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Reconstructing geothermal geological models by combining geophysical, geochemical and geological studies in Tatun volcanoes area, Northern Taiwan

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ABSTRACT

In this study, we conduct a multi-disciplinary study, including geophysics, geochemistry, and geology, with previously drilled wells, to reconstruct geothermal geological models at the shallow 3-5 km in the Tatun volcano area, northern Taiwan. Our geological profiles show that the Tatun volcanoes have a ~1-2-km thick of lava and pyroclastic deposits, erupted on top of the 6-8-km-thick fold-and-thrust belt of Miocene sedimentary rocks. The seismic velocity imaging indicates a main magma reservoir of high anomaly of Vp at the depths of 8-15, with an estimated volume of ~250-300 km^3.

Incorporating the regional geology with the newly acquired magnetotelluric results, we found three high-resistive areas at different depths, which we tend to interpret as possible “heat bodies”, overlaid by low-resistive layers, which we interpreted as “cap rocks”: 1) two shallow reservoirs, at depth 600-1200 m (150-250°C), and 2) a deeper reservoir of ~ 2-3 km, in the uppermost basement of quartz-rich sandstone.

At least four shallow high micro-seismicity zones have been observed. Two zones with cylinder shape are interpreted as conduits of hot fluid derived from deep over-pressured zones, beneath the Qixing Mt and Da-You-Keng (depth of 1~3 km). One zone is more dispersed beneath the Da-Jian-Hou shan at the depths of 1-4 km. The fourth zone occurred in the deeper part around the outer edge of the fluid saturated magma reservoir around 4-6 km depth. These hot-fluid related seismicity zones are considered of potential for “super-hot or super-critical geothermal” exploration.

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 Taiwanese national project.

This paper is aiming at presenting the updated results of geothermal exploration in Tatun volcanoes area in northern Taiwan (Fig. 1). The Tatun volcanoes group of about 10 x 15 km^2, just north of the capital city Taipei, represents the inland biggest volcanoes in Taiwan and has been one of the places for its hot spring spots and forester landscape for recreation and touristic attraction. Indeed, the government had also put great efforts on the Tatun area for exploring geothermal power potential in the years from 1960s to1980s, with more than ten 1-2-km-deep wells drilled at several sites (e.g., ITRI, 1967,1969, 1970, 1972; CPC Taiwan, 1980, 1982, 1985). However, this pioneer geothermal exploration work had ended in the years of late 1980s due to some undisclosed reasons.

In the recent years, Academia Sinica launched a geothermal research project to investigate the geothermal potential for power generation. In this study, we carried out new magnetotelluric surveys, seismological

analyses, water and gas geochemistry analyses, as well as detailed field geological investigations. By incorporating the geophysical subsurface images and geological cross sections, we reconstruct plausible geothermal geological models at the regional and site scales.

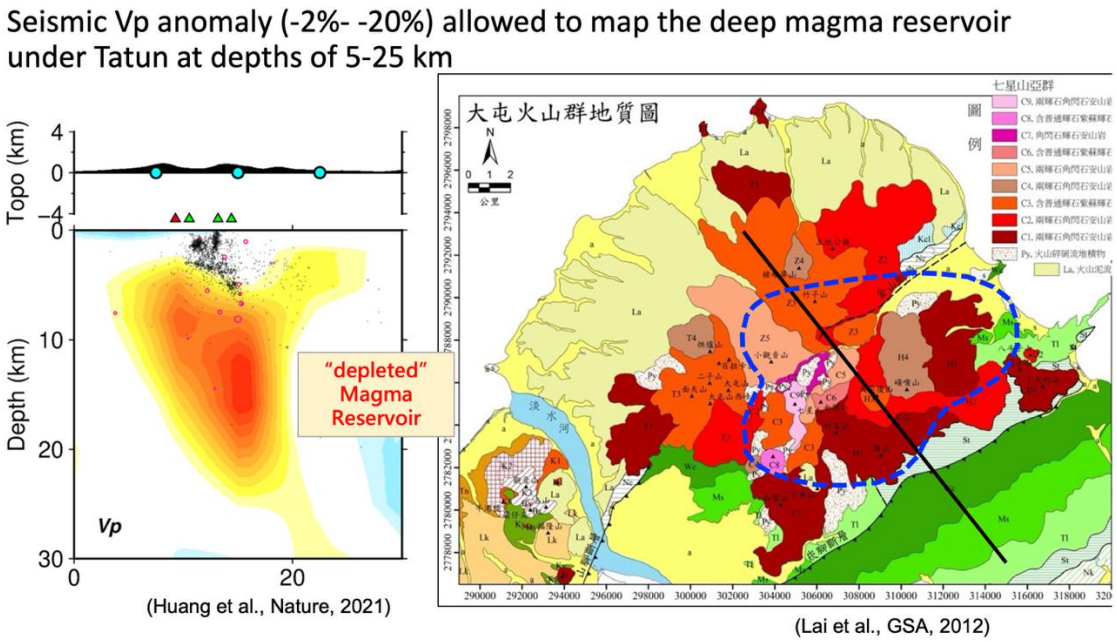


Figure 1. Geological Map of the Tatun volcanoes group in northern Taiwan (right). Anomaly contour map of seismic velocity Vp underneath the Tatun area (left). A fluid-rich magma reservoir has been mapped at the depth of 5-25 km. The surface project of the deep magma reservoir is revealed by the blue dashed lines on the geological map.

2 TECTONIC AND GEOLOGICAL BACKGROUND

The Taiwan island is a product of an active oblique convergence between the Philippine Sea plate and Eurasian continental margin, which induces the Taiwan mountain belt of about 400 km long and 150 km wide. As the Philippine Sea plate flipped to subduction underneath the Eurasian continent in the norther part of Taiwan, a series of volcanoes has been developed since 2-3 Ma in northeastern Taiwan. The Tatun volcanoes, located in the northern tip of Taiwan, represent the largest volcanoes in Taiwan, with an area of 10 x 15 km^2 (Fig. 1). The activity of the Tatun volcanoes started about 2 Ma and has its peak volcanic eruption since 0.5 Ma and developed into 5 main volcanoes groups and have been considered still active with the eruption ages as young as 6-7 ka (Chen et al., 2002; Belousov et al., 2010).

The Tatun volcanoes appear to stem from a magma reservoir at the depth of 8-20 km depth, revealed by a negative anomaly of seismic velocity Vp of -2% - -20% (Fig. 1). At the shallow crust level, the vents of the Tatun volcanoes cut through the 8-10-km thick Tertiary (mostly Miocene) shallow marine sediments in the past 2 Ma (Fig. 2), which have been forming the fold-and-thrust belt earlier during the mountain building due to oblique collision between the Philippine Sea plate and Eurasia since 3-5 Ma.

The Tatun volcanoes have been divided into four major volcano groups (Fig. 3): 1) Mt. Zhuzi, 2) Mt. Tatun, 3) Mt. Qixing, and 4) Mt Huangzui, without clear differences of ages. The former two volcano groups are located apparently on the NW side of the NE-trending Jinshan/Shanjiao faults, and latter two groups are on the SE side. There are tens of fumaroles, which are considered as geothermal surface up-flows of the Tatun volcanoes, are intriguingly distributed on the two volcano groups on the SE side of the Jinshan/Shanjiao faults and also correspond to the area of surface projection of the deep magma reservoir, imaging from the seismologic study (Huang et al., 2021).

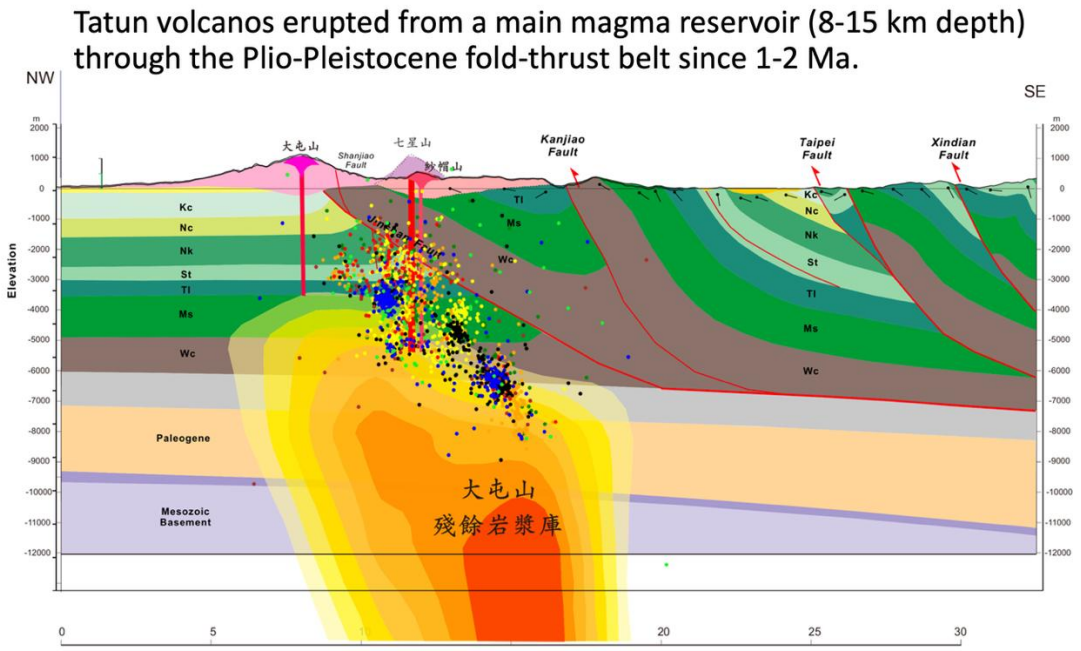


Figure 2. Geological cross section across the Tatun volcanoes area in northern Taiwan. Tatun volcanoes erupted from the deep magma reservoir at the depth of 8-25 km in the middle/lower crust since 2 Ma and is still active. The magma and intrusive volcanic bodies went through the sedimentary fold-and-thrust belt at the shallow 8-10 km and formed the Tatun volcanoes on top of 1-2 km of thickness. Recent seismicity occurred above the magma reservoirs and was related to the fluid activity to some extent.

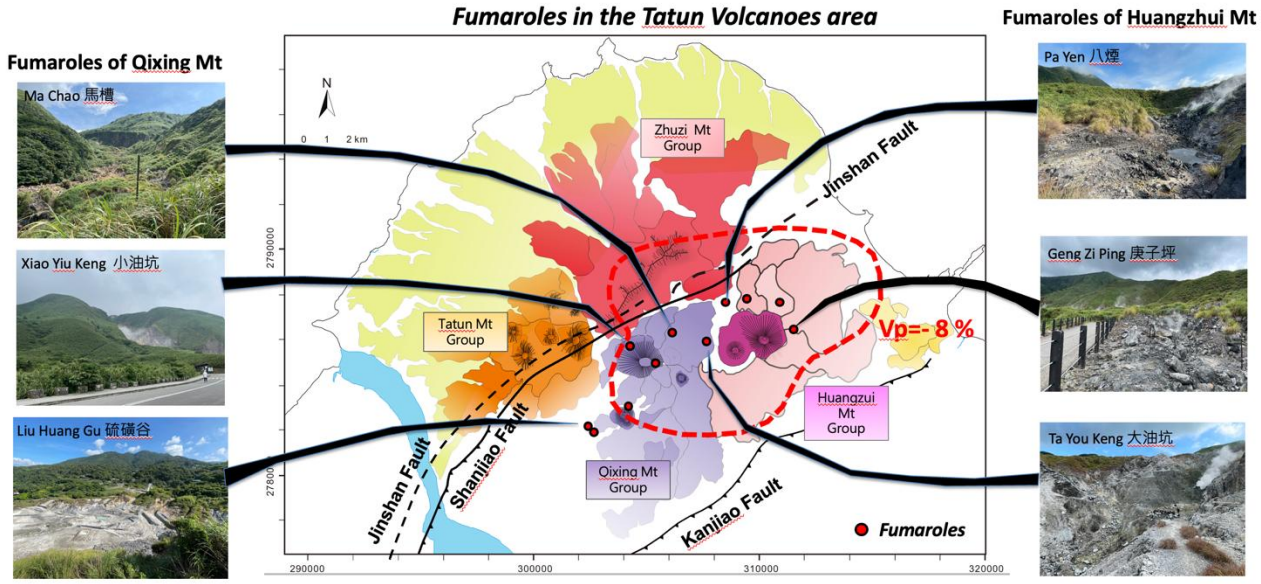


Figure 3. Surface geothermal expression, including tens of hot springs and fumaroles, in the Tatun volcanoes area. It appears that most, if not all, of them are distributed in the footwall of the Shanjiao normal fault of the southeast part of the Tatun volcanoes. Red-dashed line: surface projection of the deep magma reservoir.

3 GEOPHYSICAL AND GEOLOGICAL SUBSURFACE IMAGING

In order to better imaging the subsurface geothermal features in the Tatun volcanoes area, we conducted 1) seismological analyses to map the micro-seismicity 3-D distribution, 2) magnetotellurics (MT) survey to map the 3D resistivity structures, and 3) geological investigation to reconstruct the geological profiles.

3.1 Seismicity

A dense array of 20 seismic stations was deployed in the Tatun volcanoes area since 2014 (Pu et al., 2020). From observation in 2014-2021, five main micro-seismicity zones can be mapped (Fig. 4). Among them two shallow zones exhibited an intriguing cylinder shape: 1) SM1 at Mt. Qixing (1-3 km of depth) and 2) SM2 at Qingtiangang/Dayoukeng (0.5-3 km of depth). Regionally, focal mechanisms show two different types: normal faulting and strike-slip faulting, which combine indicates a regional WNW-ESE extension stress regime. However, a rather low stress ratio occurred in the two cylinder-shaped seismic zones (Pu et al., 2020), implying that the seismicity was mostly stem from the fluid-related activity.

What the exact relationships of the high seismic cylinder zones with geothermal fluid pathways and possible reservoirs remain to investigate. Nevertheless, we intend to explore the possible high temperature zones, hopefully up to 375°C for "Supercrtical" or "Superhot" geothermal, around these fluid related seismic zones.

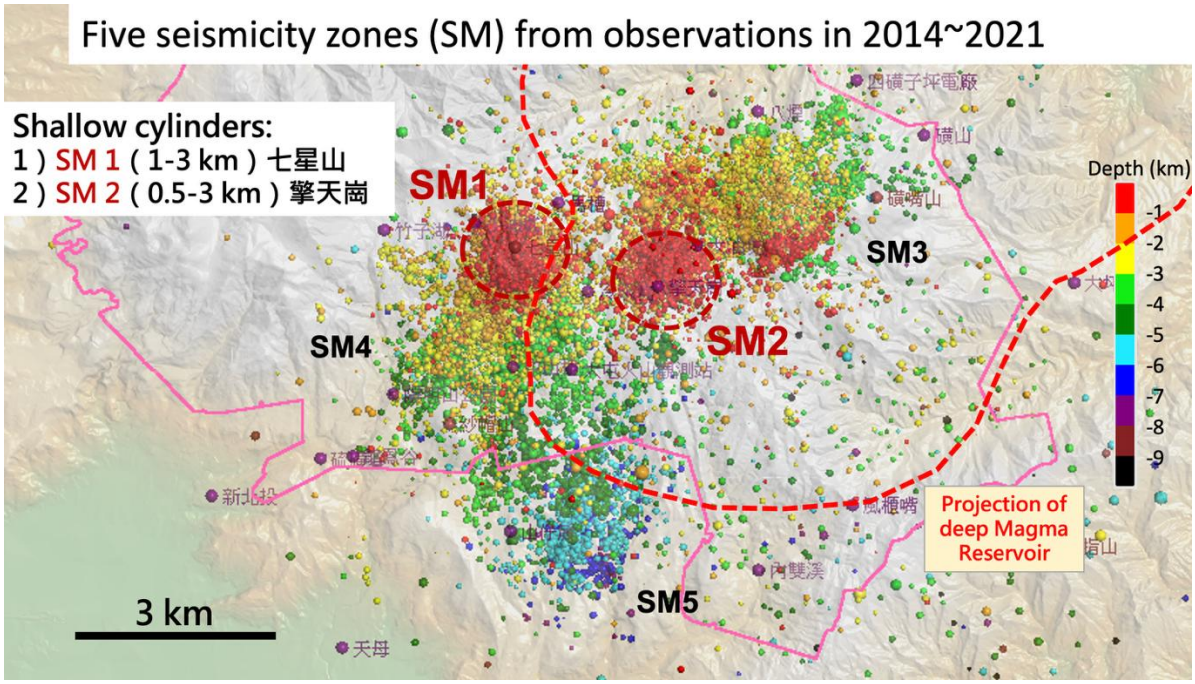


Figure 4. Micro-seismicity distribution map in the Tatun volcanoes area. From observation of dense array in 2014-2021, five main micro-seismicity zones can be found. Among them two shallow zones exhibited an intriguing cylinder shape: SM1 at Mt. Qixing and SM2 at Qintiangang/Dayoukeng. Focal mechanisms show a rather low stress ratio, implying that the seismicity derived from fluid-related activity (Pu et al., 2020).

3.2 MT Survey

We conducted a MT survey in 2024 with 90 sites at spacing of 1-2 km in the southeastern part of the Tatun volcanoes area. Each site has been occupied for 3 days with Metronix MT instruments. Accordingly, we constructed a 3-D resistivity tomography at the shallow crust of 0-3 km in the Tatun volcanoes area.

Our MT results show three major high-resistive lobs of km scale (HR1, HR2 and HR3 in Figure 5), all covered by apparently good low resistive layers, which we interpret as the possible cap layers for geothermal reservoirs. The HR1 high resistive zone is located at the depth of 1-2 km to the west of Mt. Qixing, where also locates a high seismic zone in cylinder shape at the depth of 1-3 km. The HR2 high resistive zone is located mainly under Mt. Huangzhui at the depth of 1.5-3 km, to the NE of a distributed high seismic zone under Mt. Dajianhou. The HR3 high resistive zone, the largest but deepest zone among the tree high resistive zones, is located under Mt. Chugao at the depth of 2-3 km.

The above three major high resistive lobs are set to be our primary targets to explore the possible geothermal reservoirs for electricity power generation. In the following sections, we combine the geophysical imaging, seismicity, MT, with the reconstructed geological profiles, geochemical data, and available well temperatures, to propose the drilling sites for exploring the conventional geothermal reservoirs and superhot geothermal in the Tatun area.

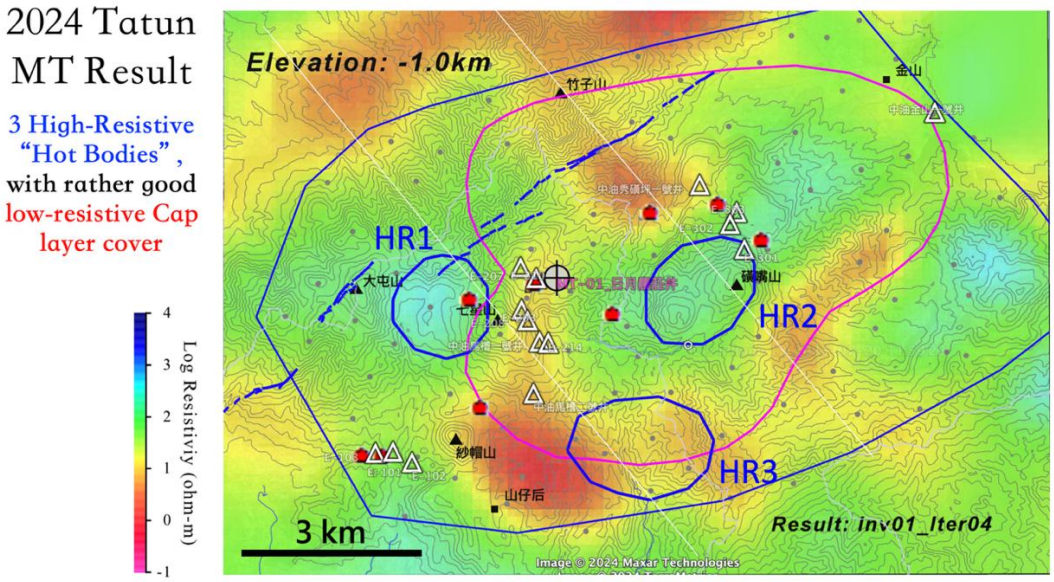


Figure 5. Horizontal slice of MT-derived resistivity tomography at the altitude of -1000 m in the Tatun volcanoes area. Our 2024 MT results indicate three major high-resistive lobs of km scale (HR1, HR2 and HR3), all covered by apparently good low resistive layers. Pink close loop shows the surface projection of the deep magma reservoir. Blue rectangular represents the area conducted the 90 MT surveyed sites.

3.3 Geological Profiles and Preliminary Geothermal Conceptual Model

By incorporating the subsurface geology revealing by available drilling wells as well as the published geological maps, we reconstruct several geological profiles across the potential geothermal reservoirs. Combing the geological profiles with the seismicity distribution (2014-2021) and the newly acquired magnetotelluric (MT) results, we hypothesize the four different depths of possible geothermal reservoirs: 1) near-surface reservoir at depth of <200 m beneath surface deposits; 2) main shallow reservoirs at the depth of 200-500 m (downhole temperature of 150-250°C), covered by low-resistive volcanic layers (possibly clay-rich altered rocks); 3) deeper reservoirs at the depth of ~ 1-1.5 km, seemingly in the uppermost basement of quartz-rich sandstone, underneath low-resistive lobs; 4) superhot geothermal at 3-4 km depth.

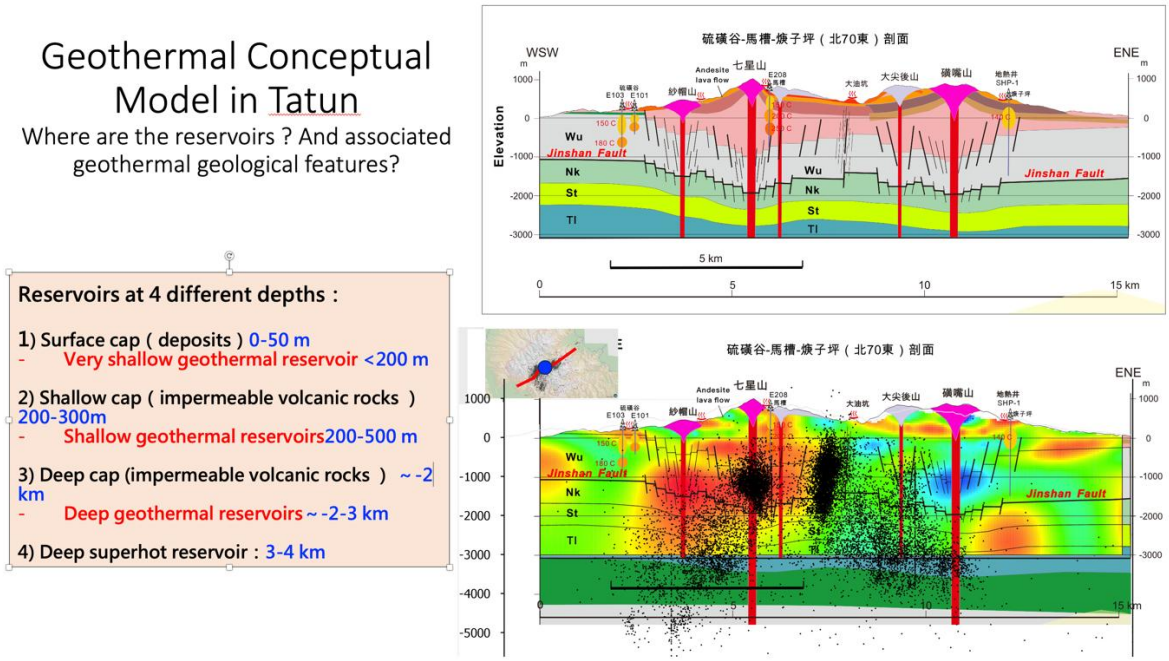


Figure 6. Preliminary regional geothermal conceptual model in the Tatun area. We hypothesize possible geothermal reservoirs at four different depths with different geological settings.

4 TEMPERATURE, GEOCHEMICAL DATA AND GEOTHERMAL DRILLING SITES

In order to accelerate the geothermal exploration in the Tatun volcanoes area, we intend to propose "good" drilling sites for not only conventional geothermal reservoirs but also superhot. Figures 7 and 8 show the locations of Site 1 and Site 2, respectively, and their relations with local subsurface geology, MT resistivity, and seismicity. We choose two potential sites around the Mt. Qixing, where a cylinder-shaped high seismic zone occurred. In Figure 7, we can observe this high-seismic zone corresponds to low resistive zone, consistent with possible fluid rich fracture zone at the depth of 1.5-3 km. It also appears that the deeper seismicity might connect the top of the magma reservoir (~5-6 km) to the cylinder seismic zone under Mt. Qixing, a likely good heat source.

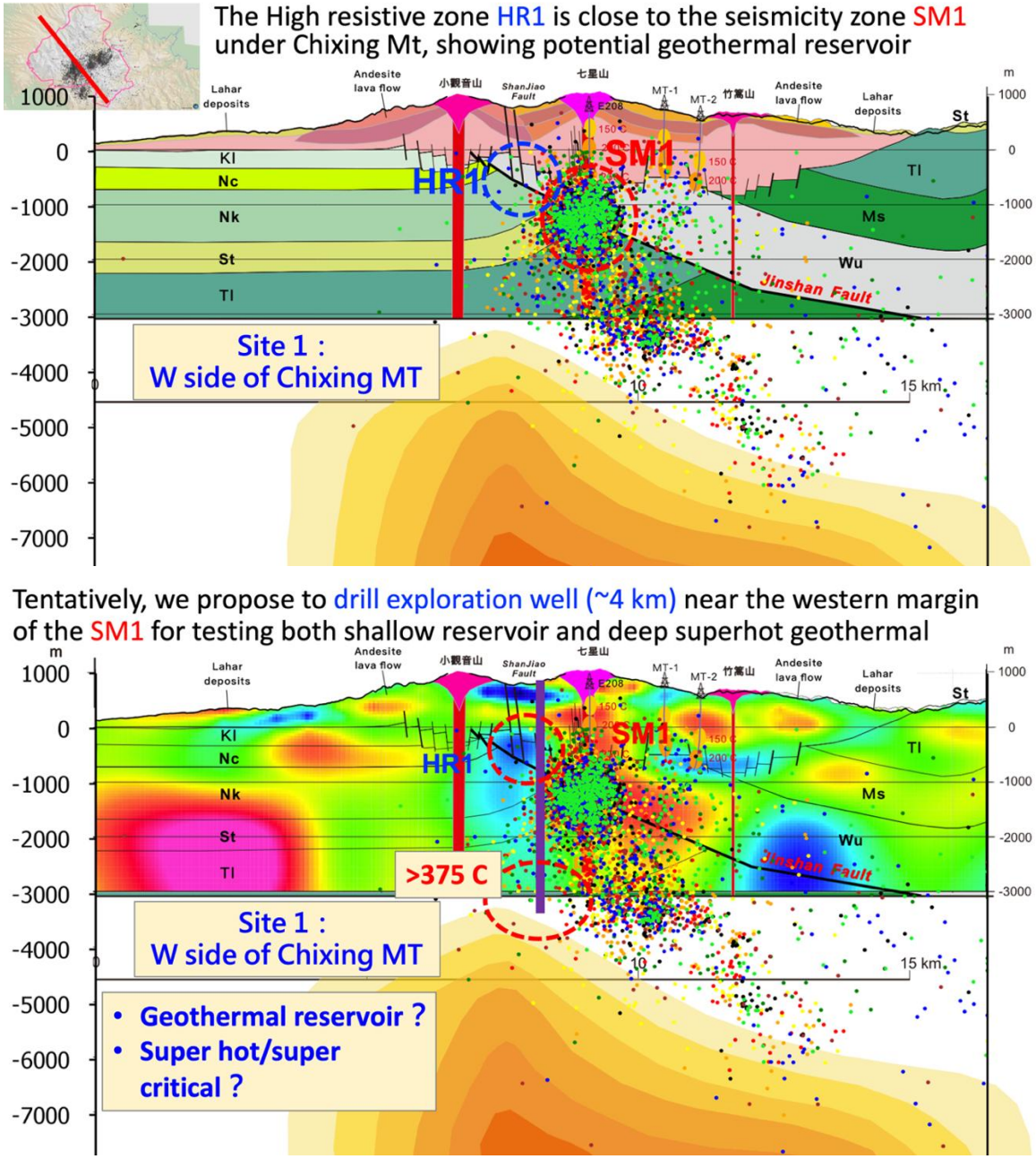


Figure 7. Tentative drilling location Site1 for geothermal exploration around Mt. Qixing in the Tatun area. In the shallower part, we are targeting the potential conventional geothermal reservoir, revealing by HR1 high resistive area at 1-2 km of depth, covered by low resistive layer. In the deeper part, we are targeting the area closed to the cylinder high seismicity zone under Mt. Qixing. With the previous drilling wells indicating the temperature up to 250C at the depth of 1.5-2 km, we hypothesize the temperature at the Site 1 well could be up to 375 C at the depth of 3.5 -4 km, where we intend to test the supercritical geothermal potential.

In Figure 8, we propose a drilling site to the east of Mt. Qixing, in-between the two cylinder seismic zones. Here we observe the Mt. Qixing high-seismic zone corresponds to low resistive zone, but the Dayoukeng high-seismic zone corresponds to moderate/high resistive zone. What caused the difference in MT resistivity on these two cylinder seismic zones is interesting and deserves to be further investigated. At this point, we argue that this suggested drilling site would have two possible heat sources from these two cylinder seismic zones, which again have been interpreted as being closely related to fluid activity.

From the previous well data, the temperatures are up to ~250°C near the bottom of the volcanic body at the depth of ~1.5 km. In both cases of Site 1 and Site 2, we would expect or hope to attend the well temperature around 375°C at the depth of ~4 km, where the target reservoir rocks are expected to be sedimentary rocks, sandstone and shale (Figs. 7 and 8).

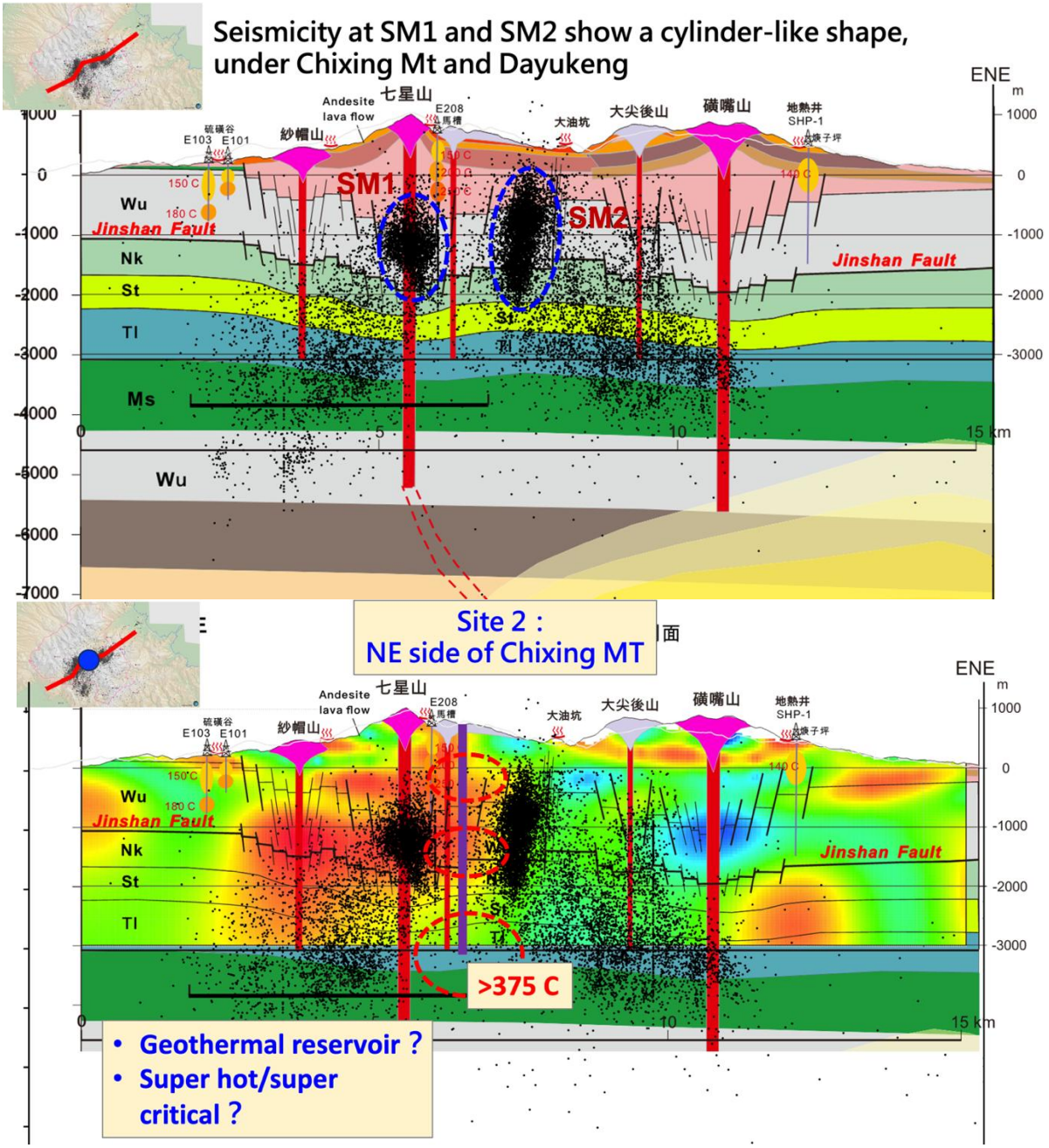


Figure 8. Tentative drilling location Site 2 for geothermal exploration on the NE side of Mt. Qixing in the Tatun area. This suggested drilling site is located in-between two cylinder-shaped shallow seismic zones at the depth of 1-3 km. With the previous drilling wells indicating the temperature up to 250C at the depth of 1.5-2 km, we hypothesize the temperature at the Site 2 well could be up to 375 C at the depth of 3.5 -4 km, where we intend to test the supercritical geothermal potential.

5 CONCLUSIONS

This paper presents the recent efforts of geothermal exploration study in the Tatun volcanoes area in northern Taiwan. Our combing subsurface imaging, including seismic activity and distribution, 3-D MT resistivity tomography and reconstruction of geological profiles, allow to reconstruct the geothermal conceptual models at the regional scale as well at site scale. We propose two drilling sites around the cylinder-shaped high seismic zones, which also corresponds to low resistive zone, implying close relation with strong fluid activity. We intend to use the next drilling opportunity to explore not only the conventional geothermal reservoirs at the shallow 1-2 km, but also the superhot geothermal at the depth of ~4 km.

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