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Geothermal Resource Evaluation of the Tatun Volcano Group (TVG) Area, Taiwan

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ABSTRACT

The Tatun Volcano Group (TVG) is a typical multi-vent volcano group covering an area of approximately 400 km^2 on the northern tip of the island of Taiwan. The TVG is composed of more than 20 Quaternary-age volcanoes, enclosed by NE-SW trending faults such as the Chinshan, Shanchiao and Kanchiao faults. The TVG is seen as a promising target for geothermal exploration due to its abundance of surface thermal manifestations associated with young volcanic rocks. There are four explored thermal areas in the TVG: Tahuangtsui, Matsao, Szehuangtzeping and Jinshan. A series of geothermal exploration studies have been carried out in these thermal areas since the 1960s including geologic, geophysical and geochemistry surveys. In addition to surface exploration data, ITRI and CPC have drilled more than 20 exploration wells (with total depths [TDs] that generally exceed 500 meters) and more than 62 shallow temperature gradient wells (with TDs generally less than 500 meters). Some of these exploration wells encountered commercial temperatures ranging from 200 to 300°C; however, they also encountered very acidic fluids which corroded casings and wellheads.

The basement of the TVG is composed of Tertiary sedimentary rocks. The Wuchihshan Formation (consisting mainly of thick beds of well-consolidated sandstone intercalated with siltstone and shale) is thought to be the primary basement unit beneath the TVG area. Porous sandstones of the Wuchihshan have been described as hosting the reservoir that feeds the Tahuangtsui and the Jinshan hot spring areas. Unconformably overlying the Tertiary formations are the Tatun volcanic rocks, which consist of lava flows (andesites), pyroclastic breccias, surges, tuffs, lahars and reworked volcaniclastic rocks. More than 15 lava layers have been identified. Most of the andesite lavas are thick and dense; unless highly fractured they are characterized as poor reservoir rock. A series of NE-SW structures within the TVG area appear to be associated with the location of some geothermal manifestations within the area. The TVG area is also transected by NW-SE and N-S trending faults, some of which are also associated with geothermal manifestations.

The TVG area is a tectonically active region that has transitioned from a zone of tectonic compression to one of crustal extension. In principle, a graben structure in this setting would be an area of crustal thinning favorable to crustal magmatic intrusion, providing a heat source for the formation of geothermal systems. Major circulation losses observed in wells drilled in the Matsao area are associated with permeable faults. Open fractures in an exploration well in the Szehuangtzeping area identified from wireline logs and core samples are interpreted to represent a dominant NE-SW strike orientation with steep dip magnitudes; these might represent damage zones around specific faults; however, they could also be due to long-lived tectonic activity that has created fractures in competent units (*e.g.*, andesite lavas).

One key aspect of the TVG geothermal system is the presence of corrosive fluids with very low pH (with produced fluids from some wells measuring < 2), indicative of significant volcanic contributions to the system either as input from magmatic fluids or through interaction with sulfur-rich rocks. Elevated helium isotope ratios measured in fumarole gas samples from the TVG indicate a significant magmatic gas component. Because the quartz-rich composition of the permeable sandstones of the Wuchihshan Formation are not effective in neutralizing acidic fluids, a focus instead could be on using the neutralizing capacity of the overlying volcanic rocks (particularly andesites) by completing production wells within these units. This can initially include a focus on areas of the field where andesitic rocks are fractured and are of suitable thickness that may allow access to commercial temperatures and less acidic fluids (*e.g.*, the Matsao and Szehuangtzeping thermal areas).

1. INTRODUCTION

1.1 Project Orientation

The TVG multi-vent volcano group covers an area of approximately 400 km^2 on the northern tip of Taiwan, about 10 km north of Taipei (Figure 1). The TVG is composed of more than 20 Quaternary-age volcanoes and enclosed by NE-SW trending faults such as the Chinshan, Shanchiao, and Kanchiao faults. The TVG has high topographic relief, with most of the composite volcanoes rising several hundred meters above sea level (m asl), and the summit of the highest volcano, Mount Chihsing, measuring approximately 1,120 m asl (Chen, 1970). Mount Chihsing is the youngest as well as the tallest volcano in the region (Chen, 1970, citing Healy, 1968).

The TVG Geothermal Area is seen as a promising target for geothermal exploration due to its abundant surface thermal manifestations (hot springs and fumaroles) associated with young volcanic rocks. There are four explored thermal areas in the TVG:

- The *Tahuangtsui* thermal area, which includes the LHK (Tahuangtsui), TRK (Hsinpeitou), SMK (Shamaoku) and TBQ (Tingbiqiao) areas in Figure 1. It lies between the city of Beitou and Mount Shamao (a young volcanic dome) at the southwest end of the hot-spring zone within the TVG area. Two small streams pass through the thermal area and many hot springs and fumaroles are present in the stream valley.
- The *Matsao* thermal area, which includes the MT (Matsao), CS (Chuitzshu), SYK (Hsiaoyukeng), DYK (Dayukeng), QG (Qigu), LSK (Lengshueiken) and YMS (Yangmingshan) areas. It is in the middle of the hot spring zone within the TVG area, between the volcanoes of Mount Chihsing and Mount Mafeng.
- The *Szehuangtzeping* thermal area, which includes the SHP (Szehuangtzeping), GZP (Gengziping) and BY (Bayan) areas. It is in the northeastern portion of the hot-spring zone within the TVG area, between the Chinshan District and Mount Huangtsui. Szehuangtzeping contains the largest sulfur mine in Taiwan (Healy, 1968).
- The *Jinshan* thermal area, which includes the JS (Jinshan) and DP (Tapu) areas. It is at the northeast end of the volcanic area, approximately 7 km northeast of Mount Huangtsui. Some of the Jinshan (JS) hot springs emerge on the seashore.

A series of geothermal exploration studies have been carried out in these thermal areas since the 1960s by several organizations and universities. The exploration studies included geologic surveys, geophysical surveys (gravity, magnetic, microearthquake, and magnetotelluric [MT]), and geochemical surveys (including analyses of liquid and gas samples) that are briefly described in the sections below.

1.2 Previous Drilling Activities

In addition to collecting surface exploration data, the Mineral Research and Service Organization (MRSO) / Industrial Technology Research Institute (ITRI) of Taiwan and CPC Corporation Taiwan (CPC) have drilled more than 20 exploration wells (with TDs that generally exceed 500 m) and more than 62 shallow temperature gradient (TG) wells (with TDs generally less than 500 m), as described by Lan *et al.* (1980) and Dobson *et al.* (2018). Well locations are shown in Figure 1. The TG wells (ranging from 35 to 622 meters in depth, and 2- to 3-inches in diameter) were mainly for collecting data on geothermal gradients and geology, whereas the exploration wells (with depths up to 2,001 meters and final diameters typically of 8.5-inches) are mainly for collecting information about variations in geology, mineralogy, temperature, flow rates and pressures, and fluid composition with depth (Lan *et al.*, 1980). The drilling undertaken in each area includes:

- At *Tahuangtsui,* a total of 29 shallow TG wells were drilled by MRSO / ITRI to depths reaching a maximum of 160 meters. The highest temperature measured was 175°C at a depth of 159.5 m (in well G-18). Three additional exploration wells were also drilled. The highest temperature measured overall was 187°C (in well E-101).
- At *Matsao,* a total of 14 shallow TG wells were drilled by MRSO / ITRI. Fourteen exploration wells were later drilled at Matsao (also by MRSO / ITRI) to TDs ranging from 577 to 1,510 m; five of these wells encountered commercial temperatures ranging from 200 to 300°C; however, they also encountered very acidic fluids which corroded the casing and wellheads. Thereafter, CPC drilled two deep exploration wells, CPC-MT-1T and CPC-MT-2T to TDs of 1,717 m and 1,605 m, respectively. Well CPC-MT-1T and CPC-MT-2 encountered a bottomhole temperatures of 200°C and 240°C respectively; circulation losses were encountered in these wells.
- At *Szehuangtzeping,* MRSO / ITRI drilled 12 shallow TG wells and 2 exploration wells (E-301 and E-303) in the Szehuangtzeping thermal area. Seven of the TG wells were drilled in and around the known hydrothermal areas, with the highest temperature recorded in well G-501 (144°C at 560 m). The maximum temperature in exploration well E-301 was 101°C (at 450 m, TD). In 1987, CPC drilled a deep exploration well (CPC-SHP-1T) to a TD of 2,010 m, encountering temperatures slightly above 160°C. In 2015-2016, ITRI drilled one exploration well (E-303) to a TD of 1,300 m, reaching a maximum temperature of 132°C. Well E-303 encountered acidic fluids (pH 2.5 to 2.9) that corroded the casing and wireline logging tool and cable.
- At *Jinshan,* CPC drilled 9 shallow TG wells in the Jinshan area. CPC also drilled a deep exploration well (CPC-CSN-1T) at Jinshan in 1980 to a depth of 2,001 m. The well showed a temperature reversal at a depth of approximately 300 to 400 m, with an estimated maximum reversal temperature of approximately 103°C (Dobson *et al.*, 2018). A final maximum temperature of 126.5°C was recorded at 1,980 m. CPC-CSN-1T penetrated the Wuchihshan Formation (mainly conglomeratic sandstones and sandstones) from 210 m to TD. A pH of 1.3 was measured in well CPC-CSN-1.

Although high temperatures are clearly present, they are accompanied by very low pH fluids which has led to severe corrosion issues. The acidity is extraordinarily high and no means were found to prevent rapid corrosion of casings and wellheads of wells producing from the Wuchihshan Formation.

1.3 Purpose

The study was undertaken to provide input on the potential for geothermal resource development within the TVG area. Data provided by CPC and data available in the public domain were evaluated to prepare a conceptual model of the geothermal resource, and recommendations are made for additional data collection and analysis as the next steps in the exploration and development process: reducing the risks associated with the next drilling campaign of deep full-diameter wells.

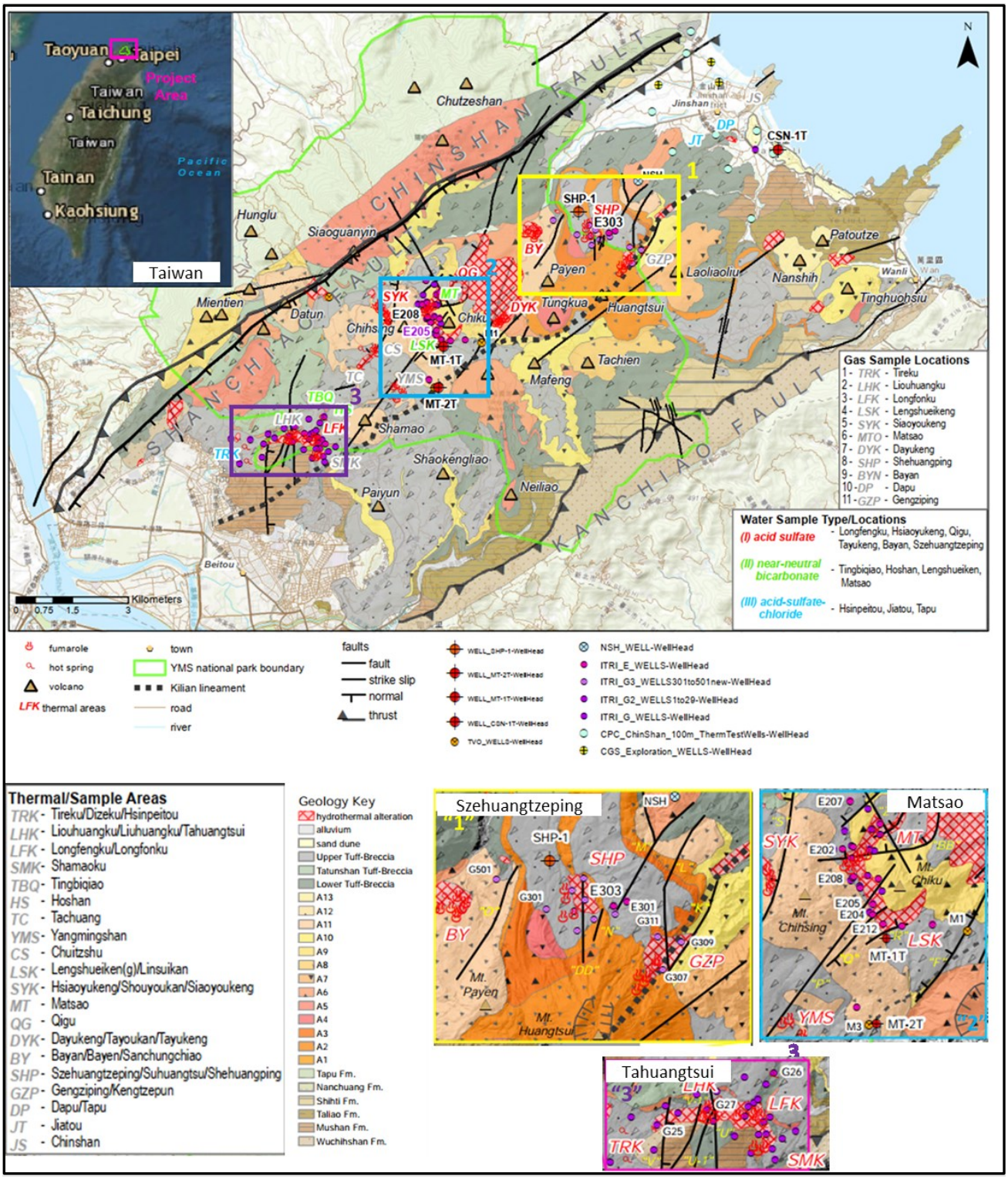

Figure 1: Location, Geologic and Thermal Feature Map of the Tatun Volcano Group (TVG) Geothermal Area, Taiwan

2. REGIONAL GEOLOGY

2.1 Lithology

The basement of the TVG is composed of Tertiary (Miocene and Pliocene) sedimentary rocks. The Wuchihshan Formation is the oldest Miocene unit exposed in the volcanic region; it is thought to be the primary basement unit beneath the TVG Geothermal Area. The Wuchihshan Formation crops out at Jinshan, Tahuangtsui, and in two other places: one lying west of Beitou and the other on the east side of the Kanchiao Fault (Figure 1). The formation thickness in the project area exceeds 900 m and consists mainly of thick beds of well-

consolidated sandstone intercalated with siltstone and shale. Porosity in some of the sandstone units have been measured to be as high as 22.6% (Meng and Chiang, 1965). Such porous sandstone has been found as aquifers in both the Tahuangtsui and the Jinshan hot spring areas. Unconformably overlying the Wuchihshan Formation are the Tatun volcanic rocks, which consist of lava flows, pyroclastic breccias, surges, tuffs, lahars, and reworked volcaniclastic rocks. More than 15 lava layers can be identified (including A1 to A13 in Figure 1). Some of the thicker flows have developed columnar jointing, and in some cases near-horizontal platy jointing is present. The most common rock type is andesite lava. Most of the andesite lavas are thick and dense; unless highly fractured these are characterized as poor reservoir rock (Chen, 1970).

In general, areas with recent volcanic eruptions have anomalously high rates of heat flow created by the emplacement of magma at relatively shallow depths in the earth's crust (typically 24 km or shallower for basaltic magmas, and 7 km or shallower for andesitic magmas). Chen *et al.* (2010) and Belousov *et al.* (2010) reported ^{14}C dating of some of the younger units of the Tatun volcanic rocks yielded ages ranging from 23,000 years (23 Ka) to as young as 6 Ka. The last eruption at Mount Chihsing was interpreted to have occurred at around 13 Ka and consisted of an initial pyroclastic eruption, followed by a lava flow, block and ash flow, and a lahar. The young carbon ages suggest that the volcanic center should be considered as still active. Some of the microseisms in the TVG area have been interpreted as volcanotectonic events occurring below the active Mount Chihsing (Konstantinou *et al.*, 2009); see further discussion below.

2.2 Structural Setting

While most of Taiwan is currently undergoing crustal shortening (compression), northern Taiwan is experiencing extensional deformation. In principle, a graben structure in this setting would represent an area of crustal thinning that is favorable for magmatic intrusion into the crust, providing a heat source for the formation of geothermal systems. Structural extension may also result in the formation of permeable faults and fractures, and local uplifts within and along the margins of the graben (where permeable units may be juxtaposed against impermeable units) that facilitate the migration of geothermal fluids to outflow points at the surface. The occurrences of warm to hot springs and hydrothermal alteration zone in the project area appear to be associated with similarly developed structural features in the TVG.

Geologic surveys indicate that the TVG area is transected mainly by NE-SW trending faults. Thrust faults and normal faults have been mapped in the area, and several strike-slip faults are also observed (Figure 1). When northern Taiwan was previously undergoing compression, two major SE-dipping thrust faults were formed:

- the NE-SW striking Kanchiao Fault, which lies to the east of Shihlin and Wanli; and
- the NE-SW Chinshan Fault, which lies to the west of Beitou and Chinshan.

Coincident with the Chinshan Fault on the NW side of the TVG is the currently active NE-SW striking Shanchiao Fault (Figure 1), a normal fault with a dip of approximately 60° to the SE (Cheng *et al.*, 2010). With all the thermal features of the TVG located southeast of the Shanchiao Fault, this fault appears to bound the geothermal activity to the NW. Another structural feature, the NE-SW striking Kilian Lineament, appears to bound the geothermal activity to the SE (Figure 1).

Based on tectonic interpretations of topographic lineaments, 32 sets of parallel and semi-parallel NE-SW trending faults have been identified in the TVG. Some of these faults appear to be associated with the location of geothermal manifestations. These NE-SW trending faults appear to define not only the major trend of recent volcanic activity, but also the extent of the geothermal system. This is demonstrated by the geographic distribution of thermal manifestations in the area between the Shanchiao Fault and/or Chinshan Fault and the Kilian Lineament. Few if any thermal features are located outside this zone. Additional NW-SE / NNW-SSE trending faults are present in the TVG area and also appear associated with geothermal manifestations in the TVG area.

Some open fractures in Szehuangtzeping well E-303 were identified from the borehole image and core samples. They demonstrate a dominant strike orientation of NE-SW, with high angle dip magnitudes (80° to 90°). Some closed (healed) fractures were also identified, mainly filled by calcite (Liu, 2017). Borehole image interpretation results also indicate that bedding in well E-303 mainly dip to southeast at 20° to 24°.

2.3 Geothermal Manifestations

A total of 20 hot springs and / or thermal areas are observed in the TVG area (Figure 1). The zone is reasonably coincident with the extent of the Wuchihshan Formation, which lies underneath the volcanic rocks (Chen, 1970). Except for the hot spring areas of Hsinpeitou (TRK), Tachuang (TC), Jinshan (JS) and Tapu (DP), all the thermal areas have boiling springs and/or fumaroles. Fumaroles in Tahuangtsui (LHK), Matsao (MT), Szehuangtzeping (SHP), and particularly Hsiaoyukeng (SYK), Dayukeng (DYK) and Gengtziping (GZP) have been characterized as rather strong. The temperature of one of the fumaroles in Gengtziping is approximately 120°C, which is the highest measured (Chen, 1970).

3. GEOPHYSICS

3.1 Gravity Survey

National Central University (NCU) conducted a reconnaissance gravity survey over the TVG area between 1979 to 1982 (Yang *et al.*, 1994, citing Tzou and Yu, 1987), measuring approximately 3,000 stations over an area of nearly 500 km^2. The results of this gravity survey were used to analyze the subsurface structures and the extension of the Chinshan Fault. The Institute of Earth Sciences - Academia Sinica conducted a detailed microgravity survey along three profiles to further delineate the Chinshan Fault and other related subsurface

structures in August-September 1987 (Chen and Yeh, 1991). These additional gravity values were tied to the NCU's gravity data. The most prominent gravity anomalies in the area are gravity highs (>10 mgal) associated with the volcanic piles of the TVG, which are denser than the surrounding sedimentary rocks (Figure 2 (A)). Broad positive and negative regional anomalies are possibly related to structural (fault) and lithologic changes in the basement rocks and to the thickness of the overlying volcanic rocks. The inferred subsurface structure modeled in profiles A-A' and B-B' indicate that the Chinshan Fault is a thrust fault with a dipping angle of about 55° to 60° to the SE (Figure 3).

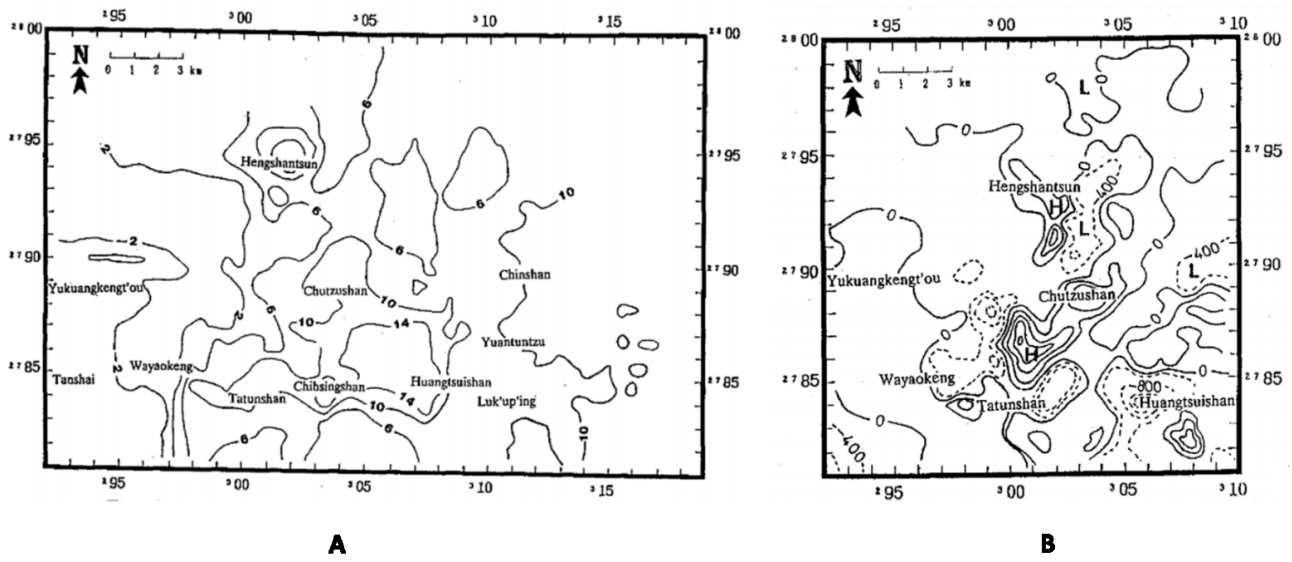

Figure 2: (A) Bouguer Gravity Anomaly Map, contour interval: 4 mgal; (B) Residual of Total Intensity Magnetic Map, contour interval: 400 gamma (images from Yang *et al.*, 1994).

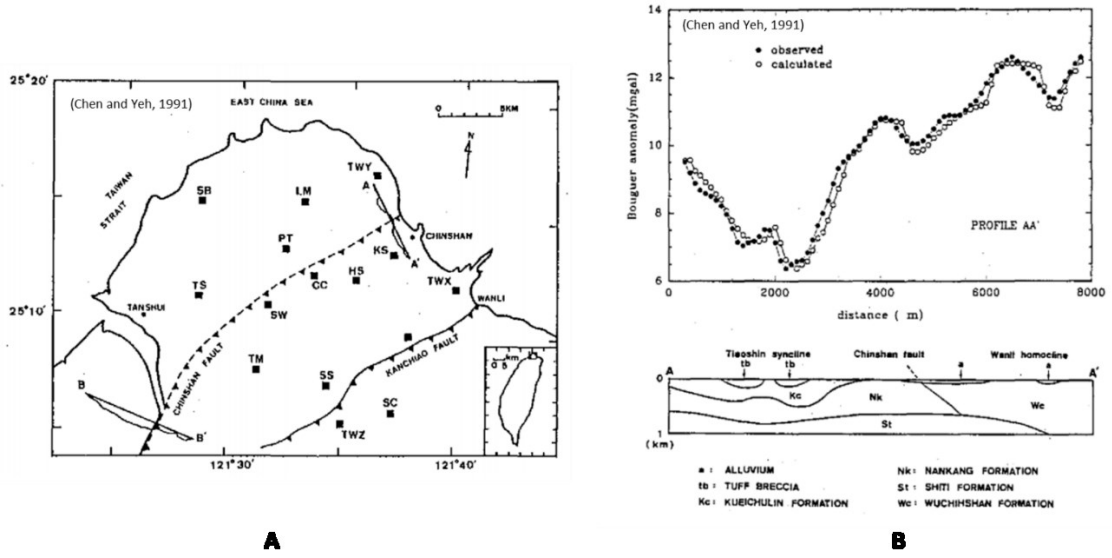

Figure 3: (A) Gravity Profiles (A-A' and B-B') and Seismographic Stations; (B) Results of Inferred Subsurface Structure along A-A' Profile (bottom) and the Calculated (hollow circle) and the Observed (solid circle) Gravity Data (top) (images from Chen and Yeh, 1991).

3.2 Magnetic Survey

A magnetic survey of the TVG region was conducted between August 1987 and July 1989. A total of 500 stations covering an area of approximately 360 km^2 were established. The magnetic survey was intended to analyze the subsurface structures and the distribution of the volcanic rock in the TVG area. Negative magnetic anomalies appear in the southeastern part of the surveyed area, likely associated with Miocene and Pliocene sedimentary rocks and an absence of magmatic intrusion in the area (Figure 2 (B)). The anomalies appear to be controlled by the NE-SW trending Kanchiao Fault. Positive magnetic anomalies at some volcanoes and in the NW part of the surveyed

area may be caused by intrusive rocks or a large volume of andesite (Figure 2 (B)). These magnetic anomalies are inferred to be controlled by the NE-SW trending Chinshan Fault and/or Shanchiao Fault.

A comparison of the gravity and magnetic results reveals that the positive magnetic anomalous zones (*e.g.*, Mount Tatun and Mount Chutze) are also high gravity zones; however, the Mount Chihsing area has a negative magnetic anomaly (Figure 2 (A) and (B)). This exception may indicate that the andesitic rocks in this area have been extensively hydrothermally altered and the ferromagnesian minerals in the rocks may have partially or completely weathered out. Since the magnetic intensity in the Mount Chihsing area is comparable to that in other low intensity areas, it may be assumed that the ferromagnesian minerals were completely leached out or transformed to the other non-magnetic minerals (Yang *et al.*, 1994).

3.3 Microearthquake Survey

In 1987, the Institute of Earth Science – Academia Sinica also installed a temporary seismographic network composed of twelve stations to observe microearthquakes that occurred inside the TVG area (station locations are shown in Figure 3 (A)). The network covered an area of approximately 200 km^2. Most of the earthquakes observed were located within the block bounded by the Chinshan Fault and the Kanchiao Fault (Figure 4). More than 95% of the events occurred at depths shallower than 10 km, and largely concentrated between the surface and 5 km depth (Figure 4). On average, about 4 events per day could be located. Chen and Yeh (1991) reported that a SE-dipping seismic zone with an angle of approximately 45° is visible; this is similar to the dip of the Chinshan Fault as modeled by gravity data, and the frequency of events may imply that the Chinshan Fault is also active. Earthquakes previously recorded during 1973 to 1985 show an epicenter distribution quite similar to that revealed by the microearthquake survey. They also exhibit some epicenters near the Chinshan Fault. The spatial distribution is more or less similar to that obtained by the microearthquake survey.

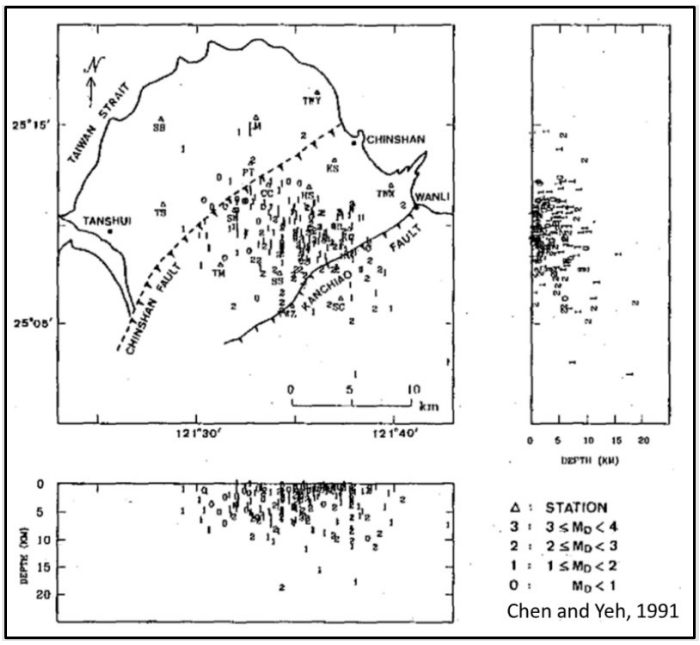

Figure 4: Epicenter Distribution and N-S and E-W Cross Sections of Hypocentral Locations (images from Chen and Yeh 1991).

3.4 Magnetotellurics

Magnetotelluric (MT) data were acquired in two separate surveys between 2008 and 2015. The resistivity model from 3D inversion of MT data collected indicates a possible clay cap extending from the central upflow area to the NE; however, there are indications that the clay alteration is more discontinuous near the Szehuangtzeping. Data were collected at additional stations in Szehuangtzeping in 2015 to improve resolution in this zone.

The results of the MT surveys indicate that some high-resistivity anomalies (>100 to 1,000 ohm.m) are present at and near the surface of some volcanoes, these may reflect unaltered volcanic rocks. There is a widespread low-resistivity anomaly (≤15 ohm.m) present at and near the surface of the Mount Chihsing, Mount Chiku, Mount Laoliaoliu and Mount Tachien areas down to approximately -3,000 m asl (Figure 5 and Figure 6). The variation in the elevation of the base of low-resistivity zones reflects the topography of the region, with higher elevation low-resistivity zones found in the higher-elevation area (*e.g.*, beneath Mount Chihsing). A similar feature was identified beneath Mount Chihsing and the Matsao and Dayukeng thermal areas in an audio-magnetotelluric (AMT) survey of the central TVG Geothermal Area (Dobson *et al.*, 2018, citing Komori *et al.*, 2014). Based on the results of petrographic studies of core and cuttings from deep wells in the Matsao and Szehuangtzeping thermal areas, these low-resistivity zones may in fact be caused by hydrothermal alteration products (clay).

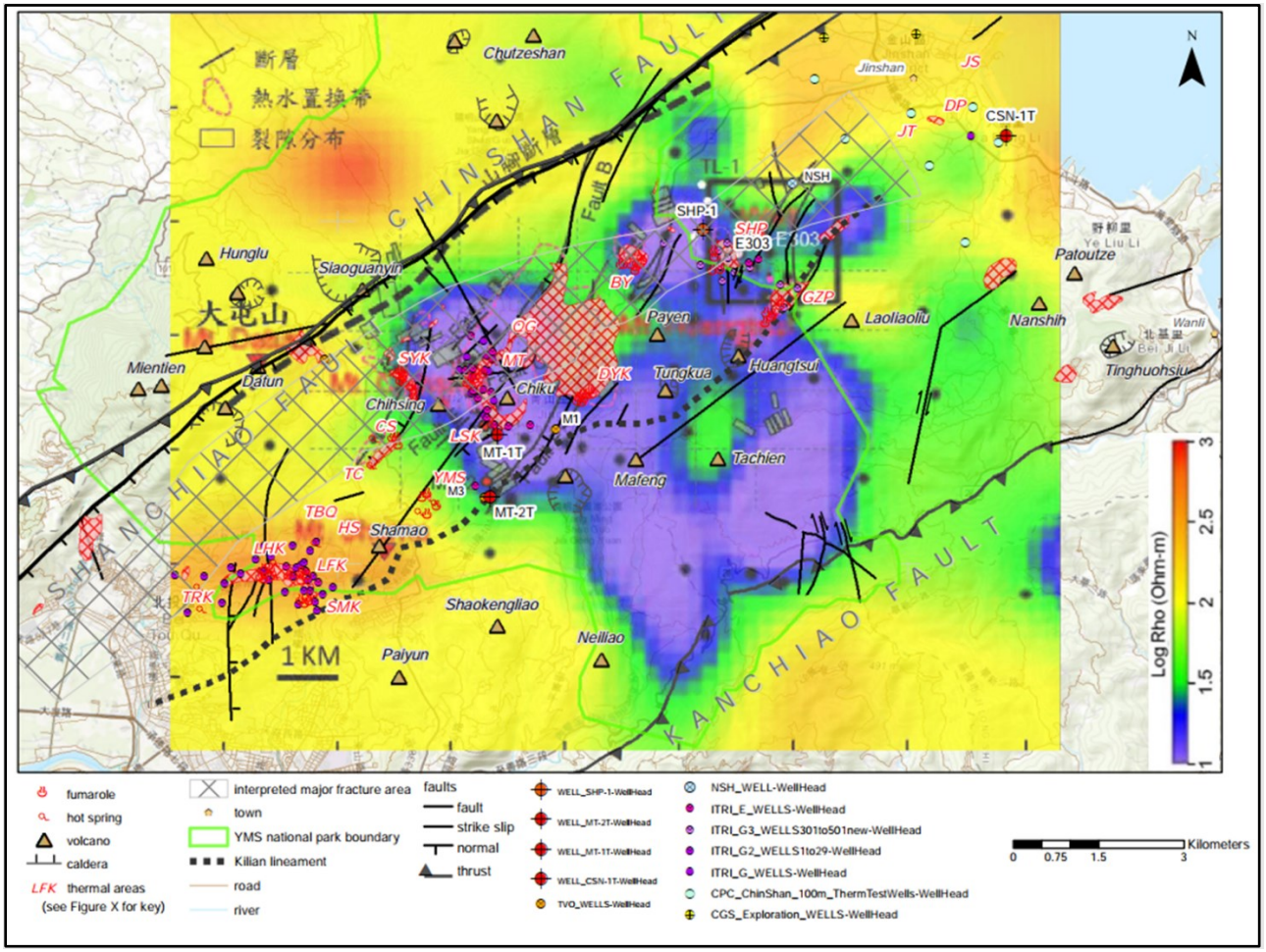

Figure 5: MT Resistivity Survey at 800 m Depth, Tatun Volcano Group (TVG) Geothermal Area, Taiwan

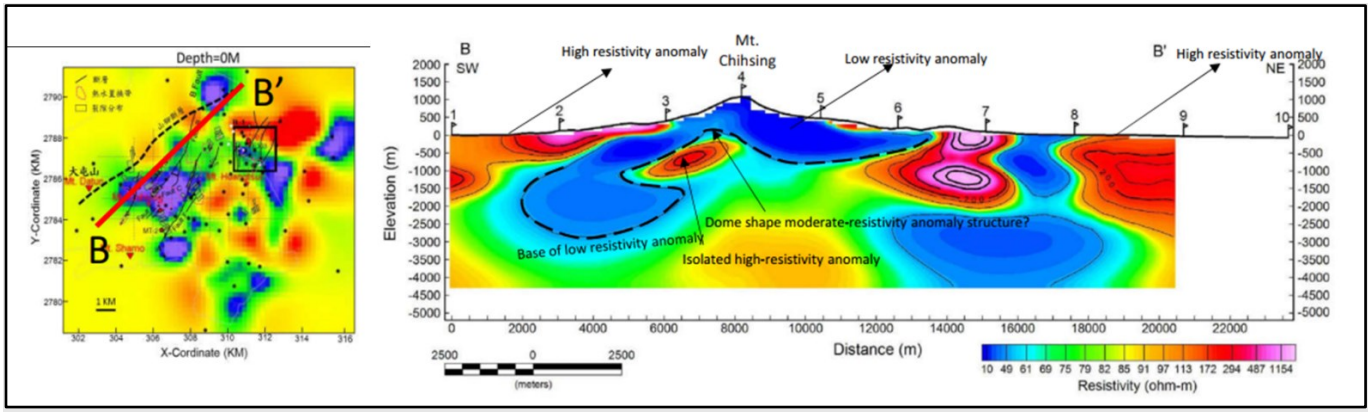

Figure 6: MT Profile B-B' Showing Resistivity Section Along Tatun Volcano Group (TVG) Geothermal Area, Taiwan

A dome-shaped, moderate-resistivity (approximately 15 to 60 ohm.m) structure is evident beneath the Mount Chihsing area; above this is a thick conductive (low-resistivity) layer, and near the surface some resistive (>100 to 1,000 ohm.m) layers are present (Figure 6). This sequence is similar to what is observed in some geothermal systems in The Philippines and Indonesia that have been explored extensively by drilling. In many systems like these, an exploitable reservoir has been located in the transition zone between the low- and moderate-resistivity zones. However, this model does not necessarily apply everywhere, so the inference that an anomaly coincides with a geothermal system cannot be confirmed until data are collected from drilling and well testing. Some deep wells in this area (TDs ranging

from 577 to 1,510 m) succeeded in encountering commercial temperatures of 200-300°C; these wells, however, encountered very acidic fluids which corroded the casing and well heads.

4. GEOCHEMISTRY

4.1 Water Chemistry Analysis

The thermal features at the TVG consist of high-temperature fumaroles and moderate-to-high temperature springs that produce a range of water types, including acid-sulfate (Type I), near-neutral bicarbonate (Type II), and acid-sulfate-chloride (Type III). The locations of these thermal features are shown on Figure 1. The chemical composition of these spring waters has been studied by numerous workers since exploration work began (Yang *et al.*, 1999; Lee *et al.*, 2008; Liu *et al.*, 2011; Ohsawa *et al.*, 2013; and Dobson *et al.*, 2018).

Spring water types have been consistently categorized by previous studies into three primary groups, based on composition (as first described by Liu *et al.* (2011) and in greater detail by Dobson *et al.* (2018)):

- Acid-sulfate (Type I): these acidic thermal waters are rich in sulfate ($SO4^{2-}$) and have pH 1.2 – 3.2, abundant sulfate, and relatively low sodium, potassium, and chloride. Where these waters are sampled from hot springs, they are associated with near-surface outcrops of the Wuchihshan Formation. Previous workers consistently describe that acid waters flowing through the Wuchihshan Formation are less likely to become buffered because the sandstones are rich in quartz and low in potassium, in comparison to andesitic rocks.

- Near-neutral bicarbonate (Type II): these waters have detectable bicarbonate (HCO_3^-), which is not found in more acidic waters, near-neutral pH (5.8 – 6.5), and relatively low chloride and sulfate. At surface, they are associated with andesitic volcanic terrane.

- Acid-sulfate-chloride (Type III): these waters have no detectable bicarbonate, high total dissolved solids (TDS) and relatively high sodium, potassium, and chloride, and low pH (1.2 – 1.9). These waters are associated with near-surface outcrops of the sandstones of the Wuchihshan Formation.

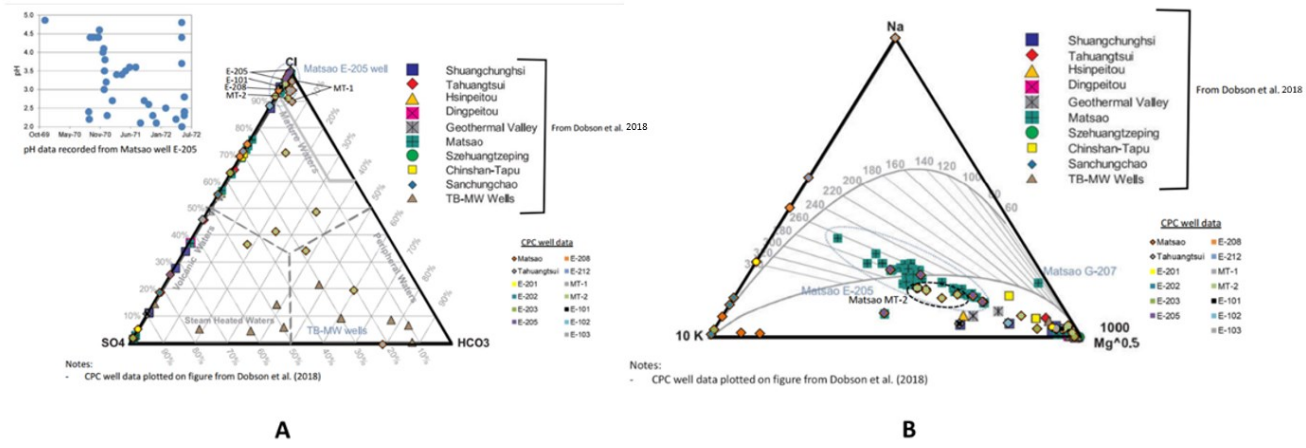

Figure 7: (A) Ternary Diagrams for Classification of Spring Water Analysis with Data from CPC for the Tatun Volcano Group (TVG) Geothermal Area; (inset) pH Measurements on Deep Well E-205 Produced Brine; (B) : Na-K-Mg Geothermometry of Water Chemical Data Provided by CPC for the Tatun Volcano Group (TVG) Geothermal Area (from Dobson *et al.*, 2018).

Figure 7 (A) is a Cl-SO_4-HCO_3 ternary plot (a method developed by Giggenbach (1991)) of water chemistry data (modified from Dobson *et al.*, 2018), mostly from wells but also including a few historic spring analyses and more recent analyses of shallow monitoring wells. Analytical data from these wells are of great interest, in particular the data from some wells in the Matsao thermal area, as they represent water chemical data that plot in or nearby to the "mature" field on Figure 7(A). For well E-205, records indicate that water chemistry samples were consistently collected during production testing from September 1969 to approximately July 1972.

More so than results of just well E-205, chemical compositions of multiple samples collected from the wells listed above provide an indication of lower-acidity fluid being present within the TVG. As first described by Dobson *et al.* (2018), analytical data from the E-205 well show a clear trend on the Na-K-Mg geothermometer plot on Figure 7 (B), indicating a deep reservoir temperature for the Matsao area of ~260 - 270°C. Other deep-well chemical data that plot in a similar position, although more in the 'immature' area, are from the Matsao MT-2 well.

Fluids sampled from the E-205 well during flow testing provide important insights into the chemical composition of the deep TVG resource in the Matsao area, especially regarding the potential presence of zones of non-acidic fluids in the deep geothermal reservoir. For well E-205, measurements of pH reported by ITRI (Figure 7 (A)) show that the pH of brine produced from E-205 fluctuated around an average of 5 from September to November 1969 (pH ~5.6 is near-neutral for fluids with temperatures ranging from 200 to 300°C)

(Figure 7 (A)). We concur with Dobson *et al.* (2018) that these measurements indicate that more neutral and likely more mature fluids were initially produced from the Matsao deep reservoir, which is consistent with its completion in a thick section of andesite. Later data for E-205 show that brine pH remained mostly in the 4–5 range from November 1969 to November 1970, but then started to show significant variability, decreasing more often, at times to values as low as pH 2. This variation in the acidity of produced brine introduces some uncertainty about the extent of neutralized fluids that may be present within the Matsao deep reservoir. We suggest two potential causes for this noted variability in pH:

- during the long flow period, the deep zone from which neutral fluid was being produced by the E-205 well was invaded by acidic fluids from the Wuchihshan Formation; or
- a more discrete acidic zone began to dominate wellbore fluid entry following a sustained period of pressure drawdown, thereby acidifying the produced brine.

Figure 8 provides a series of bi-variant chemical composition plots of well brine data for Matsao and Tahuangtsui area wells, including well E-205. Plots on Figure 8, in particular those that portray trends between pH, SO_4, and Cl, indicate that samples from well MT-1, E-201, E-202, and E-212 exhibit neutral-pH conditions (as is the case for wells MT-2 and E-205 where near-neutral and acidic brine samples were collected). Very little information is available about the characteristics of well production during collection of these samples, but if the conditions of lower-acidity in these wells persisted, the resource accessed by these wells (with maximum well temperatures of 200°, 232°, 169°, and 258°C, respectively) may be an indication of potentially exploitable conditions. We note each of these wells are completed within andesitic rocks. It is noteworthy (on the plot of pH vs. SO_4) that wells completed in andesitic rocks exhibit mainly lower acidity (*i.e.*, more neutral pH values), while wells completed in the Wuchihshan exhibit largely acidic conditions (Figure 8). The pH vs. SO_4 plot on Figure 8 also provides insight into the source of acidity from within the E-205 well. Acidity varies among samples collected at different depths, with pH being similar (and closer to neutral) at depths of 1,000 and 1,400 m, but lower (pH <4) at 1,300 m. These data may indicate entry of low pH fluids from a specific interval of the wellbore near to 1,300 m. Comparing temperature-pressure logs during flow-testing (if available) may allow for identification of an entry zone near this depth that may contribute acidic fluid. Well MT-2 (apparently completed within the Wuchihshan Formation) did intermittently produce near-neutral fluids, but also produced fluids that were highly acidic. This raises the question of whether select areas of the deep reservoir in the TVG area may have adequate ability to neutralize these corrosive fluids through water-rock interaction. Therefore, while it is not suggested that we ignore the possibility of lower-acidity reservoir fluids (with sufficient pH-neutrality that would allow for commercial production) being found in some locations within the Wuchihshan Formation, identifying these locations remains problematic with the existing data set.

This is not a new concept. The composition of acidic fluids produced from deep wells in the TVG area led early workers to hypothesize the presence of a deep fluid within the TVG with a composition similar to Type-III waters described above, which was interpreted to result from a lack of neutralization of magmatic fluids containing SO_2 and HCl. Truesdell (1991) describes a concept for the TVG in which excess chloride is not neutralized by reaction with rock because the permeable sandstone of the Wuchihshan Formation contains no minerals (such as feldspars or mica) that would be capable of neutralizing acid. This conceptual model led to a cessation of activity at the TVG geothermal field, because no means were found to prevent rapid corrosion of well casings.

The production of brine acidic enough to require neutralization (pH <4.5~5) has been documented in numerous geothermal projects. Examples include Mahanagdong (Leyte), Mt. Apo, Bacon-Manito, Tiwi, and Mindanao in The Philippines, Onikobe in Japan, Los Humeros and Cerro Prieto in Mexico, and Miravalles in Costa Rica. These fields typically have pH in the range of ~3-4 in one or more wells, with more neutral fluid produced from wells in other parts of the field. Fields where acidity is more ubiquitous and problematic include Biliran (Ramos-Candelaria *et al.*, 1995; Apuada *et al.*, 2010) and Alto Peak (Reyes *et al.*, 1993), both in The Philippines. Acidic wells have typically been handled with various approaches, including treating with caustic during production for pH management, conversion of wells to injectors, or abandonment. For more acidic fluids, a combination of downhole and surface neutralization techniques has allowed for the production and commercial utilization of acidic fluids in the Namora Langit (NIL) field at the Sarulla geothermal project, North Sumatra, Indonesia (Hirtz *et al.*, 2018). This technique has been used for a well producing strongly acidic (pH ~2.5-3) fluids initially and for wells that began producing acid fluids over time.

The conceptual model of Tatun reservoir chemistry described above appears to remain largely relevant, as there is yet to be a deep well drilled into the Wuchihshan Formation that has not encountered highly acidic reservoir fluids (including the recent well E-303, drilled by ITRI at Szehuangtzeping thermal area in 2015-2016, as described previously). However, based on lines of evidence from well data described above, the acid-Cl>>SO4 reservoir that is often described as occurring within the Wuchihshan Formation may not be entirely present in shallower zones, with instead more neutral fluids found to an uncertain degree in the andesitic rocks above.

Such a result has led the study to suggest that, rather than trying to understand the variability in reservoir composition within the Wuchihshan Formation in the hope that less acidic fluid might be found, efforts for further development of the TVG system should consider focusing attention on utilizing the neutralizing capacity of the overlying andesites by completing production wells within them, even if the result is only a modest decrease in acidity to a pH that is more tolerable for wellbore and surface facilities (requiring a focus on use of appropriate construction metallurgy and inhibition methods).

New Tatun wells targeting lower acidity would be located and completed such that there is a reasonable spatial separation between the well and the Wuchihshan Formation, thus reducing the potential for encroachment of acidic waters during production. This approach is supported by the following lines of evidence:

- Well E-205, which is completed entirely within andesitic rocks that overlie the Wuchihshan Formation, initially produced neutral-pH fluid, but production became acidic in response to pressure draw-down. It remains unclear whether the change was

caused by the depressurized formation drawing in acidic fluids en masse, or by the pressure drawdown allowing for the influence of one or more discrete acidic zones. New chemical data (as described above) indicate that the acidic fluid entries were more discrete, but survey data are required to investigate this further. Overall, however, the initial production of neutral fluid from E-205 indicates that more benign fluids are present within andesitic rocks of the TVG reservoir at temperatures great enough for commercial production.

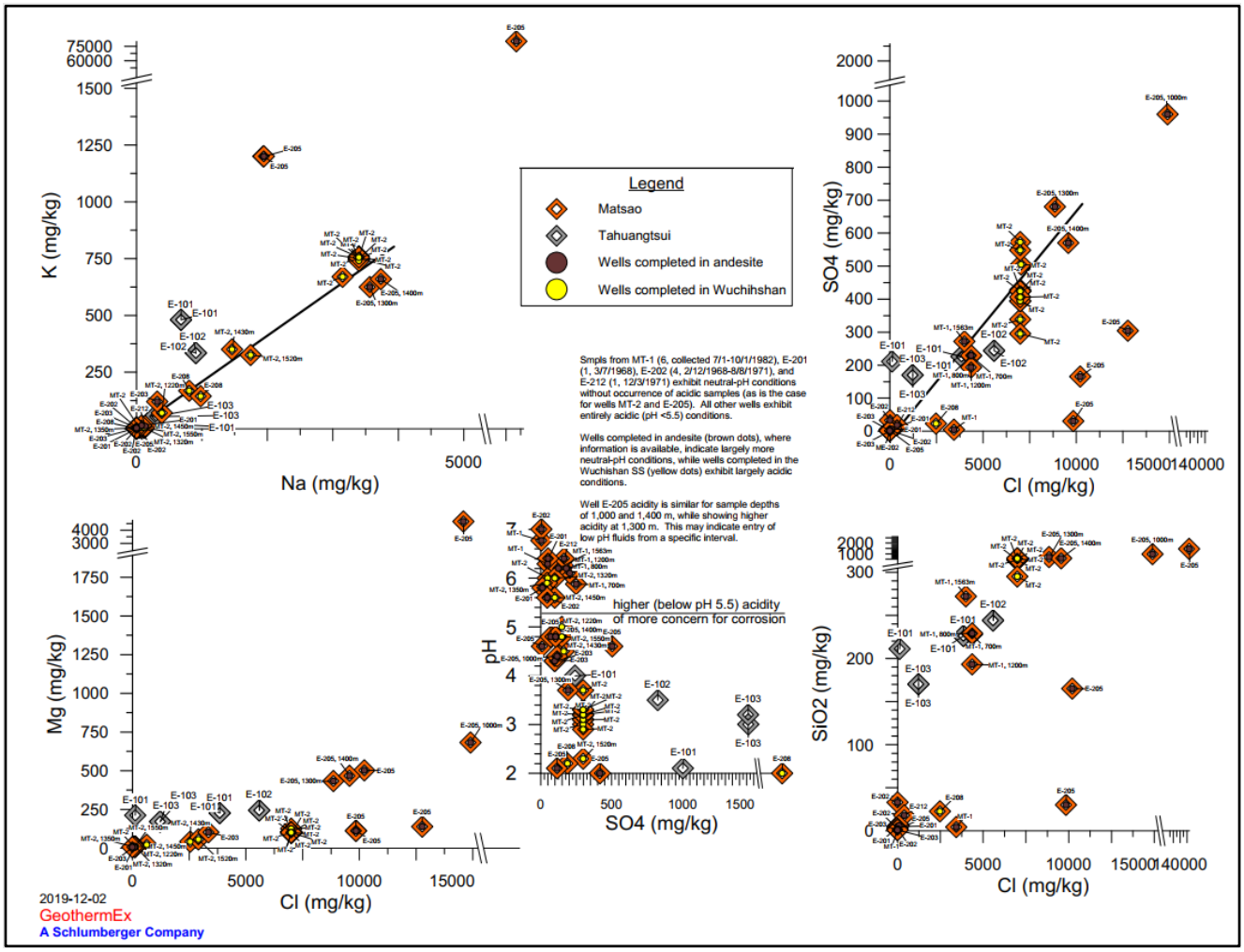

Figure 8: Plots of Produced Brine Chemistry from Matsao and Tahuangtsui Area Wells

- Though more limited than for E-205, chemical data from wells MT-1, E-201, and E-212 provide further evidence of the presence of near-neutral reservoir brine within the Matsao area, particularly in the vicinity of Lengshueiken (LSK on Figure 1) where the MT-1, E-201, E-205, and E-212 wells are located.

- Descriptions of the alteration mineral assemblage for the deep E-208 well (Dobson *et al.,* 2018) indicate that propylitic alteration (as opposed to acid alteration) and the presence of minerals with high neutralizing capacity (such as feldspars and calcite) are present throughout the andesitic rock section of this well. Propylitic mineralogy would be expected to fully dissolve under strong acid alteration. Dobson *et al.* (2018) note that CPC's exploration well CPC-MT-2 at Matsao has a similar alteration assemblage. These observations provide supporting evidence for neutralizing conditions within a thick section of the andesitic rocks beneath the Matsao area. There are some uncertainties regarding the interpretation of hydrothermal alteration for the E-208 well: there are no records about the alteration assemblage in the deeper Wuchihshan Formation, which was encountered by the E-208 well at a depth of 1,235 m. If records of alteration mineralogy for E-208 are available, and if they indicate an acidic alteration assemblage within the Wuchihshan Formation, the transition to propylitic alteration in the overlying andesites may provide insight on the separation distance required by future wells to avoid production of highly acidic fluids.

- Preliminary information on the drilling results from the E-303 well shows acidic conditions were encountered below 600 m (a depth that defines the top of a quartz-rich sandstone unit that is expected to be part of the Wuchihshan Formation). The main fluid entry zone in this well is at the contact between the overlying andesite and the underlying sandstone. Above this zone, propylitic alteration is identified within the overlying andesites (indicating more neutral fluid conditions).

As first implied by Dobson *et al.* (2018), the existing data indicate that the composition of the thick andesitic units may buffer the acidity and therefore contain a less-acidic geothermal fluid at temperatures hot enough for commercial exploitation. However, in some places within andesitic rocks of the TVG resource, condensation of geothermal gases into near-surface, oxygenated groundwater leads to formation of acid SO_4>>Cl waters. Shallow acidic waters can also penetrate to depth, primarily through faults in the geothermal system, allowing them to mix with deeper reservoir waters. Acidic fluids may persist within some areas of the andesitic rocks at depth, particularly in areas of high vertical permeability (which creates hydraulic connections between shallow aquifers and andesitic rocks deeper in the geothermal system). This may explain, at least on a preliminary basis, evidence of higher acidity at a depth of 1,300 m within the E-205 well, compared to samples collected above and below this depth. Dobson *et al.* (2018) conclude (based on mineralogical evidence from deep Matsao wells) that the presence of acidity is less likely in the deep andesite units that do not host "magmatic vapor chimneys" (direct, near-vertical conduits for magmatic gases). As found in the deeper portions of Matsao well E-205, these wells would be anticipated to exhibit propylitic alteration, indicative of liquid-dominated conditions in the andesite. Nevertheless, we suggest that the infiltration of acid fluids to depth is likely to occur within the TVG system, which could lead to acid attacks on well casings from the outside, and the production of acid fluids.

4.2 Gas Chemistry Analysis

The most comprehensive gas chemical data set for TVG, described by Dobson *et al.* (2018), includes an extensive survey of fumarole gas sampling from Beitou in the southwest to Jinshan in the northeast (sample locations are shown on Figure 1). As a complement to the Dobson *et al.* (2018) analysis of gas data, a limited set of gas analytical results have been provided by CPC for wells E-101, E-102, E-103, E-201, E-202, E-205, E-208, and E-212. A summary of observations from the gas chemistry data set salient to this analysis include:

- The gas data clearly show that the fumarolic and spring bubble gases at TVG represent a mixture of magmatic and meteoric components.
- Elevated $^3He/^4He$ ratios (4.0–7.6 Rc/Ra) measured in fumarole gas samples from TVG indicate a significant magmatic gas component.
- Wells E-102 and E-103 (Tahuangtsui area) show elevated He and H_2S indicative of closer proximity to a magmatic source of gas. In fact, gas samples from well E-103 are reported to be comprised primarily of He (we believe a large component of H_2 is likely present in these gases, which is not reported). Well E-208 shows elevated He in comparison to other Matsao wells. Other wells located in the Matsao area show more mature magmatic gases (relatively depleted in He and H_2S), with well E-205, E-202, and E-212 appearing to have less direct contribution from a magmatic source of gas.

5. DISCUSSION

5.1 Heat Source

The heat source for the geothermal systems in the TVG is interpreted to be a magma chamber(s) and associated cooling young intrusive rocks. The most recent volcanic activity is associated with the Mount Chihsing volcano subgroup. Recent studies reported that ^{14}C dating of some of the younger volcanic rocks yielded ages ranging from 23 Ka to as young as 6 Ka (Chen *et al.* (2010); Belousov *et al.* (2010)), and microseisms indicate volcanotectonic activity near Mount Chihsing (Konstantinou *et al.,* 2009). These young volcanic rocks host the most active and oxidized geothermal features: Hsiaoyukeng (SYK), Matsao (MT), and Dayukeng (DYK) fumaroles and associated acid hot springs. In general, areas with recent volcanic eruptions have anomalously high rates of heat flow created by the emplacement of magma at relatively shallow depths in the earth's crust (typically 24 km or shallower for basaltic magmas, and 7 km or shallower for andesitic magmas).

Data from shallow TG wells and exploration wells in Tahuangtsui, Matsao and Szehuangtzeping, and the water chemistry data from Matsao (particularly from well E-205), indicate high subsurface temperatures are present beneath the TVG area. Exploration wells drilled in Matsao succeeded in encountering commercial temperatures of 200°C to 300°C. CPC's exploration wells MT-1T and MT-2T in the Matsao also encountered similar commercial temperatures, indicating that a heat source may reside at relatively shallow depth.

Magmatically heated fluids are clearly rising from depth in the central portion of the TVG (near Mount Chihsing, Mount Chiku, Mount Shamao) and shallow outflow appears to occur in two directions: to the NE towards Szehuangtzeping, Jiatou and Tapu, and to the SW in the regions of Hsinpeitou and Tahuangtsui. This upflow/outflow is evidence that there is adequate permeability to enable fluid flow.

5.2 Geologic Control on Permeability

Sandstone units of the Wuchihshan Formation have good porosity and permeability; based on the well data, these units have been found as geothermal reservoirs in all thermal areas in the TVG. However, most of these units are associated with the presence of very low-pH, corrosive fluids, so this section focuses on fault and fracture permeability in the overlying volcanic units. The TVG area is transected mainly by NE-SW trending faults, which define not only the major trend of recent volcanic activity, but also the extent of the geothermal system. This is demonstrated by the geographic distribution of thermal manifestations between the Shanchiao Fault and/or Chinshan Fault and the Kilian Lineament, with few if any thermal features located outside this zone. Although some of these faults were formed by compression, the change to an extensional regime may enable enhanced permeability along them, as implied by the earthquake activity in the NE-trending zone between the two major faults. Major circulation losses observed in CPC wells in the Matsao area (CPC-MT-1 and CPC-MT-2) may be associated with permeable faults. Open fractures in ITRI's well E-303 identified from the borehole image and core samples demonstrate a dominant strike orientation of NE-SW (parallel to the orientation of major faults), with quite steep dip magnitudes (80° to 90°). These open fractures could represent damage zones that create enhanced permeability around specific faults. However, the coincidence of faults and thermal features should be treated cautiously in the context of selecting drilling targets because faults may not

be permeable at depth. Instead, the coincidence of faults and thermal features may signify the upward deflection of thermal water from a permeable zone away from the fault. That is, geothermal fluid flows laterally in a permeable geologic unit until it encounters a fault that juxtaposes low-permeability rock against permeable rock. In this way, faults can act as both conduits and barriers to fluid flow, and the deep geothermal source (*i.e.,* the reservoir) may be laterally offset from the thermal feature by a considerable distance. In addition, it is likely that isolated fractures (unrelated to a particular fault) have also developed due to ongoing seismic activity in the area.

For these reasons, other than the most obvious source of permeability (the sandstone units of the Wuchihshan Formation), it remains challenging and difficult to predict the locations and properties of permeable structures (faults and fractures) in the TVG Geothermal Area based on the available data, including within the thick andesite units that may have the buffering capacity to enable the production of less corrosive fluids.

5.3 Composition of Reservoir Fluids

As noted herein, a key aspect of the TVG geothermal system is the presence of corrosive fluids with very low pH, indicative of significant volcanic contribution to the system as either input from magmatic fluids or through interaction with sulfur-rich rocks. Elevated $^{3}He/^{4}He$ ratios (4.0–7.6 Rc/Ra) measured in fumarole gas samples indicate a significant magmatic gas component. Some samples from hot springs near Matsao stand out with higher HCl concentrations, reflecting a stronger magmatic signature at these locations.

Based on a review of gas compositions, and on concepts related to water chemistry, we support the conceptual model for magmatic vapor migration into the TVG system presented by Dobson *et al.* (2018), in which the system would have a network of narrow near-vertical vapor chimneys, possibly related to faulting, with localized surrounding liquid-dominated areas. In such a system, strong acidic alteration results from the reaction of up-flowing magmatic vapor with rocks and downward-flowing steam-heated waters from the near surface, with more neutralization expected in the andesitic rocks than in the underlying feldspar-poor sandstones. Deep zones in andesitic rocks away from the chimneys and infiltrating acidic waters (but above feldspar-poor sandstones) would be expected to exhibit propylitic alteration, as found in the deep portions of Matsao well E-205.

Based on the conceptual model elements described above, these distinctions may be a basis for the targeting of wells into the TVG resource. This approach would likely preclude production from the deeper, hotter TVG resource within the Wuchihshan Formation where an acid $Cl>>SO_4$ system is seen to be consistently present, at least initially. Through collection of drilling, well test, and fluid chemical data from wells completed within the andesitic rocks, we may begin to assess whether specific zones within the Wuchihshan Formation may have acceptable levels of acidity for development. That is, by considering 1) variations in alteration mineralogy close to the contact between the andesite and the Wuchihshan Formation and 2) the composition of fluids produced over time from wells completed in the andesite, we may obtain an improved understanding of the distribution and heterogeneity of acidity in both formations (noting this may be expected to evolve over time under production conditions). Achieving this goal would depend upon having a more robust set of well test and fluid chemistry data in the TVG geothermal field.

The thickness of volcanic rocks in the Tahuangtsui thermal area is small (< 150 m) compared to other parts of the field. Most of the wells in the Tahuangtsui thermal area were completed within the Wuchihshan Formation. We therefore recommend de-prioritizing this area for development, and instead a focus initially should be on areas of the field where andesitic rocks are of suitable thickness that will allow access to commercial temperatures and less acidic fluids (*i.e.*, Matsao and Szehuangtzeping thermal areas).

6. CONCLUSIONS

The TVG is a promising geothermal resource due to its abundant surface manifestations, associated young volcanic rocks and extensive exploration and drilling. The heat source for the geothermal systems is clearly magmatic, associated with young magma chambers and cooling intrusions. Deep geothermal fluids upwelling in the central portion of the TVG (Mount Chihsing, Mount Chiku, Mount Shamao) help to transport heat to shallower levels, outflowing laterally to the NE towards Szehuangtzeping, Jiatou, and Tapu and to the SW in the regions of Hsinpeitou and Tahuangtsui.

NE-SW trending faults define the major trend of recent volcanic activity and the extent of the geothermal system. A series of NE-SW, NW-SE, and N-S structures within the TVG area appear to be associated with the location of geothermal manifestations. Well data indicate that some of the NE-SW structures (faults and fractures) are permeable. The main source of permeability are the sandstone units of the Wuchihshan Formation. However, the presence of corrosive fluids with very low pH within this formation, likely the result of magmatic degassing, presents a major challenge for developing a geothermal project in the TVG. The quartz-rich composition of these sandstones does not enable much if any neutralization of the acidity. Using the neutralizing capacity of the overlying (andesitic) volcanic rocks by completing production wells within them should be investigated, focusing on the Matsao and Szehuangtzeping thermal areas, where andesitic rocks have suitable thicknesses. The key will be to intercept zones of high fracture permeability to enable commercial production rates of less acidic fluids that are more easily tolerated by wellbores and surface facilities (*e.g.*, pH ~3-4 is dealt with in many fields, and the NIL field in Indonesia is treating produced fluids with pH ~2.5; see Hirtz *et al.*, 2019).

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