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The Geothermal Exploration in the Last Decade at the Metamorphic Region in Northeastern Taiwan

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ABSTRACT

Taiwan is an island nation resided in east Asia that mostly depends on imports for its power generation. The search for domestic energy resources often became a crucial task during the global oil crises, and geothermal exploration has started since the 1960s at places with hot springs and geysers around the island. With the development of advanced concepts and new technologies, a multi-year national energy program initiated by the government in the 2010s began with a thorough inventory of geothermal resources surveys and chose the Yilan area with a slew of exploration activities in search of targets for the hidden and/or enhanced geothermal systems (EGS).

Topics in characteristics of geothermal resources, deep drilling surveys, reservoir engineering, and promotion of geothermal energy power plants were proposed and analyzed in full swing at Yilan Plain, the rifting basin setting at the western tip of Okinawa trough, in northeastern Taiwan. The project has systematically used methods in geology (such as field works and stratigraphy/structure mapping), geophysics (such as gravity, magnetic, seismic, and magnetotellurics surveys), and geochemistry (such as isotope, geothermometer calculation using groundwater ions concentration and temperature measures in shallow wells) in four sub-areas to compile an overall survey result and construct geological and geothermal conceptual models, along with geothermal probability map out of play fairway analysis, for selecting potential drilling sites and performing production capacity test and reservoir simulation.

Firsthand domestic knowledge in geothermal exploration at Yilan Plain has been earned from the usages and interpretations of different geophysical surveying data over the metamorphic rock terrain to the verification of deep borehole drilling for hot fluid through thick quaternary sediment layers. This study provides a review of the performed activities, executed processes, and results during the last decade that revamped the weighting of various geothermal exploration procedures and attached better means over the unique geological settings locally in Northeast Taiwan. Such invaluable experiences will significantly benefit the growth of geothermal development in Taiwan.

1. Introduction

Geothermal is one of the most important indigenous energy resources in Taiwan. After World War II, Taiwan government has been conducting pilot projects in exploration, development, and multi-utilization research for many years. The systematic and large-scaled geothermal exploration work including geological survey, geochemistry, geophysics, and drilling exploration began in the Datun volcano area in 1966, and from 1973 onwards, shifted to the Yilan region (Ching-shui, Tu-chang, etc.) and other mountainous areas (Lushan, Ruisui, Jinlun, Zhiben, etc.) that exhibit geothermal indications. (Chen, 1975; Cheng, 1985; Hwang and Cheng, 1981)

Due to the global attention on carbon emissions and climate change issues, an increased focus on renewable energy development has arisen to substitute traditional fossil fuels. In Taiwan, this led to the launch of the National Energy Program—Phase I (NEP-I) in 2009 as a series of multi-year projects initiated by the Ministry of Science and Technology. The program was based on the sustainable energy policy framework and aimed to promote energy security, reduce greenhouse gas emissions, and transform the energy industry. Then the Phase II program (NEP-II) was followed in 2014, and one of the initiatives was to develop geothermal energy explorations utilizing the concept of Enhanced Geothermal System (EGS), with estimated exploitable potential of about 33.6 GW (for elevation under 1000m and less than 4000m below surface). (Song et al., 2014, 2019)

In Taiwan, geothermal resource surveys usually relied on fieldwork and focused on areas with surface manifestations such as hot springs or geysers. As a result, the surveying areas were limited to such a premise. Inspired by the EGS concept from the FORGE project by U.S. Department of Energy, we have ushered geothermal exploration into a new era by proactively searching for locations with a high probability of geothermal development opportunities, even in cases with a blind geothermal system.

Beneficial to the geological characteristics associated with the rapid uplifting of plate collision and the mountain-building process, the development of geothermal resources has been recognized as one of the important alternatives in the key strategic and forward-thinking research programs for various sustainable energy choices. The NEP-II energy program not only successfully created a pilot project at Yilan Plain for deep geothermal exploration by gathering experts from geology, geophysics, and geochemistry fields, but also revealed encouraging results of above average underground heat, abundant groundwater systems, and mapping of geothermal potentials, among others.

However, owing to the uncertainty risk, high upfront cost of exploration, related technical advancements, and regulatory support, further geothermal activity has been put into the backseat after NEP-II without immediate breakthroughs. Other sustainable energy choices, solar and wind farms, prevailed with available measured data for cost calculation fitting our government's urgent solution and roadmap planning of energy policies in the early stage.

While the topic of net zero CO_2 emissions is continuously campaigned globally and advanced technologies are consistently developed, along with the lagging progress of the planned sustainable transition in Taiwan from the past couple years, geothermal exploration has been reconsidered as a crucial area in the government's re-apt policies.

This review archives the geothermal exploration activities done in the past decade in the Yilan area, and hands over a warm welcome to the renewed exploration effort smoothly. Through the help of the continuing improved technologies, domestic experiences related to the exploration and drilling methods, and government policy and funding support, geothermal power should soon become one of the indispensable green power options in Taiwan.

2. Background

Taiwan is located at the western Pacific rim of fire and between the convergence of Eurasian and Philippine Sea Plates and has many surface geothermal indications in hot springs and geysers (Fig.1). Those visible surface manifestations and adjacent area, exhibited higher geothermal potential, typically have elevated heat flow, fractured rock formations, and the potential for geothermal reservoirs, and hence, offer promising opportunities for geothermal energy development. (Liu, 1995; Teng, 1996)

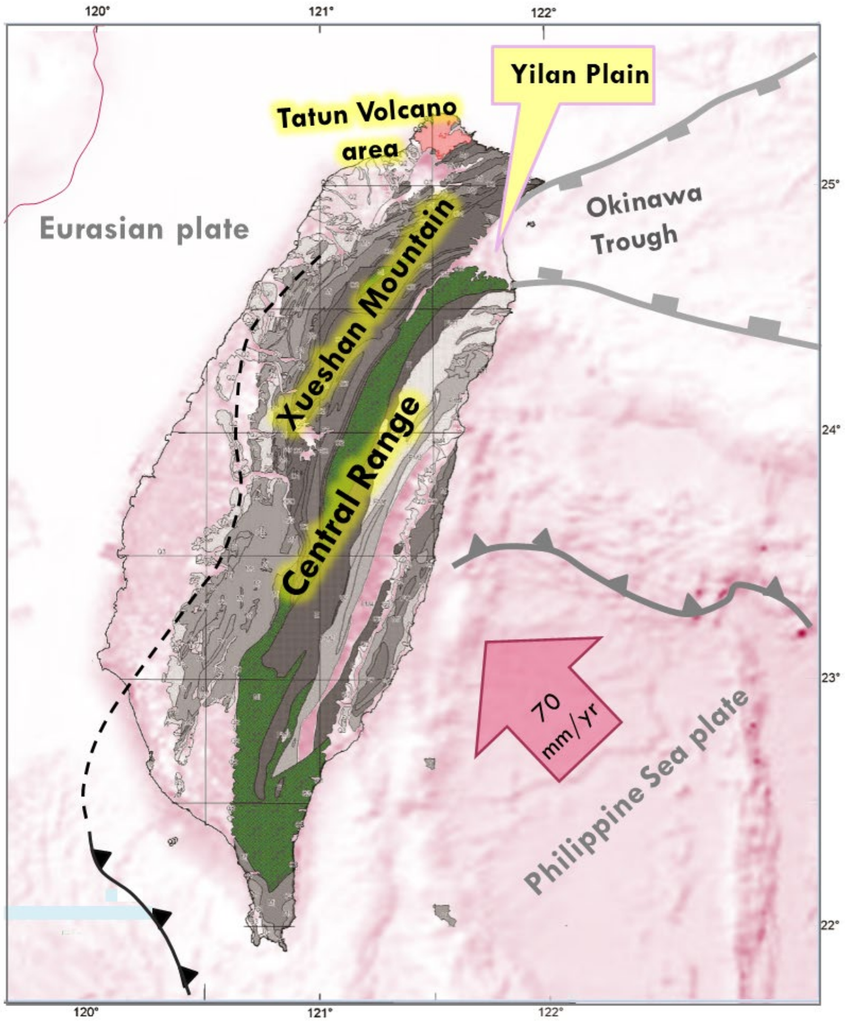

Figure 1: The geologic framework of Taiwan. (modified from Song and Lu, 2018)

Based on geological structures, origins, and international categorizations (Moeck, 2014), two major types of geothermal resources in Taiwan are Magmatic-Volcanic Field Type and Orogenic Belt / Foreland Basin Type. The energy is generated from the heat of molten rock or magma within the Earth's crust, or associated with the tectonic processes that create mountain ranges or the adjacent sedimentary basins, respectively. The Tatun Volcano area in the north of Taiwan and hot springs in the river valleys of the Central Range and Xueshan Mountain are the best examples.

The third is Extensional Domain Type that geothermal systems are in the fault-controlled extension or rifting area with openings from fractures and faults providing pathways for the circulation of hot fluids. The Yilan area resided in the northeastern Taiwan and the southwestern end of the Okinawa Trough, is a typical case of such a geothermal type. (Song and Lu, 2018)

The Niudou Fault is a major fault system parallel to Lanyang River cut through Yilan Plain downstream, and is believed to be a boundary fault between the two different stratigraphic systems in Xueshan Mountain at the northwest and Central Range at the southeast, respectively. In the macro-scale tectonic structure, the western side of the fault is dominated by the Xicun Anticline with right-side up layers. Structures at the eastern side of the fault are primarily by isoclinal or closely spaced minor folds. Rock layers are slightly metamorphic sandstone and slate and (Chen, 2016; Ho, 1975; Lin and Lin, 1995a, 1995b)

Under the rifting condition with thick Quaternary sediments covered on top of slaty formations and meta-sandstone layers in low-graded metamorphic environment, the NEP-II program selected Yilan Plain as the research target and aimed to utilize advanced exploration techniques, drilling technologies, reservoir characterization methods, and power generation systems tailored to geothermal energy. (Song et al., 2014)

3. Approach and Outcome

3.1 Project Components and Work Flow

Exploration and drilling sections proposed for the geothermal energy development and utilization in NEP were led by a team consisting of geology, geophysics, and geochemistry experts, together with drilling professional partners. Main methods for academic researches include regional geothermal and geology surveys, measurement of regional heat flow and temperature gradients, mineral and geochemistry analysis, geophysical surveys, hydrology analysis of geothermal fluids, geo-mechanical investigation, development of fracking technology, and constructing subsurface 3D geologic structures. (Song et al., 2014, 2019)

The principal of selecting proper locations for exploration wells are two folded; one was more of filling the gap within a given area to collect extra data, and the other was meant to be more precisely for getting critical information with better geothermal potential and geological information. Play fairway methodology, among other feasibility constraints, was used to select locations with higher probability of contributing favorable environment for the geothermal resource. Also, socio-economic factors were considered as a viability element for selecting wells in a populated region. As for the drilling part, the major executing items included working with the drilling company on timetable/milestones, borehole core analyses, well logging information, etc. And then the afterwork was centered around the feedback process for iterating data modification for more analysis.

To gain a deeper understanding of the overall distribution of geothermal potentials, and the characteristics of heat sources and upwelling fluid pathway in the Yilan area, other than collecting previous works, this project employed various methods to obtain data from seismic reflection profiles, natural earthquakes, airborne magnetic surveys, magnetotellurics (MT), carbon and helium isotopes in hot spring gas, sulfur isotopes in hot spring water, and fusion track dating. The information was combined with the geologic data to elucidate the potential heat sources in the Yilan area.

The most crucial task in geothermal exploration is the integration of geological, geophysical, and geochemical data to create a 3D geological and geothermal conceptual maps. Drilling is then conducted to test the accuracy of the conceptual models and gather additional data for model reconstruction. This iterative process aims to reduce the risks associated with geothermal development. Ultimately, the refined models serve as the basis of selecting sites for deep production and injection wells, minimizing the potential risks involved in geothermal exploitation.

To further mitigate exploration risks after establishing the 3D conceptual models, the common practice is to select geothermal fields with similar geological backgrounds and successful development as modern analogs. This approach provides valuable insights into potential challenges, optimal exploration techniques, reservoir characterization methods, and efficient development strategies, while significantly reducing overall risks. (Fig. 2)

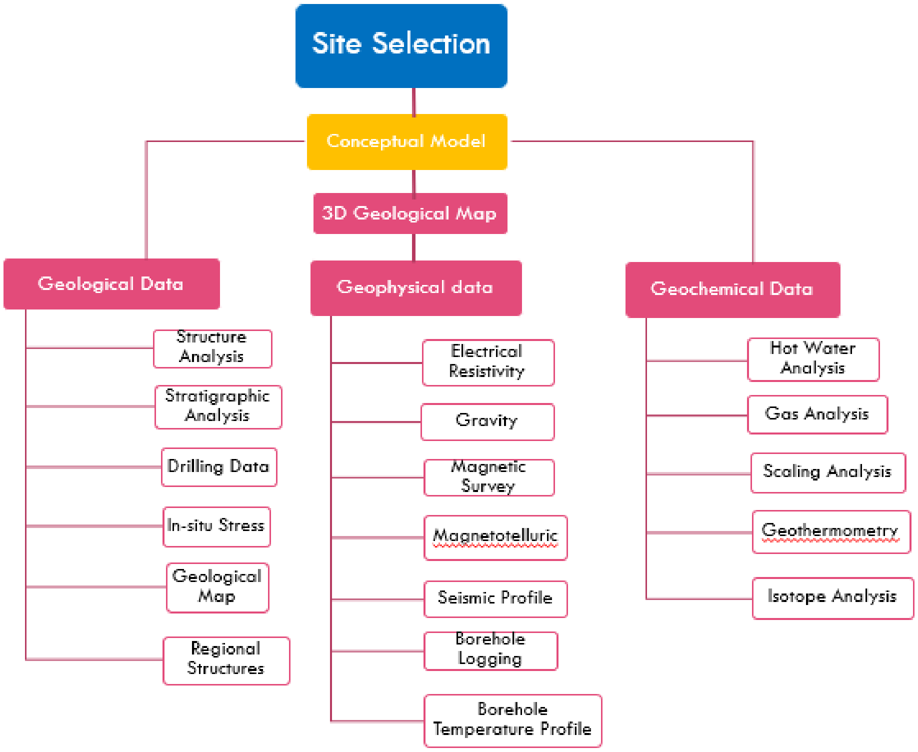

Figure 2. Project components and work flow.

After the conceptual models were completed based on the overall analysis, another pilot project of deep drilling was performed on two separated sites to establish self-owned geothermal development techniques. By conducting capacity testing and analyzing fluid samples, the project aimed to assess the viability of geothermal energy generation and gather the necessary information for the design and operation of a 1MWe geothermal power plant. It served as a stepping stone towards further geothermal development in Taiwan.

3.2 Methods and Results

We chose certain typical figures that used in various group meetings during the NEP programs, and showcased them in the following sections for the displaying purpose. The decision criteria of the crucial data integration process and discussion are not presented here for the privilege of individual owners.

3.2.1 Geological Data

Geological data in lithology division and distribution was defined by the geological map published by the Central Geological Survey (CGSMOEA, 2012, 2014). The map also includes the distribution and demonstration of geological structures. Extra field works, borehole cores from several exploration wells and two deep drillings throughout the Yilan Plain help to correlate the basement depth and lithologies from different layers with outcrops information from the surrounding mountain areas. The correlation of subsurface formations between the two different mountain stratigraphic systems from the current regional geological framework was discussed with at least two possible situations (Teng et al., 2013). (Fig. 3)

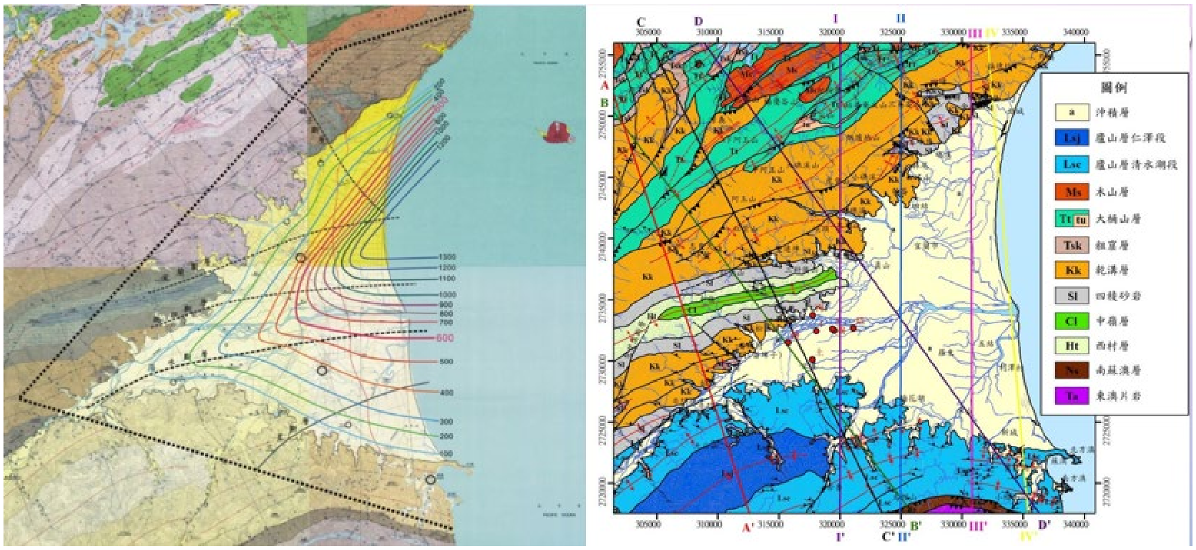

Figure 3. Geological map with basement depths and two color-coded stratigraphic systems. (NEP-II, 2019)

In-situ stress measurement were performed for understanding the relationship between in-situ stress and permeable fractures zones, based on composite focal mechanisms, surface outcrops and borehole cores, and revealed a strike-slip stress field in the Sanshing area. The horizontal maximum compression axis was approximately oriented in a north-northeast to south-southwest direction. Field investigations were carried out on fault traces in the vicinity of the Sanshing area. The results of paleostress field inversion showed the occurrence of both normal faults and strike-slip faults in the Qingshui River area. Additionally, there was a phenomenon of alternating orientations between north-south and east-west for the horizontal minimum stress axis. (Fig. 4)

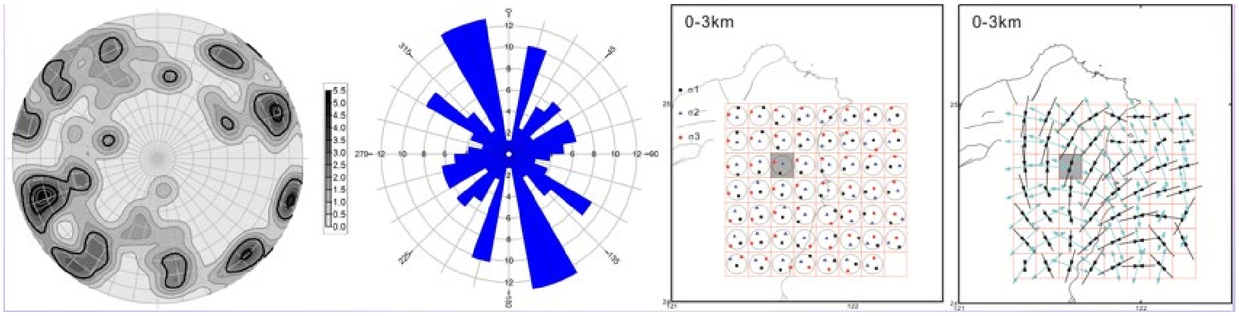

Figure 4. Examples of figures and diagrams of fracture orientations and stress fields. (NEP-II, 2019)

3.2.2 Temperature, Geochemical and Geophysical Data

Temperature and geochemical data mainly collected for heat information from different temperature measures. Direct bottom well temperature measurement from twenty shallow groundwater wells with depth from 35m to 179m were completed. Temperature profiles were measured by 10m interval on each well for temperature gradients. SiO_2 geothermometry was used to estimate fluid temperatures at the geothermal reservoir from nineteen wells (Liu et al., 2011). Other activities included the research for the characteristics of subsurface geothermal fluids (Kuo et al., 2017), chemical composition and possible scaling condition when explored, and isotopic index in hot water and gases for the history of heat sources, fluid source and its circulation rate (Yang et al., 2015). (Fig. 5)

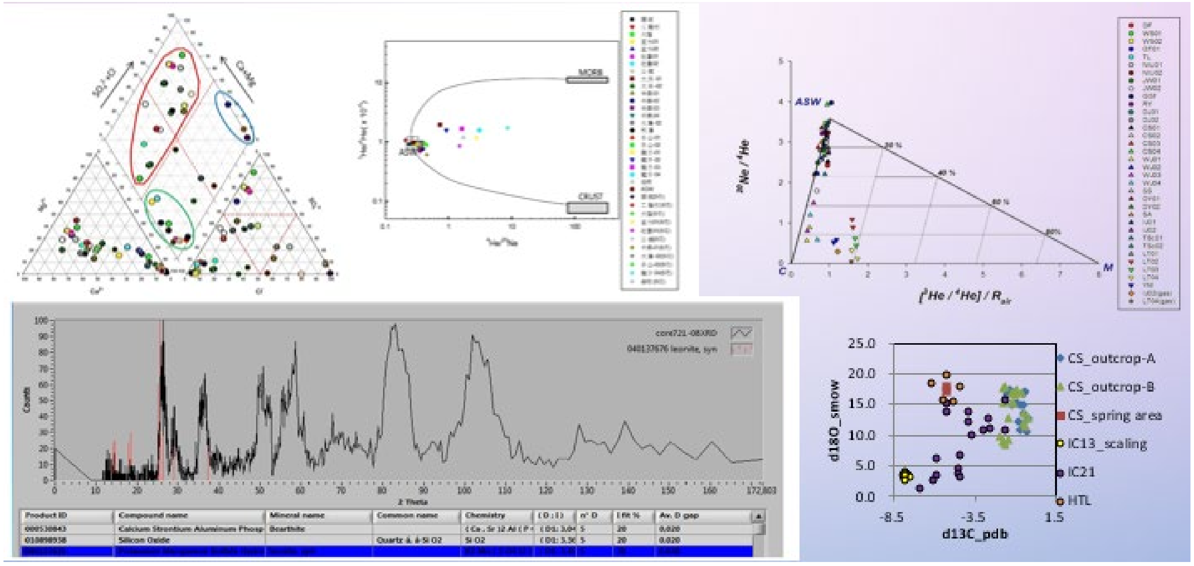

Figure 5. Examples of figures and diagrams from various geochemical data. (NEP-II, 2019)

Geophysical methods for analyzing deep geothermal structures included gravity, magnetic survey, seismic reflection data, joint imaging, and micro-earthquake data (Kang et al., 2015; Shih et al., 2018). From the gravity and magnetic surveys covering plain and mountain area with radius of 20km, a 3D subsurface density structure model should be obtained through the distribution of Bouguer anomaly. Seismic reflection method with 9 seismic lines deployed in the area, reflection profiles were processed and analyzed. Earthquake receivers were placed under shallow dry wells to collect data for analysis and detecting possible fluid movements. (Fig. 6; Fig. 7)

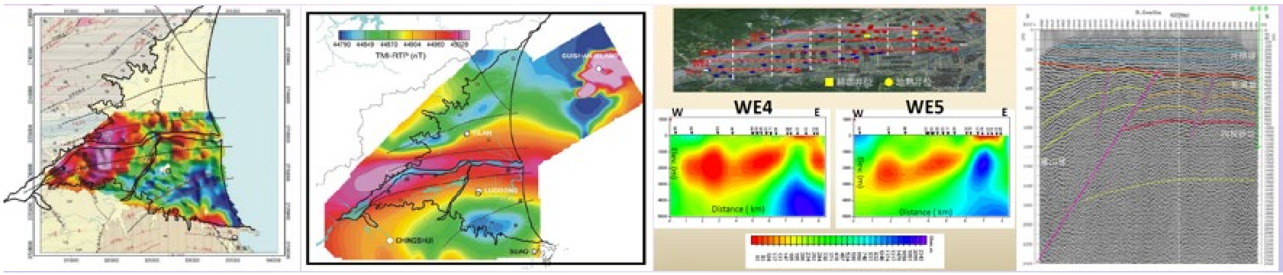

Figure 6. Examples of figures and models from various geophysical surveys. (NEP-II, 2019)

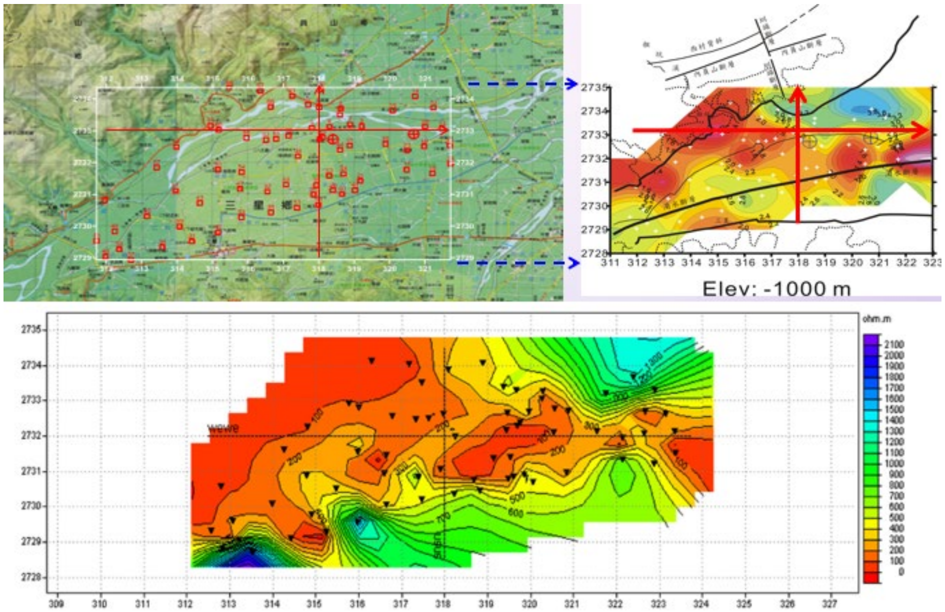

Figure 7. Represented maps showing distribution of MT stations and interpreted resistivity maps. (NEP-II, 2019)

3.2.3 Play Fairway Analysis and Geothermal Potential Mapping

Play fairway analysis was used to predict geothermal potential through quantitative and statistical methods by overlapping important element layers into a composite favorability map. Other than the major layers in heat sources and permeable fracture network, human aspect was added for heavy population. An easy-to-read composite map indicating potential targets for the early stage of the geothermal development project is shown in Fig. 8. (Wang et al., 2017, 2018)

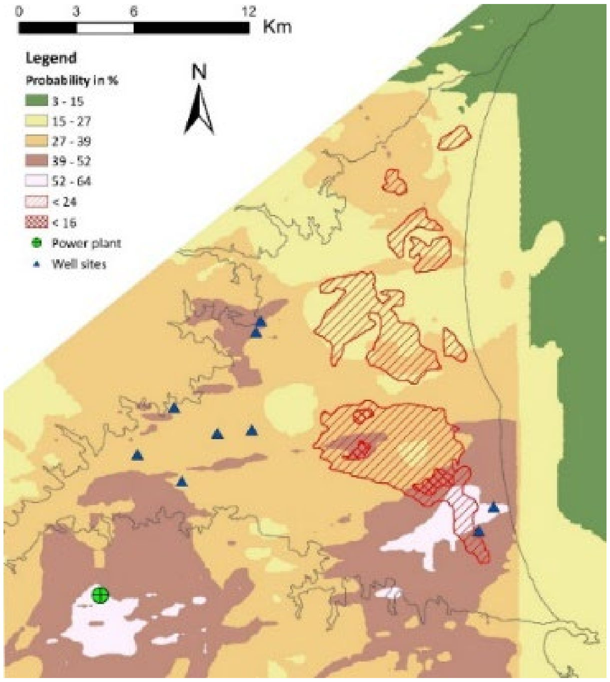

Figure 8. Favorability map of geological aspect with lesser probability areas from the socioeconomic perspective, using by play fairway methodology. (Wang et. al., 2018)

3.2.4 Conceptual Model and Two Deep Wells

The project compiled three years worth of data under limited funding and produced a 3D geological conceptual model (Fig. 9). Two deep wells were drilled based on the geological and geothermal models with precious core data obtained. However, first deep well reaching 2200 meters in depth was a dry well with bottom temperature at 80 degree Celsius. Second deep well was drilled at about 1.5 km west of the first one, with the upwelling water reaching bottom temperature at around 120 degree Celsius at the depth of 2800 meters.

The preliminary conceptual model created by the strong weighting based on the MT profiles was unsuccessful to fully explain the geothermal condition under the Yilan area because the two deep wells were drilled without expected outcome in heat and water content, and no meaningful explanation could be reached after thorough review and discussions. The final conceptual model was modified with the core and cutting data from the two deep wells, and the project was stopped short of making the two wells into the production/injection ones.

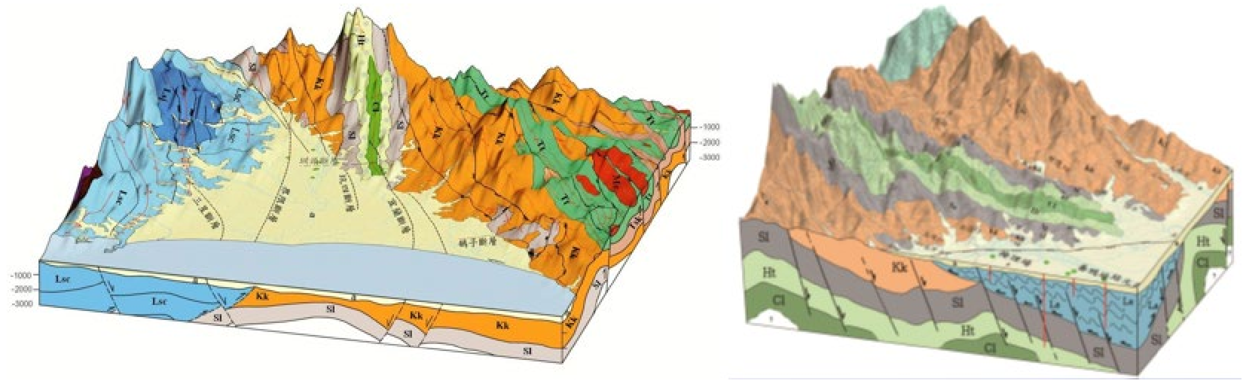

Figure 9. Subsurface geological 3D conceptual models with exaggerated vertical scale. The south-facing profile from the model to the right revealing the locations of tow deep wells in the long red vertical lines. (NEP-II,2019)

4. Discussions and Conclusions

4.1 Play Fairway Analysis with Feasibility Addition

Geothermal play fairway analysis usually uses major data elements at each layer for its strong geological implication for the favor condition. It's a fair analysis for the places such as Basin and Range area in the western United States. As for the dense populated area in Taiwan, it is unrealistic to overlook human factors for drilling and/or power plant construction projects. (Wang et al., 2021)

When considering different focuses through the many stages in the entire development project, various factors may kick into place at certain stage. For academic geothermal analysis, heat and permeability may be the two major elements, the viable business plan should be free to add human/socio-economic factors when needed. (Lautze et al., 2017)

4.2 MT Application for geothermal exploration

Among various geophysical surveying methodologies, MT has been widely used for geothermal exploration, especially around the volcanic type of plays. Using the characteristics of electrical conductivity in different earth materials, MT method allows to differentiate certain important elements of the geothermal system such as cap rock layers, heat source, underground structures or layers conducting fluid flow etc. Certain geothermal conceptual models seem fitting well with MT profiles under the volcanic geological settings in some practical applications. However, how to interpret the MT model with other geological conditions, such as in the low-grade metamorphic region, to construct a conceptual geothermal model is still in the early stage with few research reports and application results.

The NEP-II project had encountered this situation first handed. We have chosen MT data to map the electrical resistivity distribution to around 3-5 km deep under Yilan Plain, and use the MT profile as one of the critical information to identify potential hot fluid areas and determine drilling locations. However, the outcome was disappointed without any reasonable explanation, as the first deep well produced no heat and no water content.

Following efforts were conducted to improve collection and processing methods for more accurate data, such as using extended duration for each setup, filtering out locations with high background noises, and so on. More practical field works has been done for accumulating experiences in data tuning and geological interpretation. Other academic researches were carried out and future exercises or experiments are needed for correlating MT values with geothermal sensitive information in temperatures and/or rock types (Guo et al., 2018; Ho et al., 2014; Jiang et al., 2021).

4.3 Data Quality and Interpretation of Seismicity Data

Even though the images of the seismic profiles were continuously improved over the years, the quality of the seismic image obtained from metamorphic rock remains inferior to those from sediments. Because of the similarity from physical properties between slate and argillite, it was difficult to distinguish structures without the existence of key beds.

In this studied area, other than the clear boundary between the basement layers and overlaying sediments was clear to tell, it is difficult to draw the lines without well-defined stratigraphic controls and geologic structures in mind. Add that the similar lithology distribution from the two stratigraphic systems in Xueshan Mountain and Central Range, more than one geological models were proposed, and high uncertainty is inevitable.

4.4 Never Ending Effort on Geological Application

One professor once described what a geologist is about at freshman class, saying that a geologist is like an inspector attempting to reconstruct the sequence of events at the crime scene based on the available clues and evidence left behind. Many times, we keep coming back the same battle field, supported with advanced technologies for more evidence, to rebuild a better model in such a never-ending sequel. One small hiccup from the lack of enough evidence for geothermal exploration in the Yilan area did not stop geothermal projects from other locations continuously charging ahead in Taiwan.

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REFERENCES

Chen, C.H., 1975. Thermal waters in Taiwan, a preliminary study. *Proceedings of the Grenoble Symposium, August 1975. Pub. #119, International Association of Hydrological Sciences*, p. 79-88.

Chen, W.S., 2016. Introduction to Geology of Taiwan. Geological Society Taiwan. 204pp. (in Chinese)

Cheng, W.T., 1985. Geothermal update report Taiwan, Republic of China. *Geothermal Resources Council 1985 International Symposium on Geothermal Energy*, International Volume, 191-195.

Chiang, C.W., Yang, Z.X., Chen, C.C., Yeh, E.C., Chen, C.S., Wang, C.Y., 2021. "Potential geothermal structure inferred from the electrical resistivity and seismic reflection models in the western Ilan Plain, NE Taiwan." *Geothermics* 94, 102124.

CGSMOEA, 2012. Active fault map of Taiwan. *Central Geological Survey* (CGS)*, Ministry of Economic Affairs* (MOEA), Taipei, Taiwan.

CGSMOEA, 2014. Outcrops of hot springs in Taiwan. Central Geological Survey, Ministry of Economic Affairs*,* Taipei, Taiwan. Available at: https:// http://210.69.81.175/ [accessed 12 December 2020]. (in Chinese)

Guo, T.R., Tong, L.T., Huang, Y.T., 2018. Metamorphic geothermal reservoir characterisation – A case Study in the Jinlun geothermal area, Taitung, Taiwan. *Geothermics* 74, 35-44.

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.

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. *Terrestrial, Atmospheric & Oceanic Sciences*, *25*(4).

Hwang, K.-K., and Cheng, W.-T., 1981. Exploration and development of geothermal resources in Taiwan. *AAPG Studies in Geology, v. 12, Energy Resources of the Pacific Region*, 215-221.

Kang, C.-C., Chang, C.-P., Siame, Lionel, and Lee, J.-C. (2015) Present-day Surface Deformation and Tectonic Insights of the Extensional Ilan Plain, NE Taiwan. *Journal of Asian Earth Sciences*, 105, 408-417.

Kuo, C.H., Liu, C.M., Chiang, C.J., and Tsai, Y.W. (2017) The Flow Path of Geothermal Fluid Identification and the Reservoir Temperature Evaluation in Geothermal Area of Ilan, Taiwan. *Proceedings: 42nd Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, CA, 850-856.

Lautze, N., Thomas, D., Waller, D., Frazer, N., Hinz, N., Apuzen-Ito, G., 2017. "Play fairway analysis of geothermal resources across the state of Hawaii: 3. Use of development viability criterion to prioritize future exploration targets." *Geothermics*, 70, 406-413.

Lin, C.W., Lin, W.H., 1995a. "Explanatory Text of the Geologic Map of Taiwan, Scale 1:50,000, Sheet 15, Sanshin." *Central Geological Survey*, Ministry of Economic Affairs, Taiwan.

Lin, C.W., Lin, W.H., 1995b. “A Study on the Geologic Structure of the Lanyangchi Area, Northeastern Taiwan.” *Bulletin of the Central Geological Survey*, 10, 23-49. (in Chinese)

Liu, C.C. (1995) The Ilan Plain and the Southwestward Extending Okinawa Trough. *Journal of the Geological Society of China*, 38, 183-193.

Liu, C.M., Song, S.R., Lu, Y.C., 2011. Prospects of Geothermal Resources in Taiwan on the Base of Surface Silica Heat Flow. *Western Pacific Earth Sciences*, 11, 31-48.

Moeck, I. "Catalog Of Geothermal Play Types Based On Geologic Controls." *Renewable and Sustainable Energy Reviews*, 37, (2014), 867-882.

NEP-II, 2019. Data compilation and final report (2014-2018): survey and assessment of geothermal potential with R&D in key technologies. *Geothermal Energy and Gas Hydrate Focus Center, National Energy Program-Phase II, Ministry of Sciences and Technology* (MOST), Taipei, Taiwan. 321pp. (in Chinese)

Shih, R.-C., Wang, C.-Y., Chen, W.-S., Wang, Y.-K., Kuo, H.-Y., Yen, T.-C., Huang, C.-C., Chang, Y.-C., Chung, C.-T., Huang, M.-Z., Chang, Y.-F., 2018. "Seismic Reflection Profiling of the First Deep Geothermal Field in Taiwan." *Geothermics*, 74, 255-272.

Song, S.R., and Lu, Y.C., 2018. "Geothermal explorations on the slate formation of Taiwan: In: Ismail, Basel I. (Ed.)." *Renewable Geothermal Energy Explorations,* IntechOpen, DOI: 10.5772/intechopen.81157. Available from: https://www.intechopen.com/books/renewable-geothermal-energy-explorations/geothermal-explorations-on-the-slate-formation-of-taiwan

Song, S.-R., Team Members of Geothermal Focus Center, NEP-II, MOST, 2014. "Exploration of deep geothermal resources and evaluation of sites for enhanced geothermal system in the Ilan area." *Annual Report of Geothermal Focus Center, NEP-II*, Ministry of Science and Technology.

Song, S.-R., Team Members of Geothermal Focus Center, NEP-II, MOST, 2019. "Geothermal potential survey and assessment – with development of key technologies." *2014-2018 compilation of Geothermal Focus Center, NEP-II*, Ministry of Science and Technology.

Teng, L.S., 1996. Extensional collapse of the northern Taiwan mountain belt. *Geology* 24, 949-952.

Teng, L.S., Song, S.R., Yeh, E.C., Lin, A.T., Liu, C.M., Tsai, Y.L., 2013. Tectonic appraisal of geothermal potential of Taiwan. *Western Pacific Earth Sciences* 13, 1-38.

Wang, C., Lo, W., Song, S.R., 2017. Applying play fairway analysis for human impacts in geothermal exploration site selection - A preliminary study in Yi-Lan Plain, Taiwan. *Geothermal Resources Council Transactions* 41, 2359-2367.

Wang, C., Lo, W., and Song, S.R., 2018. "Geothermal play fairway analysis at a populated rifting basin area of Taiwan." *Geothermics* 75, 146-153.

Wang, C., Lo, W., and Song, S.R., 2021. "Geothermal energy development roadmap of Taiwan by play fairway analysis." *Geothermics* 97, 102242.

Yang, T.F., Geothermal Energy Research Teams of Taiwan, 2015. Introduction to the geothermal energy program of Taiwan. *Proceedings, World Geothermal Congress 2015*, Melbourne, Australia, 4 p.