Combining geophysical, isotopes and geological studies toward geothermal models at Hongchailin for geothermal power generation in NE Taiwan

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ABSTRACT

In this study, we conduct a multi-disciplinary study, including geophysics, geochemistry, and geology, to reconstruct a geothermal geological model at the shallow 3 km level, for a project of potential geothermal power generation at the Hongchailin site in the Yilan plain of northeastern Taiwan. Our geophysical techniques include seismic imaging from natural earthquakes as well as ambient noise. Three seismic arrays deployed at different time periods in the past decade were used. We also incorporate geophysical imaging results from previous studies, in particular a series of seismic reflection profiles. Three magnetotelluric (MT) surveys have been conducted in three different periods. Three test holes were drilled around the Hongchailin site in 2016-2019. Logging and on-site measurements were conducted at increment depths, including rock types, P/T measurements, fractures analyses, geochemical analyses.

Incorporating regional geological structures, geophysical subsurface imaging, we reconstruct geothermal geological models in line with detailed geological cross sections at the shallow 3 km level. We interpret a shallow geothermal reservoir within the massive quartz sandstone layers (Szeleng sandstone) at 1-2 km depth with the downhole temperature of 80-100°C. Geologically, the reservoir is located at the regional Songlo syncline and its south limb; and geophysically, it corresponds to a relatively low resistivity area. Isotope results show that the cool meteoric water came from nearby higher altitude mountain area, then flew through the Szeleng sandstone, which plunges 1-2 km depth below the Yilan plain. Hot fluid is interpreted to be derived from deeper heat source interpreted from seismicity data, which then upflows along a N-S trending vertical faults system. Drone-based thermal imagery confirmed the presence of hotter areas at surface. In addition, two E-W trending major faults, identified by the seismic reflection profiles, seem to act as hydrothermal fluid barriers to confine the hot fluid within the reservoir area.

1. INTRODUCTION

A new national geothermal project was launched in Taiwan in the years of late 2010s, after several decades of quiescence where projects of geothermal electric power have been on-hold. The new demand for green energy development in Taiwan, as well as in the world, in the recent years has mobilized people across different fields, including government officer, private sector, academic scholar, to get involved in this national project.

This paper is aiming at presenting the updated results at the Hongchailin geothermal potential field in the Yilan area of Northeast Taiwan (Fig. 1). Yilan has been one of the places in Taiwan known for its hot spring spots for recreation and touristic attraction, such as at Jiaohsi, Chingshui, and Rentze, for more than 50 years. Indeed, the government had also put great efforts on the Chingshui and Rentze sites for geothermal power potential in the years of 1970s and 1980s, with more than ten exploration wells drilled at both sites (e.g., ITRI, 1978; Tzeng et al., 1977; CPC Taiwan, 1983). The first geothermal electricity power plant had established in Chingshui site with ~1 MW_e of capacity. However, this pioneer geothermal exploration work had ended in the years of late 1980s due to some undisclosed reasons.

Hongchailin, by contrast, was not in the map of geothermal potential fields until the earlier stage of this national project, in which two 2-km deep drilling well and several geophysical surveys have been conducted in 2016-2019, including seismic reflection (Shih et al., 2018), magnetotelluric measurements (Chiang et al., 2021), and electric resistivity investigation. The results served us as the basis for the follow up and further detailed study, in order to reconstruct the geothermal geological model for the geothermal power exploration in the near future.

In this study, we carried out two sets of the magnetotelluric surveys, seismic tomography using both natural earthquake and man-made seismic sources, water and gas geochemistry analyses, a few long seismic reflection profiles, as well as detailed field geological investigations. By incorporating the geophysical subsurface images and geological cross sections, we reconstruct a plausible geothermal geological model. Our data and results show that the potential geothermal reservoir is likely within a lithological controlled layer, the massive Szeleng sandstone formation, at the depth of 1-2 km. Based on the preliminary parameters, we estimate the geothermal electricity power capacity to be 4-6 MW_e, according to our geothermal geological model.

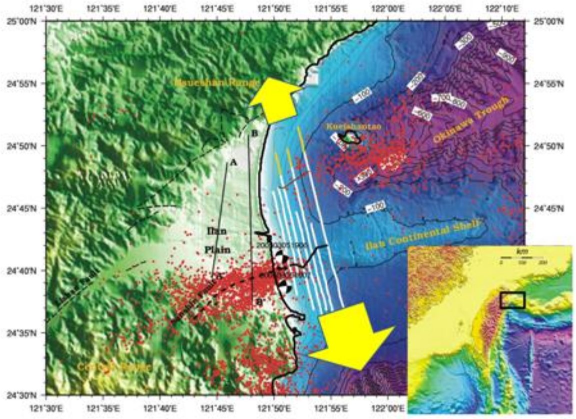

Figure 1: Tectonic framework of the Yilan plain in Northeast Taiwan. The Yilan plain is located in the western extension of the NNW-SSE opening of the Okinawa trough.

2. TECTONIC AND GEOLOGICAL SETTING

Taiwan, an island of 400-km-long and 150-km-wide, is a product of an oblique convergence between the Philippine Sea plate and Eurasia since 5-6 Ma (Ho, 1986; Suppe, 1981; Tsai, 1986) (Fig. 1). As the NW-moving Philippine Sea plate collides with the Eurasian continental margin at a rate of 8 cm/yr (Yu et al., 1997), the Taiwan mountain belt is generally subject to a NW-compression. However, in Northeast Taiwan where the Philippine Sea plate is flipping to be subducting under Eurasia, it yields back-arc opening and a series of volcanic island within the Okinawa trough.

Under this regional tectonic framework, the Yilan plain is located at the conjunction between the Taiwan mountain belt and the Okinawa trough. The GPS and InSAR measurements indicate the surface deformation of the Yilan plain is characterized by a major NNW-SSE extension and a clockwise rotation (Rau et al., 2009; Su et al., 2018). The Turtle Island, an active volcano island some 12 km offshore (Fig. 2), is a manifestation of Holocene surface eruption from the underneath magma chamber (Chen et al., 2001). Abundant seismic activities below Turtle Island (Lin et al., 2018) also support the vigorous volcanism around the island. Furthermore, the 2005 M5.9, M5.9 earthquake doublet occurred in the southern part of the Yilan plain has been interpreted as an event of volcanic dyke intrusion at the depth of 5-10 km (Lai et al., 2009). Combining the aforementioned geological and geophysical information, it appears that regional primary heat source of the relatively high geothermal gradient and spotted hot springs in the Yilan plain area comes from the active volcanism due to crust hyper-extension and mantle upwelling in the back-arc Okinawa trough.

As the Yilan plain is covered by an enormous alluvial fan of the Lanyang river, the subsurface geology and structures was hindered by fluvial deposits with thickness of several hundreds of meters to about 2 km (Chiang, 1976). Based on the regional geological units, the basement of the Yilan plain area is occupied by two slate belts: the Hsuehshan Range to the north and the Backbone Range to the south. The two ranges are separated by a major fault, the Lishan fault or the Chuoshui fault, which is running E-W through the Yilan plain, mainly parallel to the Lanyang river.

From From the geological point of view, the difference between the Hsuehshan and Backbone Ranges in the Yilan area is subtle. They share similar lithology (slate, argillite with occasional sandstone layers), similar ages of rocks (Oligocene to Miocene), and similar metamorphism (pumpellyite facies). However, an ~1 km thick massive quartzite layer, i.e., the Szeleng sandstone formation, can only be observed in the Hsuehshan Range. It is also worth noting that the Raman analysis of carbonaceous materiel indicate the rock formations are with higher peak metamorphic temperatures (275-285°C) in the Hsuehshan Range than those in the Backbone Range (230-270°C) on both sides of the Lishan fault around the Rentze area (Chen et al., 2019).

3. GEOPHYSICAL SUBSURFACE IMAGING

3.1 Seismic reflection profiles

We conducted several long seismic reflection profiles around the Hongchailin area in 2022-2023, including two N-S trending lines (10-km and 5-km-long, respectively) and three E-W trending lines (12-km, 25-km and 6-km-long, respectively). The field surveys and data analyses are operated by CPC Taiwan in cooperation with Academia Sinica.

The seismic source was used surface vibration trucks, at frequency of 4-96 /s. The receivers were employed by arrays of geophones with spacing of 5-20 m along the relatively straight survey line.

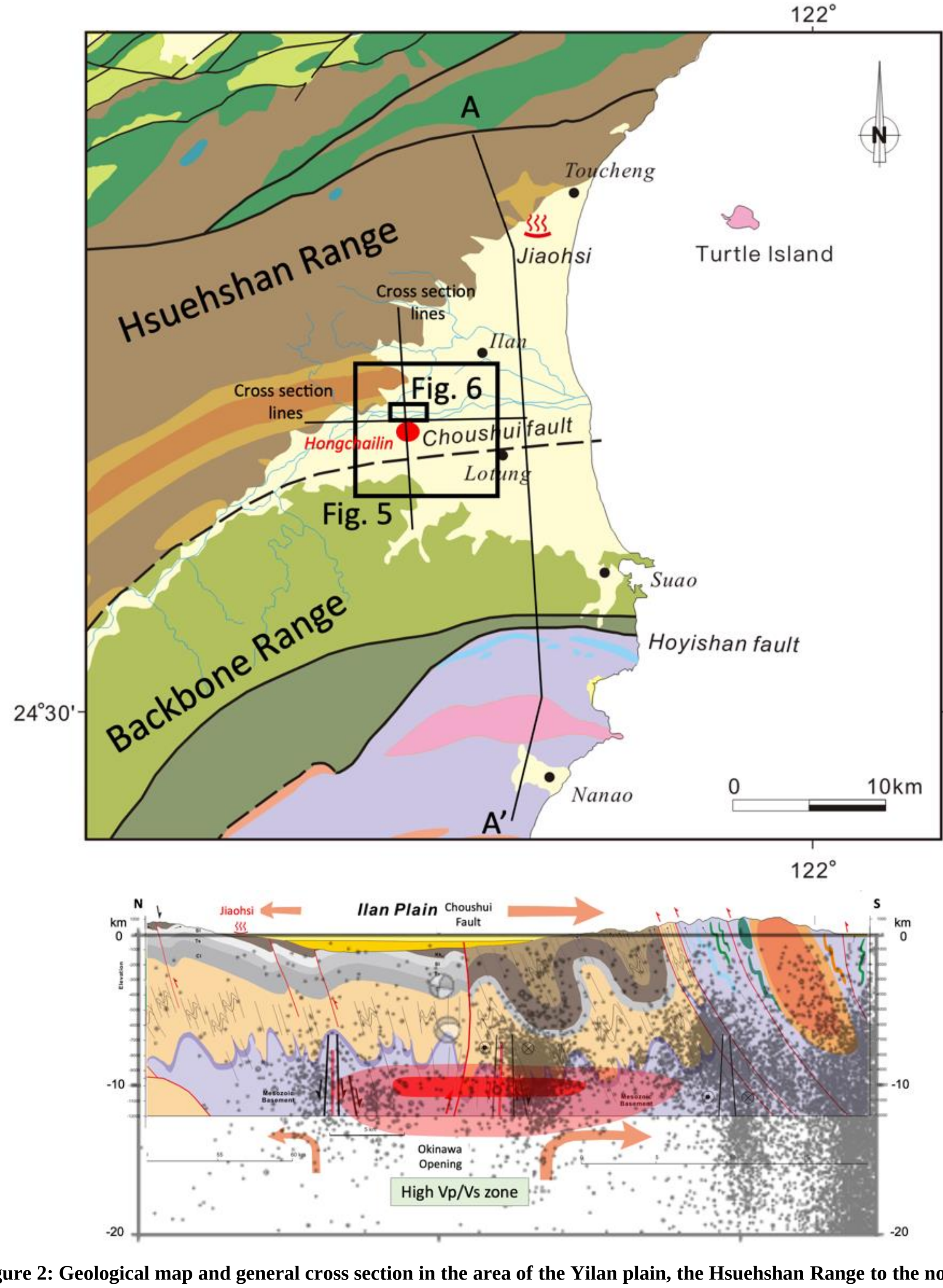

Figure 2: Geological map and general cross section in the area of the Yilan plain, the Hsuehshan Range to the north and the Backbone Range to the north, separated by the Chuoshui fault in the middle of the plain. The seismicity indicates a high Vp/Vs zone, possibly related to fluid-saturated rocks at the depth of 8-12 km.

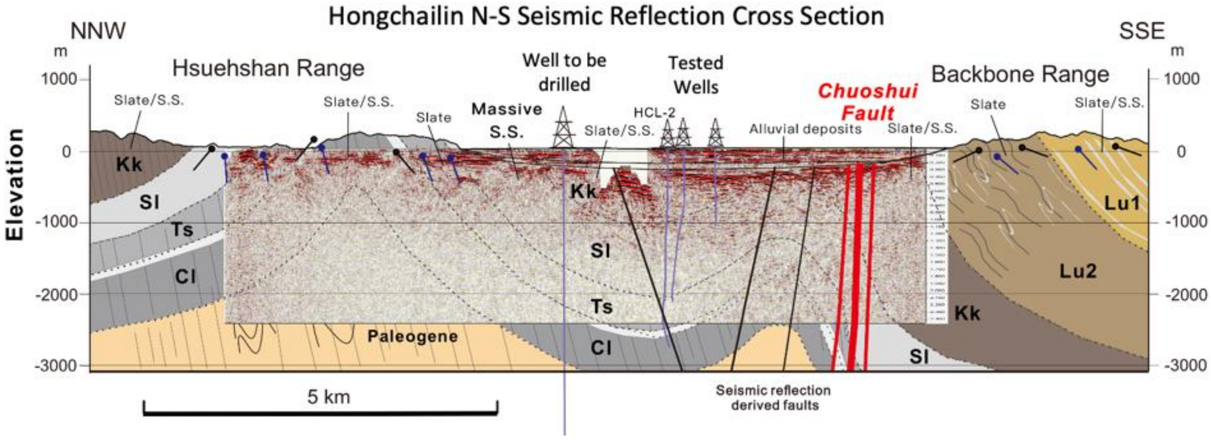

Figure 3: Seismic reflection profile on top of geological cross section across the site of Hongchailin in western Yilan plain.

In this study, we also incorporated recently published data, notably a series of relatively short seismic reflection profiles in the Hongchailin area (Shih et al., 2018; Wang et al., 2019), which were part of efforts in the earlier stage of the national geothermal project in 2016-2019.

The results of the seismic reflection profiles (Fig. 3), in particular the geometry and architecture of the rock formations and major faults, were served as key constraints for reconstructing the geothermal geological model. We shall discuss in more details later in Section 4.

3.2 MT surveys

Three magnetotelluric surveys were conducted in different periods, including 1) MT surveyed by National Central University in 2015-2017; 2) MT surveyed by GERD (Geothermal and Energy Research & Development Co.) and Academia Sinica in 2021; and 3) MT surveyed by National Central University and Academia Sinica in 2022.

In this study, we combined three data sets to invert for a 3D resistivity structure of tomography in western Yilan plain (Fig. 4). Figure 3 shows the map view of MT resistivity with three horizontal slices at the depths of 500, 1000, and 2000 m, respectively. At shallow depth of about -500 m, the low resistivity zones of 5-30 Ohm-m (warm color in Fig. 4a) are interpreted to be strongly related to the Quaternary alluvial deposits. However, the E-W alignment of the low resistivity also suggests likely fluid and/or heat interactions with the underlying metamorphic bedrocks, whic are striking E-W at the local scale.

At the depth of -1000 m (Fig. 4b), a low resistivity zone at the Hongchailin site can be observed with a ginger shape of about 3x3 km long and wide. The low resistivity zone appears to occur within a particular geological formation, the Szeleng sandstone (quartzite) formation, which we tend to interpret as the geothermal reservoir for potential geothermal power exploration. We shall discuss in more details in Section 4. The low resistivity zone around Hongchailin becomes obscure toward the depth of -2000m (Fig. 4c), which corresponds to slate formation, not favorable rock types for geothermal reservoir in this area.

3.3 Seismic velocity structures

Two seismic station arrays were used in this study. For a broader regional scale, we adopted the Formosa array, which covers the whole northern Taiwan. In the Yilan area, the seismic station coverage is rather good, with a spacing of 2-3 km. We analyzed seismicity with a total number of in a period of 25 years in 1994-2020. Our results indicate that zones of seismic clusters show high Vp/Vs ratio under Turtle island as well as in the middle-southern part of the Yilan plain at the depths of 8-12 km (Fig. 2b). We interpret these two high Vp/Vs zones correspond to magma chamber and volcanic intrusion zones, hence the plausible heat source for hydrothermal activities in the Yilan plain.

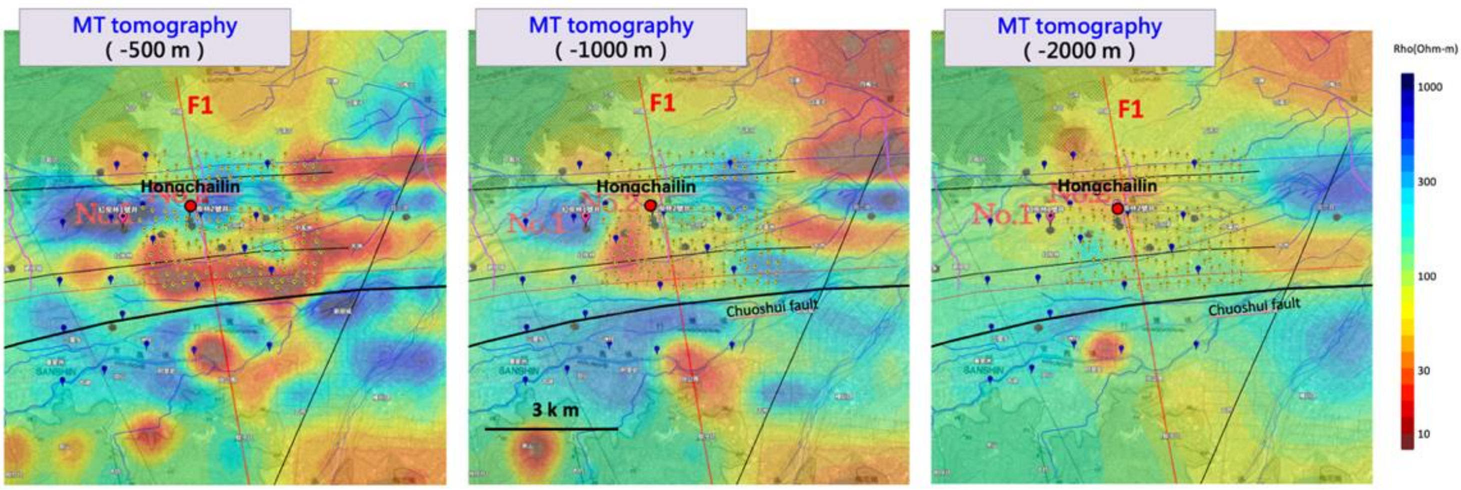

Figure 4: MT tomography with 3 horizontal slices around Hongchailin site in western Yilan plain.

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We also deployed a temporary dense array at the Hongchailin site, in an area of 3 x 5 km, with 186 stations (Fig. 5). We collected the seismic waves generated by surface vibration trucks during the field survey of the 10-km-long N-S-trending and the 30-km-long E-W trending seismic reflection lines, which across diagonally the Hongchailin site.

The results of tomography of Vp perturbation show that at the shallow depth of -400 m, relatively low Vp can be observed almost everywhere (Fig. 5a). We interpret it to be a result of a thick layer of alluvial deposits, which contain abundant shallow aquifers. At the depth of -1000 m, a rather low Vp zone occurs around and to the east of the Hongchailin site (Fig. 5b), which is consistent with the notion that the Szeleng Sandstone formation is the source of the geothermal reservoir.

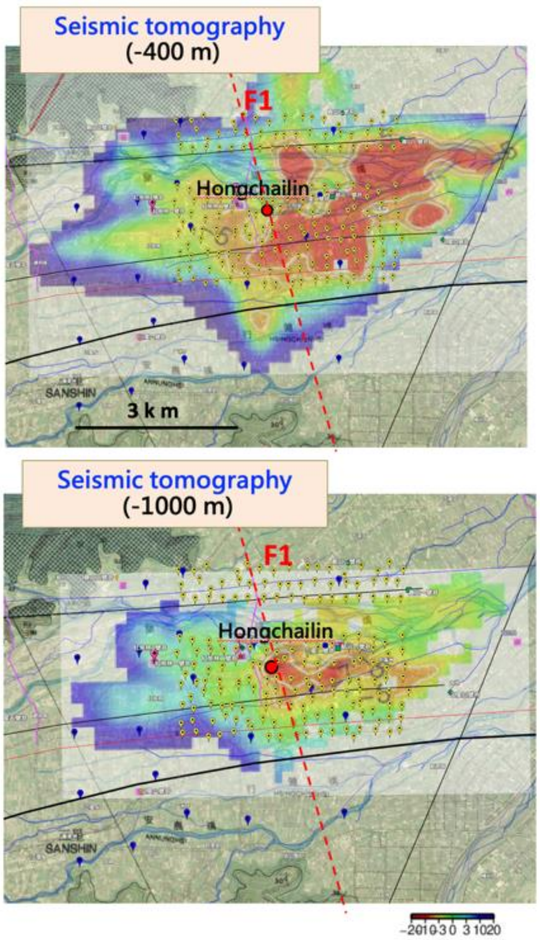

Figure 5: Seismic velocity tomography with 2 horizontal slices around Hongchailin site. The colors show Vp perturbation in %. Low Vp zones can be observed in Hongchailin site at -400 and -1000 m of depth.

4. PRELIMINARY GEOTHERMAL GEOLOGICAL MODEL

4.1 Drilling data

Two drilling wells, HCL-1 and HCL-2 have been conducted at the Hongchailin site in 2015-2017, with drilling depths of 2200 m and 2800 m, respectively (Song et al., 2019). The downhole temperatures curves were established by detailed measurements during the drilling operation. At the well HCL-2, the temperature elevated rapidly from 20°C on the surface to 70°C at the depth of 500m (bottom of the alluvial deposits), then gradually increased to 90°C around the depth of 800 m. However, the downhole temperature stayed at 90°C from 1000 m to 2000 m, where we interpret as a convection zone, before the temperature started to increase again toward the depth, i.e., 120°C at the bottom depth of 2800 m. Comparing with the rock types of the drilling cores, it indicated the convection 90°C temperature zone is in a good agreement with the Szeleng Sandstone formation.

It is worth noting that the Szeleng Sandstone formation, which is sandwiched by several-km-thick slate formations, is characterized by a 1-km-thick massive quartzite (meta-sandstone), with occasional thin interlayers of slate. Field geological investigations in the nearby mountainous area revealed three systematic, vertical joint sets are well developed within the Szeleng Sandstone formation (Lin et al., 2019). We argue that at least one joint set exhibited open mode under the influence of the NNW-SSE opening of the Okinawa trough, thus served the spacing for storage of hot fluid within the geothermal reservoir.

4.2 Hot spring geochemistry and water circulation system

Water samples have been taken during the drilling of the two wells HCL-1 and HCL-2, for geochemistry analyses, such as pH, calcium and bicarbonate concentration, carbon dioxide content, etc. The results of hydrogen/oxygen isotope ratio of the water under the well HCL-2 indicate it is composed of a large amount of meteoric water came from the altitude of 200-240 m, where the Szeleng Sandstone exposed in the nearby mountainous area. It became clear that the Szeleng Sandstone is serving as the water channels within the shallow crust, that allows the rainfall and surface water to infilter into the rocks. The 1-km-thick Szeleng Sandstone would contain tremendous groundwater, possibly with a rather high pore pressure.

4.3 Thermal remote sensing

A ~N-S trending fault has been speculated to pass through near the Hongchailin site, as suggested by the fracture analysis on the cores from HCL-2, as well as by the seismic reflection interpretation (Shih et al., 2018). In an attempt to test this speculation, we fly a drone with a thermal sensor on board to scan a rectangular area of 1 x 1.5 km on the riverbed north of the well HCL-1 and HCL-2, where the bedrock exposure is generally good (Fig. 6).

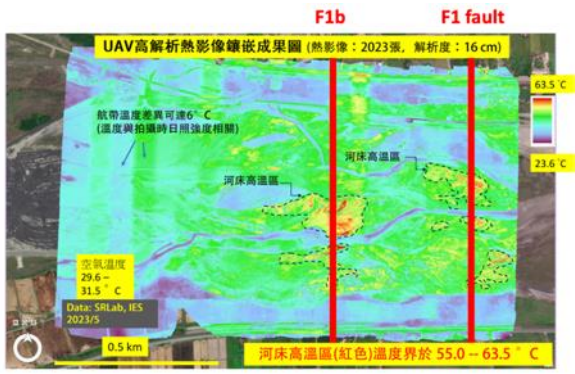

Figure 6: UAV mosaic thermal image on the Lanyang riverbed at the Hongchailin site. Two ~N-S-trending high-temperature zones were inferred and interpreted as two branches of geological fault.

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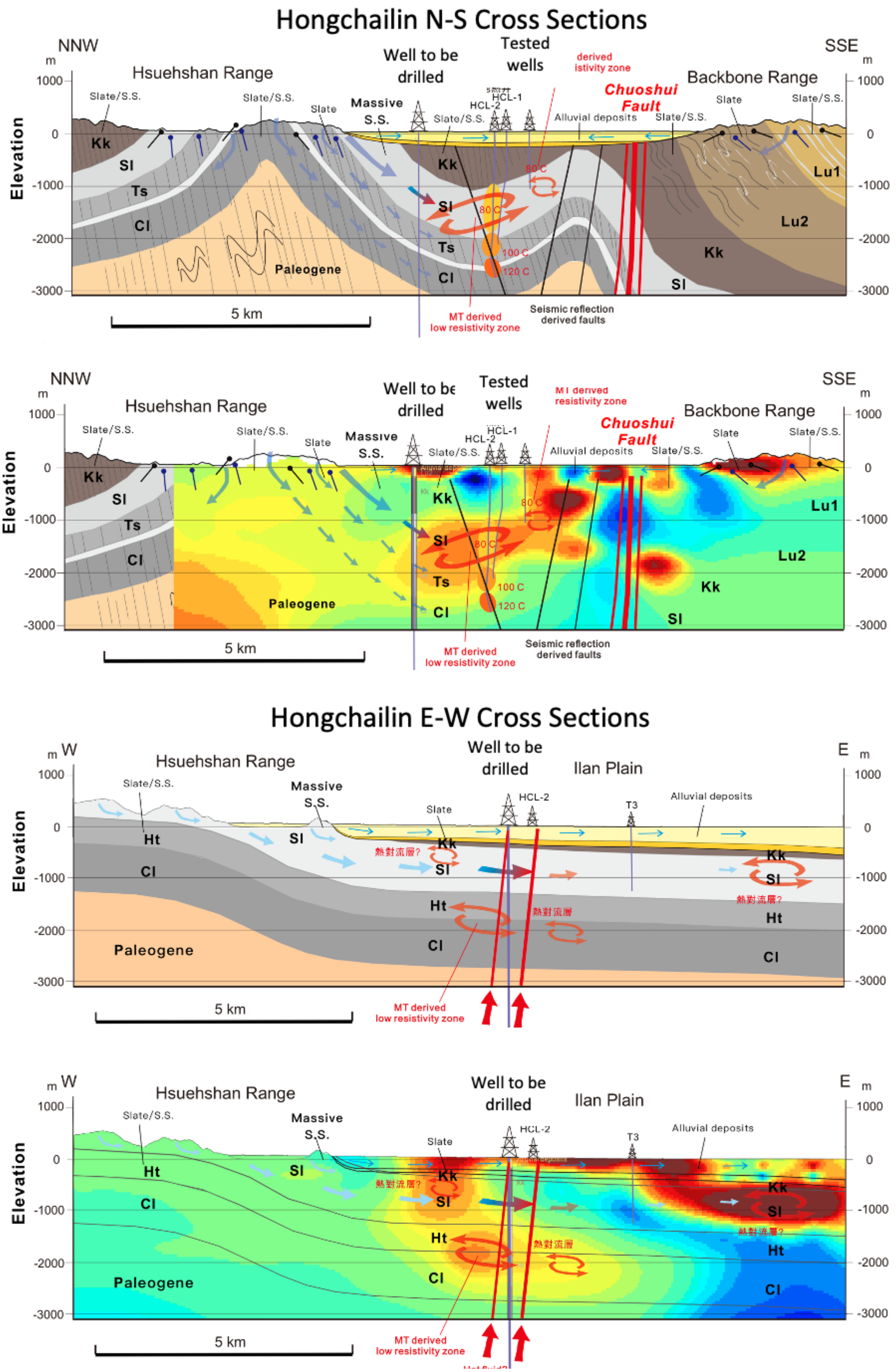

Figure 7: Geological cross sections and MT tomography at Hongchailin site in western Yilan plain.

The result, although preliminary, is quite encouraging. Figure 6 of the UAV mosaic thermal image shows two N-S-trending zones of 100-150 m wide with higher surface temperatures of 50-63°C, compared with the background bedrock temperatures of 30-40°C. We name the F1 fault for the eastern high-temperature zone, which run through very close to the HCL-2 and the F1b fault a branch fault about 400 m west of the F1 fault. We argue these two faults represent a significant geological fault zone, which can penetrate to several kilometers of depth, thus serving as a major pathway or conduit to allow the hot fluid to ascend from depth.

4.4 Synthesis toward a geothermal geological model

By incorporating the previous and new results from several geophysical imaging techniques (i.e., seismic reflection, magnetotelluric survey, seismic velocity) and results from formation temperature and water isotopes downhole and at surface, into the geological cross sections, we reconstruct the geothermal geological model for the (potential) Hongchailin geothermal field. Those results are summarized in two geological cross sections (Fig. 7).

Several points can be made from this geothermal model:

- A potential geothermal reservoir, which is mostly delineated by a relatively low MT resistivity zone, is interpreted to be located mainly within the Szeleng Sandstone formation at the depth of 1-2 km under the Hongchailin area.

- The area of the reservoir also show a low Vp seismic velocity, implying a potential fluid-saturated fractured rocks.

- We argue that a N-S trending geological fault (F1), probably with a high-angle dip, serves as the main conduit to allow hot fluid to ascend from the depth (Fig. 8). The upward moving hot fluid would mix with colder meteoric porous water within the 1-km-thick Szeleng Sandstone, which appears to be infiltered from nearby mountainous area (Figs. 7c and 7d).

- The reservoir temperatures derived from downhole measurements in the well HCL-2 appear to be about 90°C, with abundant water, from -800 to -2000 m of depth. The downhole temperature increased to 120°C at the well bottom of 2800 m, presumably in a dry rock situation.

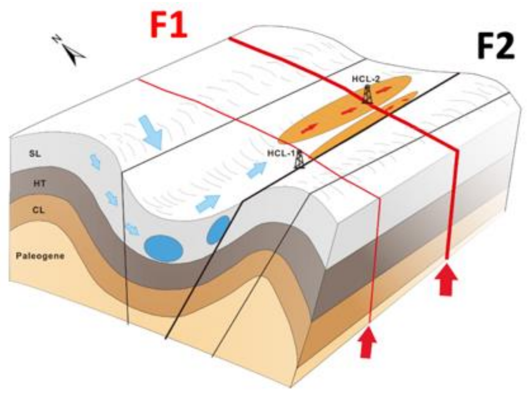

Figure 8: Conceptual geological model for geothermal reservoir at Hongchailin site.

5. DISCUSSIONS

In this section, we present a few important geological factors and reservoir parameters, which we are not able to fully understand at this moment, but hopefully will provide the answers through the progress in the near future.

5.1 Heat source: mantle upwelling and volcanic heat transfer?

From the regional tectonic framework, it seems obvious that the primary heat source(s) of the Hongchailin geothermal reservoir would be the volcanism of the back-arc opening of the Okinawa trough, with two good candidates: 1) magma chamber beneath Turtle Island and 2) dyke intrusion along the ENE-trending structure under southern Yilan plain. However, both potential heat sources are several kilometers away from the Hongchailin reservoir.

Our results of seismological analyses indicate there exists a few high Vp/Vs zones, extending from the magma chamber of the Turtle Island toward the inland Yilan plain. We speculate that the heat might be able to transfer or migrate into the Yilan plain. Indeed, the occurrence of vigorous hot springs in the Jiaohsi town is favorable for this explanation. On the other hand, the Hongchailin is farther away from the coastline, without apparent natural outflow of hot spring. Which heat source is providing the heat and how the heat transfer to the Hongchailin site are still the question to be solved.

5.2 Cap rocks and alluvial deposits

It seems that the slate formation (Kankou fm, KK in Fig. 7) overlying on the Szeleng sandstone can be considered as playing the role of cap rocks in the Hongchailin geothermal system. This is not the typical type of geothermal cap rock, such as clay-rich layers. The Kankou formation, which is composed of low-grade metamorphic fine-grained slate with occasional thin meta-sandstone layers, appears to be of low permeability. Further rock mechanics tests are required.

It is worth noting that the thick alluvial deposits in the Yilan plain (400-500 m thick at Hongchailin site) might be considered as sort of geothermal reservoir at the surface shallow level. Indeed, upward warm water in the surface paddy field has been observed at several places in the Yilan plain. However, the temperature (usually 40-50°C) is not high enough to considered for generating electricity, although it can be used for agriculture applications.

5.3 Geological fault system

It is rather difficult to map the fault system in the bedrock underneath the thick alluvial deposits in the Yilan plan. Although with help of seismic reflection profiles and UAV surface thermal survey, we tentatively conclude that it exits a significant geological fault in the N-S trend, which allow the deeper hot fluid to ascend to the surface level. Furthermore, we also adopt a few E-W-trending faults, derived from earlier seismic reflection work (Shih et al., 2018) in our geothermal model, which we interpret as barriers for geothermal fluid flow. For instance, we argue the Hongchailin geothermal reservoir is limited by a E-W fault, so that the geophysical images (i.e.., MT and seismic velocity) show a rather sharp southern boundary of the low-resistivity/low velocity zone in a E-W trend (Figs. 4 and 5). Nevertheless, we feel that there are still rooms for improvements on reconstructing the geological fault system at the Hongchailin site.

5.4 Perspective for geothermal electricity power plants

Although it is preliminary with some unknown and uncertainties, we made the rough estimate for the potential capacity of electricity power for the Hongchailin geothermal reservoir, as mentioned and discussed above.

We used MT low-resistivity zone in the Szeleng Sandstone formation as the primary constraint for the 3D dimension of the Hongchailin geothermal reservoir, which is about 1 x 2 x 1 km (although we think it could be larger by a factor of 2) (Tab. 1). The reservoir temperature is chosen to be 95°C according to downhole onsite measurements. The porosity of the reservoir (mainly fluid-saturated, fractured Quartzite of the Szeleng Sandstone formation) is estimated to be 0.14%, based on literature. However, we feel that it is necessary to re-estimate the permeability of the reservoir rocks in the next stage of exploration well tests. Based on the parameters listed in Table 1, we come up with a potential capacity of 4-6 Mw of electricity power for the Hongchailin geothermal reservoir.

Reservoir Properties	Units	Value
Reservoir area	km^2	1.8-2.2
Thickness	m	950-1100
Volume	km^3	1.60-1.63
Reservoir Temperature	°C	90-100
Abandon Temperature	°C	65-75
Porosity	%	0.14
Rock specific heat	kJ/kg-°C	0.9-1.1
Water specific heat	kJ/kg-°C	4.52
Rock density	kg/m^3	2760-2780
Water density	kg/m^3	859.6
Recovery factor	%	0.2-0.3
Conversion efficiency	%	0.09-0.12
Power factor	%	0.85-0.95
Life span	years	25

Table 1: Parameters estimates of the Hongchailin geothermal reservoir for evaluation of power capacity.

6. CONCLUSIONS

In this study, we use a multi-disciplinary approach to evaluate the geothermal potential at the Hongchailin site, western Yilan plain, NE Taiwan. Combining the geophysical subsurface imaging techniques, including MT (magnetotelluric) surveys, seismic velocity tomography and seismic reflection profiles, together with geological cross sections based on regional geological investigation and mapping, we reconstruct a geothermal geological model in the Hongchailin area.

Our model shows that a potential geothermal reservoir with a dimension of at least 1 x 2 x1 km within the massive Szeleng Sandstone formation. The images of MT and seismic velocity show the reservoir corresponds to a low resistivity, low seismic velocity (Vp) zone, implying fluid-saturated, fractured rocks.

The reservoir fluid, with a temperature of 90-100°C, appears to come from deeper heat source (presumably migrate from volcanism of the Okinawa back-arc opening) via the N-S trending geological fault and mix with the cold meteoric porous water coming from infiltration of rainfall or groundwater into the Szeleng Sandstone exposed in nearby mountainous area.

Based on the reservoir parameters, we estimate the capacity of the geothermal electricity power to be 4-6 Mw for the Hongchailin reservoir. However, the reservoir parameters are subjective to be modified, including the dimension, temperature, permeability, etc., through the exploration processes.

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