

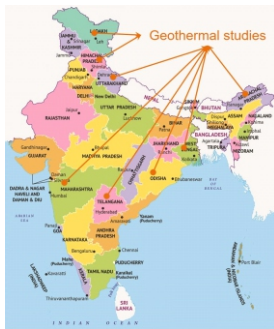
भू-तापीय अध्ययन में आइसोटोप का अनुप्रयोग

2

भारत में भू-तापीय संसाधनों की खोज में आइसोटोप तकनीक

सितांगशु चटर्जी *

आइसोटोप जल विज्ञान अनुभाग, आइसोटोप एवं विकिरण अनुप्रयोग प्रभाग, भा.प.अ. केंद्र, ट्रांबे-४०००८५, भारत



भारत के प्रमुख भू-तापीय प्रांत जहां बीएआरसी द्वारा एकीकृत समस्थानिक भू-रासायनिक जांच की गई थी

सारांश

मआइसोटोप तकनीक के अनुप्रयोग ने भारत में भू-तापीय प्रणालियों की समझ को अत्यंत प्रगत बनाया है जो तापीय जल की उत्पत्ति, विकास और धारणीयता को समझने के लिए शक्तिशाली उपकरण प्रदान करता है। स्थिर (^2H , ^{18}O , ^{13}C , ^{34}S , ^{11}B , ^{87}Sr) और रेडियोधर्मी (^3H , ^{14}C) आइसोटोप दोनों भू-तापीय जलविज्ञान में प्रमुख अनुरेखक के रूप में कार्य करते हैं, जो शोधकर्ताओं को पुनःआवेशी स्रोतों को निर्धारित करने, आवासी काल का अनुमान लगाने, मिश्रण प्रक्रियाओं का आकलन करने आदि में सक्षम बनाते हैं। भारत में सात प्रमुख भू-तापीय प्रांतों में फैले लगभग 400 तापीय स्प्रिंग हैं, जिनमें से प्रत्येक भू-क्षेत्र की दृष्टि से विविध स्थितियों में स्थित है।

ऑक्सीजन और हाइड्रोजन ($\delta^{18}\text{O}$, $\delta^2\text{H}$) के स्थायी/संतुलित आइसोटोप विश्लेषण इस बात की पुष्टि करते हैं कि भारतीय भू-तापीय जल की मुख्य रूप से उल्काय से उत्पत्ति हुई है। ये आइसोटोप पुनःभरण ऊंचाई का अनुमान लगाने और स्थैतिक एवं गतिक भू-तापीय प्रणालियों के बीच अंतर करने में भी सहायता करते हैं। डीआईसी के कार्बन आइसोटोप अनुपात ($\delta^{13}\text{C}$) प्रमुख अपक्षय प्रक्रियाओं और CO_2 के स्रोतों की पहचान करने में मदद करते हैं, जबकि सल्फर ($\delta^{34}\text{S}$) और बोरॉन ($\delta^{11}\text{B}$) आइसोटोप विलीन विलेयों की उत्पत्ति के बारे में मूल्यवान संकेत प्रदान करते हैं और समुद्री को गैर-समुद्री प्रभावों से अलग करते हैं।

ट्रिशियम (^3H) और कार्बन-14 (^{14}C) जैसे रेडियोजेनिक आइसोटोप का उपयोग तापीय जल के औसत पारगमन समय (एमटीटी) का अनुमान लगाने के लिए किया जाता है जबकि ट्रिशियम हाल के पुनःभरण और लघु भूजल के साथ मिश्रण की पहचान करने में मदद करता है, ^{14}C काल-निर्धारण, विशेष रूप से सिलिकेट-होस्टेड प्रणालियों में, तनुकरण संशुद्धियों रहित गहरे और पुराने तापीय जल में आवासी काल का विश्वसनीय अनुमान प्रदान करता है। कुल मिलाकर, आइसोटोप तकनीकें भारत के भू-तापीय अनुसंधान में अपरिहार्य उपकरणों के रूप में उभरी हैं, जो धारणीय विकास और भू-तापीय संसाधनों के उपयोग के लिए मजबूत ढांचा प्रदान करती हैं।

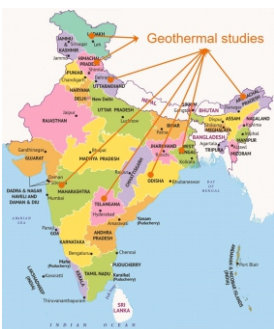
Application of Isotopes in Geothermal Studies

2

Isotope Techniques in Exploring Geothermal Resources in India

Sitangshu Chatterjee*

Isotope Hydrology Section, IRAD, Bhabha Atomic Research Centre, Trombay-400085, INDIA



Major geothermal provinces in India where integrated isotope geochemical investigations were conducted by BARC

ABSTRACT

The application of isotope techniques has significantly advanced the understanding of geothermal systems in India, offering powerful tools for deciphering the origin, evolution, and sustainability of thermal waters. Both stable (^2H , ^{18}O , ^{13}C , ^{34}S , ^{11}B , ^{87}Sr) and radioactive (^3H , ^{14}C) isotopes serve as key tracers in geothermal hydrology, enabling researchers to determine recharge sources, estimate residence times, assess mixing processes etc. India hosts nearly 400 thermal springs distributed across seven major geothermal provinces, each situated in geotectonically diverse settings.

Stable isotope analyses of oxygen and hydrogen ($\delta^{18}\text{O}$, $\delta^2\text{H}$) confirm that Indian geothermal waters are predominantly meteoric in origin. These isotopes also aid in estimating recharge altitudes and differentiating between static and dynamic geothermal systems. Carbon isotope ratios ($\delta^{13}\text{C}$) of dissolved inorganic carbon (DIC) help to identify dominant weathering processes and sources of CO_2 , while sulfur ($\delta^{34}\text{S}$) and boron ($\delta^{11}\text{B}$) isotopes provide valuable clues regarding the origin of dissolved solutes and distinguish marine from non-marine sources.

Radiogenic isotopes like tritium (^3H) and carbon-14 (^{14}C) are used to estimate the mean transit time (MTT) of thermal waters. While tritium helps in identifying recent recharge and mixing with younger groundwater, ^{14}C dating, especially in silicate-hosted systems, provides reliable estimates of residence time in deeper and older thermal waters without requiring dilution corrections.

Overall, isotope techniques have emerged as indispensable tools in India's geothermal research, offering robust frameworks for sustainable development and utilization of geothermal resources.

KEYWORDS: India, Thermal waters, Stable isotopes, Radioisotopes

*Author for Correspondence: Sitangshu Chatterjee
E-mail: sitangshu@barc.gov.in

Introduction

Isotopes (both stable and radioactive) play a fundamental role in geothermal studies, providing invaluable information regarding the origin, evolution, and sustainability of geothermal resources [1,2,3]. The application of isotope techniques enables researchers to trace fluid movement, determine the age of geothermal waters, assess reservoir characteristics, and identify interactions between different water sources. The various isotopes that are commonly used in geothermal exploration include ^2H , ^{18}O , ^{13}C , ^{87}Sr , ^{11}B , ^{34}S , ^3H and ^{14}C etc. Stable isotopes of oxygen ($^{18}\text{O}/^{16}\text{O}$) and hydrogen ($^2\text{H}/^1\text{H}$) provide valuable insights into the recharge mechanisms, identify mixing processes between thermal and non-thermal groundwater, and help to quantify isotopic fractionation associated with phase changes such as evaporation and boiling. The carbon isotopic ratio ($^{13}\text{C}/^{12}\text{C}$) of the dissolved inorganic carbon (DIC) indicates the source of dissolved carbon. Sulfur-34 (^{34}S) and oxygen-18 (^{18}O) of dissolved sulfate (SO_4) are very useful to trace the origin of salinity, while the boron isotopic ratio ($^{11}\text{B}/^{10}\text{B}$) helps to identify the source of dissolved boron. Additionally, strontium isotopes ($^{87}\text{Sr}/^{86}\text{Sr}$) provide better constraints on the nature of reservoir rocks with which thermal water interacts. Among various radiogenic environmental isotopes, tritium (^3H) serves as a dating tool for relatively modern thermal waters, while carbon-14 (^{14}C) is used to compute the mean transit time of the older geothermal waters.

India hosts nearly 400 thermal springs distributed across seven major geothermal provinces: the Himalayan region, West Coast region, Son-Narmada-Tapi (SONATA) region, Cambay region, Godavari Valley region, Mahanadi region, and Sohana region, each characterized by distinct geotectonic settings. Comprehensive isotope geochemical studies have been carried out in several states including Arunachal Pradesh, Uttarakhand, Maharashtra, Gujarat, Odisha, Himachal Pradesh, Telangana, West Bengal etc. to evaluate

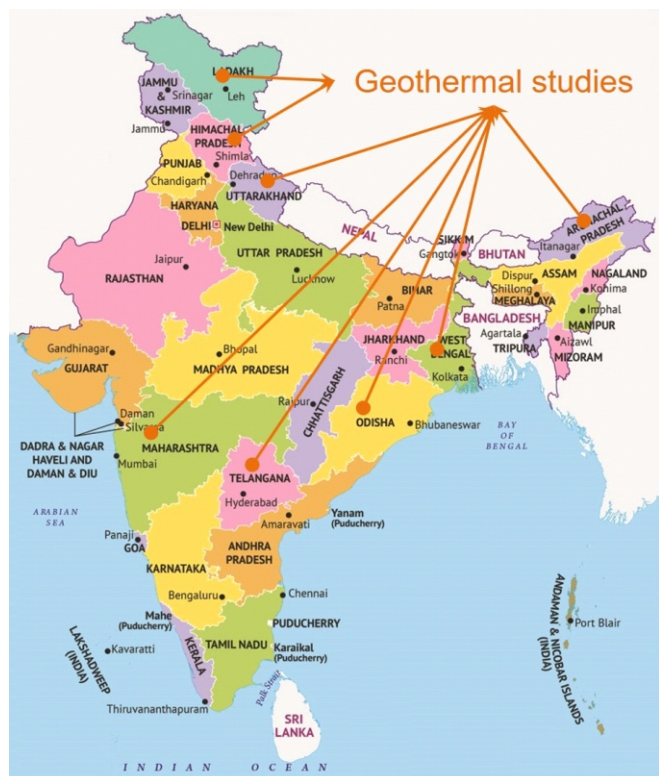


Fig.1: Map showing major geothermal provinces in India where integrated isotope-geochemical investigations were conducted by Bhabha Atomic Research Centre.

the sources and dynamics of geothermal waters for planning sustainable geothermal energy exploitation (Fig.1) [4-12]. A brief overview of the role and outcome of the isotope studies in geothermal areas is provided in this article.

Materials and Methods

Isotope ratio mass spectrometer (IRMS) is generally used to measure the stable isotope ratio of light elements like $^2\text{H}/^1\text{H}$, $^{18}\text{O}/^{16}\text{O}$, $^{13}\text{C}/^{12}\text{C}$, $^{34}\text{S}/^{32}\text{S}$ whereas thermal ionization mass spectrometer (TIMS) is used to measure the isotope ratio of elements like $^{11}\text{B}/^{10}\text{B}$ and $^{87}\text{Sr}/^{86}\text{Sr}$. Liquid scintillation spectrometry (LSC) is generally used to determine the absolute concentration of environmental radioactive isotopes like tritium and carbon-14. The detailed measurement methodology of the various isotopes has been described elsewhere [4, 9, 12].

The symbol ' δ ' (delta) is universally used to denote the variance in the isotopic ratio (R) of the reference standard compared with that of the sample according to eqn. 1:

$$\delta = \left(\frac{R_{\text{sample}} - R_{\text{standard}}}{R_{\text{standard}}} \right) \times 1000 \quad (1)$$

where ' R_{standard} ' refers the $^{18}\text{O}/^{16}\text{O}$, $^2\text{H}/^1\text{H}$, $^{13}\text{C}/^{12}\text{C}$, $^{34}\text{S}/^{32}\text{S}$, $^{11}\text{B}/^{10}\text{B}$ of the standard and the ' R_{sample} ' represents $^{18}\text{O}/^{16}\text{O}$, $^2\text{H}/^1\text{H}$, $^{13}\text{C}/^{12}\text{C}$, $^{34}\text{S}/^{32}\text{S}$, $^{11}\text{B}/^{10}\text{B}$ of the sample. Currently, 'VSMOW' (Vienna Standard Mean Ocean Water) acts as a primary standard material for measuring the $^{18}\text{O}/^{16}\text{O}$ and $^2\text{H}/^1\text{H}$ in water whereas VPDB (Vienna Pee Dee Belemnite), VCDT (Vienna Canon Diablo Troilite), NBS-951 act as a primary reference material for measuring the $^{13}\text{C}/^{12}\text{C}$, $^{34}\text{S}/^{32}\text{S}$, $^{11}\text{B}/^{10}\text{B}$ of the sample respectively.

Role of Stable Isotopes

Origin of thermal water

Before the widespread application of mass spectrometry methods, thermal waters were generally considered to be of juvenile or magmatic origin [13]. However, a pivotal shift in understanding occurred with the work of Craig and his colleagues [14,15], who demonstrated that the $\delta^2\text{H}$ values of thermal waters from several prominent geothermal fields closely matched with those of local meteoric water (Fig.2). This observation provided compelling evidence that geothermal waters are predominantly of meteoric origin, infiltrating the subsurface and subsequently gaining heat as they circulate at depth through faults and fracture networks.

While the hydrogen isotopic composition ($\delta^2\text{H}$) of thermal waters matched closely with that of local precipitation, a systematic enrichment in oxygen-18 ($\delta^{18}\text{O}$) was observed, resulting in a positive shift from the meteoric water line. This phenomenon, commonly referred to as the "oxygen-18 shift,"

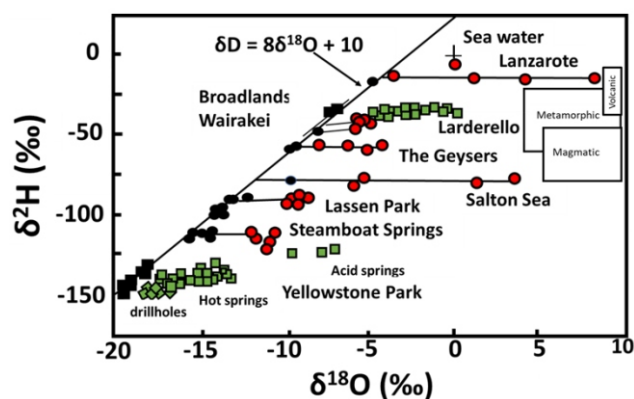


Fig.2: $\delta^{18}\text{O}$ - $\delta^2\text{H}$ plot of various types of thermal waters. Thermal waters show significant ^{18}O shift from GMWL [16].

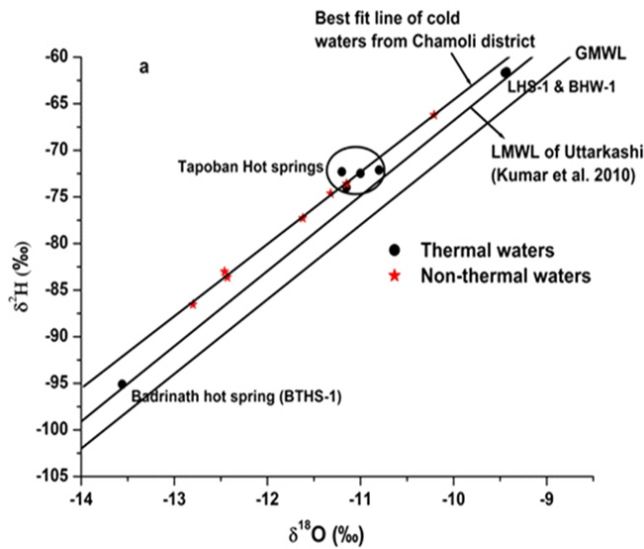


Fig.3: $\delta^{18}\text{O}$ - $\delta^2\text{H}$ plot of thermal and non-thermal waters of Uttarakhand geothermal area, India [10].

arises from isotopic exchange processes between water and aquifer-hosted minerals primarily silicates or carbonates under elevated temperatures. The extent of this $\delta^{18}\text{O}$ enrichment is indicative of the degree of water-rock interaction, which is strongly temperature-dependent and provides important insights into the thermal history and evolution of geothermal fluids.

The extent of ^{18}O shift depends on several factors, including rock mineralogy (whether carbonate or silicate rocks), fluid-rock interaction duration, reservoir temperature, water-to-rock ratio etc. [17]. As a result, not all the thermal springs around the globe exhibit this kind of oxygen-18 shift. For example, boiling thermal waters (surface temperature $\sim 93^\circ\text{C}$) from Uttarakhand geothermal area of India, hardly show any measurable oxygen-18 shift (Fig.3) [10].

Mixing Phenomenon

Oxygen-18 and deuterium also serve as effective tracers for identifying the mixing process in geothermal systems. A strong linear correlation between $\delta^2\text{H}$ and chloride (Cl^-) concentrations is often interpreted as robust evidence of mixing, as both $\delta^2\text{H}$ and Cl^- typically behave conservatively and are not significantly altered by water-rock interaction or other subsurface geochemical processes. This type of mixing phenomenon has been observed in Tural-Rajwadi geothermal field (Maharashtra) where thermal water gets mixed with non-thermal waters to produce a range of spring compositions (Fig.4) [11].

Estimation of Recharge Altitude

Stable isotopes like $\delta^{18}\text{O}$ and $\delta^2\text{H}$ are also useful in estimating the recharge altitudes of thermal springs situated in high altitude areas. Recharge altitude can be roughly determined using $\delta^{18}\text{O}$ -altitude and/or $\delta^2\text{H}$ -altitude plots, typically developed from rainwater samples collected at different elevations. In Arunachal Pradesh geothermal area, an altitude gradient of -0.19‰ per 100 m for $\delta^{18}\text{O}$ was observed (Fig.5) [5]. Using this, recharge altitudes of thermal springs in Tawang District were estimated at 6100–6900 m. This range is notably close to the elevation of Gorichen Peak (6858 meters), the highest peak in Arunachal Pradesh. These findings strongly indicate that precipitation occurring near Gorichen Peak plays a significant role in recharging the thermal springs in the Tawang District of Arunachal Pradesh, India.

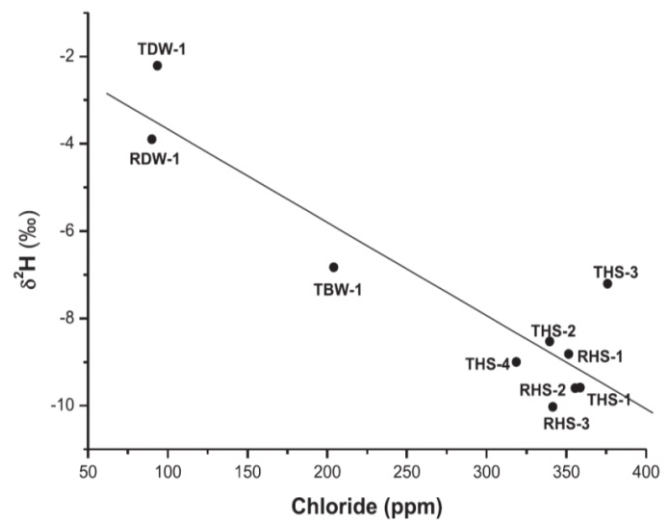


Fig.4: Linear relationship between $\delta^2\text{H}$ and chloride in Tural-Rajwadi geothermal field, Maharashtra, India [11].

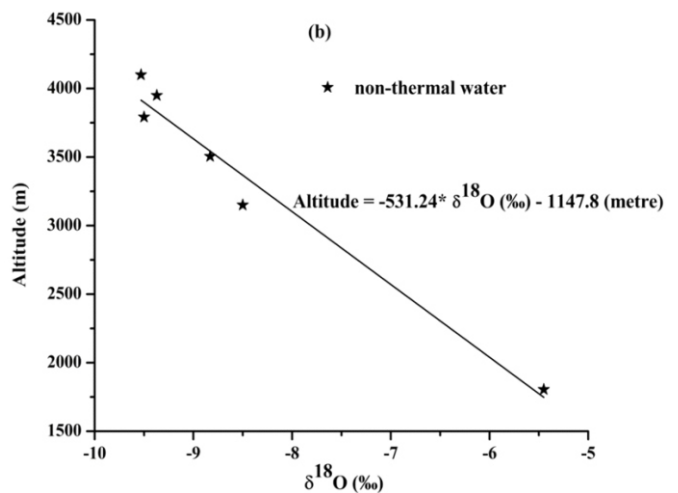


Fig.5: Altitude effect calculated from the non-thermal waters collected from the Arunachal Pradesh geothermal area, India [5].

Static vs. Dynamic Geothermal Systems

Stable isotopes like $\delta^{18}\text{O}$ and $\delta^2\text{H}$ are also effective in distinguishing between static and dynamic geothermal systems. In static systems, limited recharge leads to constant stable isotopic compositions over time and the age of thermal waters are found to be typically old [17]. Conversely, dynamic systems experience ongoing recharge from precipitation, resulting in noticeable isotopic shifts and younger water ages [17]. For example, the Odisha geothermal area shows a static system, with almost constant isotopic values between 1995 and 2016 and ^{14}C ages ranging from 13,300 to 20,700 years BP before present (Fig.6a) [12]. In contrast, the Badrinath geothermal area (Uttarakhand) demonstrates a dynamic system, with progressively depleted isotope values from 1996 to 2022, indicating recharge from high-altitude glacier melt (Fig.6b).

Tracing DIC Source

$\delta^{13}\text{C}$ ($^{13}\text{C}/^{12}\text{C}$ isotopic ratio) is a powerful tracer in geothermal studies because various carbon reservoirs (i.e. biogenic methane, magmatic CO_2 or carbonate rocks) exhibit entirely different isotopic signatures. The key applications of $\delta^{13}\text{C}$ values are given Table 1.

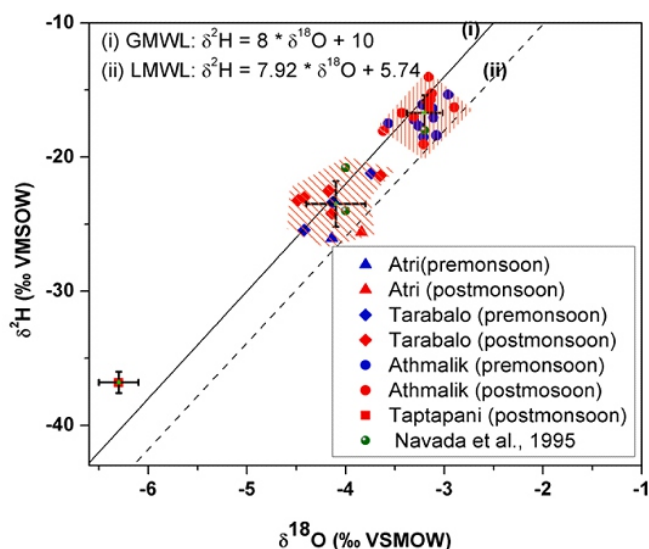


Fig. 6a: $\delta^{18}\text{O}$ - $\delta^2\text{H}$ plot of the Odisha geothermal area [12].

For example, the $\delta^{13}\text{C}$ values of dissolved inorganic carbon (DIC) in the thermal waters from Manuguru geothermal region ranged from -17.5 to -24.4‰, with an average of -20.57‰ relative to VPDB. This $\delta^{13}\text{C}$ value clearly indicates that the DIC of the thermal waters are primarily governed by the silicate weathering, with little or no evidence of calcite dissolution [7].

Tracing Salinity Source

$\delta^{34}\text{S}$ and $\delta^{11}\text{B}$ isotopes are effective tracers for identifying the sources of salinity in thermal waters. The $\delta^{34}\text{S}$ values of sulfur species can range from -30‰ to +35‰, reflecting varied geochemical origins [9]. For example, in the Tural-Rajwadi geothermal area (Maharashtra), $\delta^{34}\text{S}$ values of dissolved sulfate (+19.6 to +20.43‰ VCDT) closely match marine sulfate, indicating seawater influence due to coastal proximity [9]. Similarly, $\delta^{11}\text{B}$ values also help to distinguish marine from non-marine contributions (Fig. 7). In the Gujarat geothermal region, waters from sites like Dholera and Tulsishyam showed high $\delta^{11}\text{B}$ values (+40.5‰ to +46‰), suggesting relic seawater or diagenetically altered marine sources [4]. In contrast, lower $\delta^{11}\text{B}$ values (+26‰ to +31‰) in Varana and Maktupur region indicate non-marine inputs, likely from anthropogenic sources such as agricultural return flow [4].

Thus, these isotopic tools serve as definitive indicators of source heterogeneity and aid in the reconstruction of the hydrogeochemical evolution of the geothermal system.

Table 1: Role of $^{13}\text{C}/^{12}\text{C}$.

$\delta^{13}\text{C}$ Component	Application	Average $^{13}\text{C}/^{12}\text{C}$ values
DIC (Dissolved Inorganic Carbon)	Identify dominant weathering processes between silicate and carbonate sources	
	Determines source of soil CO_2	C_3 plants: $\delta^{13}\text{C} \approx -26\text{‰}$ (temperate forests) C_4 plants: $\delta^{13}\text{C} \approx -12\text{‰}$ (grasslands/savannas) [18]
CO_2 Gas	Differentiates between CO_2 sources	- Atmospheric: $\delta^{13}\text{C} \approx -8.1\text{‰}$ [18] - Magmatic (mantle-derived) - Carbonate decarbonation - Organic matter oxidation - Microbial methanogenesis
Methane (CH_4)	Distinguishes between various methane sources	- Thermogenic (high-temp breakdown of organic matter) - Biogenic (microbial activity) - Abiotic (e.g., graphite water reactions)

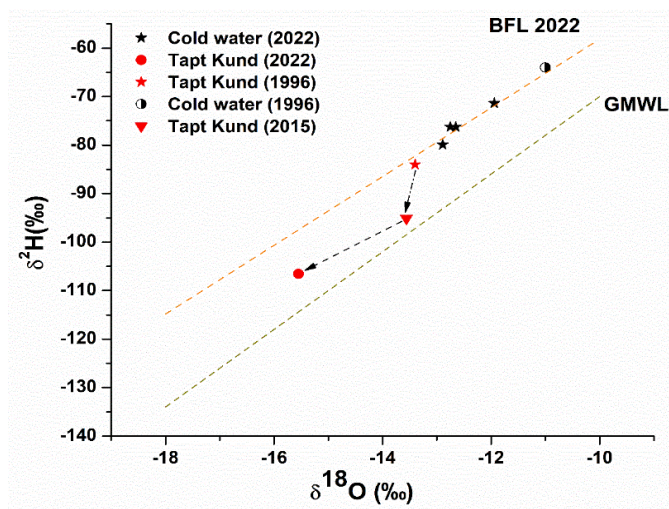


Fig. 6b: $\delta^{18}\text{O}$ - $\delta^2\text{H}$ plot showing the change in isotopic composition of Badrinath thermal water.

Role of the Environmental Radioactive Isotopes

Environmental radioactive isotopes also known as natural or cosmogenic radionuclides (e.g. tritium [^3H], carbon -14 [^{14}C]) are extremely useful in assessing the sustainability of geothermal systems.

Transit time (Residence time) Estimation

Tritium (^3H), with a half-life of 12.32 years, is a useful tracer for estimating the mean transit time (MTT) of younger waters (<50 years). However, its application in geothermal systems is rather limited due to typically long residence times (>50 years) and low tritium levels. However, in systems where thermal waters mix with modern groundwater, tritium can still provide meaningful estimation of mean transit time (MTT). For instance, in the Thane geothermal region (Maharashtra), the estimated MTTs of the younger water components in Ganeshpuri and Akloli thermal waters were found to be 70 ± 5 years and 90 ± 14 years, respectively [6]. Similarly, the estimated MTTs of the younger water components in Tural and Rajwadi thermal springs were found to be 28.0 ± 12.0 years and 29.5 ± 12.5 years, respectively [8].

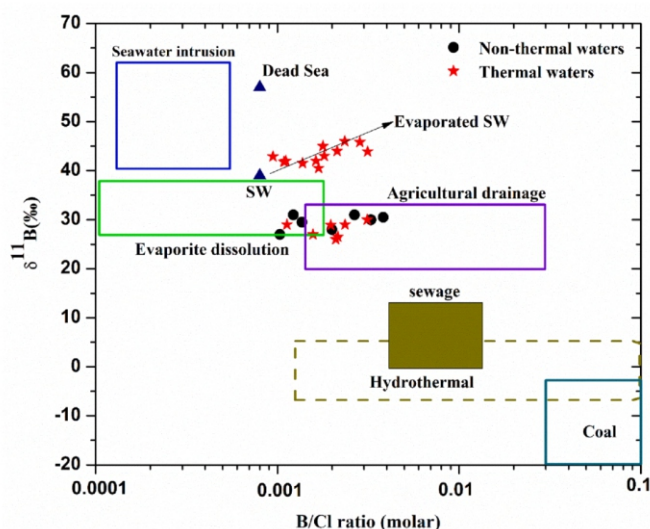


Fig. 7: Bi plot of $\delta^{11}\text{B}$ vs. B/Cl molar ratio to elucidate different salinity sources [4].

On the other hand, radiocarbon (^{14}C), with a half-life of 5730 years, is better suited for dating older thermal waters. While ^{14}C results can be skewed by carbon-free sources like volcanic CO_2 or carbonate dissolution, geothermal systems in silicate dominant area allow more reliable age estimates due to minimal dilution. In the Manuguru geothermal area (Telangana), ^{14}C ages ranged from ~9,950 to 18,660 years BP (before present), reflecting recharge during the late Pleistocene to early Holocene [7]. Similarly, in the Mahanadi region, corrected ^{14}C ages of 13,300–20,700 years BP (before present) point to recharge during the Last Glacial Maximum (LGM) [12].

These examples highlight the combined utility of ^3H and ^{14}C isotopes in assessing both modern and ancient recharge in geothermal systems which in turn throw lights on the sustainability of that particular geothermal system.

Conclusion

Application of multiple isotopic tracers including stable isotopes, tritium, and radiocarbon has significantly enhanced the understanding of geothermal water characteristics in the Indian subcontinent. This comprehensive methodological framework has enabled the interpretation of several critical hydrological processes, including the origin and recharge sources of thermal waters, the identification of the sources of dissolved solutes, and the estimation of residence times. In many instances, isotopic techniques have yielded unique insights that are not readily obtainable through conventional hydrogeological or geochemical methods. Thus, isotope hydrology has proven to be an indispensable tool in the characterization and sustainable management of geothermal resources in India.

Acknowledgements

The author wishes to acknowledge Dr. Y. K. Bhardwaj, Associate Director, Radiochemistry and Isotope Group; Dr. R. Acharya, Head, IRAD and Dr. Tirumalesh Keesari, Head, IHS for their constant support and encouragement. The author also wishes to acknowledge the effort and dedication of all the present and former colleagues of the Isotope Hydrology Section of IRAD, BARC) as well as all the collaborators associated with geothermal studies.

References

- [1] R. Cao, J. Dor, Y.Q. Cai, X.L. Chen, X. Mao, H.R. Meng, Geochemical and H–O–Sr–B isotope signatures of Yangyi geothermal fields: implications for the evolution of thermal fluids in fracture-controlled type geothermal system, Tibet, China, *Geothermal Energy*, 11 (2023) 23.
- [2] W. Liu, M. Zhang, Y. Liu, L. Cui, Y. Sano, S. Xu, Chemical and isotopic constraints on fluid origin and genesis of geothermal systems in the Tingri-Tangra Yumco rift, southern Tibetan Plateau, *Geothermal Energy*, 12 (2024) 33.
- [3] K. Wang, C. Hua, L. Ren, Y. Kong, W. Sun, S. Pan, Y. Cheng, Y. Huang, F. Tian, W. Zhang, D. Qin, F. Ma, J. Wang, Y. Dong, Geochemical and isotopic characteristics of two geothermal systems at the Nanpu Sag, Northern Bohai Bay Basin, *Frontiers in Earth Science*, 10 (2022) 844605.
- [4] S. Chatterjee, P. Mishra, K. Sasi Bhushan, P. Goswami, U.K. Sinha, Unraveling the paleo-marine signature in saline thermal waters of Cambay rift basin, Western India: Insights from geochemistry and multi isotopic (B, O and H) analysis, *Mar. Pollut. Bull.*, 192 (2023) 115003.
- [5] S. Chatterjee, A. Dutta, R.K. Gupta, U.K. Sinha, Genesis, evolution, speciation and fluid-mineral equilibrium study of an explored geothermal area in Northeast Himalaya, India, *Geothermics*, 105 (2022) 102483.
- [6] S. Chatterjee, A.S. Deodhar, U.K. Sinha, B.P. Biswal, Constraining the mean transit time (MTT) of relatively modern thermal waters in Deccan volcanic geothermal area, India using tritium tracer, *Appl. Geochem.*, 133 (2021) 105076.
- [7] S. Chatterjee, U.K. Sinha, B.P. Biswal, A. Jaryal, P.K. Jain, S. Patbhaje, A. Dash, An Integrated Isotope-Geochemical Approach to Characterize a Medium Enthalpy Geothermal System in India, *Aquat. Geochem.*, 25 (2019) 63-89.
- [8] S. Chatterjee, M.A. Gusyev, U.K. Sinha, H.V. Mohokar, A. Dash, Understanding water circulation with tritium tracer in the Tural-Rajwadi geothermal area, India, *Appl. Geochem.*, 109 (2019) 104373.
- [9] S. Chatterjee, M.A. Ansari, A.S. Deodhar, U.K. Sinha, A. Dash, A multi-isotope approach (O, H, C, S, B and Sr) to understand the source of water and solutes in some the thermal springs from West Coast geothermal area, India, *Arab. J. Geosci.*, 10 (2017) 242, 1-11.
- [10] S. Chatterjee, U.K. Sinha, A.S. Deodhar, M.A. Ansari, N. Singh, A.K. Srivastava, R.K. Aggarwal, A. Dash, Isotope-geochemical characterization and geothermometrical modeling of Uttarakhand geothermal field, India, *Environ. Earth Sci.*, 76 (2017) 638.
- [11] S. Chatterjee, S. Sharma, M.A. Ansari, A.S. Deodhar, U. Low, U.K. Sinha, A. Dash, Characterization of subsurface processes and estimation of reservoir temperature in Tural and Rajwadi geothermal fields, Maharashtra, India, *Geothermics*, 59 (2016) 77-89.
- [12] T. Keesari, S. Chatterjee, M. Kumar, H.V. Mohokar, U.K. Sinha, A. Roy, D. Pant, S.D. Patbhaje, Tracing thermal and non-thermal water circulations in shear zones of Eastern Ghats Mobile Belt zone, Eastern India - inferences on sustainability of geothermal resources, *J. Hydrol.*, 612 (2022) 128172, 1-19.
- [13] D.E. White, Thermal waters of volcanic origin, *Geol. Soc. Am. Bull.*, 68 (1957) 1637-1657.
- [14] H. Craig, G. Boato, D.E. White, Isotope Geochemistry of thermal waters, National Research Council Publication, 400 (1956) 29-38.
- [15] H. Craig, The isotopic geochemistry of water and carbon in geothermal areas, *Nuclear Geology on Geothermal Areas*, Consiglio Nazionale Delle Ricerche (CNR), Laboratorio di Geologia Nucleare, (1963) 17-53.
- [16] Y.K. Kharaka, R.H. Mariner, Geothermal systems, in: J.R. Gat, F.O. Froehlich, P.K. Aggarwal (Eds.), *Isotopes in the Water Cycle*, Springer, Netherlands, 2005, pp. 243–270.
- [17] K. Nicholson, *Geothermal Fluids: Chemistry and Exploration Techniques*, Springer-Verlag, (1993) pp. 22-23.
- [18] A. Das, S. Krishnaswami, S.K. Bhattacharya, Carbon isotope ratio of dissolved inorganic carbon (DIC) in rivers draining the Deccan Traps, India: Sources of DIC and their magnitudes, *Earth and Planetary Science Letters*, 236 (2005) 419-429.