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Seismic reflection profiling of the first deep geothermal field in Taiwan

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A B S T R A C T

The first deep geothermal energy development project in Taiwan was launched at the Ilan Plain in northeastern Taiwan, where metamorphic rock is covered by sediments and detailed subsurface structures were poorly known. An eastward plunging anticline containing a fault system was effectively imaged in our seismic sections. However, since some rock fragments recovered from the exploration wells were still questioned, two fault structure models were proposed. One is an extensional strike-slip fault system, and the other is an active normal fault system, which depends on whether the rock fragments were affiliated with the Hsuehshan Range or with the Backbone Range.

1. Introduction

In Taiwan, around ninety-eight percent of the primary energy consumption must be imported each year. Therefore, indigenous energy sources such as geothermal, solar, and wind energy are in great demand. Geothermal energy has been successfully used in many countries, especially for those located near active plate boundaries. Taiwan is situated at the collision boundary of the Eurasia and Philippine Sea plates; the island is young, active and is believed to have an abundant geothermal energy resource as well.

Northeastern Taiwan is located in a structurally complicated area. Complex plate movements, such as arc-continent collision, subduction, and back-arc extension, caused northeastern Taiwan to become very active in seismicity (Angelier et al., 2009; Lallemand et al., 1999; Lu et al., 1995; Tsai, 1986; Kao et al., 1998; Shyu et al., 2005; Wang et al., 2000). The Ilan Plain is a major plain in northeastern Taiwan. The plain is also situated at the southwestern end of the Okinawa Trough, in a structure extension area (Teng, 1996; Angelier et al., 2009; Hou et al., 2009; Liu, 1995; Liang et al., 2005, Sibuet et al., 1998). The observed high geothermal gradient (Chiang et al., 2008) and abundant hot springs indicate the existence of higher geothermal potential in the Ilan area. Since no volcanic activity was observed in the Ilan Plain and the surrounding mountain terrain, the geothermal resource in the Ilan Plain was thought to originate from magma or igneous rock intrusion beneath the plain (Tong et al., 2008; Yeh et al., 1991, Lin et al., 2004).

The Ilan Plain was selected as the first target area for developing geothermal energy in Taiwan. A clear conceptual geological model was needed to explore the geothermal field. However, the triangular Ilan plain was the delta of the Lanyang River, the largest river in the plain; the plain was covered by alluvial deposits delivered by the river. The overlying Quaternary sediments were hundreds of meters and up to a thousand meters thick; the underlying stratigraphic units, structures, and detailed distribution of faults were poorly known. In this paper, we will show seismic reflection images of the subsurface structure beneath the geothermal field as well as the proposed structural models. The results of this study were for building a conceptual model of this deep geothermal system.

1.1. Geologic setting

The triangular Ilan plane is bounded by the Hsuehshan Range and the Backbone Range at the northwest and the south, respectively. The Hsuehshan Range is covered by Eocene-Miocene fluvial to inner shelf deposits that extended westerly to the Taiwan Strait. The Backbone Range is covered by Eocene-Miocene outer shelf to slope deposits, which unconformably overlie the Cretaceous basement (Chen, 2016). The geologic map around the Ilan Plain shown in Fig. 1 is adapted from Lin and Lin (1995). The stratigraphic unit exposed in the Backbone Range is the Lushan Formation, which consists basically of slate of middle Miocene age. In this area, slaty cleavage was well developed in

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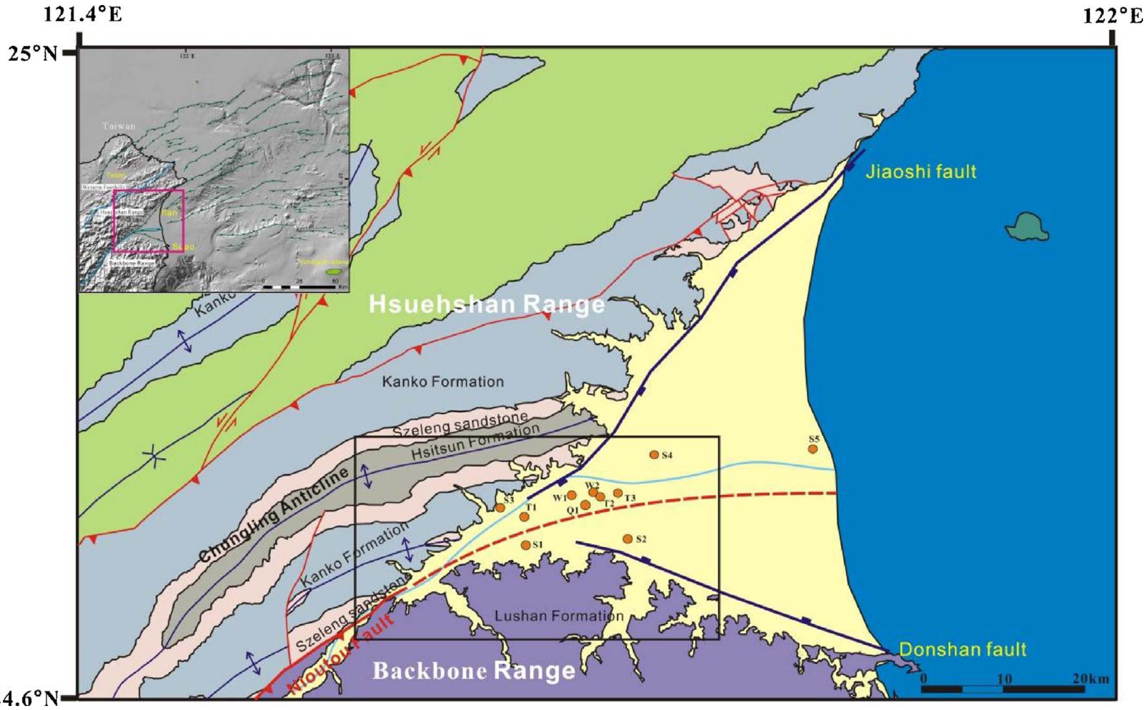

Fig. 1. Geologic map of the Ilan Plain in northeastern Taiwan. The location of the geothermal field is in the black rectangular area. The area of Hongchailin in Sanshin Township is situated at around the apex of the Ilan Plain, south of the Lanyang River. Orange dots represent the wells drilled in this area. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the slate of the Lushan Formation. Stratigraphic units exposed in the Hsuehshan Range consist of the Hsitsun Formation, the Szeleng Sandstone and the Kanko Formation. The above three stratigraphic units are conformably contacted. The Hsitsun Formation consists mainly of silty argillite and fine-grained metasandstone of the Eocene or early Oligocene. The Szeleng Sandstone is basically made up of thick-bedded medium- to coarse-grained metasandstone of the Eocene or early Oligocene. The Kanko Formation consists mainly of argillite or slate of the late Oligocene to early Miocene age in this area (Lin and Lin, 1995). The Quaternary sediments unconformably overlay the underlying metamorphic rocks.

The Hsuehshan Range and the Backbone Range were separated by the Nioutou fault in the mountain terrain west of the plain. The Nioutou fault was more likely a strike-slip fault (Lin and Lin, 1995) or a normal fault (Chen, 2016). The Nioutou fault in the mountain terrain was expected to extend from around the apex of the plain easterly to the ocean and was suspected of being situated at somewhere around the middle of the plain along the Lanyang River. The Okinawa Trough extended westerly into northeastern Taiwan and formed the Ilan Plain. The Nioutou fault could have extended offshore and connected to one of the major normal faults found in the Trough (Ku et al., 2009).

North of the Nioutou Fault, the structural pattern of the Hsuehshan Range was basically controlled by the Chungling anticline (Fig. 1). The Hsitsun Formation is exposed around the axis of that anticline, and the overlying Szeleng Sandstone and the Kanko Formation are sequentially exposed in both limbs of the anticline. Minor folds besides the Chungling anticline are seen as well. As to the Backbone range in this area, the structural pattern was mainly controlled by faults.

Chen et al. (2004) and Shyu et al. (2005) suggested that there should have been active normal faults existing at the northern and southern edges of the Ilan Plain, respectively. The two faults were also buried by the very rapidly accumulating deposits and not exposed (Chen et al., 2004).

The thickest sediment in the Ilan Plain was known to exist at around the middle of the plain (Chen et al., 2004; Su, 2011; Liu, 1995; Chen, 2013; Shih, 2011; Chiang, 1976). In the past few years, many wells were drilled in the plain and showed that the thickness of the sediments in the plain increased in an easterly direction, and the grain sizes of the sediments decreased eastward (Su, 2011). The deepest well was drilled at the mouth of the Lanyang River to a depth of 900 m (well S5 in Fig. 1), but did not yet reach the bedrock. In other words, the thickest sediments should be more than 900 m thick.

Around the apex of the plain, thinner sediments were found from the results of drilling. The locations of the wells are also shown in Fig. 1. Among them, wells S1 and S2 were situated south of the Lanyang River. Well S1 reached slate at a depth of 133 m and well S2 at 188 m, respectively. North of the Lanyang River, wells S3 and S4 reached argillite at depths of 80 m and 165 m, respectively (Su, 2011). A hot spring well was also drilled at the Cardinal Tien Junior College of Healthcare and Management, Ilan Campus (well Q1). This well reached bedrock at a depth of 470 m. More importantly, this well found hot water of 85 °C at a depth of 800 m.

A few shallow wells were also drilled for different purposes in the past 3 years for accomplishing tasks related to the geothermal energy development project. Well T1 was located next to the upper stream of the Lanyang River. This well reached slate at a depth of 260 m and then reached the Szeleng Sandstone at a depth of 400 m. Wells T2 and T3 were located in the middle of the plain, not too far away from well Q1 in the Cardinal Tien Junior College. Well T2 reached slate at a depth of 470 m, and well T3 reached slate at a depth of 520 m. The above results showed that the thickness of the sediments increased from the apex of the plain in an easterly direction, and decreased from the middle of the plain to the edges of the deltaic plain.

Two deep exploration wells (W1 and W2) were also drilled for the geothermal energy development project south of the Lanyang River. The depths of wells W1 and W2 were 2250 m and 2500 m, respectively. Well W1 reached slate at a depth of 325 m and the Szeleng Sandstone at a depth of 1280 m. Well W2 reached slate at a depth of 470 m and the Szeleng Sandstone at 1340 m.

Rock fragments of slate were recovered from all of the wells W1, W2, T1, T2, and T3. However, whether the slates at some critical depths were affiliated with the Hsuehshan Range or the Backbone Range was