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Isotope Geochemistry with Implications on the Genesis of Alkaline Bicarbonate Water Along the Himalayan High-temperature Geothermal Belt

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ABSTRACT

Himalayan geothermal belt is marked with more than 1,750 hot springs together widespread fumaroles, geysers, steaming ground and large piles of sinters. The tectonic background is the collision between the Indian and Eurasian continents after the closing of the ocean Tethys in the Cenozoic and the continuous compression thereafter has created such a hot orogeny at high elevations. The alkaline bicarbonate water dominates in these hot springs except those in Tengchong volcanic geothermal field and a few magmatic geothermal fields, such as Yangbajing. It is proposed that the geothermal water has experienced a relative rapid circulation in the hot thickened crust after being recharged by precipitation. This is the reason for the fact that thermal waters of most high-temperature geothermal systems show little or no oxygen isotope shift. Furthermore, according to the isotopic composition of $\delta^{13}C_{CO2}$ contents and the helium gas isotopic ratio, it is proposed that the crustal CO_2 is product of metamorphic limestone that was formed in the Tethys oceanic basin. The excess bicarbonate ion due to the dissolution of large amount of metamorphic CO_2 has produced alkaline bicarbonate water along the Himalayan high-temperature geothermal belt.

1. INTRODUCTION

Himalayan geothermal belt which is marked with numerous and widespread boiling springs, fumaroles, geysers, steaming ground and large scale of geothermal sinters stretches from Pamir terrane through Tibet and western Sichuan into Yunnan. It is a major part of the Mediterranean-Himalayas geothermal belt. As recorded the total number of geothermal springs in this area is more than 1,750. There is no doubt that the tectonic collision between the Indian and Eurasian continents under the control of the closing of Neo-tethys ocean in the Cenozoic and the continuous compression thereafter has created such hot orogen at high elevations. As recorded, most hot spring water has bicarbonate as dominate anionic component. It is a characteristic feature of the Himalayan high-temperature geothermal waters.

In this case, isotope geochemistry could help to identify the origin of these bicarbonate ions and delineate the evolution of the high-temperature geothermal waters in the Himalayan geothermal belt. All of the data used in this study are available in the public domain.

2. GEOLOGIC SETTING

A review of the geologic history of the Himalayan-Tibetan orogen suggests that at least 1400 km of north-south shortening has been absorbed by the orogen since the onset of the Indo-Asian collision at about 70 Ma (Yin and Harrison, 2000). The rise of the high Tibetan plateau likely occurred in three main steps, by successive growth and uplift of 300- to 500- kilometer-wide crustal thrust-wedges, which are stacked together to form a crust with a thickness of approximately 70 km. The crust thickened, while the mantle, decoupled beneath gently dipping shear zones, did not. Subduction was oblique and accompanied by extrusion along the left lateral strike-slip faults that slice Tibet's east side (Tapponnier et al., 2001). As a by-product of the tectonic motion, geothermal activity is very frequent and intense here. Similar to active tectonics, modern geothermal activities are strong in the south and weak in the north.

Since the lithosphere of Tibetan Plateau has been thickened, the mantle heat is limited depending on both heat diffusion and fluid convection. The heat source triggering the formation of these hydrothermal systems could originate from the crust, including radiogenic heat produced by the heat-producing elements (U, Th and K) and tectonic deformation. What is more, it has been shown that the relative motion between the lithospheric sectors could lead to the temperature rise up to more than 800 °C (Tang et al., 2017). Hochstein and Regenauer-Lieb (Hochstein and Regenauer-Lieb, 1998) computed the heat generation associated with collision of two plates along the Himalayan geothermal belt and state that the hydrothermal systems are largely related to the plastic deformation of the ductile crust within the Asian plate resulting from plate collision.

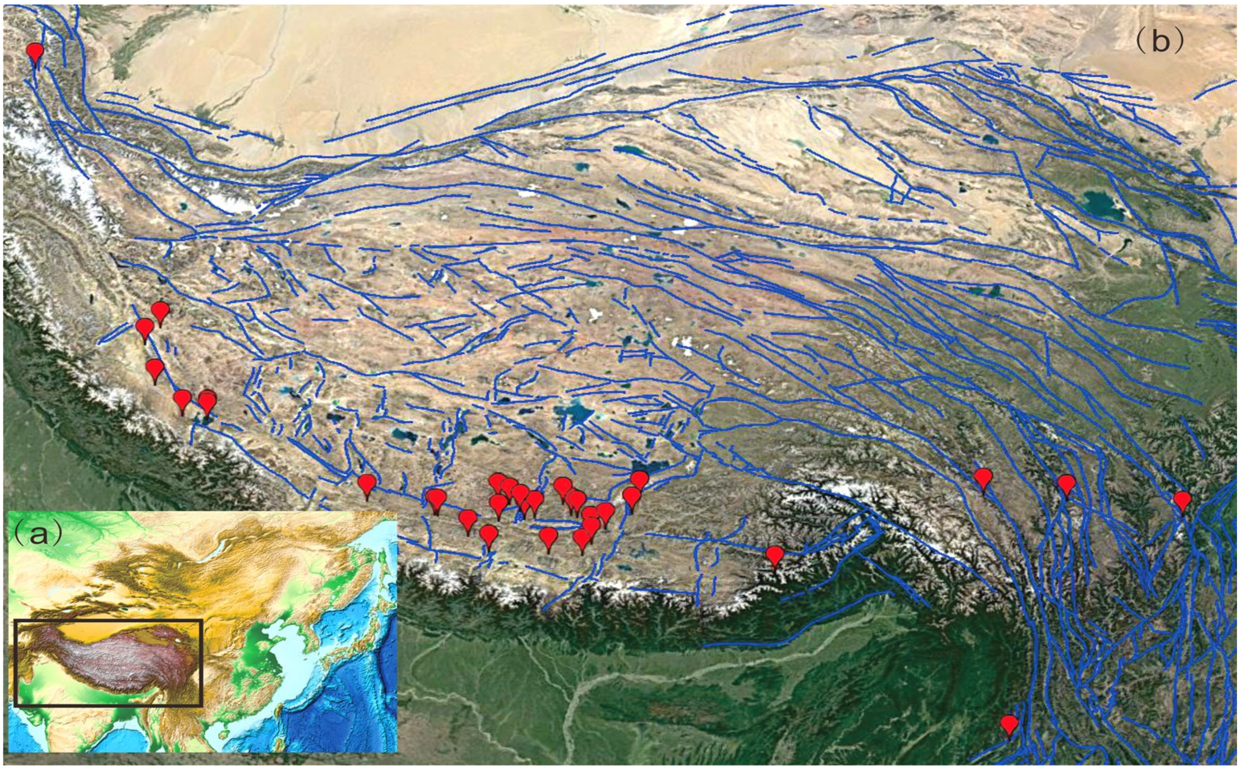


Figure 1 (a) Location of the Himalayan geothermal belt; (b) The hot springs considered in this work (red bubble) and the active faults in this area (blue line)

3. RESULTS AND DISCUSSION

3.1 Geothermal Water Chemistry

According to the analysis of geothermal waters (Figure 2), it has been found that most hot springs in the northern Tibetan Plateau, western Sichuan Plateau and Hengduan Mountain area have bicarbonate as their dominant anionic component except that only a few sulfate sodium type and chloride sodium type geothermal waters could be found in the Rehai hydrothermal system of the Tengchong volcanic area and the individual places along the Yarlung Zangbo River. For example, Yangyi geothermal field in Tibet discharges alkaline HCO_3-Na type geothermal fluid from both geothermal wells and hot springs, showing bicarbonate concentrations as much as 815 mg/L (Guo et al., 2009) while the low salinity Na-HCO_3 type geothermal water was found in the Lianghe geothermal field (462 mg/L) that came from a shallow steam-heated geothermal aquifer. Likewise, high-temperature geothermal fluids from the eastern syntaxis of the Himalayan orogenic belt, Kangding and Rekeng, were recently reported to be alkaline HCO_3 type or HCO_3-Cl type water with their bicarbonate concentrations of 1259 mg/L and 741 mg/L, respectively. According to the ^{2}H and ^{18}O analysis of geothermal water, there is no evident oxygen shift in water sample from these bicarbonate geothermal systems. It implies that the geothermal water was recharged by meteoric water and only suffered a relatively rapid circulation in the crust (Guo et al., 2017; Tian et al., 2018). Generally, the chemical reactions among water, dissolved carbon dioxide and reservoir rocks containing albite and microcline as major minerals (Eq. 1 and 2) control and dictate the composition of the alkaline HCO_3-Na type geothermal fluid. However, the following question has yet to be answered: where is the excess carbon dioxide from?

$$2NaAlSi_3O_8 + 9H_2O + 2H_2CO_3 \rightarrow Al_2Si_2O_5(OH)_4 + 4H_4SiO_4 + 2Na^+ + 2HCO_3^- \qquad (1)$$

$$2KAlSi_3O_8 + 3H_2O + 2CO_2 \rightarrow Al_2(Si_2O_5)(OH)_4 + 4SiO_2 + 2K^+ + 2HCO_3^- \qquad (2)$$

3.2 Hydrothermal Gas Chemistry and Its Isotopes

Bubbling in hot springs is one of the most typical manifestations along Himalayan geothermal belt. As recorded in the literature, the main component of the geothermal gas samples is CO_2 with volume percent generally more than 80 % or even as high as 99.8%, followed by variable amounts of N_2, Ar, He, H_2 and CH_4. It is similar to most high-temperature geothermal systems around the world. However, the H_2S concentrations are generally low in the bicarbonate hydrothermal systems. This phenomenon could be the result of two factors: (1) absence or inaccuracy of the measured data due to the nonstandard sampling and detection methods; (2) there is little H_2S, SO_2, HCl or other magmatic volatile in this area since no magma chamber lying underground. Given the following analysis, the second one seems to be the dominant factor.

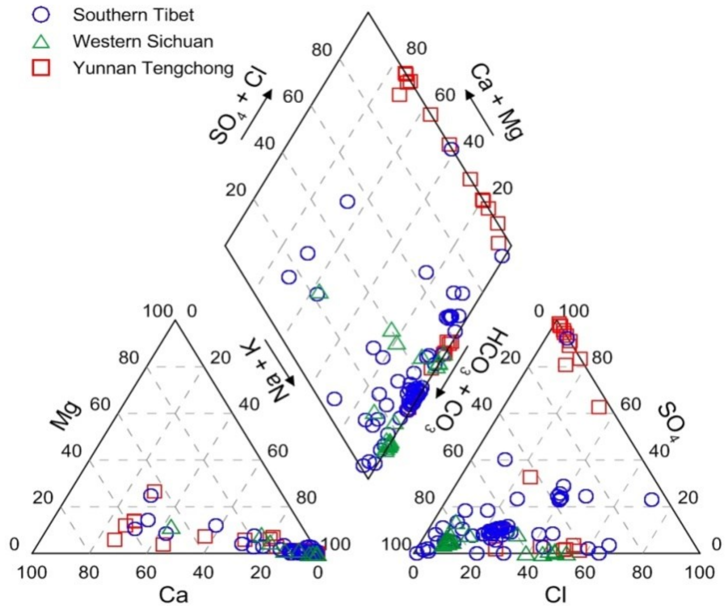
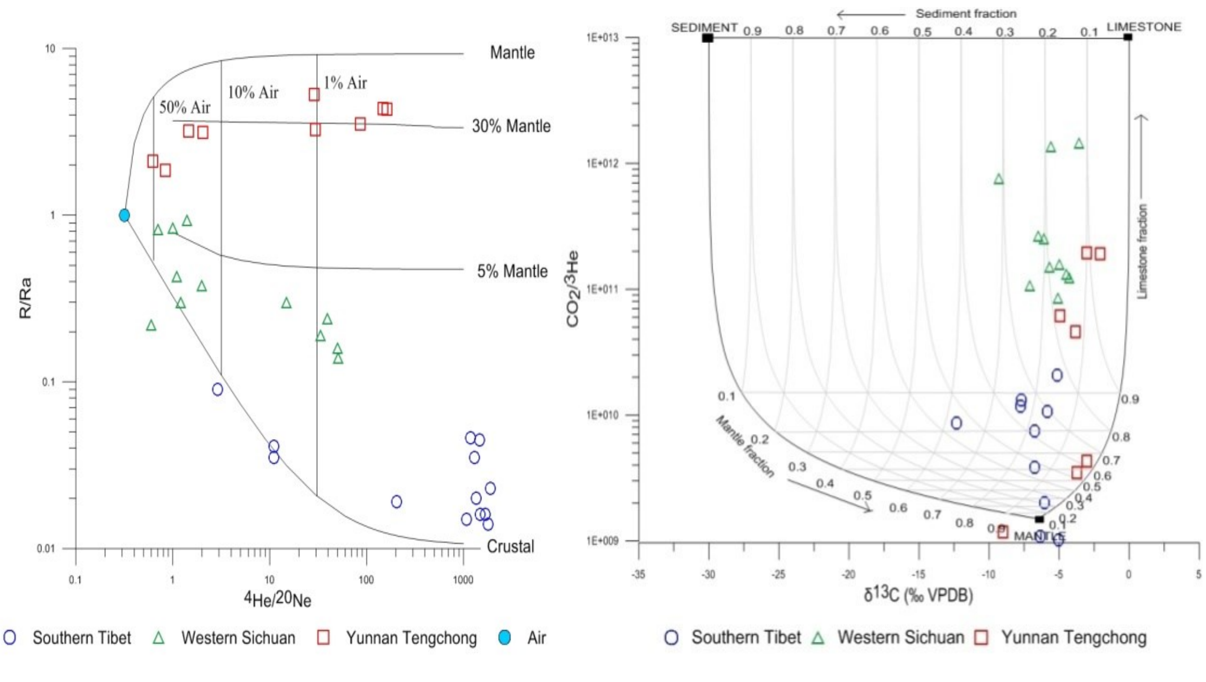


Figure 2 Piper diagram of samples collected at the Himalayan geothermal belt, data was collected from related references (Guo et al., 2014; Guo et al., 2017; Guo et al., 2009; Kunyu, 2012; Liu et al., 2015; Tian et al., 2018)

The helium isotope ratio is a key for uncovering the origin of gas components as well as the heat source of the geothermal system. As shown in Figure 3a, the helium isotope compositions of Tengchong geothermal area show obvious mantle-derived characteristics while the other samples from the Himalayan geothermal belt are dominantly product of radioactive decay in the hot crust which has been thickened to over 70 km during the last 70 Ma. Apparently, it is reasonable that neither mantle-derived volatile nor conductive heat could make a big difference in the formation of Himalayan geothermal systems except for those areas, such as Tengchong, having magmatic chamber underground. In this case, the excessive carbon dioxide in geothermal fluid could be the metamorphic product of carbonate rocks in the thickened crust rather than mantle volatiles. This conclusion is supported by the carbon isotope ratio of carbon dioxide combined with the mantle derived helium (Figure 3b).

In terms of the geological setting of the Himalayan geothermal belt, the Palaeo-Tethys and Neo-Tethys belt is the product of successive opening and closing during the Palaeozoic and Mesozoic. During the period of marine sedimentation favorable conditions caused deposition of carbonate rocks which were metamorphosed during basin closure and tectonic collision between the Indian and Eurasian continents. Consequently, there is a large carbon source for the formation of crustal metamorphic carbon dioxide.



(a) (b)

Figure 3 Correlation between the $^3He/^4He$ and $^4He/^{20}Ne$ ratios in Himalayan samples, data was collected from related references (Zhang et al., 2016; Zhang et al., 2017; Zhou et al., 2017)

Cuopu geothermal system located in Western Sichuan is one of the most typical alkaline bicarbonate high-temperature geothermal systems. The geothermal water is recharged by local precipitation and glacier water from surrounding mountains. The TDS values are no more than 834 mg/L and the constituents are mainly from the dissolution of minerals by water and carbon dioxide lacking magmatic volatile dissolved in the fluid. Thermal waters reach an almost complete chemical equilibrium with the feldspar or plagioclase-enriched reservoir rock in a reducing condition. The reservoir temperature is between 175 °C – 200 °C, while the hot crust may reach up to 400 °C in the deep crust as indicated by the carbon isotopic exchange equilibrium between CO_2 and CH_4. The infiltrated glacier water was heated during its circulation deep within the hot thickened crust and continued dissolving the crustal metamorphic gas, such as radiogenic helium and limestone metamorphic CO_2, until the junction of the two sets of faults provided an ascending channel for the geothermal fluid. Upon rising along the conduit and dispersing in the anisotropic porous Quaternary sediments, the geothermal water mixed with groundwater to different degrees, and approximately 0.015 mol/L CO_2 escaped from the geothermal fluid when it scattered as bubbling hot springs on the surface. Similarly, Rekeng geothermal system in Eastern Himalayan syntax is also found to exhibit the strongest surface manifestations in the western Sichuan plateau, with numerous boiling springs, fumeroles and geysers. The chemical type of the geothermal water is alkaline HCO_3-Na as a result of water-CO_2-rock interaction. Based on helium isotope analysis, the mantle magmatic ^{3}He signatures have been largely obliterated since it accounts for no more than 5 %, implying there is no underlying mantle-derived magma chamber acting as heat source. Therefore, a significant portion of heat is likely converted from crustal deformation in view of the regional tectonic background as Eastern Himalayan syntax. The formation of low salinity alkaline Na-HCO_3 type water in the thickened hot crust may be a typical mechanism of the high-temperature geothermal system in the Himalayas.

The Yangyi geothermal field, located 72 km northwest to Lhasa City, capital of Tibet, has a high reservoir temperature up to at least 207.2 °C. The geothermal waters from both geothermal wells and hot springs belong to the HCO_3 (+ CO_3) - Na type. Though the heat source in this area is the underlying magma which is different from those of Western Sichuan, there is excessive CO_2 in the geothermal fluid resulting in the dominance of HCO_3- in geothermal water (Guo et al., 2009).

Otherwise, the geothermal water from Tengchong geothermal system shows massive degassing of CO_2 though its hydrochemical type is SO_4-Na (Guo et al., 2014). It has been proposed that active volcanoes at oceanic subduction zone is an important pathways for deep carbon degassed from Earth's interior. In Tengchong geothermal system, mantle-derived magmas at continental subduction zone can act as important triggers for liberation of carbon stored in crustal carbonate rocks, which has the potential to be a complement to volatile recycling mechanism at subduction zones (Zhang et al., 2016).

4. CONCLUSIONS

According to the gaseous isotopic ratio analysis combined with its geologic setting, the excessive bicarbonate ion in geothermal water is ascribed to the dissolving of large amounts of metamorphic CO_2 coming from underlying carbonate rocks formed in the Tethys oceanic basin. It is the chemical reactions among water, dissolved carbon dioxide and reservoir rocks containing aluminosilicate as major minerals that results in the formation of typical alkaline bicarbonate high-temperature geothermal water in the Himalayan geothermal belt.

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