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Genesis analysis of high-temperature geothermal systems in the Western Yunnan: geochemical evidence from geothermal fluids

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INTRODUCTION

The formation of high-temperature geothermal systems is often considered inseparable from magma or volcanic activity, where "magma/volcanic" represents high temperatures. However, does a high-temperature geothermal system exist in "non-magmatic/near-volcanic areas"? This is a key focus of geothermal system genesis research. The western Yunnan geothermal region is located within the high-temperature geothermal belt on both sides of the Neo-Tethys suture zone. The major geothermal fields and strong surface thermal manifestations are primarily controlled by the Late Cenozoic NE-trending strike-slip fault zones, giving rise to the RH , RD , RL geothermal field on the Tengchong block; the JH geothermal field in the southern part of the Baoshan block. During the Pliocene to Holocene, the Tengchong block experienced vigorous volcanic activity, with extensive outpouring of andesites and basalts. Groundwater circulates deeply through the Earth's crust along major deep faults and surfaces in uplifted mountainous areas, forming high-temperature hydrothermal geothermal systems.

Are the high-temperature geothermal resources developed in the region near volcanic areas in western Yunnan? The study of the origin of geothermal fluids and the distribution patterns of geothermal reservoir temperatures will provide important information for understanding the genesis of high-temperature geothermal systems and delineating deep geothermal target zones. This research holds significant practical value for accelerating the exploitation and utilization of high-temperature geothermal resources.

METHODS

Field geological investigations are completed in the western Yunnan, 16 samples of thermal water, 4 samples from geothermal wells, and 7 samples of geothermal gases are collected. Geochemical and isotope tests on 33 samples of geothermal fluids are conducted.

The laboratory analysis and testing of water samples are divided into three parts: cations, trace elements, and anions. The determination of cations in water is carried out using ICP-AES (Icap6000, Thermo Fisher Scientific). The analysis of 46 trace elements in water is performed using ICP-MS (7500C, Agilent), with quality control employing multi-element standard solutions (90243, 51844, Fluka). The detection accuracy for cations and trace elements is less than 0.5%. Anions are determined using Ion Chromatography (Dionex ICS600, Thermo Fisher Scientific). All analytical indicators of water samples meet the quality requirements, with the relative error of ion balance for most samples being less than 5%, and some less than 10%. The detection pass rate for samples is 100%. Gas composition analysis includes CH_4, CO_2, H_2, N_2, O_2, Ar, He, and H_2S, determined using a gas chromatography-mass spectrometer (MAT 271, ThermoFinnigan), expressed as gas volume percent (vol.%), with a detection limit of 0.0001%. Noble gas isotope analysis includes ^3He, ^4He, and ^{20}Ne, determined using an inert gas mass spectrometer (Noblesse SFT, Nu), expressed as $^3He/^4He$ and $^4He/^{20}Ne$. Gas carbon isotope $\delta^{13}C$ of CO_2 is analyzed using a gas isotope mass spectrometer (Delta VTM, ThermoFinnigan).

RESULTS

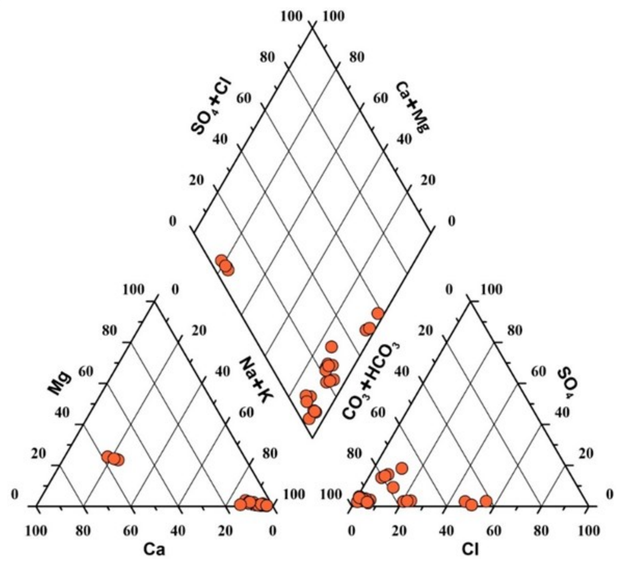


Figure 1. Piper diagram of geothermal water in western Yunnan

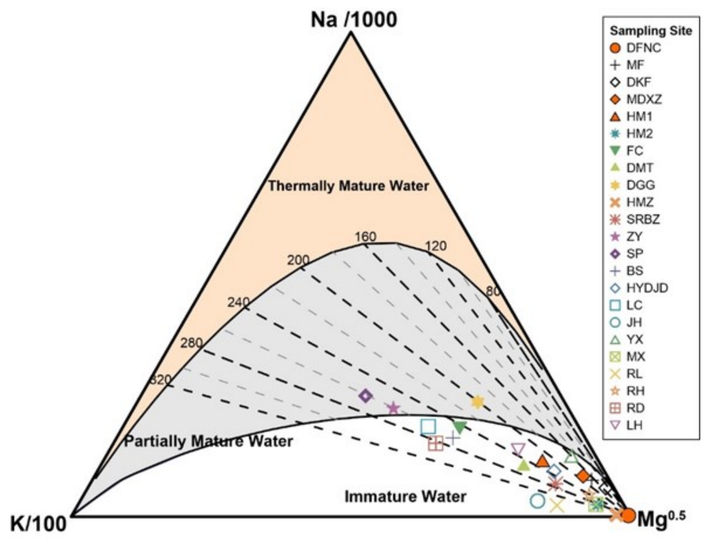


Figure 2. Na-K-Mg ternary diagrams of geothermal fields in Western Yunnan

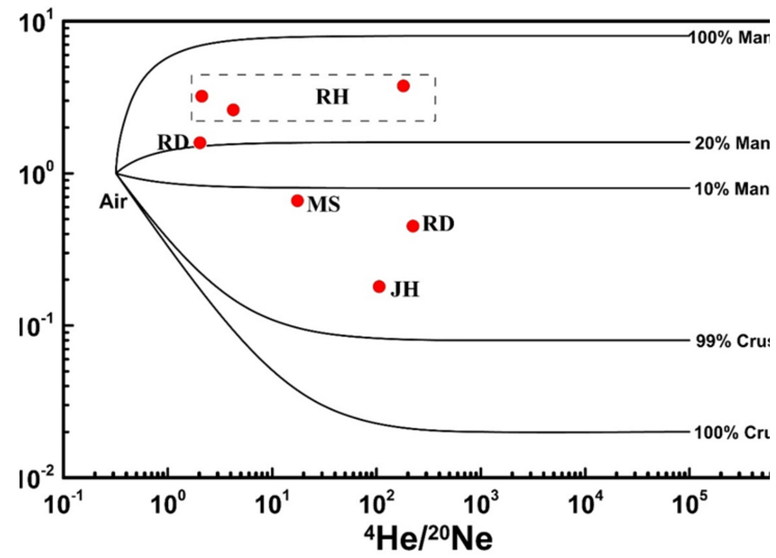


Figure 3.A plot showing the relationships between 4He/20Ne and 3He/4He isotopic ratios in several hot spring gases.

1.The water chemical types of LC, JH, YX, MS, RL, RH, RD, and LH are HCO_3-Na, HCO_3-Na, HCO_3-Na, HCO_3-Ca, HCO_3-Na, Cl-HCO_3-Na, HCO_3-Na, and HCO_3-Na, respectively.

2. The reservoir temperature in RH reach a maximum of 260°C; the RD, RL, YX, and JH have temperatures of approximately 220°C, 200°C, and 180°C, respectively.

3. RH hot spring sample exhibits distinct mantle-derived volatile component characteristics, with $^3He/^4He$ ratios reaching 2.6-3.8 Ra, significantly higher than atmospheric values (1 Ra) and crustal endmembers (~0.02 Ra). These values lie above the 30-50% mantle mixing line, and the $^4He/^{20}Ne$ ratios also indicate limited atmospheric mixing. The $^3He/^4He$ ratios at the hot spring sampling sites of RD and MS in Yunnan Province range from 0.4-1.6 Ra, with a mantle fluid admixture proportion of 5-20%, indicating that the hydrothermal fluids contain both mantle-derived gases and a significant amount of crustal-derived radioactive ^4He. The $^3He/^4He$ value of JH hot spring is 0.18 Ra, close to the 99% crustal curve shown in the diagram, clearly indicating that the gas source is almost entirely composed of crustal products, with negligible input from mantle volatiles (<3%).

DISCUSSION

Partial geothermal systems have reservoir temperatures ranging from 200–230℃, classified as typical high-temperature geothermal systems. Such reservoirs are often controlled by deep major faults and lithosphere-asthenosphere interactions, with their heat sources closely related to partial melting of the upper crust or residual heat from magmatic chambers. The hydrothermal water chemistry exhibits characteristics of Na-Cl or Na-HCO_3 types.

The thermal reservoir temperature of some hot springs is concentrated around 170–180 ℃. This type of intermediate-temperature geothermal reservoir is commonly distributed in the basin margin or foreland belt of strong fault activity. Geochemical modeling and mineral saturation indices indicate that these hot waters have not yet reached full equilibrium and show signs of mixing with shallow cool water. Their water chemistry type is primarily HCO_3-Na or HCO_3-Ca, reflecting the dissolution of carbonate and silicate minerals.

In western Yunnan, there are still some thermal reservoirs where the water temperature ranges only from 80-120 ℃, indicating a low-temperature thermal reservoir system. This geothermal water often exhibits significant dilution by cold water, with hydrochemical types mainly characterized as HCO_3-Ca-Mg, HCO_3-Ca or HCO_3-Na, reflecting their control by cold water infiltration and the dissolution of sulfate minerals during shallow circulation.

CONCLUSION

(1) Based on isotopic tracing of fluid circulation processes, geothermometers were applied to accurately evaluate reservoir temperatures. This confirmed that the RH, RD, RL, and YX in western Yunnan are high-temperature geothermal systems with reservoir temperatures exceeding 200°C.

(2) By analyzing water chemistry and gas isotope data, it was determined that the YX and JH in western Yunnan are high-temperature geothermal systems of non-magmatic origin and can serve as deep geothermal targets.

(3) Comprehensive geochemical analysis of geothermal fluids in western Yunnan revealed that the causality of the regional geothermal systems exhibits spatial heterogeneity and differences in heat source characteristics, which are controlled by tectonic variations.

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