Geothermal characteristics of the Paolai Hot Spring area, Taiwan

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ABSTRACT

In order to understand the geothermal potential of Paolai Hot Spring area, we conducted extensive geological surveys, collected seismic data, and analyzed geochemistry of hot springs in this region. Two hydrological circulation models are assessed here that are based on previous campaigns and studies: 1) the single fault (the reverse Chaozhou Fault) model and 2) a dual fault model considering the reverse Meilunshan Fault as an additional regional rupture zone. In the single fault model, the Chaozhou Fault serves as the controlling boundary with groundwater replenished from the eastern mountainous area and circulating downward into the subsurface and heated. The deeply circulated hot fluid would be directed upward along the highly ruptured, permeable zone within the fault system. In the dual fault model, the Chaozhou and Meilunshan Faults compartmentalize the hydrological circulation into two systems. To the east of the Meilunshan Fault, groundwater is replenished from the mountainous area, circulating downward, heated, and migrates to the surface along the open fissures on the hanging wall of the Meilunshan Fault to form hot springs. The western compartment would be controlled by the Chaozhou Fault. Our field results concur the occurrence of the Meilunshan Fault while the seismic and geochemical data also suggest distinct characteristics across the fault. To better evaluate the geothermal potential in Paolai area, further investigation towards the complex structures in this region should be thoroughly considered.

1. INTRODUCTION

1.1 Geothermal energy in Taiwan

Located on the convergent plate boundary between the Luzon Arc of the Philippine Sea Plate and the continental margin of the Eurasian Plate, Taiwan is one of the most active orogens in the world. Geodetic data shows that the Philippine Sea Plate is moving northwest with a rate of ca. 80 mm/yr (Yu et al., 1997) and consequently leads to the ongoing subduction and collision around Taiwan. The orogenesis in Taiwan is often illustrated by the critical tapered wedge model that contains a series of seismically active fold and thrust belts, high relief mountains with extreme exhumation rates reaching 4-7 mm/yr, and emerged foreland basins (Dahlen et al., 1984; Fellin et al., 2017; Fuller et al., 2006; Willett and Brandon, 2002; Willett et al., 2003). The island of Taiwan therefore exhibits a variety of landforms and subsurface heat flows, including volcanos, sedimentary basins, and fast emerging mountains that bear potential for geothermal energy development. According to the Single Service Window for Taiwan Geothermal Power (2023), the estimated total geothermal potential of Taiwan is about 33.64 GW.

1.2 Geological background of Paolai

The Paolai Hot Spring area is long known as one of the potential geothermal sites in Taiwan (Chang and Lee, 2001; Lee et al, 2022; The Single Service Window for Taiwan Geothermal Power, 2023). Located in the southern part of the Central Range, the village of Paolai sits along the Laonung River, a mountain river which flows across the low degree metamorphic slate strata, and is bounded by the Chaozhou Fault (aka Tulungwan Fault locally) to the west (Figure 1).

The Chaozhou Fault is a major regional fault that separates the sedimentary Changchihkeng Formation to the west and the low degree metamorphic Chngshan Formation to the east. The degree of metamorphism in the Chngshan Formation increases from west to east, with lithology that transits from argillite to slate. In addition to the Tulungwan Fault, Lin (1999) proposed the possibility of the Meilunshan fault to the east. Across the Meilungshan Fault, orientation and foliation of the exposed argillite and slate appear to be different. However, there is not much solid evidence of fault displacement and the extent of the fault is ambiguous

1.3 Conceptual geothermal models

From what we have learned via previous campaigns and studies (Chang and Lee, 2001; Lin, 1999; Sung et al., 2000), there are two conceptual models of the 3D architecture in this region which can provide the basis of hydrological cycles for further exploration of geothermal geology. Firstly, the reverse Chaozhou Fault may serve as the boundary of a single-fault system, with groundwater replenished from the eastern mountainous area circulating downward and heated. Because fault gouge of the Chaozhou Fault is potentially impermeable, the deeply circulated hot fluid would be directed upward along the highly ruptured, permeable zones within the fault system.

The second model is a dual-fault system that includes the reverse Meilunshan Fault as an additional regional structure. Like the first model, the impermeable fault gauges associated with the two faults potentially compartmentalize the hydrological circulation into two systems. The eastern compartment is primarily bounded by the Meilunshan Fault, with groundwater replenished from the mountainous area, circulating downward, being heated, and migrating to the surface along the open fissures on the hanging wall of the Meilunshan Fault. The western compartment would be within the two faults with limited recharge along the river valley.

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To validate the credibility of the two models, we conducted geological surveys, seismic monitoring, seismic imaging, and geochemical analyses of hot springs and alteration zones. By integrating the associated data, we hope increase our understanding of the spatial relationship across the Tulungwan Fault and the Meilungshan Fault, in terms of "fluid," "heat," and "fractures" and the reservoir near Paolai.

2. GEOLOGICAL MAPPING IN PAOLAI

West of the Tulungwan Fault (the Laonung River), the strata are composed of sedimentary beds, mainly sandstone and shale of the Changchikeng Formation (Figure 1). Between the Laonung River and the Meilunshan Fault, the outcrops comprise low grade metamorphic sandstone and argillite form the Upper Member of the Changshan Formation. Orientations of bedding and cleavage are similar in this section, showing the strike of NE-SW and a high dipping angle to the east.

To the east of the Meilunshan Fault, the exposed strata are mainly silty argillite and metamorphic sandstone which can be identified as the Lower Member of the Changshan Formation. The orientation of bedding in this section is NE-SW with steep eastward dips. However, the cleavage presents the strike of NW-SE with a high dipping angle to the west. In addition, abundant syn-depositional features, such as convolution and slumping structures, can be observed in this section.

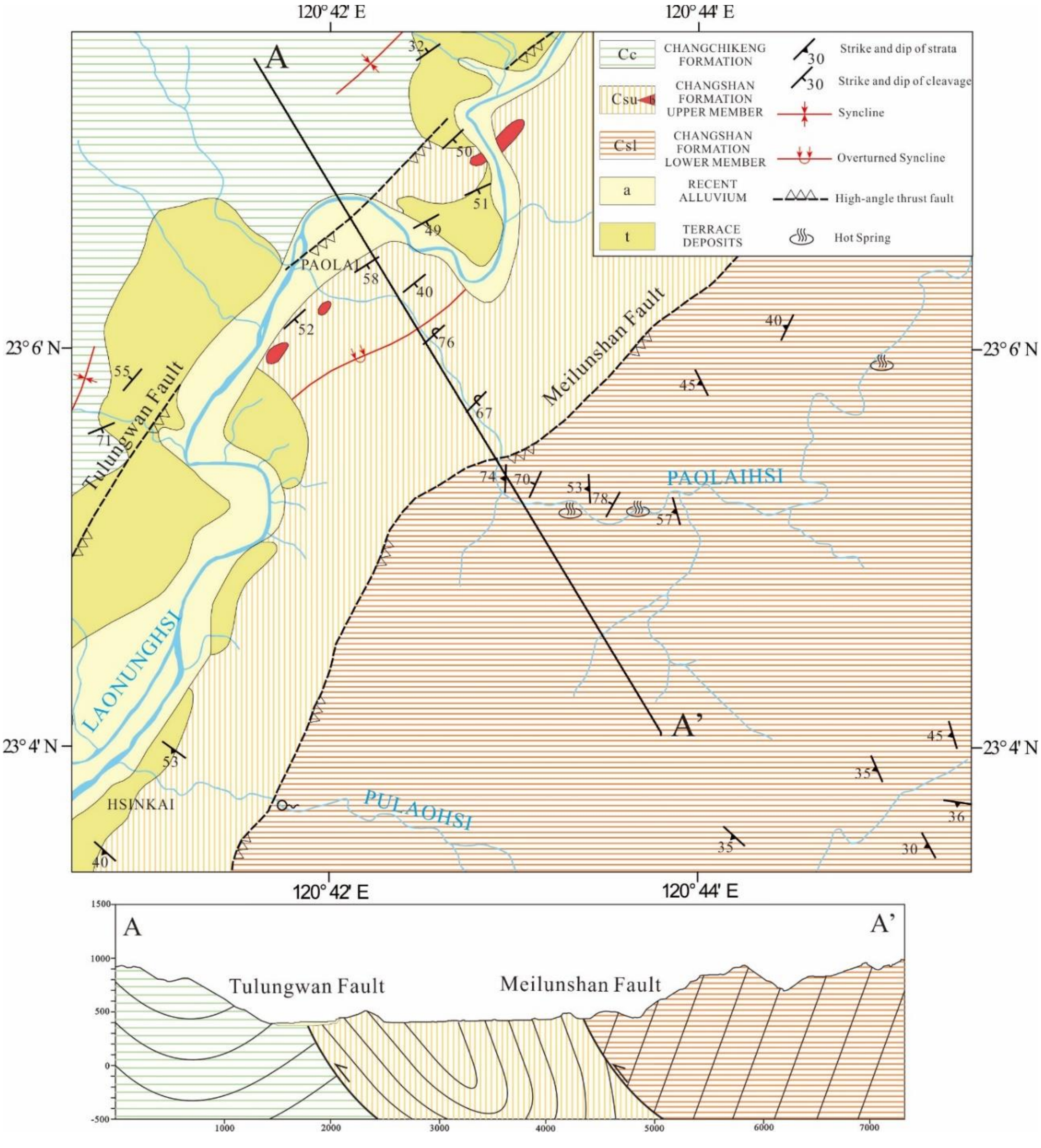

Figure 1: Geological map of Paolai area (revised from Sung et al.) and the cross section of profile A-A'.

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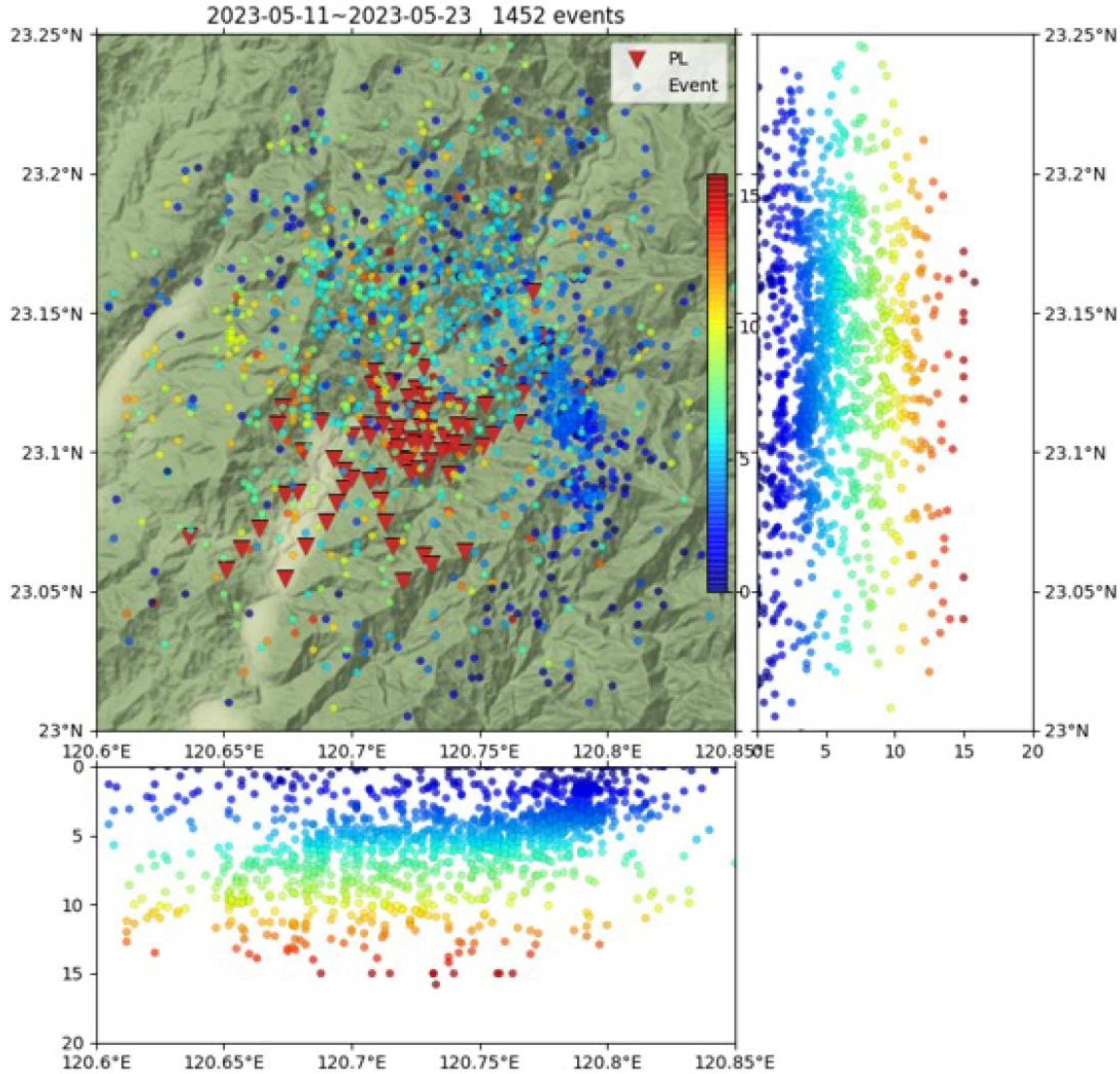

Figure 2: (a) Seismic records acquired from the period of May 11, 2023 to May 23, 2023. Red triangles (PL) are locations of the seismic stations. (b) Seismic events with respect to depth in west-east direction. (c) Seismic events with respect to depth in north-south direction.

According to our field survey, the Meilunshan Fault occurs roughly with a NE strike and a high dipping angle to the east. Bedding and cleavage are different across the fault, suggesting the disturbance induced by fault rupture in this area.

3.MICROSEISMICITY AND SEISMIC TOMOGRAPHY

In the vicinity of Paolai, we installed 80 seismic stations to record the background seismicity of this region. The dense array aims to monitor the local seismicity and image tomography with a higher resolution. With the aid of an artificial intellengence algorithm (Kuo-Chen et al., 2022), here we present a prelimilary result of earthquake catalogue for 13 days (May 11 to May 23), where over 1400 events were recorded and picked. By applying the one dimensional velocity model of Taiwan, the focal depths of these earthquakes can be inverted (Figure 2). There is a large quantity of seimic events in this period and these earthquakes appear to be very shallow, especially within the uppermost crust (0-5 km).

To better visualize the subsurface structures, we present vertical slices of tomography images along five NW-SE profiles in this area (Figure 3). The distribution of P-wave seismic velocity (Vp) and variation of Vp (dVp) reveal high velocity areas. The iso-depth contour of 5.2 km/s, which was suggested to serve as the proxy of basement depth for Taiwan Orogen (Brown et al., 2017), mostly sits within the depth of 5 km in this region while in the western foreland basin it is about 7-8 km deep. This pattern clearly suggests that the basement of Taiwan Orogen is shallow here and the exhumation of the metamorphic core consequently elevates local thermal gradient. This observation agrees with previous studies of regional heat flow and exhumation (Dahlen et al., 1984; Fuller et al., 2006; Willett and Brandon, 2002; Willett et al., 2003; Hsieh et al., 2014). In addition, our prelimilary results show that the surface projection of the high velocity areas corresponds with known hot springs. However, precise locations and the extent of these sites will require further investigation.

4. GEOCHEMICAL ANALYSES

To understand the geochemical properties of the hot springs in this area, we collected nine samples from five spring areas (Figure 4 and Table 1). Among the nine samples, three were collected in the area of Paolai Town, three from the Meilunshan area, and the rest were from Shi-keng, Chi-ken, and Shih-tung hot spring, respectively. Temperature of the samples ranges from 36 to 65°C. Alkalinity is in the range of 6.8 to 8.1 with the lowest in Shi-keng and the highest in Shih-tung. The samples are, in general, neutral sodium bicarbonate springs.

Compiled with previous data, the Piper diagram for the samples in this area suggests that water constitutes can be characterized as two distinct groups (Figure 5). At the wells in the town of Paolai, the chloride and sulphate ions are much higher while at Chi-keng, Shih-tung, and Meilunshan, the bicarbonate ions are in turns higher than the others. This suggests that the hydrological circulation cycles here may involve multiple systems instead of solely single one.

5. CONCLUSION

Results from geological investigation, seismic monitoring and tomography imaging, as well as geochemical analyses of water samples in Paolai suggest that the regional geology and hydrological cycle can not be fully accounted by the single fault model.

Geological surveys concur that in addition to the Tulungwan Fault, the Meilunshan Fault also plays an important role in the regional structural framework. The extension and orientation of the Meilunshan Fault will be the key for further assessment of hydrological cycles.

From seismic monitoring we observe intense micro-seismicity originated from shallow crust (less than 15 km in depth) in this region. The occurrence of this active belt seems to be relevant to the known hot springs and it is crucial to track down the accurate orientation of this seismically active belt in the future.

Geochemical results indicate that water properties can be separated as two groups: one with higher chloride and sulphate ions and the other one with higher bicarbonate ions. The distribution of the two group may be associated with the existence of the Meilunshan Fault and require further validation.

Overall, our data show complex characteristics of multiple domains bounded by the two faults and suggest that the dual-fault model is more appropriate for future assessments of geothermal potential.

Table 1. Basic results of water quality in Paolai area.

Name	pH	EC (mS/cm)	T (°C)	Alkalinity (meq /L)	Cl^- (mM)
Shi-keng hot spring[1]	6.84-7.72	2.56-3.34	40.0-51.1	14.3-17.6	9.4-9.8
Chi-keng hot spring[2]	7.22-7.83	2.09-2.48	63.0-63.2	19.15	0.1
Paolai Spring Park[3] (New well)	7.38-7.43	16.1-18.7	54.0-65.1	68.0-69.6	99.7-102.1
Paolai Spring Park[3] (Old well)	7.34-7.75	16.0-18.7	48.0-50.6	60.2-64.1	100.7
Shih-tung hot spring[4]	8.12	1.88	43	18	0.22
Meilunshan well[5]	7.13	2	26.6	22.9	0.1
Meilunshan hot spring[5] (White spring)	7.06	2.23	36.4	26.8	0.08
Meilunshan hot spring[5] (Brown spring)	7.67	2.47	40.5	28.9	0.09
Paolai Guo-lan well[3]	7.78	8.13	32.6	36.3	32.4

[1] Samples from Shi-keng area; [2] Samples from Chi-keng area; [3] Samples from Paolai area; [4] Samples from Shih-tung area; [5] Samples from Meilunshan area.

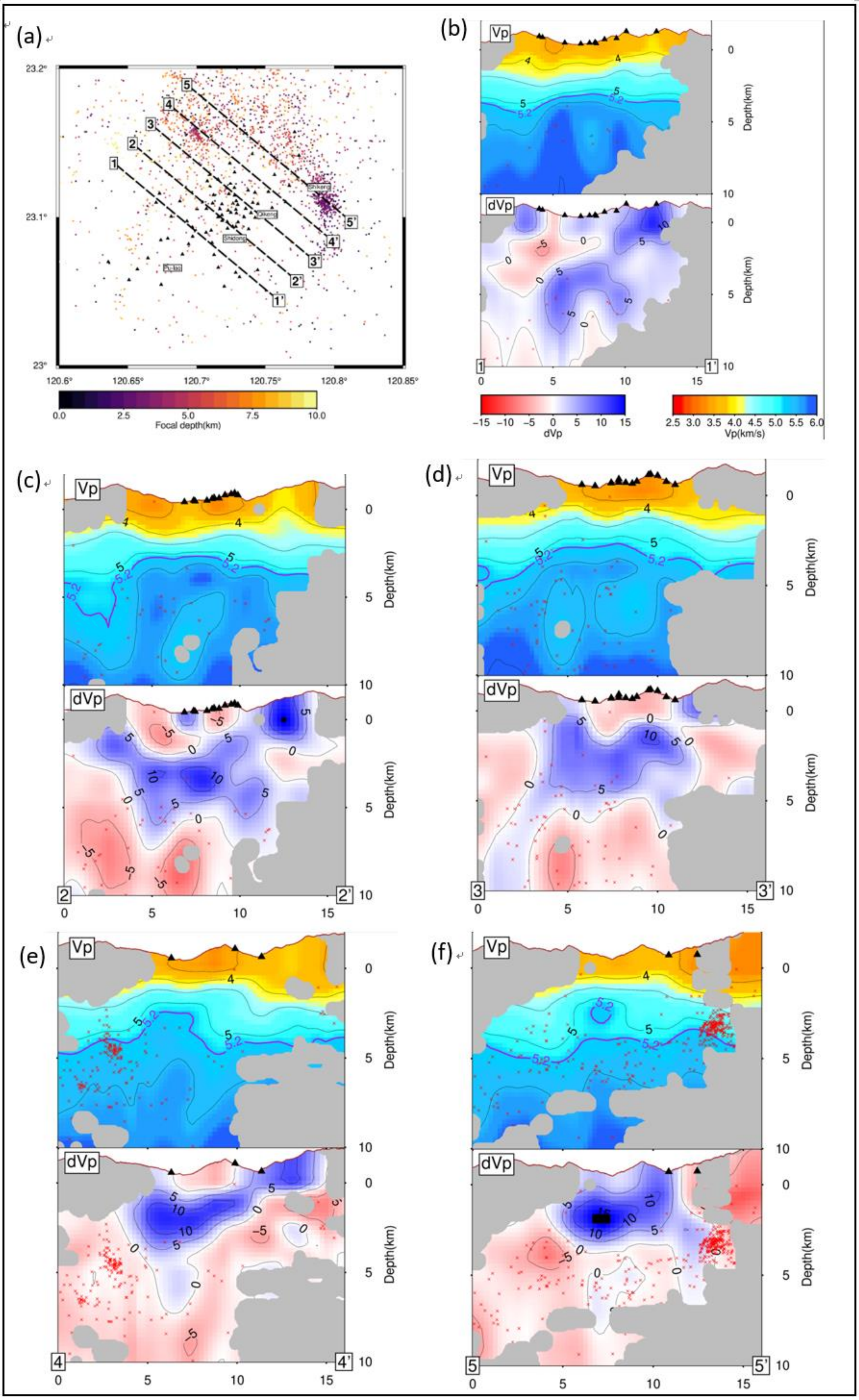

Figure 3: Tomography images calculated via one dimensional velocity model. (a) Orientations of the displayed profiles. (b)-(f) Vp and dVp profiles in this region. The iso-depth contour of 5.2 km/s is illustrated to show the contact between the basement and overlying cover (follow Brown et al., 2017).

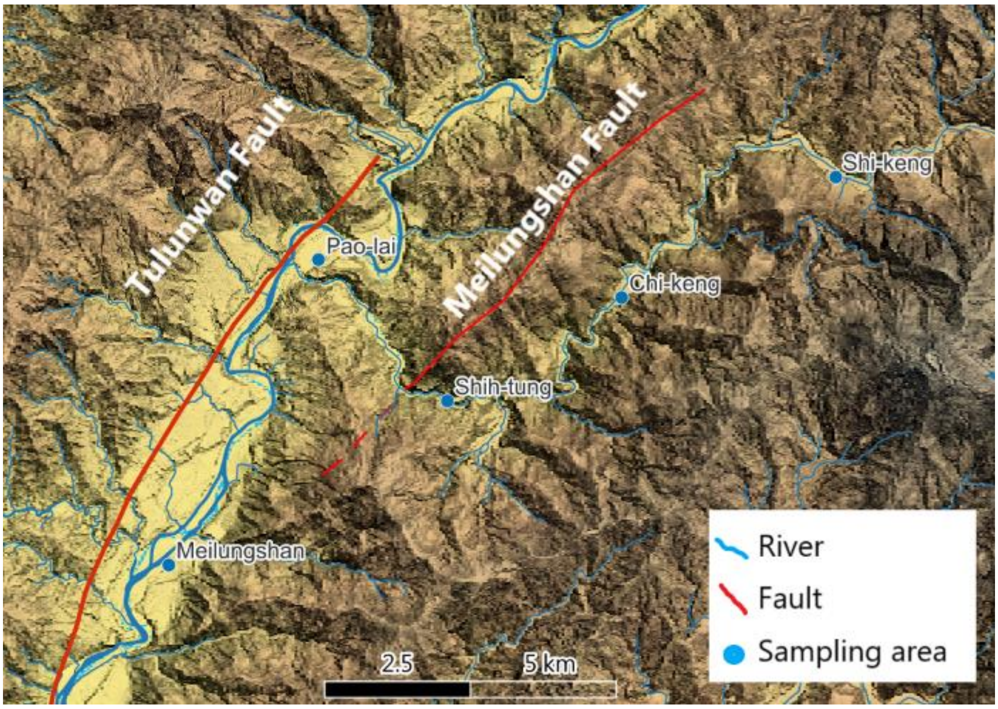

Figure 4: Localities of analyzed water samples.

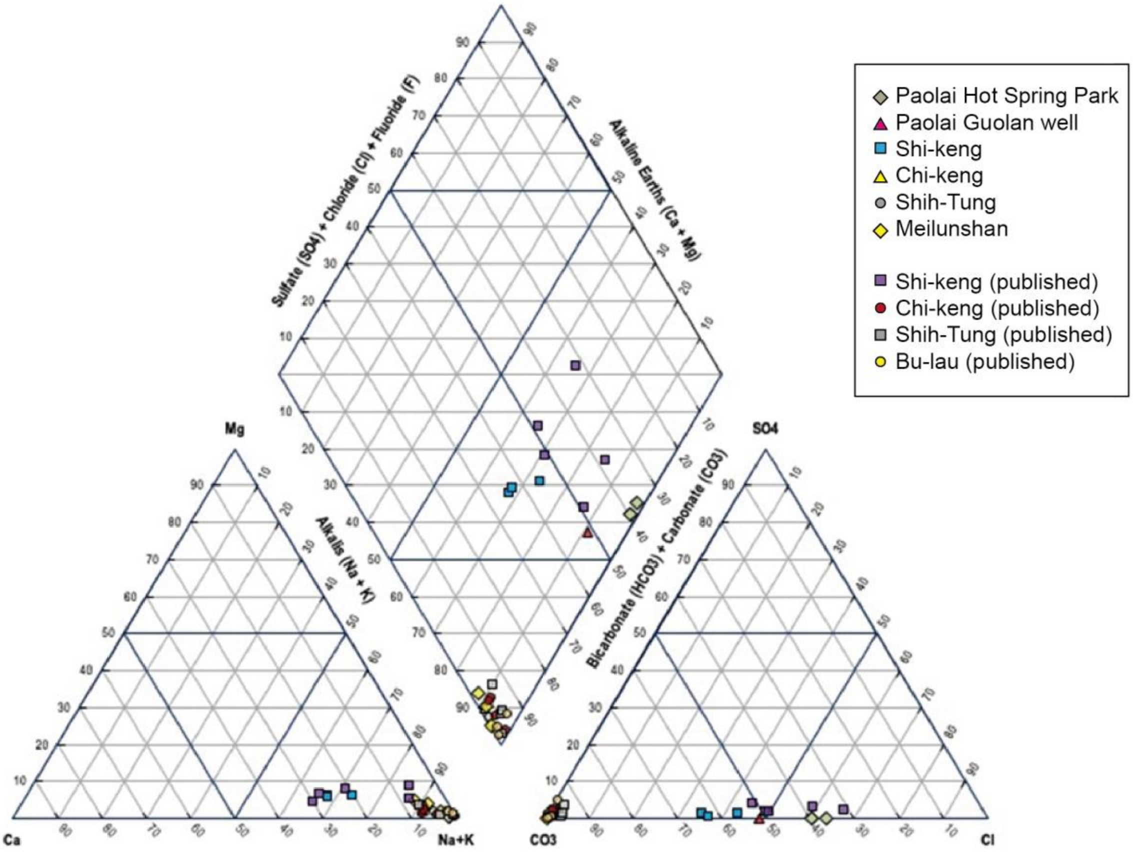

Figure 5: Piper diagram of water samples with previous data (Sung and Liu, 2003)

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