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Evaluating the Fluid Chemistry and Isotope Signature of Thermal Waters from Ladakh, India

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ABSTRACT

India is actively involved in developing and utilizing clean energy, focusing on geothermal and solar resources. The union territory of Ladakh, part of the Trans-Himalayan geothermal province, holds significant geothermal potential, as evidenced by numerous active thermal springs. This study investigates the hydro chemical and isotopic signatures of thermal waters to understand their genesis, subsurface interactions, and geothermal viability. Eighteen thermal water samples were collected from three distinct thermal clusters in Ladakh, along with eight surface water samples (avg. temp. 12°C) and four groundwater samples (avg. temp. 9°C) from nearby areas for comparative analysis. These were analyzed for major and trace elements, as well as stable isotopes of oxygen ($\delta^{18}O$) and hydrogen (δD). The thermal waters differ significantly in terms of physico-chemical parameters from surface and groundwater samples. The thermal waters fall under Na-Cl to Na-HCO_3 facies, indicating significant rock-water interaction and ion exchange with the deep-seated granitic intrusions. In contrast, surface and groundwater samples exhibit Ca-HCO_3 to mix Ca-Mg-Cl mix facies, typically indicating the shallow water circulation. Isotopic data ($\delta^{18}O$ and δD) indicates a meteoric origin of the thermal waters with partial isotope shift due to evaporation or rock-water interaction. Chemical geothermometers applied in Puga thermal waters indicates the reservoir temperatures in the range of 200°C–230°C. The Chumathang thermal water reflects medium-enthalpy conditions (≈180±20°C), while Panamik represents a low- to medium-enthalpy regime (≈100±20°C). These findings highlight the diverse geothermal potential across Ladakh's thermal provinces and provide a scientific basis for targeted geothermal exploration and sustainable energy development in the region.

1 INTRODUCTION

In recent decades, the global human population has rapidly increased, reaching approximately 8.0 billion in 2022. The rising population and higher living standards leading to an exponential increase in energy demand. India ranks as the third largest energy consumer globally, with projections indicating that energy demand may increase fourfold by 2050 (IEA, 2019). Currently, 70% of India's energy is derived from conventional, non-renewable resources, resulting in substantial CO_2 emissions. In accordance with the Paris Agreement, countries have committed to reducing CO_2 emissions and ongoing efforts are being undertaken globally in this specific area. The countries, including the USA, New Zealand, Japan, Italy, France, Mexico, China, and Iceland, have made substantial advancements in the development of their geothermal resources. India possesses significant geothermal potential, as evidenced by over 400 hot springs located throughout the country. The Ministry of New and Renewable Energy, Government of India, has established a policy to harness India's geothermal potential, aiming to achieve 500 GW of energy from renewable resources by the end of 2030. This constitutes 40% of the total installed power capacity and is likely among the most significant renewable energy expansion initiatives globally (Goswami et al., 2022).

Geothermal springs of India are spread over a various unique geological, geo-tectonic and geographic settings. Most of the hot-springs occur in a clustered manner and generally situated over high heat flow regions. The high heat flow in these regions is either due to crustal movement or shallow magmatic intrusion or high centration of radiogenic elements in subsurface rocks. Based on distinct geological and geo-tectonic settings thermal springs are classified in to the following four categories: (i) Thermal springs in orogenic belt regions (ii) Thermal springs in areas of deep-seated fault and lineaments (iii) Thermal springs occur along the rift and graben of Gondwana basin (iv) Thermal springs of deep sedimentary basin (Das et al., 2022). Literature archives show that the union territory of Ladakh which comes under the orogenic belt category has a significant number of hot spring clusters, and a limited attempts has been made to study them. Through the present study, we tried to fill this gap in the scientific knowledge. The present study is conducted with the aim to (i) evaluate the chemistry of the thermal spring water, (ii) determine the origin of thermal water, and (iii) calculate the temperature of the geothermal

reservoir.

2 STUDY AREA

The hot springs of Orogenic Himalayan Belt mainly comprises of North-West (NW) Himalayan springs and North-East (NE) Himalayan springs. There are around 112 thermal springs located along the NW Himalayan region, which are distributed in the places such as state of Jammu & Kashmir, Himachal Pradesh, Uttarakhad and union territory region of Ladakh (Shanker et al., 1991). NW Himalaya region is again divided into three belts such as Trans Himalayan belt, Central Himalayan belt and Lesser Himalayan belt. The hot springs of Ladakh region mainly falls within the Trans Himalayan belt and occur at above 3500- 4400 meters from mean sea level. The geothermal manifestation occur mainly in areas of Puga valley, Chumathang area and Panamik area in Nubra valley (Fig. 1C).

The Puga valley (~4,400 m amsl) lies south of the Indus Suture Zone, bounded by the Zildat and Kiagar Tso faults. It hosts extensive borax–sulphur deposits, and metasedimentary rocks intruded by Polokongka La granite, indicating a fault-controlled geothermal system. Chumathang, located ~40 km north of Puga, occurs along the Mahe and Chumathang faults and features sedimentary rocks intruded by Ladakh and Chumathang granites. The Panamik field in Nubra valley, along the Karakoram fault, is characterized by granitic and volcanic rocks of the Karakoram and Shyok formations and the hot springs are influenced by fault-driven circulation (Craig et al., 2013). Collectively, these sites reflect the tectono-magmatic control of geothermal activity in the Trans-Himalayan region.

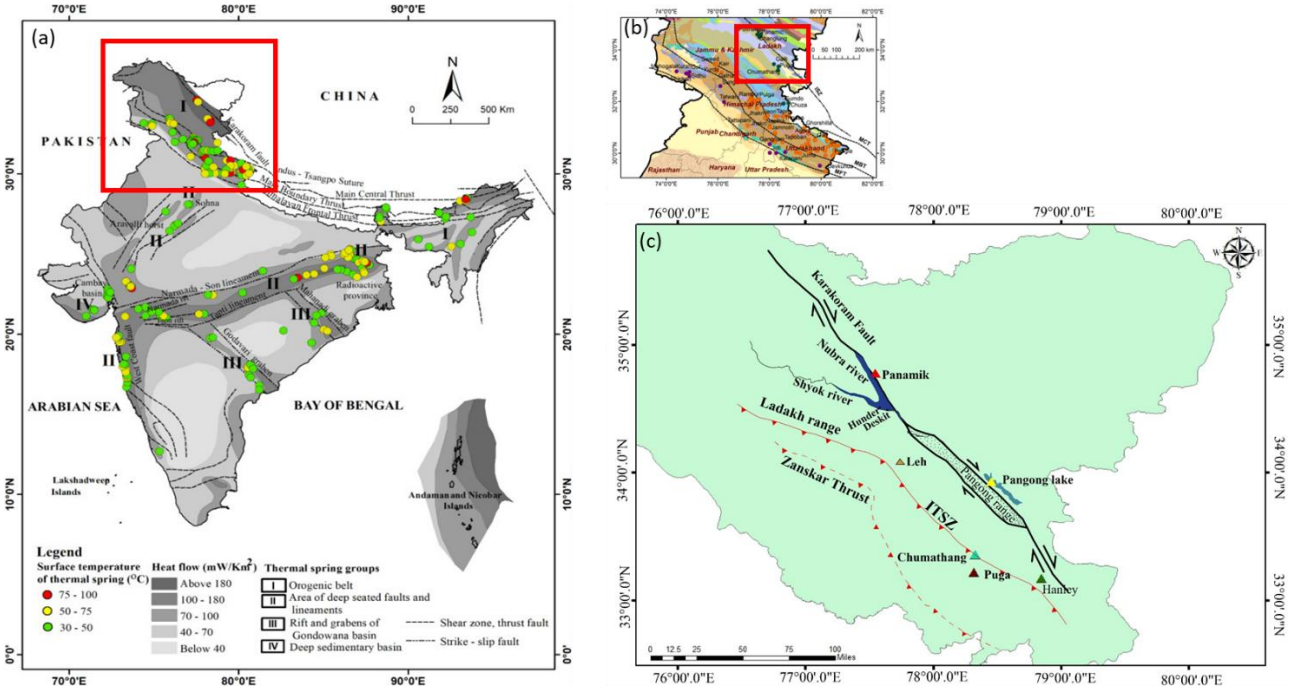


Figure 1. (a) Distribution of thermal springs in different regions (after Das et al., 2022). (b) Northwest Himalayan belt thermal spring locations are shown on a geological map of northwest India. (Das et al., 2022) (c) Sample collection locations for our study.

3 SAMPLE COLLECTION AND METHODOLOGY

To collect the water samples, a field campaign was conducted in May-June 2023. In total 30 water samples were collected, of which 18 were from active discharging thermal springs located in three thermal clusters (namely Puga, Chumathang and Panamik). 8 surface water and 4 groundwater samples from these locations were also collected for a comparisons. All the water samples were collected in pre-washed high-density polyethylene (HDPE) bottles following the standard scientific protocol (APHA 2012).

From each sampling location, three sets of samples were collected, one for the determination of cations and trace elements, one for anion analysis and the third for water stable isotope analysis. At the time of collection, each sample was filtered with a 0.45 µm cellulose nitrate filter and stored at a low temperature in airtight bottles until further analysis. The samples to be utilised for cation analysis were acidified with 2-3 drops of 14 M ultrapure HNO_3/L, while for anion and water stable isotopes remained unacidified. All the water bottles were

filled completely with water to ensure that no air bubbles to remain trapped within in the bottle. Each sampling site was geo-referenced using a Garmin Global Positioning System (Gpsmap 64s) instrument. The groundwater samples were collected from active tube wells. The tube wells were pumped for at least 5 minutes to remove the standing casing water before the sample collection.

3.1 Analytical Techniques

Physio-chemical parameters (pH, temperature, electric conductivity etc.) were directly measured in the field at the time of sample collection. The pH value was measured with Orion 261S portable pH meter with a combination electrode (pH C2401–7). Temperature of water samples was measured by a Celsius thermometer, while EC and TDS were measured by a conductivity meter (Orion 250A+). Major cations and trace elements in the water samples were analysed by ICP-OES (Agillent 5110). The major anion concentration was measured by an Ion chromatography system (883 Basic IC plus, Metrohm). The Isotopic ratios of oxygen and hydrogen were determined using Liquid Water Isotope Analyzer (model LWIA-24d). The percentage error in the analysis was calculated and was found to be within the range of ± 5%.

4 RESULT AND DISSCUSSION

4.1 Chemical Evaluation of Water Samples

The pH of the thermal water, surface water and groundwater varies within a narrow range of 7.5 – 8.9, however, no specific trend has been observed in pH. The temperature of the thermal water varied between 45 to 90° C, while for surface water and groundwater, it ranges between 3.8 - 29° C and 7.8 - 9.7° C. Though, there is no significant change in the physico-chemical parameter, however, the chemical characteristics of the thermal water are drastically different from the surface water and groundwater.

To determine the water type and identify the geochemical processes involved in modifying the water chemistry, the concentrations of major ions are plotted in a piper diagram. The resulting hydro-chemical facies indicate that water from different sites undergoes distinct, including varying degree of rock water interaction. (Zimik et al., 2017). Thermal waters from Puga, Chumathang and Panamik plot predominantly in the Na-Cl to Na-HCO_3 field, indicating extensive water-rock interaction and cation exchange with granitic and metamorphic host rocks (Zimik et al., 2017). Most of the non-thermal waters which includes groundwater and surface water falls in field-I suggesting that they are derive from precipitation without much interaction with aquifer rocks. The dissolution of carbonate rocks by the percolating water contributing Ca^{2+} & HCO_3^- to thermal water (Farooq et al., 2022). The trend of surface and groundwater samples from field-I (Ca–HCO_3) toward field-IV (Mixed Ca–Mg–Cl) indicates progressive hydro-chemical evolution along the groundwater flow path. As these waters migrate and interact with silicate and evaporite-bearing lithologies, secondary processes such as cation exchange and mixing with deeper saline fluids enrich Mg^{2+} and Cl^- ions (Das et al., 2022). This results in a compositional shift toward the mixed Ca–Mg–Cl facies, marking an increase in mineralization and relatively longer residence time within the aquifer system.

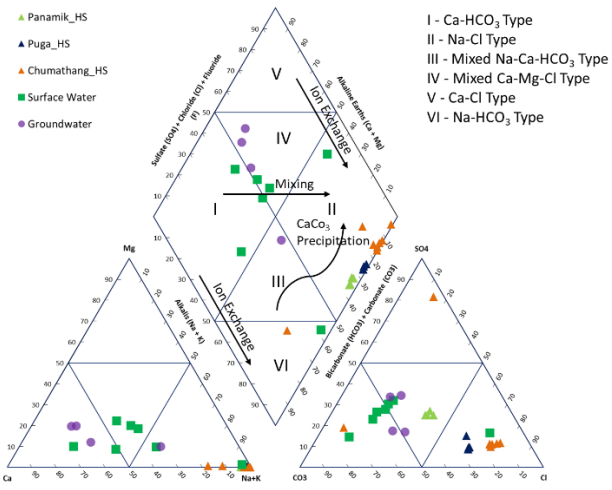


Figure 2. Piper diagram showing the chemistry and evolution of thermal and non-thermal waters

4.2 Chemical Geothermometry

Reservoir temperature is a key parameter for assessing the geothermal potential and enthalpy of a system. It is estimated from the chemical composition of geothermal fluids. Reliable temperature estimation using chemical geothermometers requires (i) an equilibrium between rock and the reservoir fluid (ii) adequate supply of all the reactants and (iii) absence of mixing of the reservoir fluid with un-equilibrated water (Farooq et al., 2022). The suitability of geothermal waters that can be utilized for geothermometry can be evaluated using the Giggenbach anion variation diagram (1988), which classifies waters into mature, peripheral, and steam-heated types based on $Cl–SO_4–HCO_3$ relationships. Additionally, the anion variation diagram also helps to infer the origin of geothermal fluids.

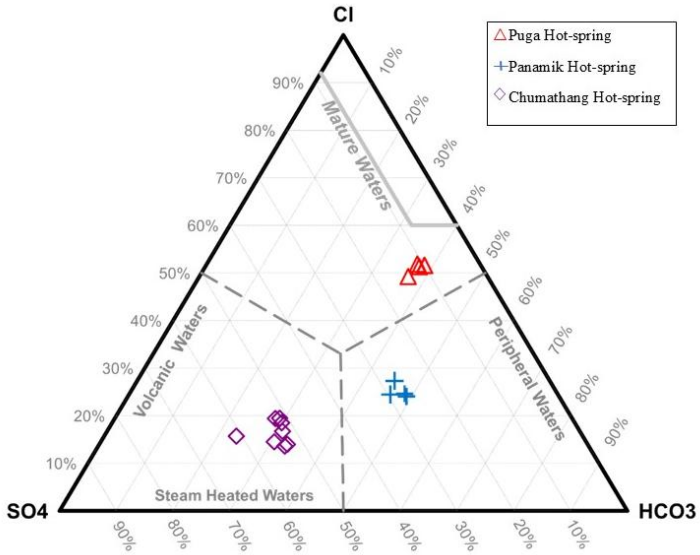


Figure 3. Anion Variation diagram showing thermal water samples into different water fields

In the anion variation diagram, Puga thermal waters falls close to the mature water indicating their suitability for application of geothemometry, however, the thermal waters from Panamik are placed in peripheral water fields indicating their meteoric origin. Further, Chumathang thermal water shows characteristics of steam-heated volcanic waters. Except Puga thermal waters, conventional geothermometers cannot be applied directly to get the estimate the reservoir temperature. The application of Quartz and Na/K geothermometers for the Puga cluster gives a reservoir temperatures ranging from 185°C to 233°C. The reservoir temperatures for Chumathang and Panamik determined by multi-mineral equilibria method indicates the temperature around 180±20°C and 100±20°C (Goswami et al., 2022), respectively.

4.3 Stable Isotope Systematics

The stable isotope ratios play a crucial role in determining the source of water as well as it describes the various secondary processes that controls the chemistry of thermal waters in a geothermal system, such as the rock-water interaction, evaporation enrichment, moisture recirculation, boiling effect, and exhibiting residence period (Farooq et. al., 2022). The thermal waters of Panamik are most depleted with $\delta^{18}O$ and δD values ranges between-16.72‰ to -15.20 ‰ and -121.1‰ to -113.1‰, respectively. The thermal springs of Chumathang also show depleted $\delta^{18}O$ and δD values in the range of -15.62‰ to -14.88‰ and -121.4‰ to -119.4‰, respectively. However, the thermal springs of Puga show an enrichment of $\delta^{18}O$ as compared to Panamik and Chumathang in the range of -13.40‰ to -12.97‰ with not much variation in δD values (-123.0‰ to -117.2‰).

The placement of thermal and non-thermal waters of Panamik along the Global Meteoric Water Line (GMWL) reflects their meteoric origin which may come from the rapid percolation of glacial melt through the Karakoram Fault with limited evaporation (Fig. 4a). Chumathang water falls near the LMWL, indicating local meteoric recharge through snow melt at high altitude with minor rock–water interaction (Fig. 4b). In contrast, Puga thermal waters display a positive $\delta^{18}O$ shift due to deeper circulation, intense rock-water interaction and longer residence time (Fig. 4c).

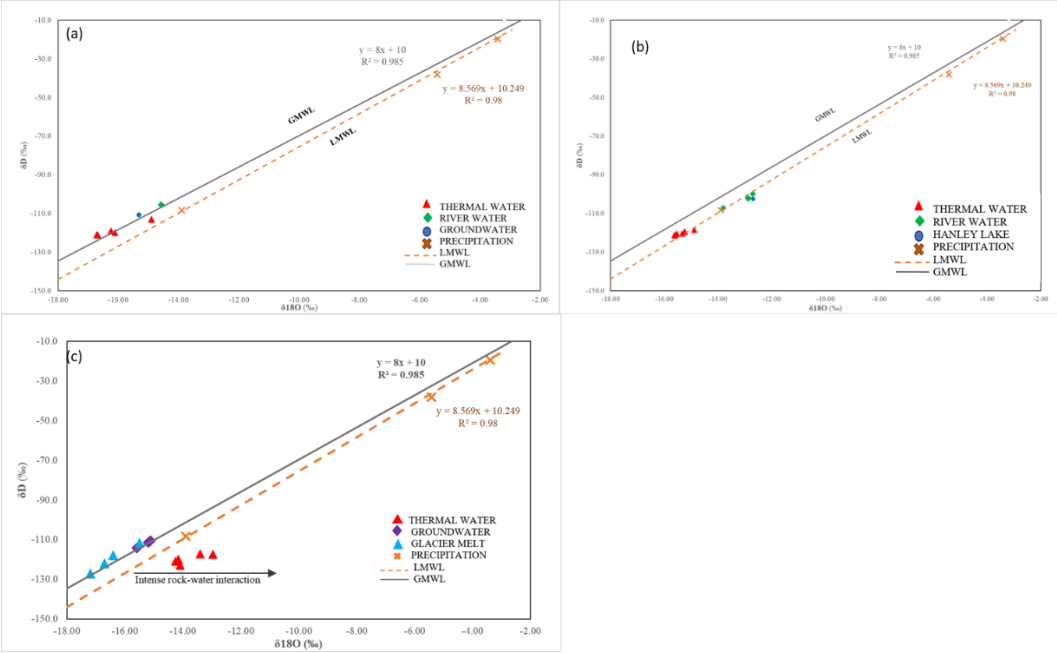


Figure 4(a-c). Plots showing the position of thermal water, groundwater, surface water, rain water and glacier melt (a: Panamik, b: Chumathang, c: Puga) w.r.t the GMWL & LMWL

5 CONCLUSION

The hydro-chemical and isotopic analysis of the Puga, Chumathang, and Panamik geothermal waters reveal distinct fluid evolution and geothermal systems along Ladakh's Trans-Himalayan region. Thermal waters are mainly of the Na–Cl to Na–HCO_3 type. This is mainly due to rock – water interaction and deeper fluid circulation that is governed by regional faults. Isotope ratio data confirm that thermal waters are of meteoric origin, exhibiting different degrees of mixing and isotopic enrichment associated with local geology and temperature. Geothermometric measurements exhibit high-enthalpy conditions in Puga (200–230°C), medium enthalpy in Chumathang (~180°C), and low–medium enthalpy in Panamik (~100°C). These findings underscore Ladakh's significant and diverse geothermal potential, building a scientific foundation for the sustainable use of geothermal resources in the region.

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