Hydrogeological controls of radon in a few hot springs in the Western Ghats at Ratnagiri district in Maharashtra, India

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Geological structures (faults, fractures and weak zones) and high heat flow in geothermal areas allow easy passage for release of radon gas to the atmosphere. Radon is constantly transported from the Earth's interior and vented out through exhalation points at permeable fault zones. ^{222}Rn concentrations were measured in a few hot springs and nearby groundwater using RAD7 at Tural and Rajwadi, Ratnagiri district, Maharashtra. The ^{222}Rn concentrations in the hot springs vary from 1087 ± 132 to 1655 ± 177 Bq/m^3 at Tural and from 152 ± 67 to 350 ± 82 Bq/m^3 at Rajwadi. Groundwaters from wells within a radius of 200 m around the geothermal fields have radon concentration between 1087 ± 132 and 5445 ± 337 Bq/m^3. We have assessed the radon activity in the vicinity of the hot springs to understand their hydrogeological control, origin of heat source and possible effect on the tourist and the human population residing nearby.

Keywords: Deccan Traps, geothermal, hydrogeology, radon, Western Ghats.

RADON (^{222}Rn) is colourless, tasteless and odourless radioactive noble gas, formed by the decay of radium-226 in uranium (^{238}U) decay chain. Average concentration of uranium in the Earth's crust is about 4 mg/kg. Uranium decays into numerous other radioactive isotopes including ^{222}Rn. In geothermal fields, radon is ejected from the solid and into the adjacent pore space, mineral grain or groundwater[1].

Radon concentration in groundwater is a function of hydrochemical features of the aquifer[2,3] or the presence of high geothermal heat flow[4] and the physical properties of the rock and sediment comprising the aquifer. Owing to its gaseous state, higher water solubility under ambient high pressure and temperature and inert chemical properties, radon is very mobile and can move either as a distinct gas or dissolved in cold or hot water or petroleum[5]. Its behaviour is basically determined by the physical processes and not by the chemical interactions. Radon emanation and movement are governed by two important mechanisms, namely, diffusion and convective flow, before the radon ultimately reaches the open atmosphere[6]. Apart from the radiogenic sources of radon (^{238}U or ^{226}Ra) and moisture content, the above mentioned two processes are also dependent on available pores through which radon can move within the materials. Therefore, the porosity of any system seems to be an important physical property that influences these processes related to radon flux[7]. Radon measurements in geothermal fields provide useful information for investigating possible correlations of radon with physical characteristics of geological formation (porosity, permeability and density), characteristics of aquifer (chemical and physical), to locate possible geothermal production area[8] and its potential[9], the origin of fluids and aquifer structure in which the fluid ascends[10]. ^{222}Rn has most important applications in geothermal field, because of the high sensitivity to changes in tectonic and geothermal conditions. Spatial and temporal changes in ^{222}Rn concentration may be used for studying reservoir thermodynamic conditions, earthquakes and estimation of fluid flow and circulation in hydrothermal systems.

In India, hot springs are broadly distributed in different geological formations in Western Ghats, the Himalaya, Godavari, Mahanadi, etc. The Geological Survey of India has identified 340 geothermal springs throughout the country[11]. The Western Ghats of India alone has 60 hot springs in 18 areas along NNW–SSE trending deep faults[12]. Giggenbach[13] and Gonfiantini[14] carried out investigation on environmentally stable isotopes (δ^{18}O and δ^2H) and environmental tritium (^{3}H) on these hot springs to find out the source of geothermal water. The aims of this study are: (i) to evaluate the radon activity in the geothermal waters and groundwater; (ii) to establish relationship between the radon activity in groundwater and the presence of high-geothermal gradient in the areas. As such, this study aims to contribute to the knowledge of the secondary control mechanisms (because of the hydrochemical and geothermal features of the aquifer) on radon distribution in the groundwater, particularly in geothermal water.

The study areas lie in Ratnagiri district of Maharashtra to the west of the Western Ghats (Figure 1). Average annual rainfall in the area is 2860 mm. Monsoon rainfall occurs from June to September and a maximum average monthly rainfall of 890 mm is recorded in July[15]. October and November receive late showers from returning monsoon. The hottest month is May with a mean monthly temperature of 32.7°C and the coldest month is January with a mean monthly temperature of 18.6°C. Geomorphologically, the area consists of chains of small hills and undulating plateaus with altitude ranging from 25 to 250 m amsl. The study area lies in the Western Ghats in Deccan Traps terrain of India. The Deccan Traps were formed because of a series of volcanic eruptions that

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occurred at the end of the Cretaceous about 65 million years ago. It is one of the largest volcanic features on the Earth's surface[16]. As a result of a series of volcanic eruptions, the traps comprise of layers near horizontal lava flows of varying thickness. Consecutive lava flows are separated by sedimentary intertrappeans which were deposited during the interval between two eruptions. Groundwater of limited quantity occurs in weathered, fractured and in lateritzed aquifers at shallow depths, in semi-confined to confined conditions in intertrappeans and vesicular basalt units between two successive layers of compact basalts and in the joints and fault/fracture zones within massive basalt units. Faults, fracture zones and joints connected to the confined deeper aquifer act as conduits for vertical movement of groundwater under *in situ* hydraulic pressure which manifests in the form of springs on the ground surface.

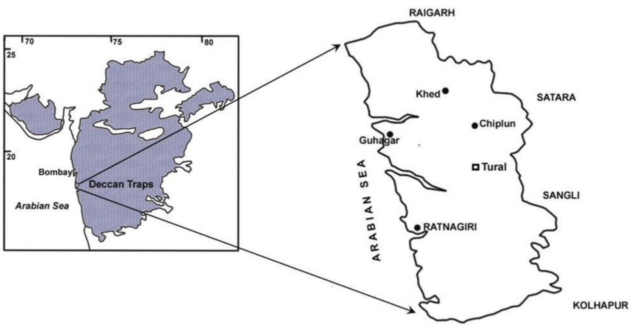

Figure 1. Location map of the study area situated in the western part of Deccan Traps, Maharashtra, India.

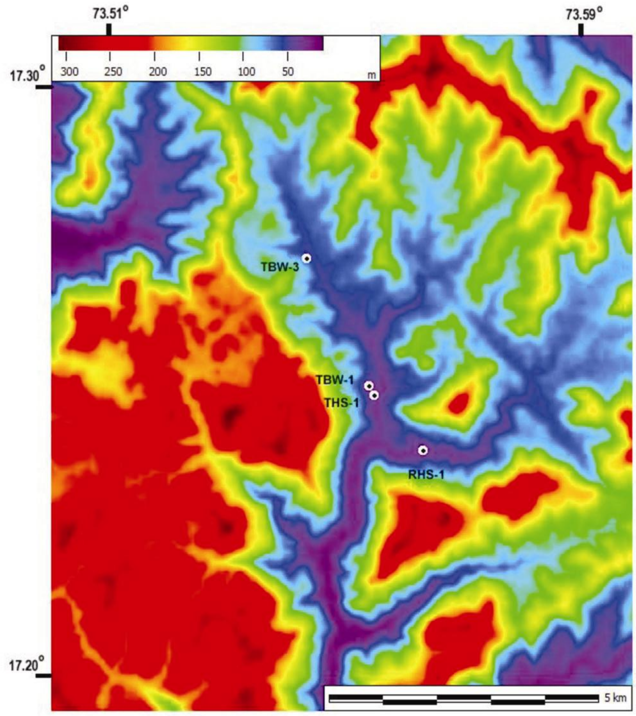

Figure 2. Digital elevation model of the study area showing sampling locations.

The physico-chemical parameters (pH, electrical conductivity (EC), temperature, TDS and dissolved oxygen) were measured at site during the sampling programme. Water samples were collected (September 2013) from hot springs and dug wells (Figure 2). The results of the analyses are given in Table 1. Radon in water is measured using RAD-7 (Durridge Co, USA, Model No. 711) with a detection limit of 10^{-4} Bq/L. The sample bottle (250 ml) is connected to the radon-in-air monitor (RAD7) in a closed air-loop mode, with a desiccant column before the air inlet of the counter[17]. The ^{222}Rn from the water samples continuously circulates through the desiccant column, RAD7, and then back to the water sample so that it reaches equilibrium between water and air. Then, the activity of ^{222}Rn is determined by counting its alpha-emitting daughters. The activity of ^{222}Rn in water is calculated from the distribution factor of radon concentration between water and air.

The environmental tritium (^{3}H) content of the water sample was measured using a liquid scintillation counter (Perkin Elmer Quantulus-Model No. 1220) preceded by electrolytic enrichment[18] (precision: 0.5TU ($\pm 1\sigma$)).

The results showed that the electrical conductivity of the hot springs was 1680 and 1484 μS/cm for Tural and Rajwadi respectively, which is dependent on their travel path and the associated rock–water interaction (dissolution of rock minerals), whereas pH lies in the range of 7.4 to 8.2. The discharge rate of Tural hot springs (THS-1) is 6.2 litres/sec and Rajwadi hot springs (RHS-1) is 4.45 litres/sec. The temperature of geothermal springs ranges from 50°C to 61.5°C. The low tritium (0.8–1 TU) of geothermal springs suggests that the waters arise from deeper zones. They are long circulating with an active heat source situated at greater depth. The ^{222}Rn concentration in the hot springs water varies from 1087 ± 132 to 1655 ± 177 Bq/m^3 at Tural and from 152 ± 67 to 350 ± 82 Bq/m^3 at Rajwadi. The low ^{222}Rn concentration in hot springs indicates that their heat source is not radiogenic, it may be the mantle.

Groundwater at a radius of 200 m around the geothermal field has radon concentration between 1087 ± 132 and 5445 ± 337 Bq/m^3 that is well below the regulatory limit of 11.1 KBq/m^3 proposed by USEPA[19] and the EU[20] reference level set at 100 kBq/m^3. These aqueous radon gases may be partly absorbed to the outer surface of the rock in the thermal spring site[21], forming bubbles on the surface that transfer some exhaled radon occurring in the rock into the water at a faster pace after they are desorbed with the assistance of small changes of gas pressure, water temperature and spring flow rate that is a plausible reason for the relatively high radon concentration of the Tural hot spring (THS-1). This is a type of micro-bubble mechanism that accounts for the up-flow of geo-gases carrying radon from deep sources all the way

Table 1. Radon concentration, physicochemical parameters and environmental tritium in geothermal springs and groundwater

Sample ID	Location	Latitude (North)	Longitude (East)	Type	Temperature (°C)	EC (µS/cm)	pH	DO (mg/l)	TDS (mg/L)	Tritium (TU)	Radon-222 (Bq/m^3)
THS-1	Tural	17°14′55.5″	73°33′26.5″	Hot spring	61.5	1680	7.38	7.17	1167	1	1310 ± 145 1280 ± 162 1490 ± 177
RHS-1	Rajawari	17°14′23.3″	73°33′42.2″	Hot spring	50	1484	8.21	5.34	1039	0.8	230 ± 62 350 ± 82 152 ± 67
TBW-1	Tural	17°14′59.6″	73°33′14″	Bore well	35	890	7.05	6.8	623	1.5	1087 ± 132 1400 ± 165 1265 ± 167
TBW-3	Tural	17°16′21″	73°32′35″	Bore well	29.3	183	7	3.72	128		2897 ± 215 5050 ± 305 5445 ± 337

to the surface[22]. As molecular formation of gases is associated with covalent bonds of energies in the low eV range, alpha-particle ionization energy could easily break down these bonds directly, leading to the decomposition of the gas molecule into its constituent atoms that can be ionized by alpha particles.

The measured fluctuating radon exhibits temporal variations; which are controlled by various geophysical driven factors such as Earth tides, variations in groundwater levels, changes in sub-surface heat flux in the geothermal area, etc. This variability is caused by chemical and/or physical processes. The low environmental tritium of geothermal water (0.8–1 TU) indicates the long travel path for the geothermal water.

Radon concentrations of some thermal springs and groundwater located at Tural and Rajwadi near Chiplun in Ratnagiri were determined using the active method of alpha detection performed by the commercial radon measuring device (RAD7). The radon level of the Tural hot springs varies from 1087 ± 132 to 1655 ± 177 Bq/m^3; and for the Rajwadi hot springs, it varies from 152 ± 67 to 350 ± 82 Bq/m^3. Groundwater in a radius of 200 m around the geothermal field has radon concentration between 1087 ± 132 and 5445 ± 337 Bq/m^3 which is well below the regulatory limits proposed by widely accepted international institutions[19,20]. The low tritium of geothermal springs suggests that the waters are coming from deeper zones and the heat source is present at greater depth. It was observed that the radon concentration in groundwater has a relationship with geological and geohydrological patterns of the study area.

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Fire and soil temperatures during controlled burns in seasonally dry tropical forests of southern India

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Fire and soil temperatures were measured during controlled burns conducted by the Forest Department at two seasonally dry tropical forest sites in southern India, and their relationships with fuel load, fuel moisture and weather variables assessed using stepwise regression. Fire temperatures at the ground level varied between 79°C and 760°C, with higher temperatures recorded at high fuel loads and ambient temperatures, whereas lower temperatures were recorded at high relative humidity. Fire temperatures did not vary with fuel moisture or wind speed. Soil temperatures varied between < 79°C and 302°C and were positively correlated with ground-level fire temperatures. Results from the study imply that fuel loads in forested areas have to be reduced to ensure low intensity fires in the dry season. Low fire temperatures would ensure lower mortality of above-ground saplings and minimal damage to root stocks of tree species that would maintain the regenerative capacity of a tropical dry forest subject to dry season wildfires.

Keywords: Biligiri Rangaswamy Temple Wildlife Sanctuary, fuel load, fuel moisture, Mudumalai Wildlife Sanctuary, temperature indicating lacquers, weather.

OF the various aspects of fire regimes in natural ecosystems, varying intensity and severity of fires[1] are known to affect soil properties and below-ground processes[2], plant species demography[3,4] and plant community structure[5]. In a comparison of the effects of low and high intensity fires on soil properties in dry forests of Bolivia, lower levels of soil organic matter as well as altered physical properties were found after a high intensity burn, but such changes were not observed after low intensity fires[6]. The high post-fire mortality in small-sized individuals of tree species in seasonally dry tropical forest[7] could be due to high intensity fires, as observed for resprouts of a chapparal shrub species[3], and juveniles and saplings of Australian savanna tree species[4] after high intensity fires during experimental burns. Dissimilar floristic composition between plots burnt at differing intensities at sandstone woodland and shrubland sites in Australia[5] was due to an increase in the number of fire-tolerant species in plots subjected to high intensity burns. It is therefore important to characterize fire intensities for a region to assess the potential impact on the ecosystem and design appropriate fire management plans.

Fire temperature is one such measure of fire intensity[8] influenced by factors such as fuel load, fuel type, fuel moisture and weather conditions[9–13]. While a definite relationship of increasing fire temperature with increasing fuel loads has been established in many cases[6,9,11,12,14], the relationship between fire temperatures with fuel moisture is unclear. For example, a strong positive correlation of fire temperature with fuel moisture was reported in a study in mixed grassland sites in Texas[9], whereas another study in Texas conducted in grassland sites dominated by an invasive shrub (*Prosopis glandulosa*) did not find any correlation[12]. Fire temperatures were not correlated with wind speed in most studies[9,12,13], as well as with relative humidity[9,12], whereas ambient temperatures appeared to have an effect on fire temperatures in one study[9], but not in another[12]. However, all of the studies cited so far have examined the effect of the variables considered on fire temperature as single correlations. The combined effect of these factors on fire intensity in natural ecosystems has, yet, not been assessed. A multiple regression framework would allow an assessment of which variables are important in influencing variations in fire temperature.

In the present study we assess the combined effect of fuel load, fuel moisture and weather parameters on

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