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Characterizing Reservoir Dynamics Using Hydrochemical and Structural-Geological Data in a High-Enthalpy Geothermal System, Indonesia

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ABSTRACT

Aim of this study is to provide a recent reservoir characterization with a focus on the dynamics of a structurally controlled system in a high-enthalpy geothermal field in Indonesia. Combination of hydrochemistry and structural geology allows an integrated view on historical changes in deep reservoir behaviour and surface thermal manifestations as result of 15 years exploitation.

Implemented methods throughout the study include detailed fault surface mapping in the field, analysis of physicochemical properties and major and minor ions.

The combination of recent fault mapping and previous studies confirms the existence of four general fault trends in the area including NE-SW, NW-SE, N-S and E-W. Along these faults and at intersections points surface thermal springs occur, which show physical and chemical evolution over the exploitation time. At present time, spring waters generally turn into more acidic followed by significant changes in physical features (e.g. size, steam fraction). The reservoir fluids generally become more saline nowadays with boiling as a possible reason.

The physical and chemical changes in thermal springs and the deep reservoir indicate recent fluid dynamics in the geothermal system. The exploitation of the system triggers changes of fluid flow pathways, leading to mixing and changing fluid volumes in springs and wells. Observing these processes in a continuous and careful reservoir monitoring is highly important to ensure the long-term sustainability of the system.

1. INTRODUCTION

During utilization, geothermal reservoirs are in non-equilibrium state (Guanghui et al., 2015) and hydraulically in a transient state. The dis-equilibrium is due to a difference between the withdrawal of heat and mass via the wells, and the natural heat and mass recharge to the system. At this stage, the reservoir should be carefully monitored in order to prevent or mitigate undesired changes in the geothermal system. For example, a decrease of productivity as geothermal silica is deposited sealing a permeability zone, etc. Changes in the reservoir can also have a significant impact on the productivity related to pressure drawdown. Besides reservoir size, reservoir storage capacity and water recharge, geological controls and permeability distribution are two crucial factors in geothermal systems (Axelsson, 2008). Understanding the detailed distribution of permeability and structures in relation to reservoir dynamics provides a guidance on reservoir management (Brehme, 2015).

A combined comprehensive understanding of fault structures and a detailed hydrochemical analysis is the main approach presented on this study. The study area is controlled by an active tectonic regime, therefore knowledge on faults and fractures as fluid pathways is essential. This study reviews fault maps from previous research and describes current fault investigations in the study area. Hydrochemical analysis focus on characterizing changes in the fluid chemistry and its relation to rock-permeability.

2. SITE INFORMATION

The geothermal field in this research is located in North Sulawesi, Indonesia and generates 80 MWe. The field is a liquid-dominated system (Koestono, 2010) and separated into two sub-reservoirs (south and northern) (Yani, 2006). Lake Linau as a caldera lake has a main control on the north system by its volcanic activity, while Mount Lengkoan and Kasuratan control the southern system.

3. RESULTS

Fault Analysis

The review on fault investigations has been carried out from various studies (Utami et al., 2004; Koestono, 2010; Brehme, 2015). Four main faults are present in the area trending NE-SW, NW-SE, E-W and N-S; although some of them are still inferred. Therefore, new data were collected in November 2018 to seek confirmation of the inferred faults through field work at 17 locations (signed by red star in Figure 1). The measurements include fault orientation (strike and dip). The study area covers 7.82 km2 with measurement points distributed over this area (Figure 1). The first six observation points were in the west region of the study area, followed by 4 points in the north, 4 points in the east, and 3 points in the south.

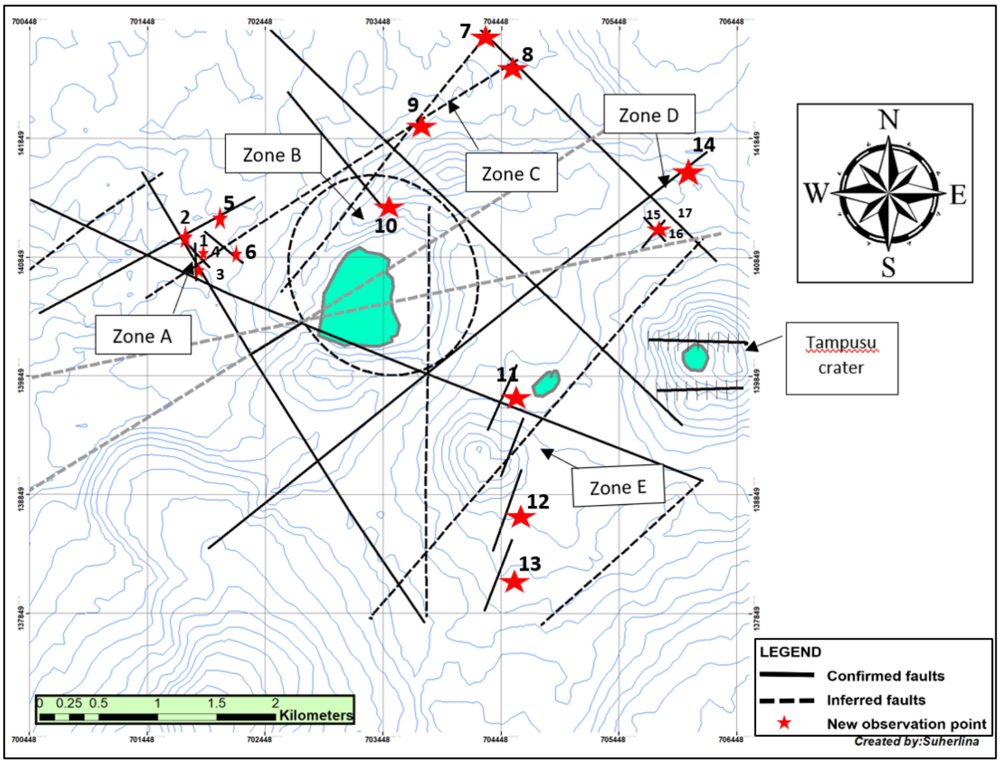


Figure 1: Recent structural map shows the newest observation points of fault measurement (marked by red stars), confirmed and inferred faults by previous and this recent study (black line), and non-confirmed faults (gray line) (source: internal communication with project partner).

Knowledge and understanding of the location and type of faults is improving throughout the different studies by time. The measurements in early studies dominantly used air photography to identify faults at the surface. A detailed geological field survey covering the whole study has been applied in Brehme, 2015. Observed structures are caldera rims, fracture planes, alignments, topography steps, hard-rock exposures, alignment intersections accompanied with thermal springs. These structures indicate the presence of faults.

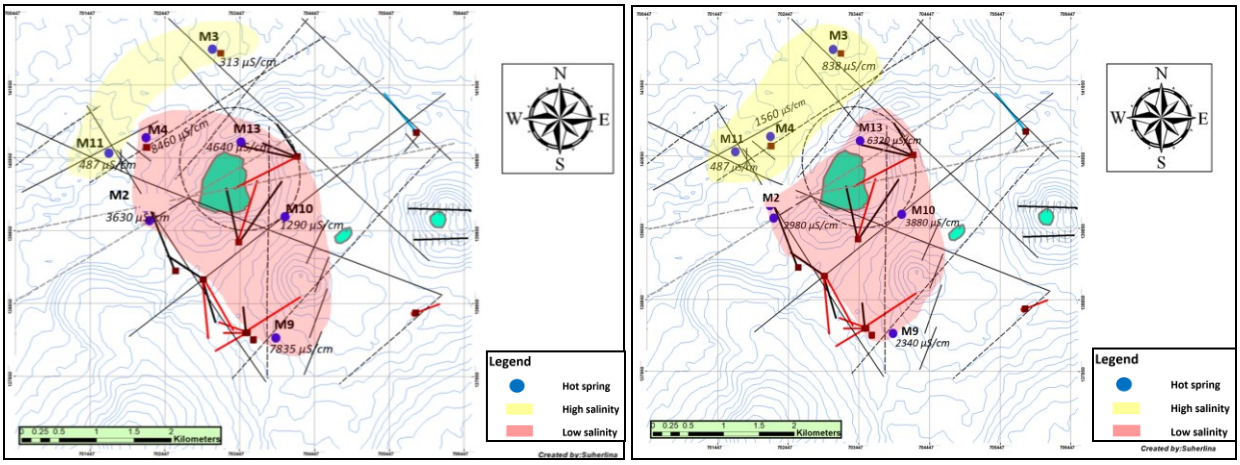
As a main result of this work a new fault map is shown in Figure 1. It confirms four general trends of faults in the study area consisting of: (1) NE-SW, striking 5° to 80°, acting as strike-slip, (2) NW-SE, striking 130° - 170°, dipping 20°, acting as thrust fault, (3) N-S and E-W. According to a previous study, the N-S and E-W faults are normal faults originating from a second faulting phase striking at between 0° and 15 ° and dipping between 78° and 88 ° (Brehme, 2015). The latter fault was observed in Tampusu crater.

This recent study confirms several inferred faults from the older studies. All confirmed faults in the final map (Figure 1) are shown in bold. The dip of some faults still needs further investigation and are labeled with dashed lines. Additionally, the recent study revealed new faults which were not seen in the earlier investigations. Investigating faults in geothermal fields is fundamental to identify possible fluid flow pathways in the system. Although fault measurements were done at surface, we assume that they mostly represent fault orientations in subsurface affecting fluid flow in the geothermal reservoir. Hence, knowing characteristics of the faults can guide us to a proper understanding of the permeability structure of the geothermal area.

Hydrochemical analysis

Physicochemical parameters were measured in situ during a fieldtrip in April 2018 including Temperature (T), Electrical Conductivity (EC), pH and bicarbonate concentration. Additionally, water samples have been taken from wells and hot springs. Mostly hot springs are apparently located near to or on intersection points of fault as shown in Figure 2. The electrical conductivity map shows a clear difference in the spatial distribution between 2012 (Figure 2.a) and 2018 (Figure 2.b), while more saline waters are located further in the northwestern area in 2012. At present time, the high salinity waters distribute only in central and southern parts of the system. The most obvious change in salinity is observed in hot spring M4. Two possible reasons for the changes in chemistry of hot spring M4 are; (1) permeability of fluid pathways in the vicinity of the hot spring has changed due to mineral deposition, (2) fluid composition changed as a response to changing reservoir pressure and an inflow of cold water as it is facilitated by permeable fault nearby M4 at depth or in the very shallow reservoir.

In addition, most of hot springs recently show increasing acidity compared to 2012. One probable reason is an increasing volcanic degassing H_2S generated by volcanoes near to the field. The physical appearance of hot springs changed with respect to size, ebullition, color and water level. The changes are mostly observed in the springs near to or intersected with faults as a permeability provider.



(a) (b)

Figure 2: Comparison hot springs spatially based on electrical conductivity measured in 2012 (a) and 2018 (b) show chemistry change in M4.

The well waters generally show increasing electrical conductivity at recent time. A probable reason is boiling as result of pressure drawdown in reservoir. The increasing pH of well waters over time can be caused by boiling mechanisms, which induce raising pH due to proton consumption leading to loss of carbon dioxide (CO2) (Nicholson, 1993).

The general temporal changes shown in a trilinear diagram for well waters (Figure 3**)** suggest well discharges were acid sulfate-chloride water during 2010-2011. The origin of the sulfate is by oxidation of H_2S into sulfate, sulfate dissolution in rocks followed by oxidation (Armarsson, 2007), or degassing and oxidation of H_2S and SO_2 from active volcanoes surrounding the study area (Surachman et al., 1987). The mixture of acid sulfate-chloride water leads to slightly acidic pH waters in wells during 2010-2011 (Figure 3**)**. The migration pathway of all wells in 2018 to the chloride group indicates the well waters have increasing concentrations of chloride compared to sulfate and bicarbonate. The increasing chloride in the fluid can be due to boiling.

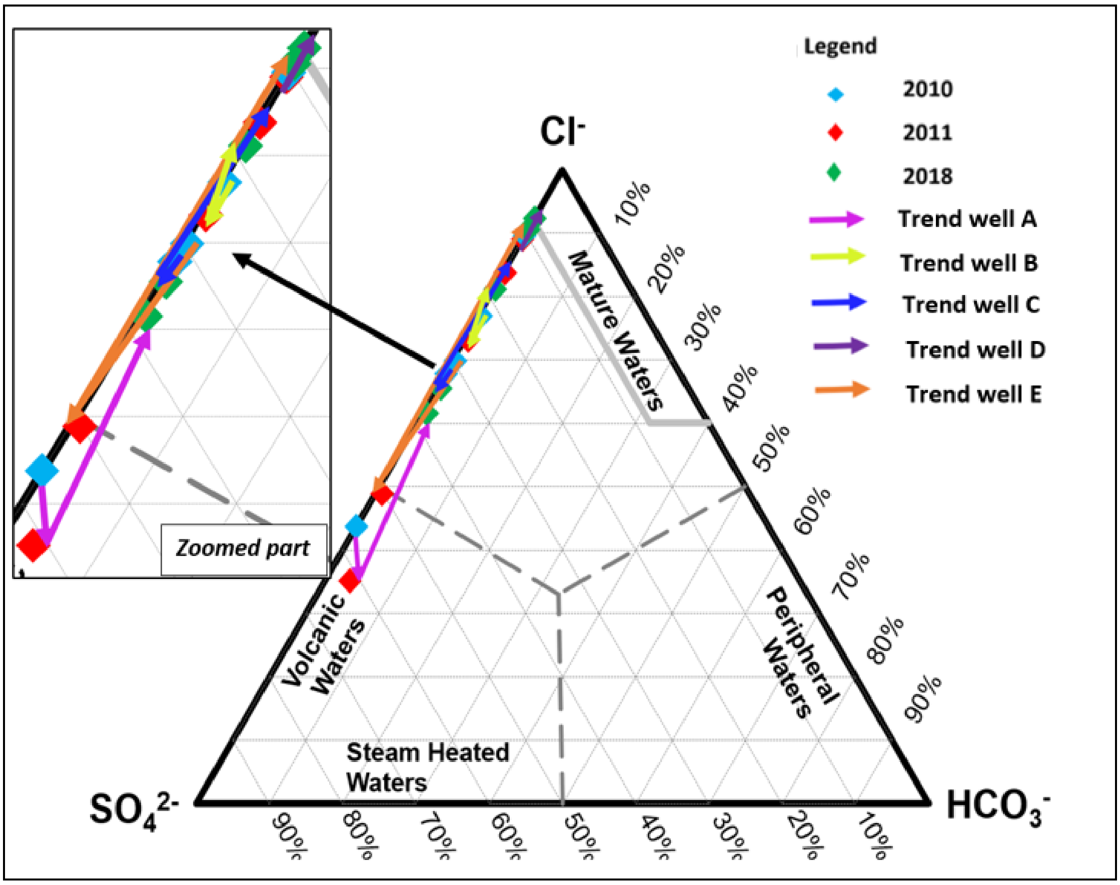


Figure 3: Triangle Giggenbach diagram showing the temporal trends for each individual well between 2010, 2011 and 2018.

4.CONCLUSION

Combining structural geology and hydrochemistry measurements is a successful approach for reservoir characterization and to see the dynamical behavior as reservoir processes in this geothermal system during exploitation. The structural mapping reveals general trends as well as the type of faults controlling the geothermal area. The faults play an important role for the fluid flow system and could be responsible for changes observed in chemistry spring waters, physical appearance hot springs in surface, and chemistry of well waters through permeability changes. More steam in springs recently could be due to boiling, reservoir exploitation and or permeability sealing, which allowing steam rises easily along the faults and appear on the surface (on top of faults). The recent increasing acidity in springs could be due to increasing volcanic degassing H_2S and or reservoir boiling. When fluid in a geothermal reservoir boils due to pressure drawdown, the H_2S travels with steam. This is supported by increased steam fraction in the wells. Increasing chloride in Figure 3 is recently observed as result reservoir boiling occurs in the reservoir. The spatial change of M4 based on salinity could be due to permeable fault presently appears between M4 and M13.

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