bandyopadhyay, A.K., and Sinha, R.K.: Geothermal Atlas of India, *Geological Survey of India, Special Publication*, **19**, (1991), pp 144.

Sharma, S.K.: Geothermal: a sustainable energy outlook for India, *Proceedings,* World Geothermal Congress, (2010), 1-4.

Singh, H.K., Chandrasekharam, D., Trupti, G., and Singh, B.: Geochemical Characteristics of Bakreswar and Tantloi Geothermal Province, India, *Proceedings,* World Geothermal Congress, (2015), 1-4.

Singh, H.K., Chandrasekharam, D., Trupti, G., and Singh, B.: Geochemical Investigations on Thermal and Cold Springs at Dumka District, Jharkhand, India, *Int. J. Earth Sci. Eng*., **7**,1, (2014), 190–194.

Singh, R.P., and Nabetani, S.:Resistivity structure of Puga geothermal field, *Proceedings,* World Geothermal Congress, (1995), 1-6.

Thussu, J.L.: Geothermal energy resources of India, *Geol. Surv. India, Spl. Pub*., **18**, 69, (2002), pp 210.

Zimik, H.V., Farooq, S.H., and Prusty, P.: Geochemical evaluation of thermal springs in Odisha, India, *Environmental Earth Science*, **76**:593, (2017).