The geothermal reservoir characteristics of metamorphic terrain, an initiative of geological and geophysical survey of Qingshui, Tuchang, and Renze, NE Taiwan

Gong-Ruei Ho[1], Jian-Cheng Lee[1], Chien-Chih Chen[2], Hsin-Hua Huang[1,3], Sheng-Rong Song[3], Chih-Wen Chiang[4], Yi-Chia Lu[5], Chyi Wang[3]

1 Institute of Earth Sciences, Academia Sinica;

2 Department of Earth Sciences, National Central University;

3 Department of Geosciences, National Taiwan University;

4 Institute of Earth Sciences, National Taiwan Ocean University;

5 Graduate Institute of Applied Geology, National Central University

gongruei@earth.sinica.edu.tw

Keywords: *Metamorphic terrain, Ilan geothermal system, Taiwan*

ABSTRACT

Tectonic investigation of northeast Taiwan using seismicity, structural mapping, and geochemistry supports that the rocks and fluids have experienced post-collisional extension. Active rifting and lateral spreading can be observed in this metamorphic terrain (e.g. slates, phyllites, metasandstones, and quartzites mapped with normal faults). GPS and palaeomagnetic observations also show about 45-50° clockwise rotation along the Lanyan River. Since the 1970s, the Ilan area has been the largest exploration and development area for geothermal exploitation in Taiwan, such as Qingshui (an experimental power plant from 1981, transferred to commercial in 2021), Tuchang, and Renze, where ~50 exploration wells have been drilled.

A synthesis of available data of magnetotellurics (MT), seismic profiles, drilling, and field measurements has resulted in interpretative geological cross sections along the Lanyang River at different depths, and here we document: (1) the geothermal pathway is confined by faults and secondary fractures near the surface. Mineral veins strike 320 and indicate the late-stage of extension of about 050; (2) normal faults and reactive strike-slip faults may play an important role as the upflow zones at depth of ~2 km. (3) MT measurements suggest two electro-stratigraphic packages within 3 km, high resistivity caprock sitting on top of the geothermal reservoir; low resistivity hydrothermal fluids were recognized from high porosity sandstones and fault zones. (4) seismic tomography also observed two different heat sources from 10-15 km. (5) two geothermal systems are suggested at different depths: one with a deep upflow at ~2 km, entering a fractured zone at <200°C and generating ~5 MW of electricity; the second in rocks at 4-5 km close to the brittle-ductile transition where deep-seated fluids are probably produced, and present-day temperatures are in the range of 400-500°C.

1. INTRODUCTION

The Ilan geothermal fields (Qingshui, Tuchang and Renze) are located in the plate boundary of northeast Taiwan. The Lanyang river flows through the whole area from west to east, covering an area of 320 square kilometers. The site is covered by an extensional basin near the plate boundary, with sediment about 300-800 meters thick. The Ilan geothermal reservoir consists of Tertiary metasandstones, with argillite and slates as cap layers in some places, which were exposed in the cores of the nearby Hsuehshan and Central mountain ranges.

Since the late 1960s, the Qingshui, Tuchang, and Renze sites, and nearby Jiaoxi hot springs investigated geothermal development with multiple geophysical and geochemical studies. The new phase of study commenced in 2011, as part of the process for site selection for the geothermal power plants. The Chinese Petroleum Corporation Taiwan (CPC) drilled ~10 geothermal wells with a depth of 1.5-2 km in Tuchang and proved wellhead temperature between 120-180°C and a maximum production capacity of 76 ton/hr; the exploration wells in the Renze site were drilled to 1.5 km in depth, with wellhead temperatures between 130-140°C, and maximum productivity of 56 ton/hr. In 2016, the Qingshui site built a 4 MW geothermal power plant and started commercial operation. The current state of knowledge is now understood by a wide range of geological, geophysical, and geochemical data derived from surface and well measurements.

2. GEOLOGICAL SETTING

The Ilan Plain is thought to have taken shape from the extension of the back arc basin of the Okinawa Trough within the Eurasian continental lithosphere (Lai et al. 2009). The recent extension of the Okinawa Trough started from approximately 0.1 Ma and involves ENE- and WSW-trending normal faults dipping toward the Okinawa Trough axis with offsets of a few meters to tens of meters (Sibuet et al. 1998; Lai et al. 2009) in the westernmost part of the trough. Unconsolidated alluvial deposits from the Lanyang River were laid over the faulted basement rock (Lin and Lin 1995). Orogenic folds and faults are ubiquitous in the mountain range, leading to rapid uplift at a rate of 5-10 mm/year in the past few million years (Chen, 1982; Ching et al., 2011; Lee, 1977; Liu et al., 1982). Previous studies have identified ENE-trending faults beneath the unconsolidated deposits by means of seismic reflection and refraction images and magnetic anomaly analysis around the Ilan Plan (Chiang 1976; Hsu et al. 1996; Deffontaines et al. 2001; Chen 2013).

The Lishan Fault extends from the Niudou Fault which separates the Hsuehshan Range from the Central Range and has previously been interpreted as a backthrust being reactivated as normal faulting (Ho 1975; Lee et al. 1997). The fault systems separate the Eocene to Oligocene metasandstone and the slate of the Hsuehshan Range in the west from the Miocene slate with thin beds of argillite and metasandstone of the Central Range in the east.

Stratigraphic units exposed in Hsuehshan Range from bottom to top include Chungling Formation, Hsitsun Formation, Szeleng Sandstone, Kanko Formation, and the Lushan Formation in the Central Range. The Chungling Formation (Cl) is mainly composed of black argillite or slate; the Hsitsun Formation (Ht) consists of silty argillite and fine-grained metasandstone; the Szeleng Sandstone (Sl) is composed mainly of thick-bedded, grayish white medium-to-coarse-grained metasandstone, occasionally with thin beds of slate or argillite intercalation. About 1000-1500 meters thickness of Eocene or Oligocene quartzites and metasandstones may play an important role in geothermal reservoirs in Sl. The Kanko (Kk) Formation is mainly composed of slate and conformably overlies the Szeleng Sandstone. This relatively fine-grained formation could be a good cap layer candidate for the Ilan geothermal fields. The Miocene Lushan Formation can be divided into the upper Jentse Member (Lsj) consisting of mainly dark-grey slate, and the lower Chingshuihu Member (Lsc) composed of alternating argillite and meta-sandstone. The Chingshuihu Member conformably overlies the Nansuao Formation (Ns) composed of slate, occasionally intercalated with thin beds of fine-grained sandstone (Huang and Peng 1976; Chou et al. 1977; Fan 1978; Torng and Young 1978; Lee 1984). Local faults and fractures can be found in the Jentse Member, where a shallow geothermal reservoir within 2 kilometers may bring good geothermal fluids and hot springs near the surface (Lin and Lin, 1995).

Several NE-trending, high-angle normal faults are reported in the area, including the Dachi, the Xiaonanauo, and the Hanchi Fault (Tseng 1978; Lin and Lin 1995; Ho et al., 2014) (Fig. 1). The geothermal field is thought to follow the surface trace of the NW-trending Qingshuichi Fault along the Qingshuichi Valley, which is perpendicular to the dominant NE-trending fault system (Su 1978; Hsiao and Chiang 1979; Tong et al. 2008). The upper Lushan member outcrops in the Qingshui hot spring region. Normal faults are often found in outcrops in river cross sections. There are high-angle normal faults with fault gouge and breccia around the Dachi fault and the Hanchi fault. Many regional faults cut off bedding and cleavage, and leave multiple sets of slickensides, in Taingou and Duowang rivers. In order to clarify the possible geothermal reservoirs and pathways from the Hsuehshan terrain to the Central Ranges, we integrated survey results as two profiles that cross two members of upper and lower Lushan Formation, and the fault system. However, some outcrops of other faults cannot be found on the surface due to heavy weathering and erosion in this area. In order to evaluate these structures, we studied the geophysical images and wells drilled around this region.

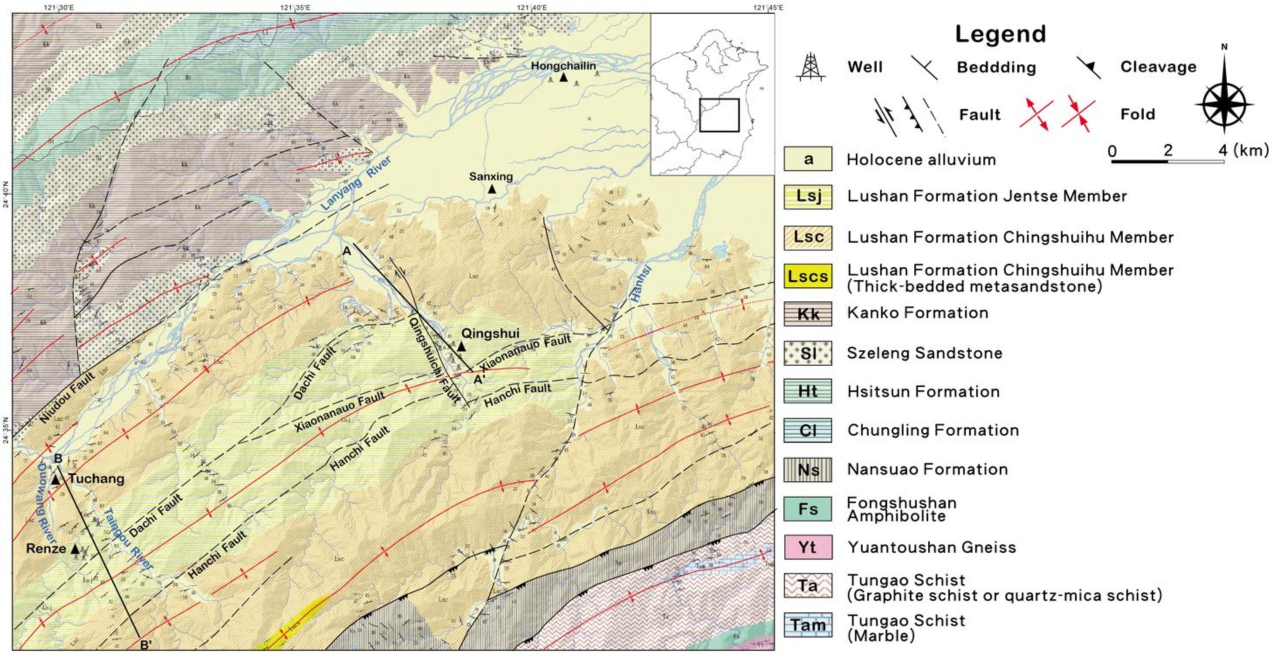

Figure 1: The geological map for the Qingshui, Tuchang, and Renze geothermal fields and structural interpretations based on the field observations, seismic reflection profiles, and published Sanshin map, Tuchang map from Central Geological Survey (Lin and Lin, 1995; Sinotech, 2008).

3. ILAN GEOTHERMAL SURVEY: STRUCTURES, HISTORY, CHARATERISTICS AND KEY RESULTS

3.1 Qingshui

Based on subsurface geological reports and field investigations, we compiled field measurements, drill cuttings and cores from 12 wells, with vertical depths from ~800 to 3000 m, which provide information on the subsurface stratigraphy and structures of the Qingshui geothermal field (Fig. 2). The rock type within the Qingshui geothermal field is composed of Eocene to middle Miocene, fine slate, silty sandstone and argillite rocks of the Lushan Formation. Slickensides and minor folds are often found in Lushan Formation implying the late stage subduction and collisional orogenesis. Secondary foliations are well developed in the metamorphic terrain, with pencil cleavage in the low-grade slates and slaty cleavage in the thick-bedded metasandstone with orientations from 090-120 and moderately dipping to the south. Surface fractures are generally found within joints and veins with sub-vertical dipping and various orientations (N-S, 030, 300-330). There are a series of normal faults that have a north-eastern extension distributed in the Qingshui river, and many landslides have occurred along this fault scarp.

The exploration of Qingshui Geothermal Power Plant began in the 1970s, when the CPC and ITRI (Industrial Technology Research Institute) launched 8 years of geothermal exploration and drilled 8 exploration wells with a depth of about 500 m, and build the first 1.5 MW pioneer power plant for various research and tests on geothermal power generation. Then, in 1980, the second geothermal power plant with an installed capacity of 3 MW was constructed. Taiwan Power Company was responsible for the operation and maintenance of the power plant. However, due to scaling problems, the hot fluid production capacity gradually decreased, and the power generation efficiency was very poor, leading to 12 years of commercial operation ending in 1993. About 20 years later, a new team composed of Taiwan Cogeneration Corporation and Fabulous Power rebuilt the 4 MW Qingshui geothermal power plant in 2016. Improvements in generator design and scaling inhibition were noticed. The geothermal power plant officially obtained the certification of renewable energy equipment in November 2010 and started commercial operation immediately.

3.2 Tuchang-Renze

Tuchang-Renze geothermal area is located in Datong Township, Ilan County, which is located in hills and mountains between 500m to 800m above sea level. Two rivers flow through the area and are used to establish the main geological profile (Fig. 3). The Duowang and Taingou rivers run from the southeast and cut through the Lushan Formation. The exposed rocks are mainly argillite and slate from the upper Lushan Formation and the slate with thin-bedded metasandstone in the lower Lushan Formation. The cleavage (S1) is often parallel to the bedding (S0) with NE strike and shallowly dipping, and some observed isoclinal folding can be interpreted as a strong shortening in the Tuchang-Renze geothermal field. The surface geology in Tuchang-Renze contains ample observations of multiple faults. For instance, 120-150, 200-240 fault traces are observed along the Taingou river. Three faulting regimes can be defined by crosscutting relationships and superposed slickensides: 1) dip-slip regime; 2) strike-slip regime and 3) normal fault regime. Three sets of joints can be recognized striking 030, 070-090, and 130-160 with moderate-to-steep dips, and 130-160 striking veins are spread throughout the region. Various mineral veins can be found here, such as bladed calcite, fibrous travertine, cluster gypsum and quartz veins, which can be explained as multiple fluid activities at different depths and temperatures.

From the 1970s to1980s, the ITRI drilled a total of 11 geothermal exploration wells in the Tuchang area, with a depth from 161 m to 556 m, where IT-11 has a maximum temperature of 180℃, and maximum productivity is 60 ton/hr. The ITRI then built a 260 kW double-cycle geothermal power generation system in the Tuchang site. The first Tuchang Geothermal Power Plant operated for a few years but was damaged by a landslide event in 1982. From 2012 to now, CPC has drilled more exploratory wells with a depth of 1,500-2,000m and a maximum temperature between 120-180°C in the Tuchang geothermal field.

Further south, two geothermal exploration wells with a depth of 2,200 m with a max temperature of up to 190°C were drilled in the Renze geothermal field (Jiuzhize Hot Spring), which is the highest geothermal productivity in Taiwan. In 2011, CPC sold 2 wells (JT-1 and JT-2) to the Forestry and Nature Conservation Agency-Luodong for the hot spring and recreation. From 2012 to 2015, the CPC drilled 2 new exploration wells (JT-3, JT-4) for geothermal exploration at a depth of 1,500 m, of which JT-3 has a wellhead temperature of 137℃ and production capacity of 46 ton /hr. JT-4 has a wellhead temperature 142℃ and production capacity of 56 ton/hr. Today, the Taiwan Power Company is building a test power plant in the Renze geothermal area, which is expected to have a geothermal power capacity of 1-2 MW.

3.3 Geophysical survey

Geophysics, including studies of seismic reflection and refraction, microseismicity, magnetotellurics, electrical resistivity, and magnetic anomaly surveys, has been utilized extensively at Ilan geothermal fields for early exploration drilling through to field development and operations. In this study, we selected 196 survey sites, and ~28 km of seismic lines distributed in Ilan geothermal fields. Each time-series data of these stations was measured at least every 36 hrs to improve the data quality. These MT data sets were compiled from the National Energy Program (NEP-2010~2016) and Geothermal Energy Research and Development (GERD-2021~2022), with processed remote reference control. In order to increase the seismic resolution, we choose a denser geophone network, in which the station distance is between 5-20 m, with the seismic records collected from 2.5-5km in depth. We also compiled well-logging data from CPC in the 1970s to 1980s and reconnaissance geophysical surveys from Industrial Technology Research Institute (ITRI) in 2021-2022. Details of the subsurface structures and the location of the faults were expected to be delineated by using the above geophysical surveys.

According to the seismic tomography and resistivity model obtained by seismic and magnetotelluric surveys. We found two possible heat sources in the Ilan geothermal field: 1) the volcanic heat source from Guishan Island, which is composed of volcanoes at the western end of the Ryukyu Arc; 2) the orogenic heat source from the plate subduction and late-stage extension. There are several major faults (Dachi, the Xiaonanauo, and the Hanchi Fault) and minor faults with steeply dips which can be identified from the seismic reflection profiles. Normal faults and reactivated strike-slip faults may play an important role as the upflow zones at a depth of ~2 km. Interestingly, there is a fracture zone with water influx at the bottom of the Tuchang-Jentse site, where we observed lower resistivity in JT-1 and JT-2.

4. EVOLUTION OF THE ILAN GEOTHERMAL SYSTEM

The geothermal system in the Ilan geothermal field can be divided into two different heat sources: (1) volcanic heat source and (2) young orogenic heat source. The first one is related to the volcanism of Guishan Island (Tong et al., 2013), and the second one is related to plate subduction, rapid exhumation and denudation (Lee et al., 2015; Lee et al., 2019; Ho et al., 2022). Either way, volcanic geothermal structures and young orogenic geothermal pathways are all controlled by the fracture system at depth and/or fault kinematics, which is the key target of geothermal exploration. Knowledge of a geothermal field constantly evolves and therefore stepped development of geothermal reservoirs over time can reduce the risk that installed capacity exceeds the sustainable capacity of the resource.

4.1 Qingshui

Monitoring the geochemical response of hot springs, there is about 13% contribution from mantle composition in the Qingshui geothermal field, which is neutral to weakly alkaline carbonate thermal fluid (ITRI, 2022). It shows that the heat source of the Qingshui geothermal field may come from the deep groundwater circulation and mixing with the upper mantle induced by the Okinawa rifting. Field observations suggest that the major permeable zone contains wide joints, normal faults, and fractures oriented N-S, 030, 300-330, all at high angles, paralleling the regional tectonic extension. Abundant quartz-carbonate veins in similar fracture and joint populations are also observed, implying long-term hydrothermal fluid events. SiO_2 geological thermometers suggest the reservoir temperature is between 226°C and 272°C (ITRI, 2022). A low resistivity belt is found between -1000m-asl and -1500m-asl dipping SE (GERD, 2022), suggesting the Lushan Formation may play an important role as the caprock. In the shallow part, these low resistivity belts are separated by Qingshuichi, Xiaonanauo, and Dachi faults, which are interpreted as the up-flow zones. In-situ stress field measurements are also consistent with an E-W extensional tectonic regime. It appears that the Qingshui site is located on the high-capacity geothermal reservoir, with 000 to 030-oriented, structurally controlled pathways.

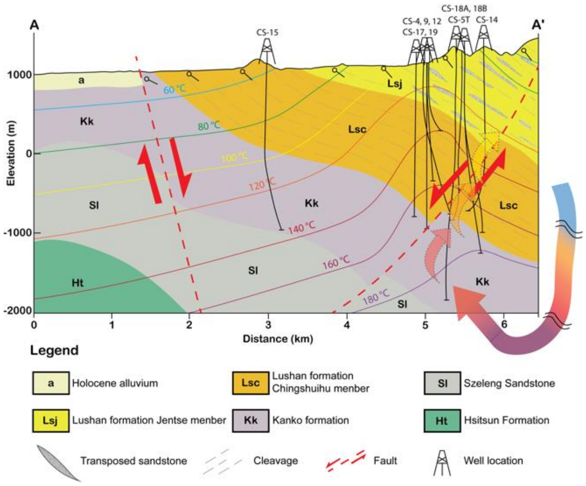

Figure 2: Cross section and geothermal conceptual model in the Qingshui site, along lines shown in Figure 1. Isotherms are based on downhole temperature measurements.

4.2 Tuchang and Renze

Monitoring the geochemical response of hot springs, the Tuchang-Renze site is neutral to weakly alkaline carbonate thermal fluid with a total ion concentration of up to 3000 mg/L. The source of the thermal fluid is mainly the crustal and atmospheric(ITRI, 2022). Field observations measured approximately 1800 natural fractures at outcrop scale, including three generations of faults (reverse, strike-slip and normal fault) and three sets of joints (strike 030, 070-090, and 130-160 with moderate-to-steep dips). The in-situ stress field shows high-angle fracture systems with NE-SW extension (ITRI, 2022), which interpreted that three are two possible conduits in the Tuchang-Renze geothermal fields: 1) deeper conduits (> 2 km) which might be related to the regional faults system, and 2) shallower conduits (< 1 km) which may connect to the 130-160 joint sets and fractures. Various mineral veins can be found in joints and faults, showing the crystallization of minerals in paleo-thermal fluid from the reservoir. The MT resistivity model shows few low resistivity belts (< 60 ohm-m) identified at different depths, -200m-asl in the Duowang river; -600m-asl to -800m-asl in the Taingou river. However, according to the borehole data, the highest temperature is measured at a depth of 400m, suggesting the geothermal fluid infiltrates from the up-flow zone in the Tuchang-Renze site. It appears that these thermal reservoirs are cut by NW-striking faults and distributed in fractured sandstone/slate layers in the upper Lushan formation.

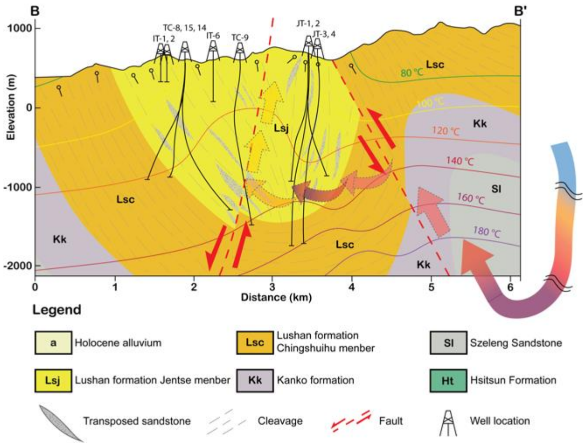

Figure 3: Cross section and geothermal conceptual model in the Tuchang-Renze site, along lines shown in Figure 1. Isotherms are based on downhole temperature measurements.

5. Summary

A large multidisciplinary geoscientific dataset has been acquired at the Qingshui, Tuchang and Renze geothermal sites, including the outcrop observations, drilling and stratigraphic logging from more than 18 wells. Geophysics, including seismic reflection, microseismicity, magnetotellurics and electrical resistivity, was also used to evaluate the geothermal reservoir and pathways. The proposed reservoir occurs between 1 and 3 km, and it is composed of hot metasandstone that is laterally extensive (~150 km^3). The reservoir rocks are also fractured and fluid flows along the normal faults and 000-030, 130-160 striking joints. Mineral veins strike 320 and also indicate late-stage extension at about 050. The geological record indicates that the Ilan geothermal sites are located in a subduction-related basin, consistent with the long-term monitoring of seismic activity.

ACKNOWLEDGEMENTS

The authors acknowledge funding support from the Academia Sinica Research Fund (IESAS 2419-Investigation of the geothermal potential and extraction-related techniques in Taiwan). Qingshui Geothermal Power Plant is thanked for access to rock samples and field data.

REFERENCES

Chen, C.H., (1982). Analysis of topographic effect on ascending thermal water in the Central Range of Taiwan. *Proc. Natl. Sci. Counc.*, Part A, 6: 241-249.

Chen, T. C., (2013). Seismic images of the southwestern tip of the Okinawa trough - the Ilan Plain, Taiwan. Master Thesis, National Chung Cheng University, Taiwan, 1-149.

Ching, K.E., Hsieh, M.L., Johnson, K.M., Chen, K.H., Rau, R.J., Yang, M., (2011). Modern vertical deformation rates and mountain building in Taiwan from precise leveling and continuous GPS observations, 2000–2008, *Journal of Geophysical Research*, 116, B08406, 16pp.

Chiang, S. C., (1976). Seismic prospecting in the Ilan Plain. *Miner. Tech.*, 215-221.

Chou, H. L., Chang, S. Y., Peng, D. H., (1977). Subsurface Geological Report of the TIC-5 Geothermal well in the Chingshui Geothermal District, Ilan, *Taiwan Petroleum Exploration Division,* 1-13.

Deffontaines, B., Liu, C. S., Angelier, J., Lee, C. T., Sibuet, J. C., Tsai, Y. B., Lallemand, S., Lu, C. Y., Lee, C. S., Hsu, S. K., Chu, H. T., Lee, J. C., Pathier, E., Chen, R. F., Cheng, C. T., Liao, C. W., Lin, C. C., Hsu, H. H., (2001). Preliminary neotectonic map of onshore-offshore Taiwan, *Terr. Atmos. Ocean. Sci.*, 339-349.

Fan, K. W., (1978). Subsurface Geological Report of the CPC-CS-15T Geothermal well in the Chingshui Geothermal Area, Ilan, *Taiwan Petroleum Exploration Division,* 1-15.

Geothermal Energy Research and Development-GERD, (2022). MT measurement at Ilan plain in Taiwan Report, Geothermal Energy Research & Development Co. LTD.

Ho, C. S., (1975). An Introduction to the Geology of Taiwan: Explanatory Text of the Geologic Map of Taiwan, Central Geological Survey, Ministry of Economic Affairs, Taiwan, 1-163.

Ho, G. R., Chang, P. Y., Lo, W., Liu, C. M., Song, S. R., (2014). New evidence of regional geological structures inferred from reprocessing and resistivity data interpretation in the Chingshui-Sanshing-Hanchi area of southwestern Ilan County, NE Taiwan, *Terr. Atmos. Ocean. Sci.*, 25, 491-504.

Ho, G. R., Byrne, T. B., Lee, J. C., Mesalles, L., Lin, C. W., Lo, W., Chang, C. P., (2022). A new interpretation of the metamorphic core in the Taiwan orogen: A regional-scale, left-lateral shear zone that accommodated highly oblique plate convergence in the Plio-Pleistocene, *Tectonophysics*, p.229332.

Hsiao, P. T., Chiang, S. C., (1979). Geology and geothermal system of the Chingshui-Tuchang geothermal area, Ilan, Taiwan, *Petrol. Geol. Taiwan,* 16, 205-213.

Hsu, S. K., Sibuet, J. C., Shyu, C. T., (1996). High-resolution detection of geologic boundaries from potential-field anomalies: An enhanced analytic signal technique, *Geophysics*, 61, 373-386.

Huang, J. S., Peng, D. H., (1976). Subsurface Geological Report of IC-4 well Chingshui, Ilan, *Taiwan Petroleum Exploration Division*, 1-13.

Industrial Technology Research Institute-ITRI, (2022). Executive Summary of Geothermal Exploration Data in Tuchang-Renze and Qingshui geothermal fields, Ilan, Central Geological Survey, Ministry of Economic Affairs, Taiwan.

Lai, K. Y., Chen, Y. G., Wu, Y. M., Avouac, J. P., Kuo, Y. T., Wang, Y., Chang, C. H., Lin, K. C., (2009). The 2005 Ilan earthquake doublet and seismic crisis in northeastern Taiwan: Evidence for dyke intrusion associated with onland propagation of the Okinawa Trough, *Geophys. J. Int.*, 179, 678-686.

Lee, C. Y., (1984). Subsurface Geological Report of the CPC- CS-12T Geothermal well (Work Over) in the Chingshui Area, Ilan, *Taiwan Petroleum Exploration Division*, 1-7.

Lee, J. C., Angelier, J., Chu, H. T., (1997). Polyphase history and kinematics of a complex major fault zone in the northern Taiwan mountain belt: The Lishan Fault, *Tectonophysics*, 274, 97-115.

Lee, J. C., Ho, G. R., Byrne, T. B., Lee, Y. H., Yeh, E. C., (2019). Coeval exhumation or subduction channel extrusion of the high pressure Yuli belt? Insights from the Shoufeng fault in eastern Taiwan. *In: JpGU Meeting*, Chiba, Japan.

Lee, P. Y., (1977). Rate of the Early Pleistocene uplift in Taiwan, *Mere. Geol. Soc. China*, 2: 71-76.

Lee, Y. H., Byrne, T. B., Wang, W. H., Lo, W., Rau, R. J., Lu, H. Y., (2015). Simultaneous mountain building in the Taiwan orogenic belt, *Geology*, 43 (5), 451-454.

Lin, C. W., Lin, W. H., (1995). Geologic map and explanatory text of Taiwan-Sanshin. Geological map of Taiwan scale 1:50,000, Central Geological Survey, Ministry of Economic Affairs, Taiwan.

Liu, T. K., (1982). Tectonic implication of fission track ages from the Central Range, Taiwan, *Proc. Geol. Soc. China*, No. 25, pp. 22-37.

Sibuet, J. C., Deffontaines, B., Hsu, S. K., Thareau, N., Le Formal, J. P., Liu, C. S., Angelier, J., Collot, J. Y., Dominguez, S., Foumier, M., Lallemand, S., Lu, C. Y., Malavieille, J., Schnürle, P., Wang, C., (1998). Okinawa trough backarc basin: Early tectonic and magmatic evolution, *J. Geophys. Res.*, 103, 30245-30267.

Sinotech Engineering Consultants Inc., (2008). Geologic map and explanatory text of Taiwan-Tuchang. Geological map of Taiwan scale 1:50,000, Central Geological Survey, Ministry of Economic Affairs, Taiwan.

Su, F. C., (1978). Resistivity survey in the Chingshui prospect, Ilan, Taiwan, *Petrol. Geol. Taiwan*, 15, 255-263.

Tong, L. T., Ouyang, S., Guo, T. R., Lee, C. R., Hu, K. H., Lee, C. L., Wang, C. J., (2008). Insight into the geothermal structure in Chingshui, Ilan, Taiwan, *Terr. Atmos. Ocean. Sci.*, 19, 413-424.

Tong, L. T., Lin, W., (2013). The Airborne Geophysical Survey of Igneous Bodies and Geological Structures in Northeast Taiwan, Central Geological Survey, Ministry of Economic Affairs, Taiwan, 1-188.

Torng, P. K., Young, C. S., (1978). Subsurface Geological Report of the CPC-CS-13T Geothermal well in the Chingshui Geothermal District, Ilan, *Taiwan Petroleum Exploration Division*, 1-17.

Tseng, C. S., (1978). Geology and geothermal occurrence of the Chingshui and Tuchang districts, Ilan, *Petrol. Geol. Taiwan*, 15, 11-23.