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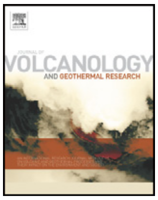

Self-organizing maps in geothermal exploration–A new approach for understanding geochemical processes and fluid evolution

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ABSTRACT

Understanding geochemical processes is an important part of geothermal exploration to get information about the source and evolution of geothermal fluids. However, in most cases knowledge of fluid properties is based on few parameters determined in samples from the shallow subsurface. This study presents a new approach that allows to conclude from the combination of a variety of these data on processes occurring at depth in a geothermal reservoir.

The neural network clustering technique called "self-organizing maps" (SOMs) successfully distinguished two different geothermal settings based on a hydrochemical database and disclosed the source, evolution and flow pathways of geothermal fluids. Scatter plots, as shown in this study, are appropriate presentations of element concentrations and the chemical interaction of water and rock at depth. One geological setting presented here is marked by fault dominated fluid pathways and minor influence of volcanic affected fluids with high concentrations of HCO_3, Ca and Sr. The second is a magmatically dominated setting showing strong alteration features in volcanic rocks and accommodates acidic fluids with high SO_4 and Si concentrations.

Former studies, i.e., Giggenbach (1988), suggested Cl, HCO_3 and SO_4 to be generally the most important elements for understanding hydrochemical processes in geothermal reservoirs. Their relation has been widely used to classify different water types in geothermal fields. However, this study showed that non-standard elements are at least of same importance to reveal different fluid types in geothermal systems. Therefore, this study is an extended water classification approach using SOM for element correlations. SOM have been proven to be a successful method for analyzing even relatively small hydrochemical datasets in geothermal applications.

1. Introduction

Geothermal energy plays a key role for a future energy supply based on renewable resources. In this scope, performance of existing systems should be improved while exploration for new reserves proceeds. These geothermal reserves mainly rely on the temperature and fluid flow in the reservoir: Thus, characterization of these properties is essential to sustainably develop the geothermal reservoir.

Fluid flow in geothermal reservoirs depends on reservoir geology, geometry and permeability. The reservoir temperature depends on the depth or, if existing, the proximity to a magmatic source and classifies the system into low-, intermediate- or high-temperature resources (Hochstein, 1990). Altogether, the hydrogeological setting, temperature and magmatic influence define the chemical characteristics of geothermal fluids. Comprehension of fluid properties is an inherent part of geothermal exploration. However, knowledge is in most cases based on shallow subsurface data (Nicholson, 1993). That limits the understanding of processes occurring at depth, which could reveal the source and evolution of geothermal fluids.

Traditional approaches for understanding deep fluid evolution are e.g. geothermometers or triangle plots of chemical elements. The principle of geothermometry is based on the assumptions that rapid fluid ascension along fault structures, without mixing with other waters, would preserve the temperature dependent fluid composition (Nicholson, 1993). Reservoir fluid temperature can be estimated from different ion concentrations, such as silica concentration or sodium/potassium ratio that serve as traditional geothermometers (e.g. Fournier, 1989). In addition, anion relations of chloride, sulfate, and carbonate may give indications about the distance to the source of a geothermal fluid from the heat source (Giggenbach, 1988).

However, the potential use of many ions or ion ratios as indicators of fluid temperature or fluid source is still unknown. Understanding the source and evolution of fluids in combination with deep fluid flow pathways in geothermal systems is important for drill site selection. Therefore, new approaches are needed to obtain a better understanding of deep-seated hydrogeochemical processes.

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In this study a neural network clustering technique called "self-organizing maps" (SOM) was applied using ion concentrations and their correlations from a geochemical database for understanding fluid source and pathways. SOM can identify relationships and patterns in multidimensional data sets without including external information such as reservoir geometry or evolution (e.g., Manukyan et al., 2012). Therefore, the method is also known as "unsupervised pattern recognition" (Kohonen, 2001). SOM can be utilized in solving pattern recognition and classification problems for a wide range of applications in geosciences (e.g., Penn, 2005). In geothermal exploration SOM were recently introduced as a tool to support the combined interpretation of different geophysical data sets (Bauer et al., 2012; Muksin et al., 2013a; Pussak et al., 2014). Another application in recent studies is on environmental and ecological problems, such as groundwater quality (Choi et al., 2014; Hong and Rosen, 2001). To our knowledge, the SOM technique has never been applied for the analysis of hydrochemical data in the context of geothermal exploration.

In this study comprehensive hydrochemical data from two geothermal fields in Indonesia were used as examples. Samples have been taken from springs, surface water and wells in the Lahendong area in North Sulawesi and from springs in the Sipoholon area in North Sumatra. The idea is to compare these geothermal fields, which represent two different geological settings, with respect to the geochemical composition and evolution of their fluids. Lahendong is a magmatically controlled geothermal field, while Sipoholon is strongly influenced by the Sumatran Fault. The main question is how the geological setting is traceable with hydrochemical data. In other words, what does the hydrochemical pattern of a system tell us about fluid source, evolution and flow pathways in the subsurface?

The aim of this study is 1) to prove SOM as a successful method for analyzing hydrochemical datasets in geothermal applications and 2) to show that hydrochemical patterns reveal insights into geothermal fluid evolution and flow pathways.

2. Geological setting

2.1. Introduction to the Sipoholon field

Sipoholon (SIP) in North-Sumatra is a medium-temperature (<175 °C) geothermal prospect area in North Sumatra, 35 km southeast of Lake Toba at 900 m asl (Fig. 1, Hochstein and Sudarman, 1993; Nukman, 2014). The area is dominated by the NW-SE striking Sumatran Fault (SF) and associated tectonic elements (Fig. 2). Along the SF, a series of graben structures (e.g. the Sarulla graben) and pull-apart basins (e.g. the Tarutung basin) were formed in response to step-over of fault strands at segment boundaries of the fault system (Sieh and Natawidjaja, 2000). The co-existence of pull-apart basins and large caldera structures was discussed as an expression of the interplay between volcanism and tectonics along the Sumatran Fault (Bellier and Sébrier, 1994). Interestingly, the geothermal site of Sipoholon is located at the intersection between the Tarutung pull apart basin and a caldera-like structure located at the NE side of the basin. The caldera-like structure was also mentioned by Nukman and Moeck (2013). However, its morphology is weakly expressed. In fact, a recent ambient seismic noise tomography study revealed a low velocity anomaly at this location, which was interpreted as the seismic expression of a hidden caldera (Ryberg et al., 2016). These authors speculate that the interplay of the caldera with the tectonic activity around the Tarutung pull-apart basin is the major controlling factor of the geothermal system in Sipoholon.

Topographic highs are Martimbang volcano (Fig. 2) and a mountainous ridge in the W. Main geological units are meta-sedimentary rocks (crystalized limestone, sandstone, quartz-arenite), metamorphic (phyllite) and volcanic rocks (andesite, pyroclastics, tuff, granite). Basins are commonly filled by the pyroclastic fall from Toba volcano and alluvial sediments. The topographic structures also control the regional fluid flow direction, which is assumed to be from the mountainous ridge (NW) towards the Tarutung basin (SE) and from NE towards the basin (SW).

Recent structural-geological studies show a prevalent fault network oriented along the right-lateral SF. Fault parallel strike-slip faults and orthogonal normal and thrust faults dominate the local fault pattern (Fig. 2). Hot springs of varying sizes issue along these faults (Muksin et al., 2013a, 2013b, 2014). Along the eastern Tarutung basin, huge fractured travertine areas give rise to chloride and carbonate rich springs where high discharge rates and CO_2 degassing has been observed at several manifestations. Low chloride, sulfate springs occur at the western and northern edge of the study area (e.g. at sample sites H5–8, H18, H19, Nukman and Moeck, 2013; Nukman, 2014).

2.2. Introduction to the Lahendong field

The operating geothermal field Lahendong (LHD) in North-Sulawesi is currently producing about 80 MWe from ten production wells. The site is located at the northeastern tip of Sulawesi near the city of Tomohon about 800 m above sea level (asl) (Fig. 1). The topography is dominated by two volcanoes (Mount Lengkoan, Mount Tampusu, Fig. 3). The crater Lake Linau is situated in the center, while Lake

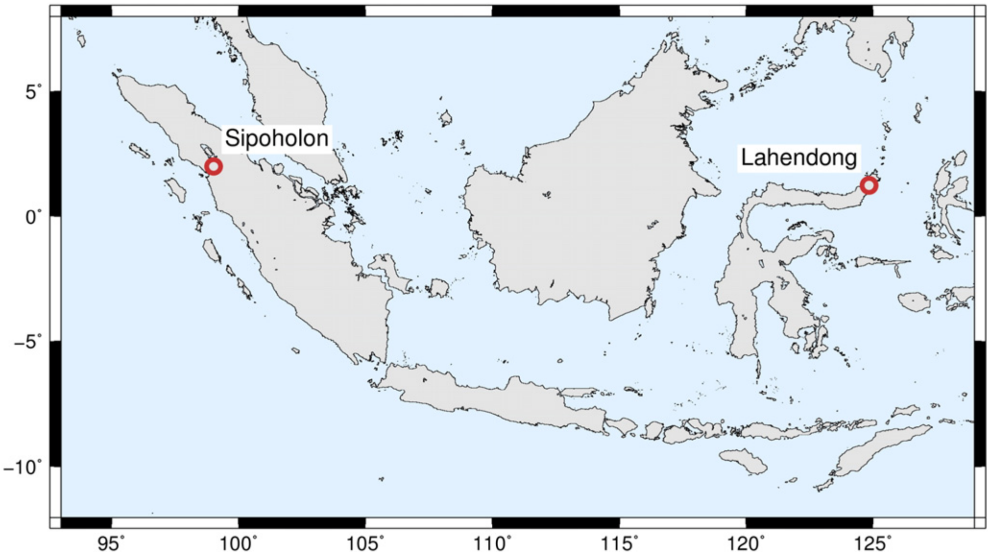

Fig. 1. Location of the two study sites.