# A Conceptual Model of Slate Formation: A Case from the Lushan Geothermal Field, Taiwan

Sheng-Rong Song[1], Ting-Jui Song[2], Yi-Chia Lu[3], Yu-Jie Lin[1], Yueh-Iuan, Ko[4], Mien-Min, Chen[5], Chi-Hsuan Chen[5], and Wan-Chi Chiang[5]

[1]Department of Geosciences, National Taiwan University, Taipei, Taiwan; srsong@ntu.edu.tw; [2]Fabulous Power Co. Limited, Taiwan; johnnysong@fabulousgroup.com.tw; [3]Graduate Institute of Applied Geology, National Central University, Taipei, Taiwan; yichialu@cc.ncu.edu.tw; [4]Yuetech Geological Office, Taiwan; [5]Geological Survey and Mining Management Agency, MOEA

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**ABSTRACT**

Slate is a low-grade metamorphic rock commonly found in orogenic belts like the Taiwan Mountain Range. There are very few geothermal fields with power plants around the world, making the Lushan geothermal field in central Taiwan quite unique. Geologically, this area is mainly composed of metamorphosed mudstone known as the Lushan Formation, which is one of the dominant rock types in Taiwan's orogenic belt. The rapid uplift and erosion from arc-continent collisions on the island have created a high geothermal gradient of over 50-60°C/km. This leads to a wide distribution of hot springs and thermal features along the river valleys.

In response to the growing demand for renewable energy and the need to reduce greenhouse gas emissions in Taiwan, we have conducted extensive geological, geophysical, and geochemical explorations in this region, resulting in a wealth of valuable data. We have integrated this information into a 3D geothermal and geological model using: (1) Data from a surface digital elevation model. (2) Local geological maps and profiles. (3) Core data and logging information from drilling wells. (4) 3D distribution results from MT surveys. (5) Borehole temperature measurements and up-to-date field surveys.

Preliminary results suggest that the shallow heat sources (less than 1,000 meters below the surface) in the Lushan geothermal field may originate from deeper locations to the southeast. However, when we take a broader view of the MT data, it appears that potential heat sources may actually be coming from the west or southwest, deep beneath the Chunyang area.

## 1. INTRODUCTION

More than 90% of geothermal power plants are situated within magma-related geological systems, such as the Geysers in the United States and Larderello in Italy, which are formed by granitic magmas intruding into sedimentary formations (Dalrymple et al., 1999; Lazzeri, 2016). Additionally, nearly all geothermal fields in Japan, New Zealand, Iceland, and the Ring of Fire are associated with volcanic activity. In contrast, geothermal occurrences within metamorphic terranes, particularly those involving slate formations in orogenic belts, are exceedingly rare. The geothermal field located in Taiwan's Central Mountain Range, exemplified by the Lushan geothermal field, represents a notable exception.

Geologically, Taiwan is positioned at the arc-continent collision zone, where the Philippine Sea Plate collides with the Eurasian Plate, forming one of the youngest orogenic belts globally (Figure 1). This region is characterized by rapid uplift and limited volcanic activity (Ho, 1986; Song et al., 2000), conditions that contribute to its geothermal potential. In Taiwan, four distinct geothermal play types have been identified based on geological controls (Moeck, 2016; Song, 2018): the magmatic-volcanic field type, the extensional domain type, the orogenic belt/foreland basin type, and the geopressured type, which correlate to the Tatun volcanic group, the Ilan Plain, the Central Mountain Range, and the Chilan-Kuanzuilin area, respectively.

Since the 1960s, extensive geothermal explorations have been conducted on the island, resulting in the establishment of two pilot geothermal power plants within slate formations in northeastern Taiwan (MRSO, 1978). However, these power plants were decommissioned after approximately ten years of operation and remained inactive for nearly three decades. In 2005, the Bureau of Energy of Taiwan revisited the slate formations for geothermal exploration, initiating plans for future power generation in the Chingshui geothermal field. Furthermore, the Ministry of Science and Technology (MOST), formerly known as the National Science Council (NSC), has actively promoted geothermal explorations and developments as a major national energy project (NEP I and II) since 2008. This initiative includes comprehensive geological, geochemical, and geophysical surveys, coupled with drilling activities aimed at constructing future geothermal power plants (Song, 2012).

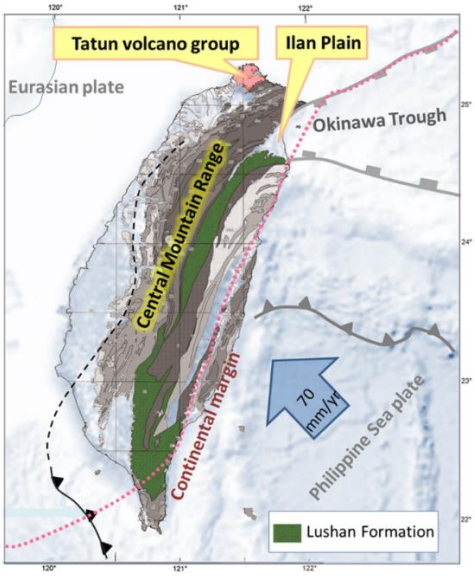


Figure 1、The tectonic framework of Taiwan.

The Lushan geothermal field has undergone a variety of surveys, including geothermal geology, geophysical explorations utilizing resistivity and micro-seismicity, and thermal water chemistry, since the 1970s (Chang and Chiao, 1979; Hsiao et al., 1980). These studies have indicated significant geothermal potential in the area. Geothermal manifestations, such as high-temperature hot springs, travertine (calcite) and/or sinter (silica) precipitations, and hydrothermal alterations, are widely distributed in outcrops (Fig. 2; Photos I, II, III). More than nine wells, with depths ranging from several hundred to over one thousand meters, have been drilled in this region. The highest recorded bottom temperature in these wells exceeded 170°C, with thermal water production rates of 50-60 tons per hour.

In 2022, the Geological Survey and Mining Management Agency (GSMMA) of the Ministry of Economic Affairs in Taiwan revisited the Lushan geothermal field to conduct high-resolution geothermal explorations aimed at assessing the potential geothermal resources in the area. The objective is to advance the exploration status from G2 (inferred) to G3 (measured) and to evaluate the feasibility of constructing a geothermal power plant. The work includes the collection, analysis, and interpretation of published exploration data, as well as conducting magnetotelluric (MT) surveys and supplementary investigations. These investigations encompass detailed geological mapping and assessments of fractured systems, micro-seismic monitoring and reflection, fluid geochemical analyses, and studies on carbonate scaling. Additionally, two slim holes have been drilled for logging.

The integration of this comprehensive dataset aims to enhance the resolution and reliability of constructing a 3D geothermal conceptual model. This model facilitates a better understanding of the heat sources, fluid circulation, and reservoir characteristics, and allows for the estimation of geothermal potential in the study area. This paper presents the preliminary results of the work conducted over the past two years.

## 2. Geological Background and Settings

Taiwan is situated along the Ring of Fire and is renowned for its active orogenic processes. Currently, the Philippine Sea Plate is moving west-northwest at a rate of approximately 70-80 mm per year (Seno and Maruyama, 1984), suggesting that the mountain-building process is ongoing (Tsai et al., 1981; Yu and Chen, 1994). The island has formed over the last 5 million years (Ho, 1986; Teng, 1990, 1987), characterized by rapid crustal movements and a wide distribution of active geological structures (Chen, 1984; Peng et al., 1977; Yu et al., 1999, 1997). A significant collision zone exists in central Taiwan, frequently inducing folding and thrusting, leading to a rapid uplift rate of approximately 6 mm per year (Ching et al., 2011). In the southern region, the Philippine Sea Plate is subducting over the continental shelf of the South China Sea. Concurrently, an oceanic portion of the Eurasian Plate is subducting beneath the Philippine Sea Plate along the Manila Trench, resulting in the upward and westward displacement of shelf sediments. This subduction also contributes to the formation of the Ryukyu Arc to the north (Fig. 1). The Okinawa Trough, a back-arc basin, extends from southwestern Kyushu Island (Japan) to the Ilan Plain, which marks its southwesternmost extent. Three distinct stages of opening have been identified since 15 Ma, with the latest phase characterized by normal faulting with vertical offsets observed since the late Pleistocene (Furukawa et al., 1991; Kimura, 1985; Sibuet et al., 1998). The age of normal stress affecting the Ilan Plain may date to the latest Pleistocene, as evidenced by thermoluminescence (TL) dating of 7.0 ± 0.7 ka from a siltstone xenolith found at Kueishantao, an offshore volcanic island located 10 km from the Ilan Plain (Chen et al., 2001). Several active volcanoes have been identified in both inland and offshore areas, and a prominent mountain range exists in the eastern and central regions of Taiwan. These tectonic settings create an environment rich in geothermal energy, leading to the designation of “Geothermal Formosa” for the island.

The slate belt of Taiwan outcrops on the fore-wedge side of the Taiwanese orogenic wedge, sandwiched between deformed, unmetamorphosed continental shelf sediments of the Western Foothills and the exhumed continental margin basement of the Tananao Complex. This belt comprises two north-south trending zones: the Hsuehshan Range and the Backbone Range Slate Belt (Figure 1). The Hsuehshan Range contains a continuous succession of Eocene to mid-Miocene continental margin sediments (Teng, 1987), deposited in eastward-deepening rift grabens associated with the opening of the South China Sea (Teng, 1990). The Backbone Range Slate Belt, located east of the Hsuehshan Range, is predominantly composed of metamorphosed Miocene pelagic sediments. These two formations are separated by the Lishan Fault in northern Taiwan. The Backbone Range Slates are juxtaposed to the east against the intermediate and high-grade metamorphosed Tananao Complex along a basal unconformity, which has been reworked into a major shear zone (Fisher et al., 2002; Suppe et al., 1976).

The Lishan Fault serves as the eastern boundary of the Hsuehshan Range, following a topographically prominent valley that extends from the western apex of the Ilan Plain to central Taiwan for approximately 200 km (Tsan, 1971; Biq, 1971). The fault has been interpreted as an oblique left-lateral shear zone (Biq, 1971) and as a major structural and stratigraphic boundary (Ho, 1975; Tsan, 1971) separating the two principal mountain ranges in northern Taiwan: the Hsuehshan and the Backbone Ranges (Fig. 1). Paleogene normal faulting along the continental margin was subsequently inverted following the initiation of the collision between the Eurasian and Philippine Sea Plates (Teng et al., 1991; Lee et al., 1997; Brown et al., 2012). However, it has also been interpreted as a suture between the continental margin and the late Miocene accretionary prism (Lu and Hsu, 1992; Huang et al., 1997). Based on field data, Lee et al. (1997) posited that reverse sinistral high-angle fault slips occurred during the late Cenozoic era, with extension at the northeastern end of the fault attributed to the opening of the Okinawa Trough. Brown et al. (2012) inferred that the fault acts as a backstop for the detachment beneath the fold-and-thrust belt of western Taiwan, emphasizing the ductile nature of the fault. Following the 1999 Chi-Chi earthquake, a dense linear array of seismic stations in Taiwan provided data that precisely located a cluster of seismic events near the Lishan Fault (Kuo-Chen et al., 2015), indicating that the Lishan Fault is an active fault.

The slate formation, referred to as the Lushan Formation, is extensively distributed within the Backbone Range belt of the Central Range in Taiwan (Fig. 1). This formation consists primarily of argillite and slate from the early to middle Miocene. The type locality is situated in the Lushan area, east of Wushe in Nantou County. Miocene foraminifera have been identified within the slates and marly nodules of this formation, which extends for at least 14 kilometers in an east-west direction along the western slope of the Central Range (Chang, 1962a, 1962b). The Lushan Formation

predominantly comprises black to dark gray argillite, slate, and phyllite, with occasional interlayering of gray sandstones, and is estimated to have a thickness of several thousand meters. This formation is exposed in northern Taiwan at the mouth of the Lanyang River in Ilan County and extends southward along the crest zone of the Central Range through Hohuashan, Nengkaoshan, and Hsiukuluanshan, covering a length of approximately 150 kilometers and a width ranging from several to over ten kilometers (Chen, 2016). South of Yushan Mountain, the Lushan Formation occurs east of the Laonung River, extending southward to the eastern mountains of the Pingtung Valley and down to the Hengchun Peninsula. It also crops out in southeastern Taiwan, particularly in the Chihpen and Tawu areas (Chen, 2016).

On a broader scale, the Lushan Formation exhibits a consistent west-vergent shear structure. The deformation pattern, however, differs from that of the adjacent Hsuehshan Range, characterized by tighter folds and two primary cleavages, rather than a single cleavage observed in the Hsuehshan Range. Due to the scarcity of fossils, the age range of the Lushan Formation remains inadequately defined. A Miocene age (N6-N9 zones) has been suggested based on fossils found in the upper part near the contact with the Hsuehshan Range (Chang, 1976). For the lower portion, in the absence of stratigraphic data, a Late Oligocene age cannot be excluded (Chen, 2006).

## 3 METHOD OF EXPLORATION

Several exploration methods have been employed in the Lushan geothermal field, including detailed geological surveys, geophysical and geochemical analyses, drilling with coring, and the utilization of the Leapfrog program for constructing a conceptual model. These methods are summarized as follows:

1. Detailed Geological Surveys: These surveys focus on the outcrops of thermal manifestations, such as hot springs, hydrothermal areas, and steam fumaroles. Key aspects include the lithological distributions and the orientation of fractured systems, which encompass fault zones, joints, and microfractures induced by shearing. Surface lineaments are also analyzed using LiDAR data. This information is crucial for detecting conduits through which thermal fluids ascend from deeper to shallower depths.

2. Geophysical Surveys: The surface resistivity survey, employing magnetotellurics (MT), is a method used to measure electrical potentials in the ground around a current-carrying electrode. This technique relies on the electrical resistivity and distribution of surrounding sediments and rocks. An electrical current is applied between two electrodes implanted in the ground to measure the potential difference between two additional electrodes that do not carry current. The distribution of potential can theoretically be correlated to ground resistivity and the distribution of rock bodies, which are arranged in a horizontally stratified manner and separated by vertical planes (Wightman et al., 2003). This survey represents one of the most critical components of the study.

3. Geochemical Studies: Geochemical analyses of geothermal fluids involve three primary steps: (1) sample collection, (2) chemical analysis, and (3) data interpretation (Mwangi, 2013). The results provide parameters sensitive to subsurface temperatures, fluid salinity, and gaseous chemical compositions in the areas of interest. The constituents of fluid chemistry, particularly stable isotopes such as $^{2}H$ and $^{18}O$ along with boron (B) and chloride (Cl), are instrumental in tracing the origin and flow of geothermal waters. Additionally, chemical constituents of rocks and geothermometers, such as $SiO_2$, $Na^+$, $K^+$, $Ca^{2+}$, $Mg^{2+}$, and $HCO_3^-$, are valuable for estimating subsurface temperatures and identifying potential production issues such as scaling and corrosion (Mwangi, 2013).

## 4. RESULTS AND DISCUSSIONS

The study area, the Lushan geothermal field, is predominantly composed of slate formations located in the western fringe of the Central Mountain Range in Taiwan. A detailed field survey was conducted to document the geothermal manifestations and rock formations, resulting in the creation of a geological map at a scale of 1:10,000 (Fig. 2) and a corresponding 3-D model (Fig. 3). Field investigations, along with subsurface geological reports, indicate that the Lushan Formation in this area is primarily composed of dark gray and black argillites and slates, interbedded with thin layers of meta-sandstones and occasional dark gray compact sandstones containing disseminated marly nodules. This formation can be divided into three members: the Chungyang Slate, the Yuanfeng Meta-sandstone, and the Kunyang Slate.

Several strike-slip faults with NW-SE orientations were identified in the field, which may serve as conduits for the upward migration of thermal waters. Fracture analysis was performed using rose diagrams to illustrate the directions of lineaments derived from remote sensing imagery. The results reveal predominant orientations of N10W, N60W, and N45W in the Lushan/Jingying area (Fig. 4). Additionally, a major thrust fault, known as the Meisi Fault, exists to the west of the Lushan area, while several strike-slip faults and complex fold systems are present in the remote mountainous regions.

The field survey documented three sets of joints, with orientations as follows: N55-70W dipping 70-90° SW, N15-35E dipping 10-30° NW, and N50-60W dipping 65-85° SE (Fig. 5). A strike-slip fault striking N50E and dipping 60° SE was observed locally in the Lushan area, alongside a high-angle normal fault trending NW-SE. Two types of veins—silica and carbonate—were identified, which exhibit cross-cutting relationships with the different sets of joints.

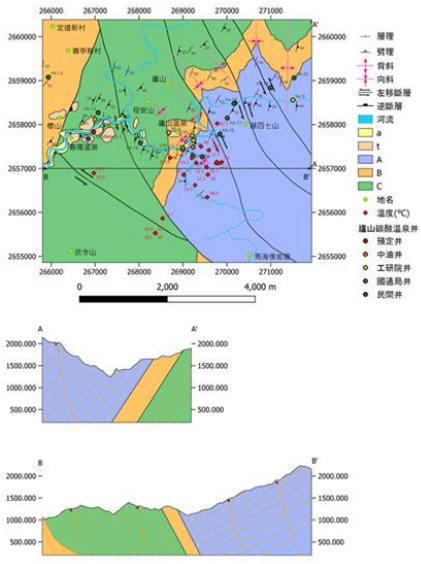


Figure 2：Geothermal geological map and cross sections of Lushan area.

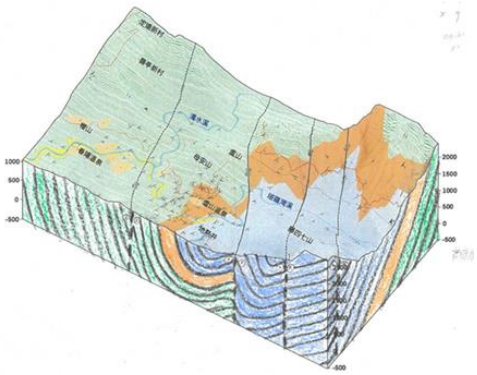

Figure 3：3D geothermal geological map of Lushan area.

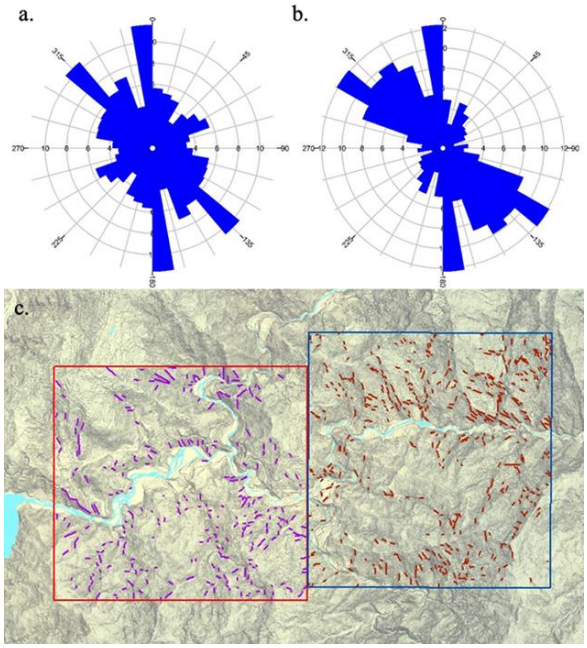


Figure 4：Rose diagram of surface lineament distribution (a: Chunyang; b: Lushan/Jingying; c: lineament drawing off LiDAR DEM map of Chunyang area (red square) and Lushan/Jingying area (blue square).

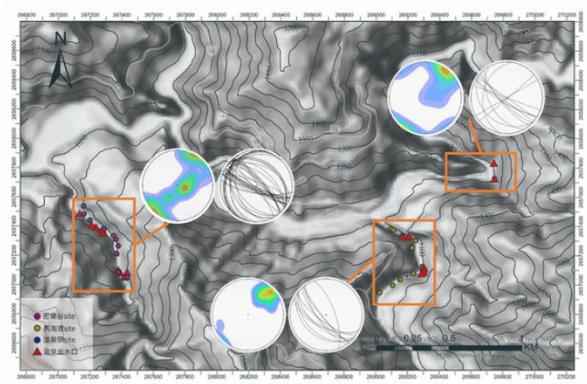

Figure 5：Plots of stereo-net of joints in the Lushan area.

The magnetotelluric (MT) survey stations established for this project are strategically positioned, focusing on the key exploration area extending from Chunyang to Mahebo. The configuration includes an appropriate outward expansion, resulting in a total of 37 MT survey stations. The results of the three-dimensional inversion are summarized as follows (Fig. 6):

1. Low-resistivity zones (<100 ohm-m) are predominantly located at depths shallower than 500 meters, primarily distributed along the Zhusui River, Tarowan Creek, and Mahebo Creek in the Lushan and Chunyang areas. The boundaries between these low-resistivity zones and adjacent high-resistivity zones exhibit a westward dip.
2. At depths ranging from 500 to 5,000 meters, the resistivity boundary is approximately located at the confluence of the Zhusui River and Tarowan Creek. To the west of this boundary lies a low-resistivity zone (<100 ohm-m), while to the east, a high-resistivity zone (>300 ohm-m) is observed. The boundary separating the low-resistivity zone from the high-resistivity zone dips eastward.
3. A connecting channel dipping westward is identified between the low-resistivity zone beneath the Lushan area and another low-resistivity zone at subsurface depths of 1,500 to 5,000 meters. This feature may represent a significant fissure zone or a pathway for the transmission of deep geothermal sources to the surface..

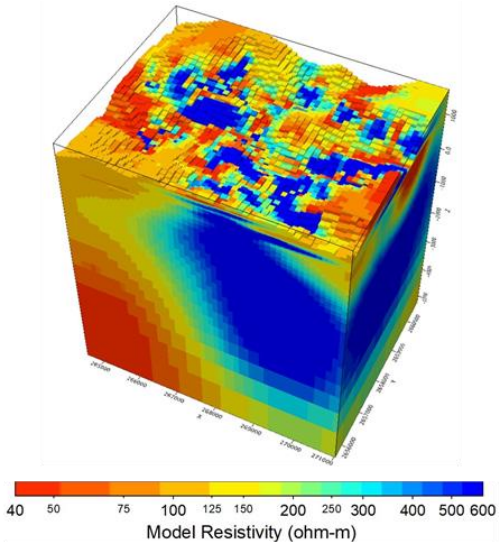


Figure 6：The 3D resistivity model.

Geochemical analysis of the hot springs located in the Chunyang, Taruwan, Mahaipu, and Lushan areas reveals that these springs predominantly exhibit characteristics of sodium bicarbonate waters (Fig. 7). The oxygen isotopic composition of the water samples collected during this study ranges from -7.3‰ to -10.7‰, while the hydrogen isotopes range from -72.6‰ to -57.2‰, aligning closely with the meteoric water line. Notable deviations from this line are observed, particularly in sample LS-1021, which may be attributed to boiling fractionation effects.

Silica geothermometry analysis indicates that reservoir temperatures in the Chunyang area may reach as high as 133°C, while temperatures in Mahaipu could exceed 160°C, and in Lushan, temperatures may reach 170°C.

In terms of rock sample analysis, the precipitates within the wells predominantly consist of spherulites. The vein deposits, on the other hand, contain calcite, quartz, and dolomite, with calcite serving as the primary constituent, accompanied by

minor quantities of spherulites. Scanning electron microscopy (SEM) analysis reveals the presence of needle-like structures within the spherulites, as well as blocky morphologies.

The 3D geothermal and geological model has been constructed using several data sources: 1) surface digital elevation model data; 2) local geological maps and profiles; 3) core data and logging information obtained from drilling operations; 4) 3D distributions from magnetotelluric (MT) surveys; and 5) borehole temperature measurements combined with recent field survey results.

Preliminary results suggest that the shallow heat sources (at depths less than 1000 meters from the surface) within the Lushan geothermal field may originate from deeper locations to the southeast (Fig. 8). However, the overall MT data imply that, when considered on a broader scale, the potential heat sources may actually be situated to the west or southwest, beneath the Chunyang area.

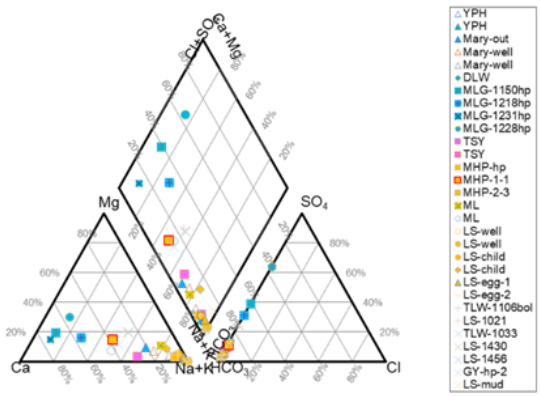


Figure 7：Piper diagram of thermal water in the Lushan area

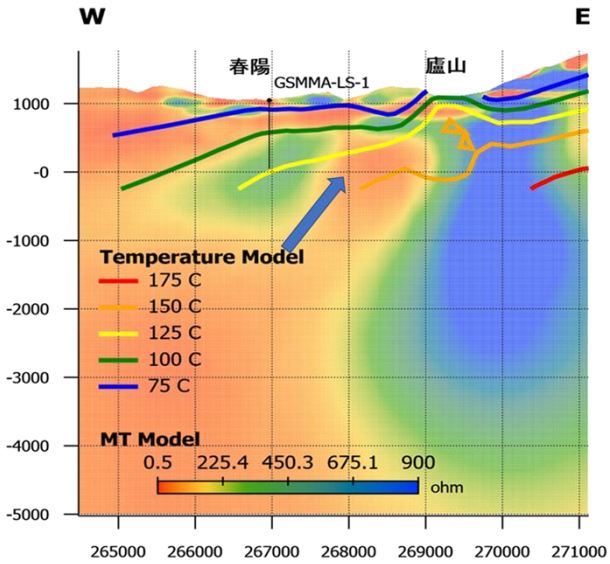


Figure 8：Conceptual model of Lushan geothermal field

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