Regional geothermal exploration and potential assessment in the Taitung Hongye area, Eastern Taiwan

Pei-Shan Hsieh[1], Tai-Rong Guo[1], Lun-Tao Tong[1], Wayne Lin[1], En-Chao Yeh[2], Hsin-Yi Wen[1], Sung-Yang Huang[1], Chao-Yen Lin[1], Chuan-Wei Chung[1], Chi-Hsuan Chen[3], Mien-Ming Chen[3] and Zong-Zheng Su[3]

[1] Material and Chemical Research Laboratories, Industrial Technology Research Institute, Hsinchu 31040, Taiwan

[2] Department of Earth Sciences, National Taiwan Normal University, Taipei 11677, Taiwan

[3] Taiwan Central Geological Survey, New Taipei 235055, Taiwan

pshsieh@itri.org.tw

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ABSTRACT

This study compiles various geothermal exploration reports and academic papers since the 1980s, and conducts supplementary geological, geochemical, and magnetotelluric surveys and geothermal potential assessment. The three-dimensional geothermal conceptual model of the Taitung Hongye area shows that under plate compression, the rock uplift resulting in a high geothermal gradient may act as the heat source of the geothermal system. A deep circulation of meteoric water accompanied by some deep crustal hot water forms a bicarbonate-type hot water with temperatures possibly exceeding 150°C. It migrates upward from the fracture zones and after being blocked by a relatively intact rock mass in the shallow depth, the hot water then migrates laterally along the fracture zone. Some of it infiltrates through river channels to form hot springs.

The geothermal resource is the phenomenon of high-temperature and high-salinity hot water stored in fractured rock masses, which often shows that the resistivity is more than a hundred times lower than that of the intact rocks. In the three-dimensional resistivity model, a low-resistivity structures resembling mushroom shapes is recognized, with the hot water up-flow zone as the stem and the out-flow zone as the cap. The up-flow zone has the highest temperature and is ideal for the geothermal production wells. Based on these characteristics, this study has identified six potential geothermal structures. An 800-meter deep geological borehole commissioned by the Central Geological Survey was completed in the out-flow zone. The significant hot water feed zones are between 300-400 meters deep, with a maximum measured temperature of 142°C, which corresponds well to the interpreted depth range of the low-resistivity geothermal structure obtained from the magnetotelluric survey. A high correlation between the low-resistivity structure and the geothermal structure is confirmed. Preliminary estimation of the potential generating capacity using the Monte Carlo stored heat method ranges from 51 to 181 MWe.

1. BACKGROUND

1.1 Regional Geology

The study area covers the geological region of Backbone Range and Longitudinal Valley (Fig. 1). The Luye fault is a N-S trending thrust fault and located in the contact zone between slate belt and conglomerate (Lin and Lin, 2005). The Mali anticline with northeast-trending is located in the upper reaches of Luye Creek and Danan Creek. The Miocene Mali Formation (thick meta-sandstone) exposes in the core of the anticline and conformable contacts with Miocene Hongye Formation (slate and phyllite with meta-sandstone and diabase) (Lin and Lin, 2005; Chen et al., 2016).

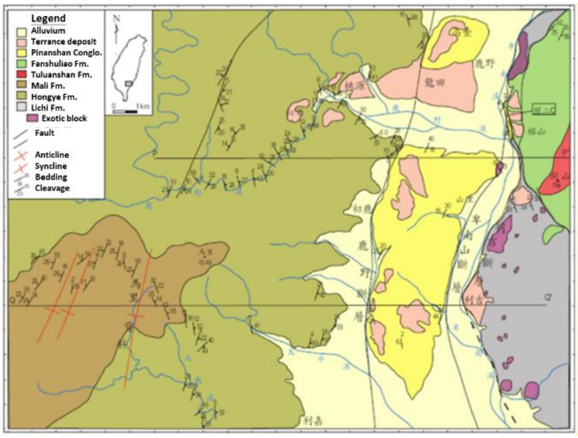

Figure 1: The geological map of the Hongye area (modified from Lin and Lin, 2005).

1.2 Previous geothermal investigation

In 1984, CPC Corporation, Taiwan carried out exploration of geothermal resources in the Hongye Hot Spring area. At that time, it drilled 5 temperature-measuring wells (HY-1 to HY-5) with a depth of 200 m, and the downhole temperature of 3 wells exceeded 100°C. The temperature of HY-4 is as high as 140°C, the geothermal anomaly ranges up to 8 square kilometers and the hinterland is flat (Huang, 1984). After CPC, various exploration and surveys in the Hongye area focused on the use of leisure hot springs. Since then, various exploration surveys in the Hongye area have focused on the use of leisure hot springs

We integrate the publicly available exploration well data in this area in the past, and conduct the geothermal gradient distribution as shown in the figure 2. The high temperature is mainly distributed on the west bank of Luye Creek, indicating that the geothermal potential area is likely to be located in the east and northeast of Hongye Valley Green Energy Hot Spring Park (TCC01). Since the strategy of geothermal exploration must first carry out large-scale survey and then screen the potential areas for site investigation, this study takes Hongye Valley as the center and conducts exploration within a radius of about 4 kilometers.

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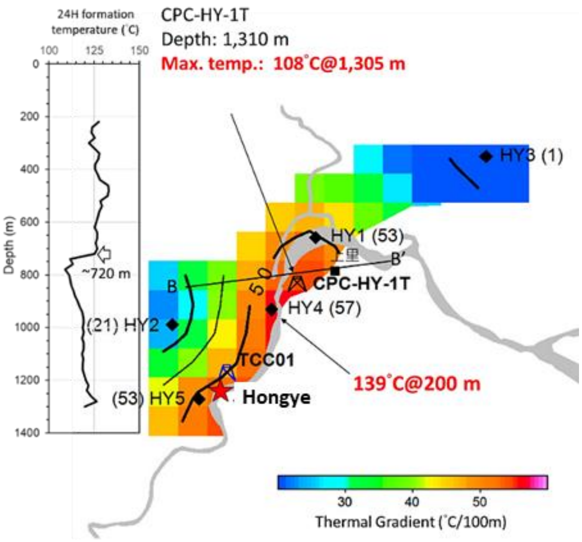

Figure 2: Thermal gradient distribution in the Hongye area (compiled from Huang, 1984 and Wu, 1985).

2. THREE-DIMENSIONAL RESISTIVITY MODEL

The up-flow zone and out-flow zone of high-temperature fluid are important features of geothermal potential site in the metamorphic rock area. Because the high-temperature geothermal water with high salinity in the fracture zone shows low resistivity, the distribution of low-resistivity bands can be used to indirectly indicate the location of geothermal structures. The hot water up-flow zones interpreted by resistivity structure in the Hongye area are shown in Figure 3.

There are total six geothermal up-flow zones (UF01~UF06) correlated to the mushroom-like low-resistivity structures (Tong, 2022). The UF04, UF05, and UF06 adjacent to the Liji Formation reflect the same low resistivity of Liji Formation, or the high-temperature geothermal structures are needed to be confirmed. UF01 and UF02 are adjacent to Hongye Valley Green Energy Hot Spring Park and the depth is relatively shallow.

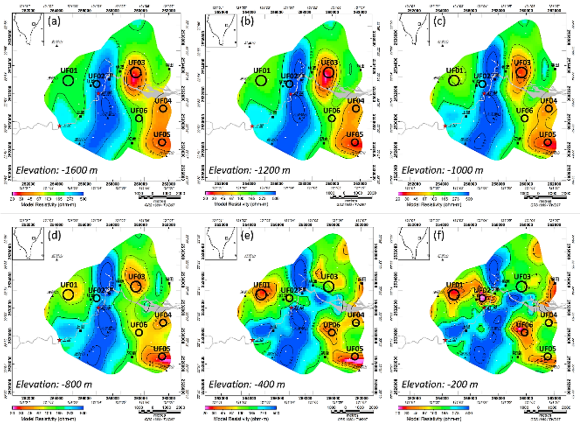

Figure 3: The hot water up-flow zones interpreted by resistivity structure.

Both UF01 and UF02 low- resistivity belts tend to expand from the center along the northeast or northwest direction, making the overall low-resistivity structure slightly asymmetrical cross-shaped, and the up-flow zone is located at the intersection of the cross. The small and ring-shaped low-resistivity zone in the deep part can be interpreted as the hot water up-flow zone, while the laterally expanded low-resistivity zone as the hot water out-flow zone (Fig. 4).

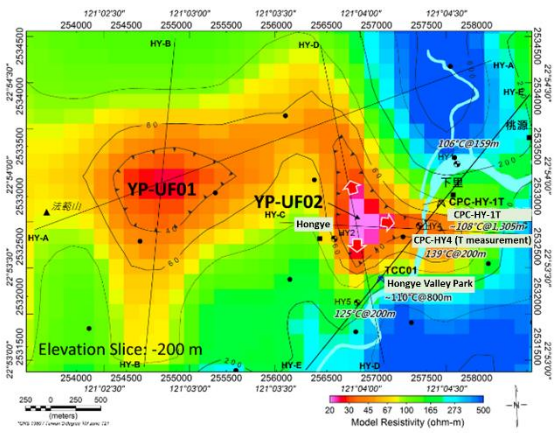

Figure 4: Resistivity structure overlapping the borehole temperature in the Hongye area.

3. HYDROTHERMAL FLUID CHARACTERISTICS

In the Hongye area, the composition of hot water from hot spring outcrops (THY-RH, THY-WH) and wells (THY-H1, THY-H2) all fall in the zone II of Piper diagram, which belongs to the $NaHCO_3$ type deep confined aquifers. The calcium concentration of hot water from hot spring outcrop is slightly higher than that from wells. Spring water and stream water samples (THY-WC, THY-R1, THY-R2) fall in zone I of the Piper diagram and belong to $Ca(HCO_3)_2$ type, showing the characteristics of shallow free aquifer, river water and meteoric water. According to the water quality, the probability of pipeline acid corrosion is not high, but there may be problems of scaling.

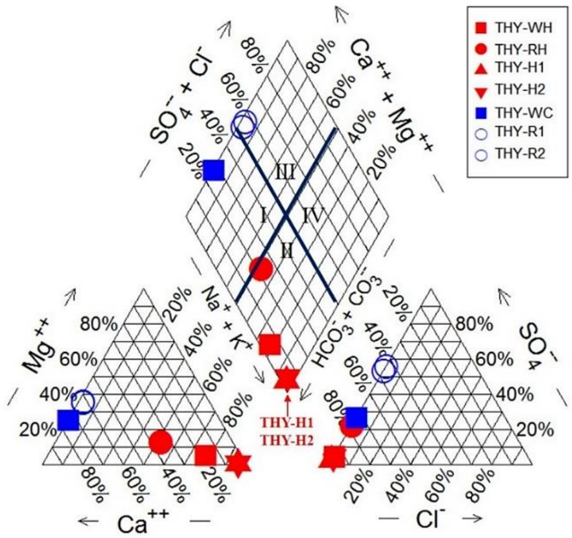

Figure 4: Piper diagram of thermal water in the Hongye area.

Figure 5 is the three-end member mixing model of Helium isotope (Sano and Wakita, 1985), which can be used to estimate the mixing proportion of hot water from the atmosphere, mantle and crust. The results show that the gas

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from the Hongye hot spring outcrop (THY-WH, RF-1, THY-1991) is mainly the mixing of the crust and the atmosphere with a slight contribution of the mantle component (6%), which may be a signal of deep geothermal fluid or be affected by the adjacent residual magma reservoir. The hot water from wells (THY-H1, RF-2, THY-H2) shows that the gas source is dominated by the crust and atmosphere, which is similar to the characteristics of most hot springs in the Central Range of Taiwan (Yang, 2000).

Based on the H-O isotopes and helium isotopes, it is speculated that the hot water is mainly derived from groundwater heated by deep circulation, and mixed with deep geothermal fluids migrating from crust structures.

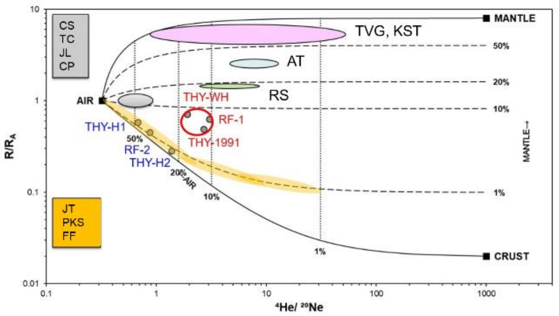

Figure 5: $^{3}He/^{4}He$ vs. $^{4}He/^{20}Ne$ plot for the fluid samples in the Hongye area.

4. DISCRETE FRACTURE NETWORK

For the simulation of discrete fracture network (DFN) in this study, the horizontal range is set to 2 km×2 km, and the vertical direction is simulated from the surface to 2 km below the sea level. The model covers as much as possible the geothermal signatures and existing geothermal well in the region. According to the structure information obtained from the on-site geological mapping, 5 fault systems are set in our model (Fig. 6). These faults are all on a regional scale, but their extension still needs to be confirmed by detailed investigation. In this study, the preliminary simulations based on the current information provides an overall results.

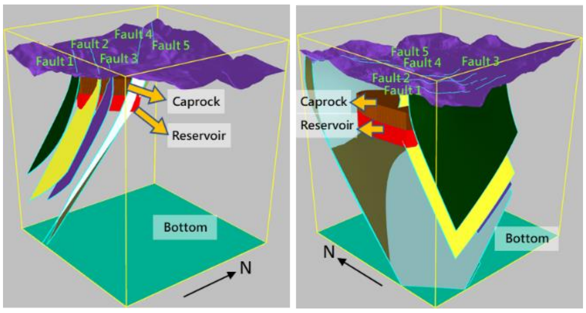

Figure 6: Geological concept model of DFN simulation of the Hongye area.

According to the depth with resistivity anomaly, it is assumed that there is a metamorphic caprock with rare fractures and low hydraulic permeability at a depth of 200 m. The hydrothermal fluid is therefore confined to the reservoir below, and the surface geothermal features may represent faults or large fracture zones, which control the hydrothermal fluid transport. We believe that the hydrothermal fluid rises to the shallow formation through the fault (or large fracture zone) connected with the thermal reservoir, and then reaches to the surface through the connectivity of fractures. Taking the first realization (TaiTung_DFN#1) as an example, the simulation result indicates that the second, fourth, and fifth fault planes can cut through the caprock to the potential thermal reservoirs. The fractures intersecting these three fault planes represent the secondary channels for hydrothermal transport. The model of fissure connected to the surface is shown in Fig. 7.

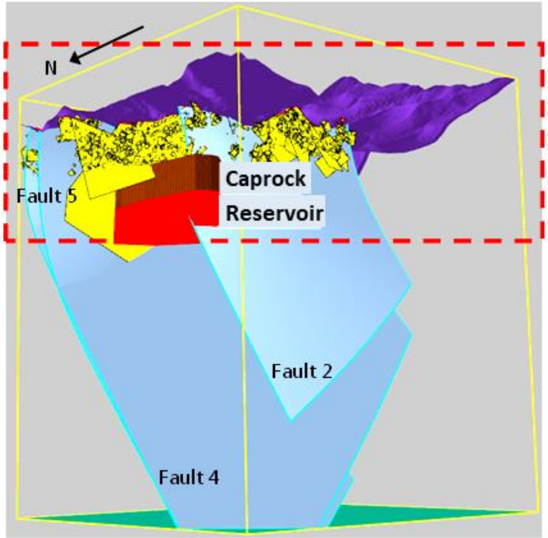

Figure 7: Conductive fractures of the caprock case.

5. GEOTHERMAL CONCEPTUAL MODEL

Integrating the results of various geothermal geological investigations conducted in the Hongye area and the information of exploration wells from CGS (YP01), CPC (HY-1 to HY-5) and TCCGE (TCC01), the downhole lithology and temperature field are all consistent with the 3D resistivity model of this study which confirms the geothermal structure characteristics of the exploration area. We propose a geothermal conceptual model of the Hongye area (Fig. 8). The ring-shaped low-resistivity zone, interpreted as an up-flow zone of hot water, is the suitable location to drill a geothermal well.

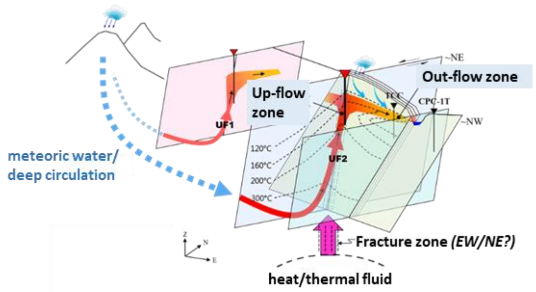

Figure 8: 3D geothermal conceptual model of the Hongye area.

After upwelling from YP-UF02, geothermal fluids seep out to the northwest, south and east, respectively. The eastward out-flow zone reaches Luye Creek along with the northwest trending normal fault and gushes out from the riverbed to become a hot spring. Both CPC-HY-1T and TCC01 wells are

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located at the outer edge of the out-flow area, so the characteristics of these two deep boreholes can be explained by the model (i.e., highest temperature in the shallow part of the well, the temperature remained around 110°C as the depth increased, the limited water volume and the low fracture density). However, the 200 m deep well, HY4, is located in the center of the out-flow zone, so its temperature exceeds 100°C at a depth of 50 m. At a depth of 107 m, the well self-discharged liquid with a steam plume that reached 14 m.

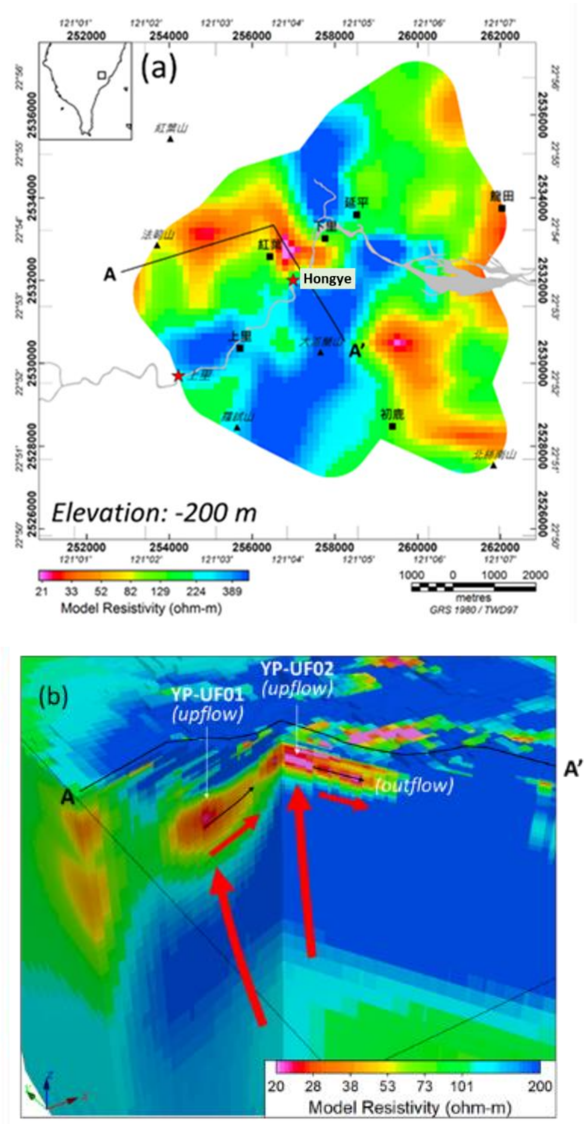

Figure 9: 3D display of the hot water upwelling path and out-flow zone in the Hongye area.

The temperature logging shows that the geothermal gradient is between 58.8°C/km and 91.7°C/km, which is 2 to 3 times higher than the normal geothermal gradient. The hot water activity is obvious at the depth of 300 m to 400 m, and corresponds to the main fracture zone. The temperature is about 35°C higher than the temperature estimated by the geothermal gradient. Therefore, it is suggested that this section correlated to the low-resistivity section is the main feed zone of hot water.

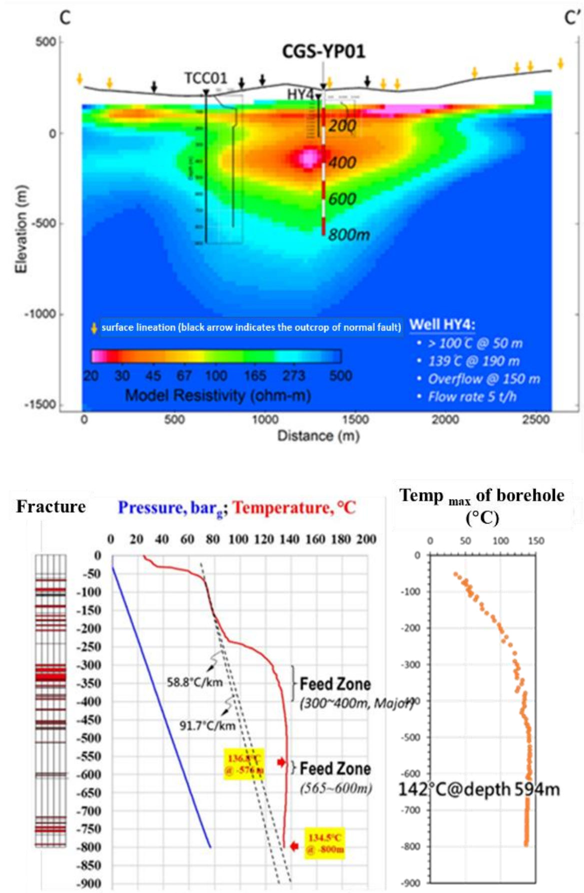

Figure 10: Comparison between MT resistivity profile and CGS-YP01. The depth and density of fracture are determined from the drilling cores.

6. POTENTIAL GENERATING CAPACITY

The stored heat method is widely used in the exploration stage to estimate the potential geothermal generating capacity (Ofwona, 2013; Zarrouk and Simiyu, 2013). We roughly delineate the range of 6 geothermal structures with resistivity equal to 80 ohm-m. This study uses the Geosoft oasis montaj software to extract the iso-surfaces with resistivity of 40 ohm-m, 50 ohm-m, and 65 ohm-m respectively, calculate the volume enclosed by the iso-surfaces. and then import the parameters into Montaj Carlo Simulator for calculations.

The geothermal power potential estimation in the Hongye area is shown in Table 1, and the used parameters are listed in Table 2. When the reservoir temperature is between 130°C and 180°C, the estimated total power generation potential is between 51 MWe and 181 MWe. Among them, the geothermal structural interpretation of UF12 (UF1+UF2) and UF3 is relatively reliable, and the total power generation potential of these two blocks is between 21 MWe and 69 MWe.

Table 1: The geothermal power potential estimation in the Hongye area.

#	volume (km^3)			Estimated Capacity (MWe)		
	Lower bound (ρ = 40 Ωm)	Most likely (ρ= 50 Ωm)	Upper bound (ρ = 65 Ωm)	mean	90% confidence interval	
UP12	0.635026674	1.225480584	2.231256111	8.00	4.01	13.52
UP3	2.750522164	5.356766008	8.863826304	33.18	17.15	55.18
UP456	3.861461661	10.837901180	18.559503100	64.85	30.02	112.02

Table 2: Parameters used to estimate the geothermal potential by using Monte-Carlo simulator in the Hongye area.

Item	Unit	Distribution type	Data used for calculation
Rock density	Kg/m^3	Triangle	2.40-2.57-2.65[1]
Rock specific heat	J/kg/°C	Triangle	800-900-950[2]
Reservoir temp	°C	Triangle	150-170-200[2,3]
Abandonment temp	°C	Triangle	100-100-100[2]
Porosity	%	Triangle	7-15-17[2]
Recovery rate	%	2.5 x porosity	17.5-25-42.5[2]
Energy conversion efficiency	%	Triangle	11-12-13[2]
Capacity factor	%	Fixed value	90[2]
Operation period	Year	Fixed value	30[2]

Data source:
[1] terrain gravity from Yen et al. (1994).
[2] WestJEC's parameter from BOE (2008)
[3] YP, JL and RS borehole temperature from CPC (1984, 1985).

7. CONCLUSION

In addition to compiling the existing exploration data within the Hongye area, this study carried out the field geological surveys, geochemical analyses, magnetotelluric surveys, DFN simulation and shallow geothermal assessments. Based on the results, a 3D geothermal conceptual model was proposed. The fracture zones mainly control the geothermal structures in the area, and the higher the reservoir temperature, the lower the corresponding electrical resistivity. The resistivity of the reservoir is far lower than the resistivity of intact rock due to the combined effects of high temperature, rock fracturing, and high salinity, which can act as critical identification conditions for hot water reservoirs.

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