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Geothermal play fairway analysis at a populated rifting basin area of Taiwan

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ABSTRACT

Taiwan is located in the active mountain belts on the west side of the Pacific Rim with promising potentials for geothermal resources. The triangular shaped Yilan Plain, our study area chosen for a geothermal development pilot project, resides at the southwestern end of the Okinawa Trough behind the Ryukyu Arc-Trench where the Philippine Sea Plate is subducting beneath the Eurasian Plate with low-grade metamorphic rocks exposed in the surrounding mountain ranges.

Play Fairway Analysis (PFA) is adapted to demonstrate important aspects, predicting geothermal potential through quantitative and statistical methods in a given type by overlapping each element layer into a composite favorability map with properly calculated weights accounting for uncertainty levels. Highlighted exploratory sweet spots on a regional scale can be identified with the easy-to-read map for decision-making stakeholders.

Three components are selected for this analysis: they include (1) heat sources: with temperatures of hot springs, geothermal gradients, and silica geothermometry, (2) permeable fracture networks: with fault lines, drainage network, micro-earthquake activities, and dilation rate distribution, and (3) human activities: with population density, sediment thickness, and hazardous risk. Expert opinion on factor weighting for two geological components and Analytic Hierarchy Process (AHP) for the socioeconomic component are utilized to determine weightings representing the assigned confidence and uncertainty levels. ArcGIS software is used as the platform for data processing and map demonstration.

The final map displayed the combined geothermal favorability from the two geological aspects blocked out with the riskier zones from the socioeconomic aspect. It indicates two potential prospects with one in the southwestern hillside where the Chingshui power plant resided and another in the southeastern portion of the Yilan Plain, which could interfere with certain human activities.

1. Introduction

Following the global awareness of climate change, developing clean energy has been one of the main targets in Taiwan's sustainable energy policy since 2008. A geothermal development program was included in the National Energy Program Phase-II (NEP-II) by the Ministry of Science and Technology in 2014, the first major effort since the closure of the pioneering Chingshui geothermal power plant in 1993, aiming to achieve industrial development targets and foster opportunities to strengthen energy-related industries (Song et al., 2015).

The program team followed the initiative from U.S. Department of Energy, called Geothermal Play Fairway (Weathers et al., 2015), to identify potential geothermal hot spots through constructing conceptual models, performing geothermal assessments, selecting drilling sites, and using other tools and methods for integrating geological information.

The Yilan Plain in the northeast of Taiwan (Fig. 1) was chosen as the targeted area for the program because of its three main characteristics: (1) the existence of several surface hot springs and fumaroles providing direct evidence of heat, (2) the locality of the southwest end of extending Okinawa Trough representing the extensional domain type of a fault-controlled, convection-dominated geothermal system (Moeck, 2014; Sibuet et al., 1987), and (3) a favorable local government and residency environment for the project at an early stage.

As geothermal exploration projects share the high risks and upfront costs experienced by oil and gas industry, the PFA method is adapted to integrate data at the regional scale in order to define exploration targets (relatively broader areas) with limited available information before examining more data for prospects (more focused locations) with higher success rates (DeAngelo et al., 2016; Garchar et al., 2016; Ito et al., 2017; Lautze et al., 2017a; Nielson et al., 2015; Siler et al., 2017). PFA can also be a management tool for decision-makers eyeing return-on-investment opportunities with additional socioeconomic factors throughout the project (Lautze et al., 2017b; Seubert, 2012).

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Fig. 1. Left is shown an administrative map of Yi-Lan County, Taiwan and at right, is the Google satellite image of Taiwan for topography reference.

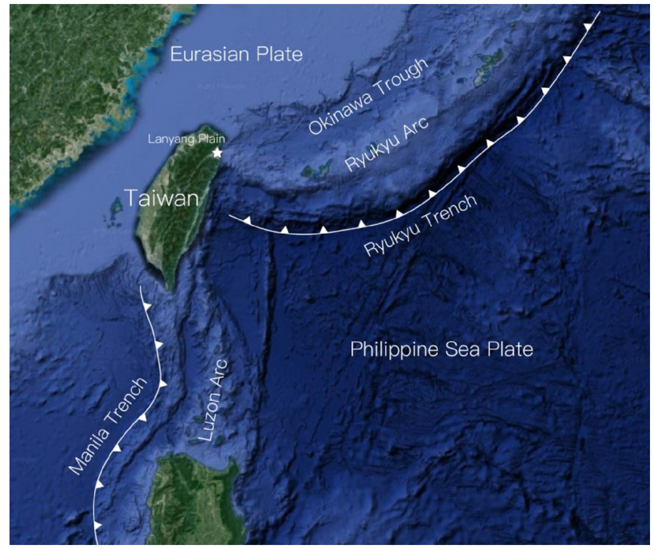

Fig. 2. Google map image of tectonic figures around Taiwan and the study location in the Yilan Plain, at the NE of Taiwan and the SW end of Okinawa Trough.

ArcGIS is utilized to perform data processing, handle statistical functions, classify value ranges, calculate normalized values onto raster grids for each designed Common Risk Segment (CRS) colored map, and finally, produce the easy-to-understand Composite Common Risk Segment (CCRS) map (DeAngelo et al., 2016; Nielson et al., 2015; Seubert, 2012). The knowledge-based approach in factor weighting method and the paired comparison method of AHP determine proper weights for factors in each group to represent the uncertainty level from all the input data (Garchar et al., 2016; Forson et al., 2015; Goepel, 2013; Saaty, 2008; Yalcin and Gul, 2017).

This study surrounding the Yilan Plain area is the first case in Taiwan using PFA methodology to develop a commercially viable process with statistical methods and display potential opportunities for a geothermal project. We intend to achieve that by (1) introducing a systematic procedure to evaluate available data and integrate it with proper weights to reflect reliability and quality, (2) constructing resulting information into easy-to-read composite favorability maps showing the best areas of geothermal development opportunities for decision makers, and (3) providing industrial players with a risk reduction framework to continuously examine the progress with newly obtained data.

2. Background

2.1. Geological conditions

Taiwan has long been a favorable place for geothermal development, characterized by widespread hot springs and high geothermal gradients (Chen, 1975; Cheng 1985; Hwang and Cheng, 1981; Teng et al., 2013; Yang and Geothermal Energy Research Teams of Taiwan, 2015). A series of research started around 1965 and a 3MWe power plant was installed in 1981 at Chingshui Valley, just west of the Yilan Plain (Chiang et al., 1979; Hsiao and Chiang, 1979; Lin, 2000). However, geothermal power has never been the focus of the energy production by the national government, and the short-lived power plant closed in 1993 due to scaling issues (Lu et al., 2011). Continued studies of this area have improved understanding of the subsurface structures, heat source, and geothermal reservoir (Tong et al., 2008; Zhang et al., 2016; Chang et al., 2014).

The NEP-II awarded three -year funding for a project in the Yilan Plain to perform detailed analysis for geothermal resources including geological, geophysical, and geochemical surveys, drill exploration wells, build conceptual models, and suggest a production well site for a geothermal power plant (Song et al., 2015). This area is located at the southwestern end of the Okinawa Trough, an active back-arc rifting basin formed behind the Ryukyu arc-trench system in the West Pacific where the Philippine Sea Plate is subducting under the Eurasian Plate (Liu, 1995; Suppe, 1984; Teng, 1996; Tsai, 1978; Yu and Tsai, 1979) (Fig. 2). About 300 square kilometers in area, the triangle-shaped plain has its east side facing the Pacific Ocean and other sides against the elevated mountain ranges to the south and northwest, with low-grade metamorphic rocks in outcrops (Ernst and Jahn, 1987; Teng et al., 2013) and a series of hot springs and fumaroles along the mountain foothills. It also has a helium isotope ratio result that suggests active magmatic activity under a volcanic islet 10 kilometers offshore (Yang et al., 2005).

This constitutes the basic assumptions of our initial geothermal conceptual model with the normal fault zones in a graben area located under the Yilan Plain, such as the case in Blue Mountains, NV, USA (Cashman et al., 2012; Faulds et al., 2013). A thinner crust of the extensional back-arc basin may bring magmatic activity closer to the surface with higher temperature gradients through conductive heat flow, and fractures for fluid pathways could exist in the normal and transform fault zones in the graben or in any weak surfaces of the low-grade metamorphic rocks in slate and/or argillites caused by shear forces. Such a description of the area fits into the fault-controlled, convection-dominated geothermal system of the extensional domain play type (Moeck, 2014; Sibuet et al., 1987).

2.2. Development realities

Taiwan is a densely populated island country. It is ranked second highest, only behind Bangladesh, in the world population density for countries with a land area greater than 100,000 km^2 at more than 600 people/km^2 (United Nations, 2017). While the Yilan Plain is an alluvial plain formed by the Lanyang River and its branches for a typical agricultural environment, its population density reaches over 500 people/km^2 outside the two city boundaries. Unique geological conditions like quick rising mountain ranges and erosion rates produce a thick layer of sediment under the Yilan Plain that is over 1000 m thick along the coast. Weather hazards like tropical storms and seasonal monsoons bring in heavy rainfall and cause flash floods, while the average annual precipitation is around 2600 mm in Taiwan's subtropical climate zone.

These unique conditions all require consideration of socioeconomic factors; human activities associated with urbanization and agricultural development alongside natural hazards undoubtedly create many barriers for geothermal exploration (Lautze et al., 2017b; Wang et al.,