Regional geothermal exploration in Dongpu Geothermal Field of Central Taiwan

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ABSTRACT

Dongpu geothermal potential field is located in the shale belt of the Hsuehshan Range in Nantou County, central Taiwan. The key exploration area will cover an area of approximately 53 square kilometers, including the Dongpu Hot Spring and the Lele Hot Spring. The major interest of geothermal exploration is to understand the location of heat source and geological information. Geothermal fluids included thermal water and gas, which emitted from geothermal reservoir through faults and/or fissures. In general, geothermal fluids formed hot springs and fumarolic gas (or bubbling gas) at the Earth's surface, and in which the information of geothermal reservoir was preserved. Therefore, based on chemical and isotopic composition of fluids can provide the information of the origin and evaluation. In this study, we conducted fluid geochemical survey at geothermal fluids outcrops in the region of Dongpu Hot Spring and the Lele Hot Spring. We measured the fluid composition and also helium isotope composition of the sampled hot spring water and bubbling gas. Together with previous studies, we discussed the geochemical characterization, which may provide further insights on geothermal resource assessment.

1. INTRODUCTION

Dongpu, which is located 180 kilometers southwest of Taipei City, is one of the important geothermal field in central Taiwan (Figure 1). Taiwan is located at the Pacific Ring of Fire, situated at the convergent boundary between the Eurasian Plate and the Philippine Sea Plate. This geological setting results in volcanic activity, mountain formation, frequent earthquakes, and an abundance of hot springs and geothermal features. Based on geological setting, heat source and international geothermal classifications, geothermal systems in Taiwan can be categorized into four types (Song, 2021):

1. Magmatic-volcanic type: The heat source is high-temperature magma that rises to the shallow crust formed geothermal reservoir through convection or conduction, such as the Tatun Volcano Group (TVG).

2. Extensional domain type: This type is related to the Ryukyu Trench subduction of the Philippine Sea Plate beneath the Eurasian Plate, creating extensional tectonic regions in northeastern Taiwan where upwelling hot material could be sourced from magma intrusion. An example is the Chingshui (CS) geothermal area.

3. Orogenic belt/foreland basin type: Driven by rapid uplift due to orogeny, leading to accumulation of heat in the shallow crust. This stored heat is then released as geothermal fluid ascends along fault zones or fractures, forming geothermal reservoirs, seen in areas like Ruisui (RS), Hongye (HY), Jinlun (JL), and Dongpu (DP).

4. Geopressured geothermal system type: In this type, the heat source might arise from the thermal and mechanical energy within the Earth's crust. This type is found in sedimentary basins in the southwestern part of Taiwan, such as the Chunglun and Guanziling geothermal fields.

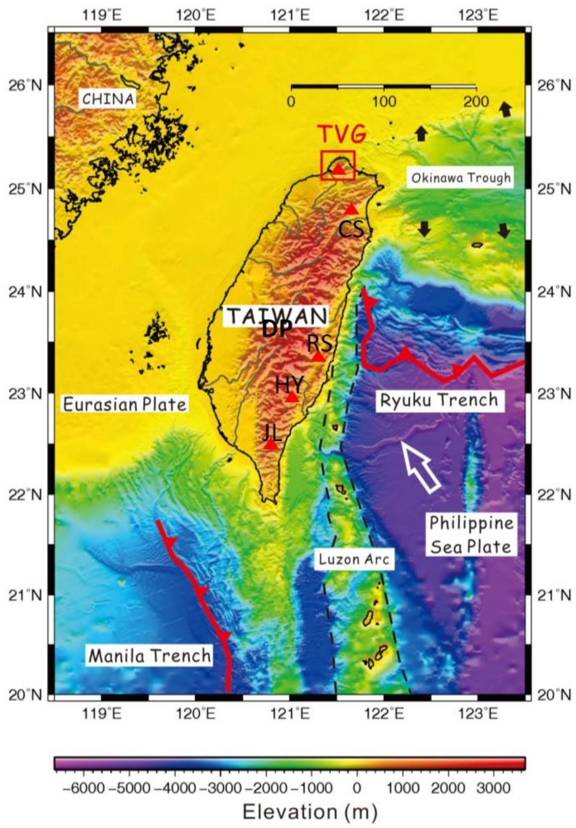

Figure 1: Tectonic setting of the study area, Dongpu geothermal potential field (DP), is located in the Central of Taiwan (modified from Wen et al., 2016). The red triangles are the important geothermal fields in Taiwan.

The Dongpu geothermal potential field has been studied since the 1960s for its geological and tectonic features (MORS, 1971; Yui et al., 1994; Chen et al., 2016) and water geochemistry (Chang, 1984; Lee et al., 2000). There are four hot springs in the Dongpu geothermal potential field, which

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are named from north to south: the Shihpachungchi hot spring, the Hoshe hot spring, the Dongpu Hot Spring, and the Lele hot spring. However, nowadays only the Dongpu Hot Spring and the Lele Hot Spring remain. The preliminary geochemical survey of geothermal exploration results reported the hot spring water chemistry. Despite these studies carried out, the underground geological information and gas geochemistry of Dongpu geothermal potential field are scarce. However, the gases chemical and isotopic compositions are good tracers of understanding the geothermal fluid characteristics and heat source (Kennedy et al., 1985; Sano et al., 1985; Pinti and Marty, 1995; Yang et al., 1999; Yang et al., 2003; Kennedy and Van Soest, 2006; Pinti et al., 2013; Wen et al., 2016; Chen et al., 2019).

Helium is a chemically inert noble gas, and this characteristic is advantageous in deciphering the source of the gas. There are three potential sources of terrestrial helium: the atmosphere, the crust and the mantle. The atmospheric component has a very homogeneous $^3He/^4He$ ratio (1.39 $\times10^{-6}$) and is commonly used as a global standard (1 R_A). The helium isotopic ratios of the crustal component are lower than air (0.1~0.01 R_A) because abundant ^4He gases are produced by the radiogenic elements in the crust. The mantle component exhibits a narrow range of helium isotopic ratios (8 ± 1 R_A). The isotope ratio $^3He/^4He$ is known to be correlated with global geotectonic settings (Hilton et al., 2002; Sano and Fischer, 2013).

Geothermal fluids migrate upward to the surface through deep-seated faults or hydrothermal pathways, forming hot springs or fumarolic/bubbling gas. During their ascent to the surface, the geothermal fluids might interact with country rocks to form alteration minerals. Additionally, the decrease in temperature and pressure can lead to the formation of mineral deposits. Therefore, during the initial stages of resource exploration, hot spring water, fumarolic/bubbling gas, and minerals are regarded as important windows for deciphering underground hydrothermal activity and are the primary subjects of investigation.

In this study, we investigate the fluid composition and helium isotope ratios in the Lele Hot Spring and Dongpu Hot Spring regions to characterize geothermal fluids and depict the gas sources. This information would provide as reference data for constructing a three-dimensional geothermal geological conceptual model in the future.

2. GEOLOGICAL BACKGROUND

The Dongpu geothermal potential field is situated in Xinyi Township, Nantou County, in central Taiwan. According to geological mapping (Figure 2), the strata of this studied area include the Eocene Shihpachungchi Formation, the Tachien Formation, the Yushanchushan Formation, and the Chiayang Formation. The Shihpachungchi Formation (Sp) consists mainly of slate with thin layers of metamorphic sandstone. The overall orientation of the rock layers is a north-northeast strike with an eastward dip. The greenish metamorphic volcanic rocks are found in the region of Dongpu hot spring, which might be caused by the Eocene igneous activity (Yui et al., 1994). The Tachien Formation (Tc) is characterized by thick-bedded of metamorphic quartz sandstone with interlayers of slate and argillite. The Yushanchushan Formation (Ys) comprises interbedding of metamorphic sandstone and slate, while the Chiayang Formation (Cy) is primarily composed of slate with thin layers of metamorphic sandstone (Chen et al., 2016).

To the west of the Shuilikeng Fault - Shalixianxi Fault belongs to the Western Foothills. The predominant formations are the Middle Miocene Hoshe Formation (Ho) and Nanchuang Formation (Nc). The Hoshe Formation is primarily composed of finely grained sandstone interbedded with dense shale, occurring in the hinge zone of the Hoshe syncline. The Nanchuang Formation consists mainly of finely grained sandstone and sandy shale interbeds, with coal seams, tuffaceous sandstone, and coarse-grained sandstone layers (Chen et al., 2016).

The main outcrops of hot spring are located in the region of Dongpu Hot Spring and the Lele Hot Spring. According to literature records, the Dongpu Hot Spring is situated in the Pashawn Streams, a tributary of the Chenyoulan River. This region serves as a source of hot water for local hot spring hotels. There are two major outcrop points: one emerges from fractures at the contact between sandstone and mudstone, measuring the highest temperature at 45°C; the other originates from the streambed, recording a maximum temperature of 66°C (MORS, 1971). The Lele Hot Spring is located approximately 2 kilometers southeast of the Dongpu Hot Spring. And the hot springs are exposed on the riverbank of the Chenyoulan River. The thermal water, reaching a temperature as high as 81°C, emerges along the Shuilikeng Fault, and precipitates of white calcium carbonate minerals are observed (Chang, 1984).

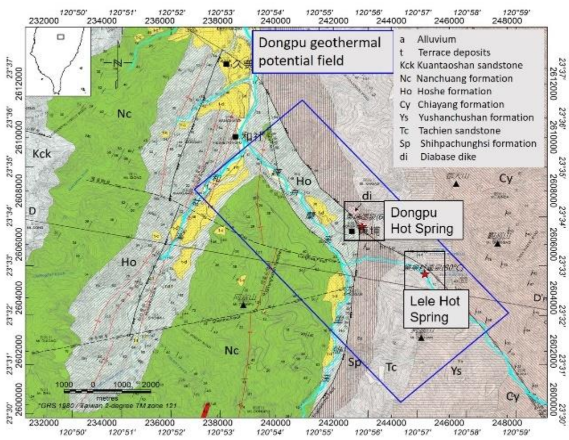

Figure 2: Regional geological map of the Dongpu geothermal potential field (modified from Chen et al., 2016). The geothermal fluid samples of this study are collected from Dongpu Hot Spring area and Lele hot spring area.

3. SAMPLING LOCATION AND ANALYTICAL METHODS

At the end of June 2023, in order to study the geochemical characteristics and origin of geothermal water in the Dongpu geothermal potential field, a total of 9 thermal water samples were collected from springs. Six water samples were mainly collected from the two major hot spring areas: Lele Hot Spring and Dongpu Hot Spring. Three thermal water (DP-H1-W, DP-H2-W and DP-H3-W) were sampled from hot spring outcrops along the Chenyoulan River in Lele Hot Spring area. Three of them (DP-H4-W, DP-H5-W and DP-H6-W) were located at the Dongpu Hot Spring area. The remaining three thermal samples (DP-H7-W, DP-H8-W and DP-H9-W) were obtained from hot spring hotels in the surrounding area of Dongpu. Additionally, we collected 5 gas samples, including two bubbling gas samples (DP-H2-

G1 and DP-H2-G2) from Lele Hot Spring area and three dissolved gas samples (DP-H1-G, DP-H4-G and DP-H6-G) from the two major hot spring areas. The distribution of these sampling sites is illustrated in Figure 3.

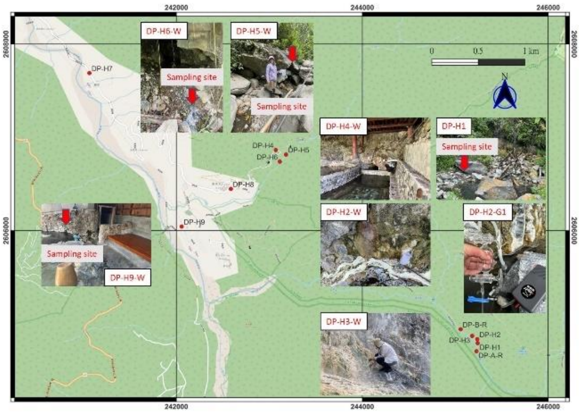

Figure 3: The geothermal fluid sample locations of this study in the Dongpu geothermal potential field. A total of 14 geothermal fluid samples were collected, including 9 thermal water samples and 5 gas samples.

3.1 Thermal Water Analysis

Portable water quality analyzers (Mettler-Toldedo SG78 and Mettler-Toldedo S8) were used to measure the basic physical properties of the thermal water, including temperature, conductivity, pH, total dissolved solids (TDS), and oxidation-reduction potential (ORP). Samples were filtered on-site with a 0.45 μm cellulose acetate membrane filter to remove impurities and then divided into four HDPE or PP bottles. One bottle was used for major ion analysis, while one had concentrated nitric acid added to acidify the water and prevent metal ion oxidation and precipitation for silica and metal elements analysis. The third bottle was preserved for hydrogen and oxygen isotope analysis. The rest bottle was used for alkalinity analysis.

Samples for major ion determination (Na, K, Ca, Mg, F, Cl and SO_4) were analyzed using Ion Chromatography System (Dionex ICS-5000$^+$, Thermo Scientific). Samples for silica and metal elements determination (Li, SiO_2, B, Rb, Cs, Sr, Ba, Fe and Mn) were analyzed using High Resolution Inductively Coupled Plasma Mass Spectrometry (HR-ICP-MS, Element XR, Thermo-Fisher Scientific). For carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) ion concentration, the titration method was applied (Metrohm 702 SM Titrion) to measure the total alkalinity, and then calculation together with the pH value. The hydrogen and oxygen isotope ratios in water samples were measured using Isotope and Gas Concentration Analyzer (Picarro L2130-i).

3.2 Gas Sample Analysis

The glass bottles were pre-evacuated and used for collecting bubbling gas samples through the water replacement method. For dissolved gas samples, the glass bottles were filled with water. The composition of bubbling gas and dissolved gas were analyzed by a quadrupole mass spectrometer (QMS, SRS RGA100), which includes methane, water vapor, oxygen, nitrogen, hydrogen sulfide, argon, ethane, carbon dioxide, and sulfur dioxide. Trace gas partial pressures under high vacuum conditions (10^{-6} mbar) were measured using partial pressure analysis (PPAs) to quantitatively determine component gas percentages after deriving the total pressure.

The $^3He/^4He$ ratios measurement were conducted using a Noble Gas Mass Spectrometer (HELIX SFT^{TM}) in the Department of Geosciences at National Taiwan University. The system includes several vacuum pumps (two rotary pumps, two turbo molecular pumps and one ion pump), a purification line and a cryogenic pump with a charcoal trap. The gas purification line consists of a U-shaped cold trap with liquid nitrogen, a Ti-sponge furnace at 600°C, and a cold charcoal trap with liquid nitrogen, and a Zr/Al alloy getter to remove active gases (H_2O, CO_2, N_2, O_2, H_2, SO_2 and H_2S) and heavy noble gases (Ar, Kr, Xe). Purified gas is then trapped in a cryogenic pump. The $^4He/^{20}Ne$ ratios were measured via quadrupole mass spectrometer (Prisma QME-200, Pfeiffer Vacuum). Helium and neon are subsequently released for sequential isotopic measurement using mass spectrometry. Air is routinely run as a standard for calibration. A 20 R_A pure helium gas standard (Matsuda et al., 2002) is also prepared and run as working standard to reduce the analytical errors.

4. RESULTS AND DISCUSSIONS

4.1 Thermal water physical characteristic

Although the distance between the Lele Hot Spring and the Dongpu Hot Spring is only 2 kilometers, there are slight difference in their thermal water characteristics. Overall, the Lele Hot Spring exhibits higher water temperature ranging from 57°C to 80°C, with neutral pH values between 6.98 and 7.25. It also has relatively higher conductivity, ranging between 1096 μS/cm and 1403 μS/cm and total dissolved solid contents of 548 mg/L to 701 mg/L. In comparison, the Dongpu Hot Spring has relatively lower water temperature ranging from 37°C to 50°C, with weakly alkaline pH values ranging from 7.23 to 7.91. Additionally, it has lower conductivity, ranging between 426 μS/cm and 490 μS/cm and total dissolved solid contents of 213 mg/L to 245 mg/L. The thermal water from surrounding hot spring hotels, the measured pH values ranging from 7.63 to 8.13, conductivity between 614 μS/cm and 755 μS/cm and total dissolved solid contents of 307 mg/L to 377 mg/L.

In order to understand the geochemical characteristics and identify the geothermal fluid type in Dongpu area, a Piper diagram was plotted using the measured data (Figure 4). As shown in Figure 4, the dominant cation of Dongpu is Na^+, with some place richer in Ca^{2+}. HCO_3^- comprises a large proportion of the anions, followed by SO_4^{2-} and Cl^-. Therefore, it can be concluded that the groundwater of the Dongpu region is of the HCO_3-Na type.

The thermal water quality analyses of Dongpu Hot Spring and Lele Hot Spring demonstrate similar characteristics, falling within the category of neutral bicarbonate springs with a slight presence of sulfate. These springs exemplify the thermal water quality found in metamorphic rock regions of the Central Range. The presence of a substantial amount of dissolved silica in the spring waters suggests the potential occurrence of high-temperature hydrothermal fluids in the deeper subsurface (Lee et al., 2000).

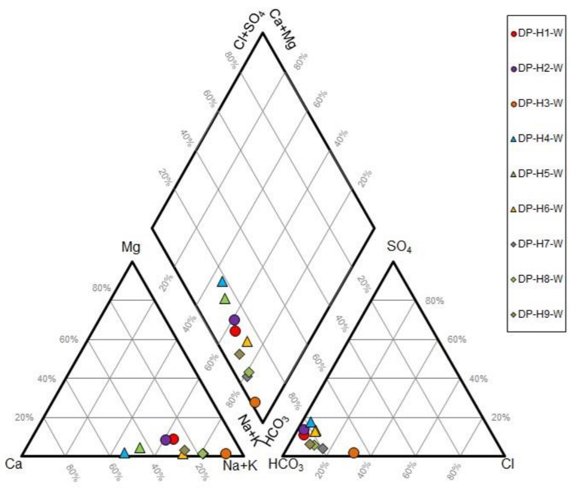

Figure 4: Piper diagram for thermal water samples in the Dongpu geothermal potential field.

4.2 Geothermal fluid chemical characteristic

The results of gas analysis in this study are represented in a ternary plot primarily based on carbon dioxide, nitrogen, and methane (Figure 5). The gas composition of bubbling gas samples (DP-H2-G1 and DP-H2-G2) collected from Lele Hot Spring area is composed of nitrogen, followed by carbon dioxide, methane, and argon. The dissolved gas from Lele Hot Spring (DP-H1-G) is characterized by a high concentration of carbon dioxide concentration (~79%). In the Dongpu Hot Spring area (DP-H4-G and DP-H6-G), the dissolved gas composition is dominated by nitrogen, followed by carbon dioxide. These results are consistent with data from other metamorphic hot spring of Taiwan, where the component gases are CO_2 and N_2 (Chen, 2011).

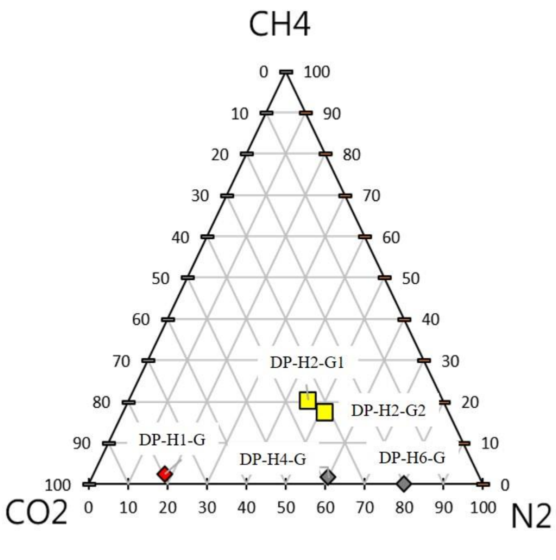

Figure 5: CH_4-CO_2-N_2 triangular plot for the Dongpu geothermal potential field.

4.3 Geothermal fluid potential source

4.3.1 Stable hydrogen and oxygen isotopes

The characteristics of hydrogen and oxygen stable isotope ratios (δD and δ^{18}O) can help explain the recharge source of geothermal waters. The δD versus δ^{18}O diagram of thermal water samples is a useful tool for investigating potential water sources that feeding geothermal fluid discharges. The stable isotopic composition of all thermal water samples is presented in Figure 6. It is observed that both δ^{18}O and δD values closely align with the Global Meteoric Water Line (GMWL). Therefore, the thermal water in the Dongpu geothermal potential area is considered to be of meteoric origin.

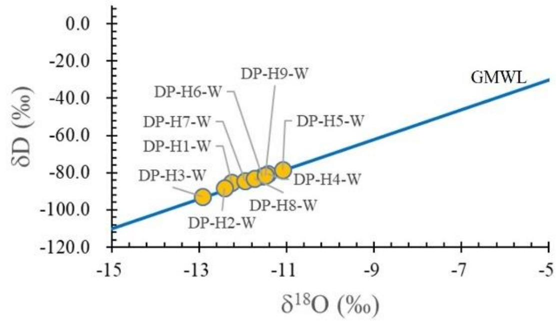

Figure 6: Plots of δ^{18}O and δD of the geothermal fluid in Dongpu geothermal potential field. GMWL represents the Global Meteoric Water Line (Craig, 1961).

4.3.2 Noble helium isotopes

Helium isotopes are a valuable tool for investigating the potential sources of geothermal fluids. There are three distinct sources of geothermal fluids: (1) the atmosphere, (2) the crust, and (3) the crust. The contributions of these sources can be determined using the $^3He/^4He$ ratios and $^4He/^{20}Ne$ ratios. The measured $^3He/^4He$ ratios (R_A) normalized to the present atmospheric value (1.39×10^{-6}), and the air corrected helium isotopic ratios (R_C) assuming all the Ne is derived from the air (Poreda and Craig, 1989).

The $^3He/^4He$ ratios of geothermal fluid in Lele Hot Spring area and Dongpu Hot Spring area range from 0.09 R_A to 0.14 R_A and 0.21 R_A to 0.22 R_A, respectively. The $^4He/^{20}Ne$ ratios of geothermal fluid in Lele Hot Spring area and Dongpu Hot Spring range from 4.790 to 17.303 and 1.614 to 1.911, respectively. The air-corrected helium isotopic ratios of geothermal fluid in Lele Hot Spring area and Dongpu Hot Spring range from 0.07 R_C to 0.09 R_C and 0.06 R_C to 0.08 R_C, respectively.

Figure 7 shows the relationship between the $^3He/^4He$ and $^4He/^{20}Ne$ ratios of geothermal fluid in the Dongpu geothermal potential field, revealing a mixture of crustal and atmospheric sources.

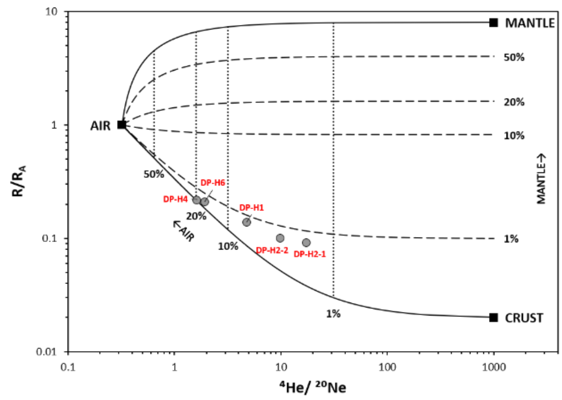

Figure 7: Plots of $^3He/^4He$ and $^4He/^{20}Ne$ ratios of the geothermal fluid in Dongpu geothermal potential field.

Sano and Wakita (1985) proposed a three-component mixing model to calculate helium contributions based on $^3He/^4He$ and $^4He/^{20}Ne$ ratios. The three principal components for helium are: atmospheric component (A), radiogenic crustal component (C) and mantle component (M). We estimate the proportion of each component in the Dongpu geothermal potential field based on the following formulas:

$$(^3He/^4He)_{obs}=(^3He/^4He)_{air}*A + (^3He/^4He)_{mantle}*M + (^3He/^4He)_{crust}*C$$

$$1/(^4He/^{20}Ne)_{obs}=A/(^4He/^{20}Ne)_{air} + M/(^4He/^{20}Ne)_{mantle} + C/(^4He/^{20}Ne)_{crust}$$

$$A+M+C=1$$

where subscripts of obs represent the observed values. The end components are defined as follows (Sano and Wakita, 1985):

A: $^3He/^4He$ ratios of 1 R_A and $^4He/^{20}Ne$ ratios of 0.318

C: $^3He/^4He$ ratios of 0.02 R_A and $^4He/^{20}Ne$ ratios of 1000

M: $^3He/^4He$ ratios of 8 R_A and $^4He/^{20}Ne$ ratios of 1000

The mean relative proportions of M:A:C for the Dongpu geothermal potential field are 0.5:9.6:89.9. This suggests most of geothermal fluid are domain with crustal component (80~ 97%).

4.4 Preliminary result of geothermal geological survey

Based on geological field survey, the hot spring outcrops in Lele Hot Spring area are situated within a northwest-southeast trending strike-slip fault zone (left-lateral) that creates a weak zone within the valley, leading to the development of a valley along this zone. The valley exhibits feature such as fault gouge, fault breccia, and fractured shear zones, with fault gouge and fault breccia extending up to ten meters in width.

The Lele Hot Spring area displays geothermal features, such as hot spring outcrops. Furthermore, structural observations around the hot spring outcrops reveal the formation of water-conducting fractures through two mechanisms:

1. High-angle foliation structures that experienced stress-induced fracturing, forming shallow-level conduits.
2. High-angle joint structures within the range of 140° to 160° and high-angle joint structures within the range of 60° to 80° can be measured simultaneously.

These structures can serve as conduits for the upward flow of thermal water.

5. CONCLUDING REMARKS

A total of 9 water samples and 5 gas samples were collected from the Dongpu geothermal potential field to analyze their geochemical and isotopic characteristics. The HCO_3-Na type geothermal waters are of meteoric origin without magmatic input.

The gas samples exhibit consistent low helium isotopic compositions, ranging from 0.09 to 0.22 R_A. The estimated proportion of crustal components range from 80-98%. It implies that the deep-seated reservoir may exit under the Dongpu area. Together with geological survey results, the crustal fluid may upward via the Shuilikeng Fault.

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