Geothermics 74 (2018) 197–209

Contents lists available at ScienceDirect

Geothermics

journal homepage: www.elsevier.com/locate/geothermics

# Understanding the evolution of thermal fluids along the western continental margin of India using geochemical and boron isotope signatures

Trupti Chandrasekhar[a], A. Minissale[b], O. Vaselli[c], D. Chandrasekharam[d,*], H.K. Singh[e]

[a] Department of Earth Sciences, Indian Institute of Technology Bombay, Mumbai, 400076, India
[b] C.N.R. Institute of Geosciences and Earth Resources, Section of Florence, Via La Pira 4, I-50121 Florence, Italy
[c] Department of Earth Sciences, University of Florence, Via La Pira 4, I-50121 Firenze, Italy
[d] Indian Institute of Technology Hyderabad, Telangana, 500089, India
[e] Rajiv Gandhi Institute of Petroleum Technology, Amethi, 229304, India

ARTICLE INFO

*Keywords:*
Boron isotope
Hydrogeochemistry
West coast
Water-rock interaction
Rare earth elements

ABSTRACT

Thermal springs lined up for about 350 km along the Western coast of Maharashtra, India, have been studied for major, minor, trace and rare earth elements, along with the boron isotope ratios for selected samples, to understand their evolution pattern. These alkaline springs have discharge temperatures varying from 40 to 72 °C. Based on the major ion composition, it is established that most of the thermal springs are of Na(Ca)-Cl or Ca(Na)-Cl type, with a few of Na-Cl($SO_4$) type. Only one thermal spring at Rajapur is Na-$HCO_3$ type behavior. Trace elements concentration vary significantly e.g., Li (19–386 ppb), B (104–1362 ppb), Sr (16–13560 ppb), Rb (13–220 ppb), Cs (0.75–44 ppb) and Ba (3–2077 ppb). Chondrite-normalized REE patterns indicate a pronounced 'Eu' anomaly probably due to the involvement of plagioclase, but the effect of temperature reaching more than 250 °C cannot be ruled out in case of some springs. First-time study of $\delta^{11}B$ isotope (range between 2.5‰ to 27.0‰) of the West Coast thermal fluid suggests role of leaking marine sediments in their evolution. Water-rock interaction experiments with granite, basalt and diluted seawater at elevated temperatures and pressures have given an insight into the evolution of the thermal springs. Based on all the findings, a conceptual model has been prepared, which gives an overview of the evolution of the thermal springs.

## 1. Introduction

West Coast Geothermal Province (WCGP) (19° 42′ 43″N - 72° 50′ 55″E to 16° 38′ 44″N - 73° 31′ 52″E) is the one of the potential geothermal areas among the seven geothermal provinces defined in India (Chandrasekharam, 2000; Fig. 1). WCGP hosts more than sixty thermal springs at eighteen locations, with discharge temperatures ranging from 40 to 72 °C. These thermal springs follow a linear trend and pass through the Palghar, Raigad and Ratnagiri district of Maharashtra, covering a linear distance of about 350 km.

Although these thermal springs are issuing through the 65 Ma Deccan Volcanic Province (DVP), the major ion and isotope chemistry indicates the influence of underlying formations (Kaladgi and Dharwar sedimentary and meta-sedimentary basins), which overlie the Precambrian granite-gneiss (Chandrasekharam, 2005; Kumar et al., 2011; Singh et al., 2014). Large outcrops of these high heat producing granites (about 5 $\mu Wm^{-3}$, Singh et al., 2014) can be located towards the south and southeast of the DVP.

Chemical constituents of thermal waters have been widely studied as a tool for exploration development and subsequent monitoring of geothermal resources (Arnórsson, 2000). WCGP thermal spring waters have been widely studied in terms of major ions and oxygen and hydrogen – stable isotopes (Minissale et al., 2000, 2003; Singh et al., 2014; Gurav et al., 2015). Though these studies have pointed out the involvement of seawater-basalt interaction, no direct evidence of the marine source had been established. Concentrations of major ions, trace and rare earth elements (REE) are used to decipher the fundamental processes taking place in a geothermal system with application to geothermometry, mineral fluid equilibrium, mixing models, extent of water-rock interaction, origin of fluid and also to study potential environmental impacts of the geothermal exploitation (Pope and Brown, 2014; Kaasalainen et al., 2015; Lu, 2015). A boron isotope study has been used to decipher the origin of geothermal fluid (Vengosh et al., 1991, 1994; Yuan et al., 2014). Thus, the overall understanding of the chemical make-up of the fluids assists in the interpretation of physicochemical processes that take place during their ascent to the surface.

* Corresponding author.
*E-mail addresses:* trupti@iitb.ac.in (T. Chandrasekhar), minissa@igg.cnr.it (A. Minissale), orlando.vaselli@unifi.it (O. Vaselli), dchandra@iith.ac.in (D. Chandrasekharam), hksingh@rgipt.ac.in (H.K. Singh).

https://doi.org/10.1016/j.geothermics.2018.03.007
Received 3 October 2017; Received in revised form 7 March 2018; Accepted 10 March 2018
0375-6505/ 

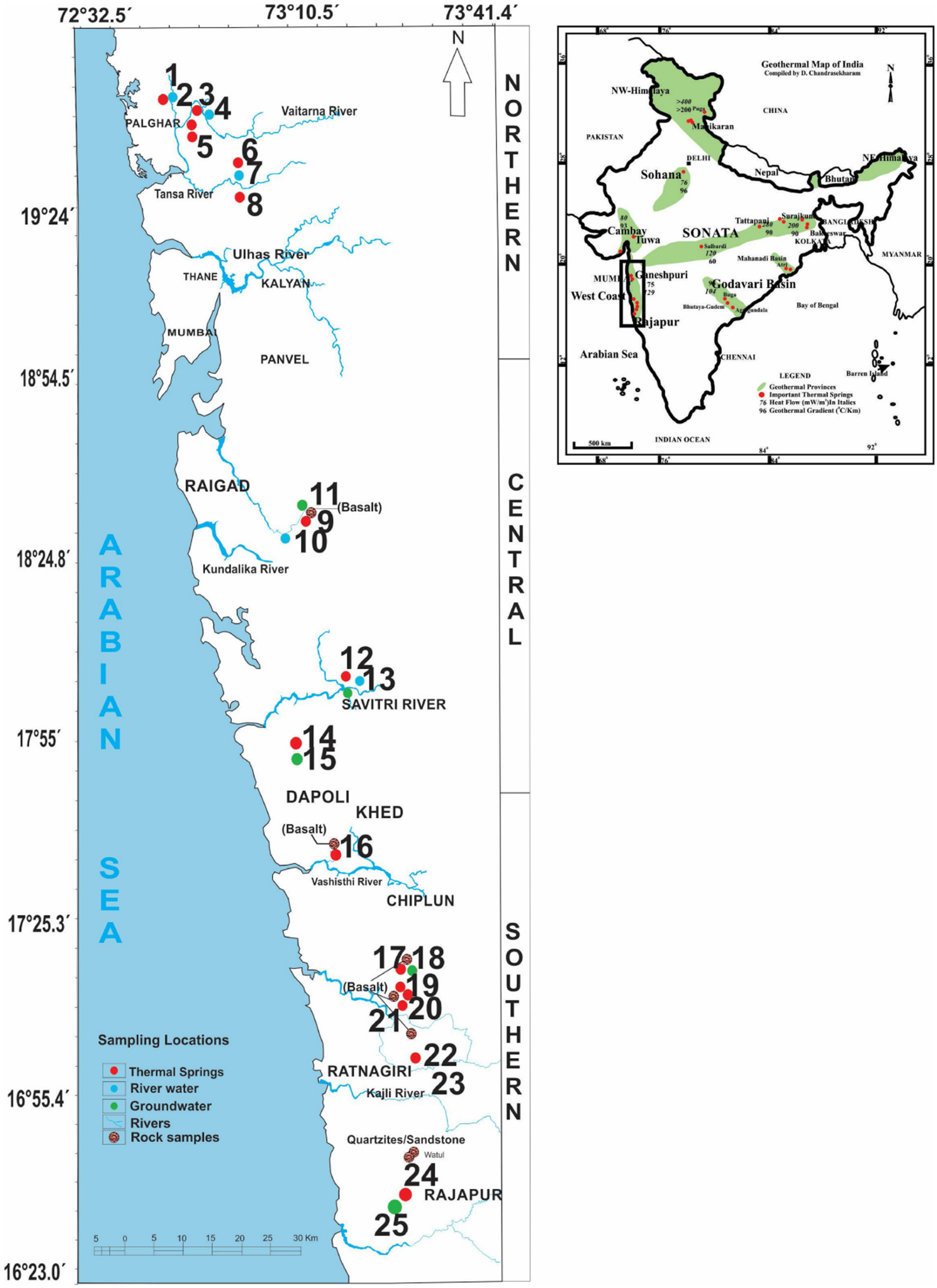


**Fig. 1.** Geothermal provinces of India showing the location of study area with sampling locations for thermal waters, groundwater and rock samples.