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Geochemical fluid characteristics and some findings of tracer tests in the Ilan Geothermal field, Taiwan

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ABSTRACT

Three wells drilled at a depth of about 1500 to 2800 m in metamorphic slates for National Energy Project (MOST-NEP-II), initiated in 2014, in the site of Ilan, Taiwan with the aim of establishing an Enhanced Geothermal System (EGS) power plant. To improve the understanding of well injectivity and the quality of interwell connections, a single-well tracer test was conducted at well JY-01 in 2015 and 2016 and a six-month cross-hole tracer test in 2017 between the injection well HCL-2 and the production well JY-01 was carried out. Those tests are mostly experimental nature. Two separated deep flow channels were identified by both geochemical fluid characteristics and results of tracer tests. In addition, it shows that a strong groundwater flow exists at depth 1500m and below.

1. INTRODUCTION

The exploration of geothermal resources in Taiwan can be traced back to the 1970s. A 3-MWe geothermal energy power plant was installed in Chingshui, Ilan in 1981, but it was shut down due to the deterioration of efficiency in the early 1990s (Yang, 2015) mainly due to scaling. A 5-year National Energy Program-Phase II (NEP-II) was launched in 2014 to resume the development of the potential geothermal energy in Taiwan with the aim of establishing an Enhanced Geothermal System (EGS) power plant.

The Single-well Injection and Withdrawal(SWIW) method involves rapidly injecting a given volume of traced water near the borehole. Water then is pumped back after a waiting period and the tracer concentration in the pumped water is recorded and analyzed (Neretnieks, 2007). SWIW tests have also been performed extensively to study the dispersion of non-sorbing and interaction of sorbing tracers with the rock fractures in geothermal related fields (Altman et al., 2002; Ghergut et al., 2009). On the other hand, an interwell test involves at least a pair of injection well and production well or even involves one or more injection wells and maybe multiple extraction wells with single pair tracer combination or multi-pairs of tracers.

Rose (1998) proved uv-fluorescent polyaromatic sulfonates to be excellent tracers in geothermal reservoirs because they are environmentally benign, very detectable by fluorescence spectroscopy, affordable, and thermally stable. Naphthalene sulfonates, a subset of the polyaromatic sulfonates, have been used extensively as tanning agents, cement dispersants, and intermediates in the synthesis of dyes. Rose (1998) first successfully used the polyaromatic sulfonate 1,3,6,8-pyrene tetrasulfonate as a tracer at the Dixie Valley, Nevada geothermal system. Naphthalene sulfonates were subsequently used at other geothermal sites (Rose et al., 1997; 2001; 2002). Since polyaromatic compounds are strong absorbers of ultraviolet light, they can be easily analyzed by high performance liquid chromatography (HPLC) with uv-absorbance detection (Rose et al., 2001) with excellent detection limits of less than 0.1 ppb by standard HPLC and fluorescence detection methods. Naphthalene sulfonates have been successfully developed in the laboratory and demonstrated in liquid-dominated geothermal reservoir field experiments to be thermally stable and resistant to adsorption on geothermal reservoir rocks possessing negative surface charges (Rose et al., 2000; Rose et al., 2001; Rose et al., 2002). 2,6-nds and a reversibly adsorbant tracer, Safranin O and Amino G, were used in a test in the Ilan geothermal field using SWIW and interwell tests.

1.1 The study area

Located in the Ring of Fire (circum-Pacific belt,) Taiwan possesses rich geothermal resources due to not only volcanic activities but also dynamic plate collision. These activities are particularly pronounced in northern Taiwan which belongs to a collapse/subduction zone based on geophysical data and regional tectonic models (Huang et al., 2000). The study area, the Ilan geothermal field, is located in northeastern Taiwan with a triangular shape (Fig. 1) and with an active volcano, Turtle Island, to the east off the coast. The Xueshan Mountain Range, a thick continuous Eocene to Miocene succession (Teng et al., 1991), lies to the north and west of the plain; and to the south is the Backbone Range, a tectonized pre-Tertiary basement (Tananao Schist) and a metamorphosed Cenozoic sedimentary cover. There are three major fault systems, Kengsi, Zhuoshui, and Sanxing, from North to south in the Ilan Plain area. They are, however, all covered by hundreds of meters of Holocene alluvium sediment including gravel, sand and mud. The Zhuoshui fault could be the boundary between the Xueshan Mountain Range and the Backbone Range in the study area. The Lushan Formation is composed of argillite and slate from the Miocene age in the Backbone Range. However, the sequence lies Kankou Formation, Szuling Sandstone and Hsichun Formation from the Eocene to Oligocene periods in the Xueshan Mountain Range on the other side of the fault (Fig. 1). A volcanic intrusion along the Zhuoshui fault system inferred by magnetic anomaly could be the major heat source of the study area (Chiang et al., 2008).

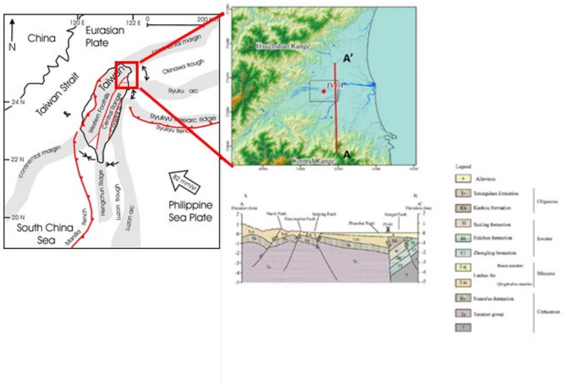

Figure 1: The location map of the study area, Ilan, Taiwan. The first testing well, JY-01 is located on the bank of the Lanyang River near Sanxing Township and in the vicinity of Zhuoshi Fault which is considered the major heat source conduit. AA' profile represents the north-south cross-sectional geological structure of the area.

2. RESULTS AND DISCUSSION

Three field experiments were carried out by SWIW with 10-day, 3-day and 14-day shut-in periods, respectively. The combination of 2,6-nds and Safranin O was used for the first experiment, with a 10-day shut-in period, and resulted in a double peak breakthrough curve (Fig. 2a). The combination of 2,6-nds and Amino G were used for a 3-day and 14-day shut-in period. Two different breakthrough curves, single peak and curves without any peaks, were observed (Fig.2band c) from the experiments of a 3-day and 14-day shut-in period. A preliminary result of an inter-well experiment also reported in this paper.

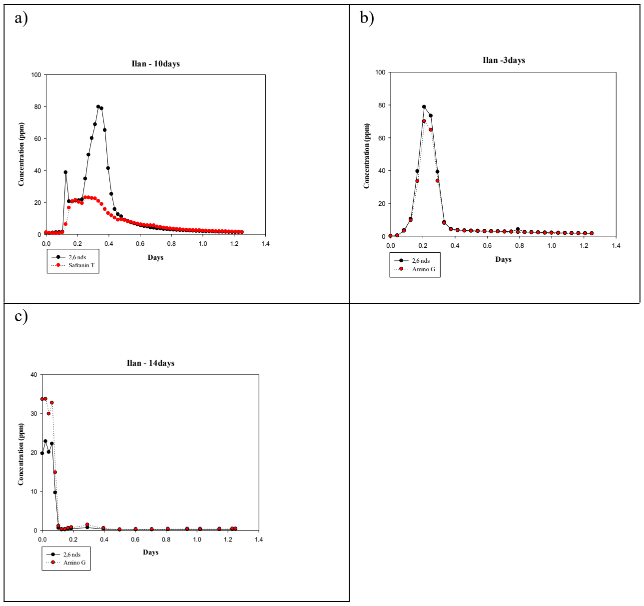

Figure 2: Breakthrough curves of SWIW experiments with different shut-in periods,10 days, 3days and 14days. The red dots with dash line represent concentrations of conservative tracers (Sarfmin O and Amin G) with time while blue dots represent 2,6nds concentrations with time.

2.1 The 10-day test

The combination of tracers, 2,6-nds and Safranin O, mixed with 25 m^3 chaser was pumped into the 1500 m well, JY-01. The duration of shut-in,10-day, was selected arbitrarily at the beginning. Water was then pumped back for 30h continuously with a constant flow rate at 1.2 m^3/h. Water samples were collected at a frequency of one sample every 30 min. Fig. 2a shows the breakthrough curves of 2,6-nds and Safranin O of the experiment. The first peak of the conservative tracer arrived at 3 h after withdrawal started with concentration 38.74 ppm. In contrast, the first peak arrival of the reactive tracer was one hour later than the conservative tracer with concentration 20.65 ppm. An interesting second peak of the conservative tracer appeared at 8h after withdrawal started with concentration 79.80 ppm, and the second peak of the reactive tracer was also observed at 6 h after withdrawal started with concentration 22.95 ppm. The concentration of the second peak was even higher than the first one for both conservative and reactive tracers. The mass recovery rate of the conservative tracer, 2,6-

nds, was 41% while reactive tracer, Safranin O, was 22% (Table 1). The recovery rate of conservative tracer being much less than 100% may imply the influence of groundwater flow.

2.2 The 3-day and 14-day tests

A three-day shut-in period and using the combination of 2,6-nds and Amino G tracer test were performed with the same amount of chaser and of manner sampling, at WellJY-01. A single peak breakthrough curve was observed resulted from the test. The arrival of the conservative tracer, 2,6-nds, peak was observed at around 5 h after withdrawal started with concentration near 78.76 ppm, while the peak of the reactive tracer, Amino G, arrived almost at the same time with concentration near 70.04 ppm. The separation between 2,6-nds and Amino G was rather insignificant, indicating that insufficient reaction took place between the reactive tracers and the ambient rocks perhaps due to lack of time to react. The mass recovery rate of the conservative tracer, 2,6-nds, was 44% while reactive tracer, Amino G, was 39% (Table 1). The recovery rate of conservative tracer was also much less than 100%, possibly implying the existence of groundwater flow. In addition, the mass recovery of Safranin O was 22 for 10-day shut-in compare that with 28 for 14- day shut-in for Amino G. It suggests that Amino G reacts as well with metamorphic rocks at lower temperature as it does in the lab.

The third experiment took place on April 21, 2016 with a 14-day shut-in period and the combination of 2,6-nds and Amino G with the same amount of chaser and of manner sampling. Breakthrough curves without peaks were found for both conservative and reactive tracers (Fig. 2c). The breakthrough curves declined from the highest concentration all the way down to the baseline for both conservative and reactive tracers. However, the highest concentration of reactive tracer, Amino G, 33.67 ppm, was higher than conservative tracer, 2,6-nds, 19.75 ppm. This may indicate reactive tracer, Amino G, reacted properly with the ambient rocks during this experiment while the conservative tracer was not properly presented. This implies that other processes could have been involved in producing the three types of breakthrough curves from the experiments. In addition, the mass recovery rate of the conservative tracer, 2,6-nds, was 18% while reactive tracer, Amino G, was 28% (Table 1). The recovery rate of conservative tracer was surprisingly less than 100% and much less than the previous tests. The existence of in situ groundwater flow was evidenced.

A heterogeneous groundwater flow conceptual model was proposed to incorporate the three types of breakthrough curves (Fig. 3). The solution of tracer propagated as a circle outward when tracers were pumped into well JY-01. The plume circle was influenced by groundwater, resulting in skewing of the circle in one direction instead of outward like a circle as had been assumed. The groundwater flow should be from west to east in this case. The longer the tracer stayed in the aquifer, the more severe the skewing of the circle became (Fig. 3). The single peak breakthrough curve as the result of the Jan., 2016 experiment represents the tracer plume skewing outward but still pretty much in the shape of a circle, so concentrations of tracers withdrawn from all directions retained relatively high concentration of both reactive and conservative tracers. With the reactive tracer interacted with the ambient rocks more as time passed, the circle of tracer plume moved outward and flowed toward one direction gradually. When the withdrawal processes started, the near ring of the plume came back first and then was followed by the farther one, resulting in a double-peaked returned curve as we observed. On the other hand, the no peak breakthrough curve could be explained as the plume having been carried away beyond the withdrawal capability to reach the farther ring. When tracers stay in the reservoir long enough, the reactive tracer can have enough time to react with rocks, resulting in higher concentration in the returned curve than the conservative one. This concept is also supported by the higher mass recovery rate of reactive tracer than the conservative one in the third experiment.

Table 1. Estimation of the recovery rate of tracers of the field experiments

Shut-in	Tracer	Recovery Rate (%)
3-Day	2,6 nds	44
	Amino G	39
10-day	2,6 nds	41
	Safranin O	22
14-day	2,6 nds	18
	Amino G	28

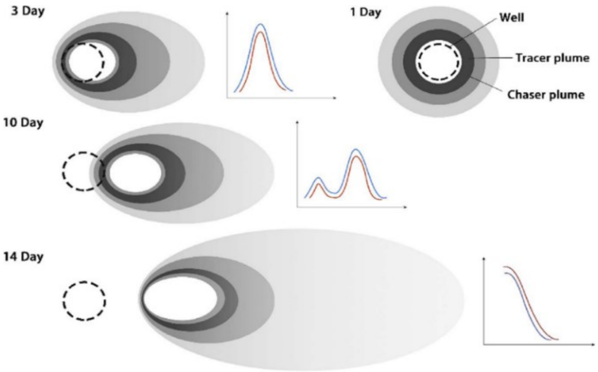

Figure 3: A conceptual model for in situ heterogeneous groundwater flow. The plume circle was influenced by groundwater flow resulting in skewing of the circle toward one direction instead of outward like a circle. The longer tracers stay in aquifers, the greater the skewing of the circle will become.

2.3 An inter-well experiment

50kg of 2,6nds and Amino G were well mixed at water tank before pumped into injection well followed by 150m^3 chaser. The interwell experiment was conducted at HCL-2 and sampled at JY-01(Fig.4). Water samples were taken at two different outlets of Well JY-01 due to the in situ measurements indicates two possible separated deep flow channels may exist (Fig.5). The sampling frequency is set to be once per week.

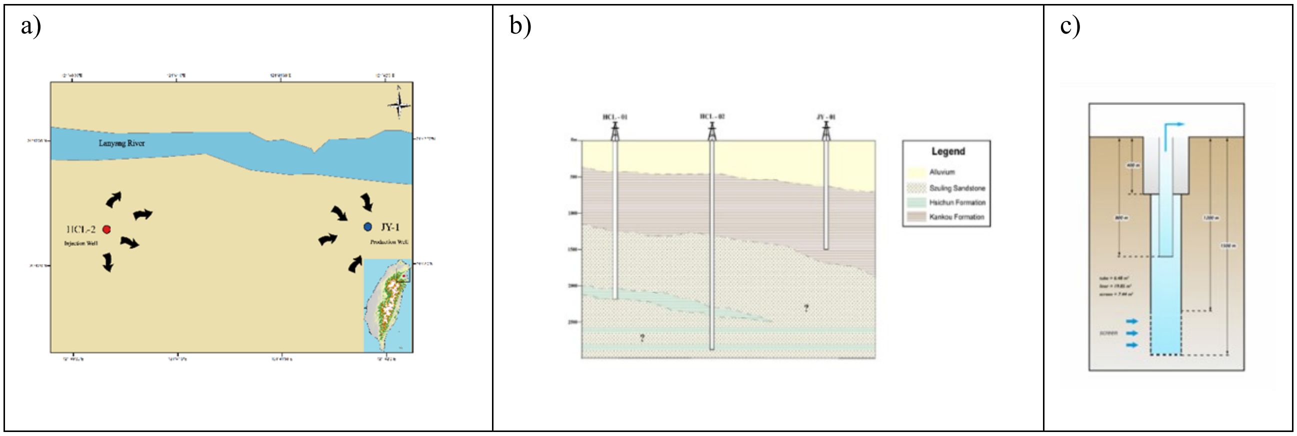

Figure 4: a) The location map of interwell tracer experiment with injection well and receiving well. b) cross-sectional map of the experiment and c) the configuration of the receiving well, JY-01.

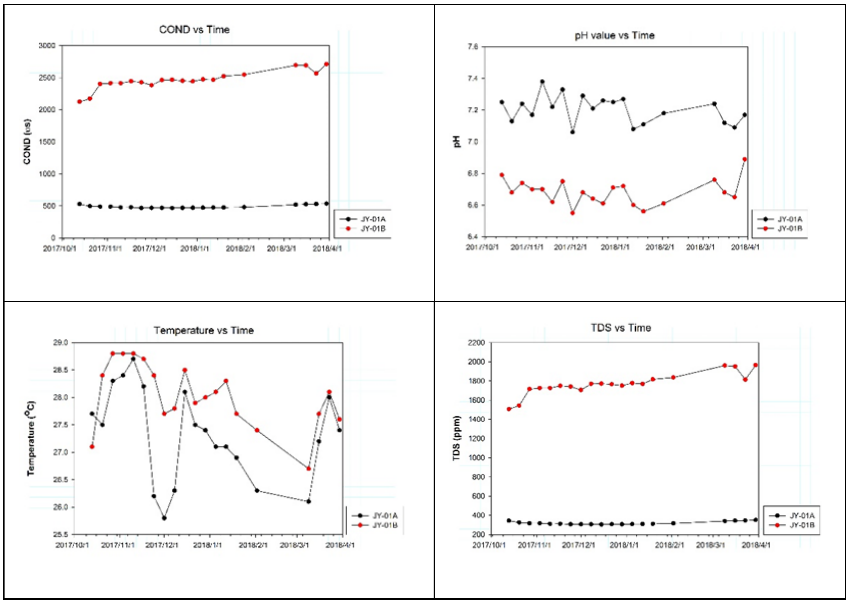

Figure 5: In situ measurements including conductivity, pH temperature, and TDS indicates two separate aquifers at 700 and 1500m.

The preliminary result shows no tracer observed/received at 700m screen but at 1500m and it may indicate that there are two different water flow channels in the bed rock and support the result obtained from single well experiments.

3. SUMMARY

Three different breakthrough curves, i.e. a single peak, a double peak and a curve without peak, were observed in the field experiments which were conducted under different shut-in periods with various combinations of tracers. A conceptual model explains the existence of a strong in situ groundwater flow at the depth of 1500 m with assistance of mass recovery rate. Groundwater flow at such a depth is rare and unexpected. An interwell tracer tests were conducted and resulted in support the idea of strong groundwater existence.

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