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Characterizing permeability structures in geothermal reservoirs – A case study in Lahendong

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ABSTRACT

Subsurface fluid flow of reservoirs in active tectonic regions is mainly controlled by permeability structures, like faults and fractures, in the subsurface. Therefore, the location and characterization of permeability structures is an important step towards estimating the ultimate productivity of a reservoir. Moreover, subsurface fluid flow controls pressure and temperature conditions in the reservoir. In this study, the influence of fault zones on subsurface fluid flow in geothermal reservoirs is investigated using advanced exploration methods including fluid-rock interaction and numerical simulation.

The results show, that the Lahendong, Indonesia, geothermal field consists of two geochemically distinct reservoir sections of which one is characterized by acidic water, considerable gas discharge and high productivity, while the other is characterized by neutral water and lower productivity. The two reservoir sections are separated by faults, which are less permeable across strike than along strike. Hydrochemical studies show, that increased fluid flow in these highly fractured areas enhance, in an alteration stage, chemical reactions resulting in strong induced hydrothermal alteration of surrounding rocks. Numerical simulations result in a detailed permeability and fluid flow pattern for the Lahendong geothermal reservoir. Adjusting model permeability values reveals the location of fractured zones, which have not been traceable in former surface studies. A further result is the subsurface temperature distribution, which suggests convective heat flow driven by fluid buoyancy. This hydraulic gradient causes a pressure drop along the reservoir. High pressure occurs in recharge areas at a foot of a volcano, while discharge is through permeable zones towards hot springs at the surface.

Detailed investigation of subsurface fluid flow in geothermal reservoirs is crucial for sustainable exploitation avoiding drilling into less productive areas. Although the target area is Lahendong, our approaches are applicable for other geothermal sites consisting of similar boundary conditions.

1. INTRODUCTION

The productivity of a geothermal field mainly depends on subsurface fluid flow, which in active tectonic regions is controlled by permeability of fault zones (Moeck 2014). In that frame, the primary focus is on locating and characterizing faulted areas in geothermal fields.

In the past various methods have been presented to investigate geothermal resources. Hochstein (1988) suggests to study surface thermal springs and the geochemistry of surface and groundwater as a first step in reservoir characterization. Further, Cumming (2009) proposes to combine geological observations, analysis of geophysical investigations especially magnetotelluric resistivity, hydrogeological models, and chemical composition of fluids in thermal springs to provide insight into the internal functioning of a reservoir system. Geochemical data are often used as an instrument to interpret the potential of a geothermal field, because they indicate the geothermal field size, subsurface temperatures, and rock compositions (Arnorsson 2000).

Additionally to field methods, numerical models for hydraulic and thermal conditions have been increasingly used to understand the set up and productivity of geothermal systems. A general overview of geothermal models has been given by O'Sullivan et al. (2001). Additionally, there are several sites exemplifying similar characteristics as in Lahendong. The Kakkonda geothermal site, e.g., consists of two reservoirs at various depths with different fluid properties. There, results from fluid flow analysis show the importance of fractures for fluid transport enhancing the recharge or discharge in the reservoir (McGuinness et al., 1995). Generally, faults acting as preferential fluid path ways significantly change the pressure and temperature field in the reservoir (Cherubini et al., 2013). Models for the Seferihisar–Balçova field focus on the fluid flow inside of faults. Results show an enhanced upward heat transport through fluids from bottom of the geothermal system (Magri et al., 2011).

This study presents a three-step workflow investigating the effect of fault zones on behavior of geothermal reservoirs. The fault zones are characterized using various methods designed for hydraulic conductivity determination. First structural-geological mapping, hydrogeological experiments and borelog-analysis have been combined to obtain information on the local fault network, fluid flow as well as pressure and temperature distribution. In a second step geochemistry is used to understand fluid and rock composition, recognition of alteration patterns and numerical simulation of geohydrochemical patterns. The third step presents numerical models, which are developed based on all data gathered during the geological and geohydrochemical investigations. Models reveal additional permeability information in areas, which could not have been addressed in the first steps.

Our test ground is the Lahendong geothermal field located in Sulawesi, Indonesia. The field is owned and operated by P.T. Pertamina Geothermal Energy and hosts a power plant with a production capacity of 80 MWe. There, geothermal exploration started in the early 1970´s including geophysical and geohydrochemical approaches. It is a water-dominated magmatic structurally controlled system. Faults generally act as across-fault fluid barriers and along-fault fluid conductors (Brehme et al., 2014). As a result, hot springs mainly appear on the top of vertically permeable faults at the surface. Available numerous drilling and surface measurements allowed a detailed characterization of the geological and hydrogeological setting of the area (Brehme et al., 2011, 2013, 2014, 2016; Wiegand et al., 2013).

Detailed investigation of subsurface fluid flow is a crucial step for site selection and smart drilling strategies. The studies presented will provide insight into understanding the subsurface fluid flow considering the hydraulic conductivity of faults. It ensures productive as well as sustainable operation of geothermal fields avoiding risks, such as drilling into non-fractured or cold zones, and targeting highly corroding waters. Although the target area is Lahendong, the general workflow is applicable for other geothermal sites consisting of similar constraints.

2. CHARACTERIZING PERMEABILITY STRUCTURES

2.1 By Structural Geology, Hydrogeology and Borehole Data

Structural-geological mapping, hydrogeological experiments and data from borelogs revealed first information on fault location and their permeability characteristics in the Lahendong geothermal field. Mapping disclosed information on fault orientations, discontinuities and joints and location of thermal springs. We measured orientation (strike and dip) of faults and fractures as well as the slip direction (indicated by slickensides). Hydrogeological experiments concentrated on discharge measurements in rivers using tracer dilution method with instantaneous injection. Borehole-data include lithology, temperature, circulation loss zones and hydraulic heads. Temperature and hydraulic heads have been measured before start of production and, therefore, represent initial conditions. The main outcome from structural geological mapping is a structural-geological map showing orientation of faults and fractures, while hydrogeological experiments reveal permeability characteristics of these structures by showing infiltration zones and flow direction of deep groundwater (Fig.1, Brehme et al., 2014).

The main fault strike in the Lahendong geothermal field is in NE-SW orientation. The azimuth is roughly 40° and the dip between 72° and 81° towards SE. Riedel shears and slickensides indicate left-lateral movement along the NE-SW faults. Between the faults dilational step-over regions evolve at left step-over and compressional zones at right step-over zones. Dilational zones are dominated by normal faults, while thrust faults characterize compressional areas. The extensional basin in the middle of the study area coincides with the Linau crater. A second dominating fault pattern is characterized by N- S and E-W striking faults. The strike ranges between 0° and 15°, the dip between 78° and 88° ESE, SSW, respectively (Fig.1). Fractures observed at hot springs and sinters can be assumed to be recently generated and they therefore provide a measure of currently active movements and stresses. Our observations indicate that the fractures mostly develop in a direction of NE-SW, N-S and E-W, and to some extent NW-SE. They correspond to the fault-related stress-regime. Especially, E-W and N-S sinter joints are of a dilative nature and evolve near to hot springs.

Fault evolution is split into two phases based on stress inversion of slip data. A stress tensor with maximum principal stress in N-S direction generated NE-SW striking sinistral strike-slip faults. The pattern of N-S and E-W striking faults might have developed because of a regional uplift and break-up of the shallow crust into orthogonal fault patterns. A local to regional uplift could have been induced by individual magma chambers out of extensive melting processes of the subducted slab below North Sulawesi. Outcrop observations showed N-S striking normal faults cutting across NE-SW striking lateral faults. Therefore, we conclude that N-S and E-W striking faults are younger than the NE-SW oriented strike-slip faults and their accompanying secondary structures.

Local groundwater flow in the Lahendong area is obviously dominated by fault structures. Three independent groundwater systems can be distinguished with an average flow direction from SW to NE. They are separated by impermeable fault structures. In the SE and North of Lahendong groundwater flow is from SW to NE. Beneath Lake Linau the local flow is approximately from W to E. Similar to these areas the Lahendong geothermal field shows different reservoir characteristics in the SW and NE. The NE part shows an average pressure of 117 bar and an average temperature of 237°C at 1700 m bgl (below ground level). On the other hand, the SW is characterized by 121 bar and 319°C at 1500 m bgl.

For understanding hydraulic properties of faults in the Lahendong area, the discharge of rivers and creeks has been measured before and after crossing fault zones. We qualitatively tested if the infiltration into fault zones is an issue at the site investigated. A significant drop of discharge in the vicinity of faults is observed. The water volume in the river decreases by 12L/s while crossing the normal fault SW of Lake Linau and by 5 L/s at the NE fault zone (Fig.1). This infiltration of cold surface water has been also proven by borelogdata. In the NE of Lake Linau temperatures decrease by >50°C in the vicinity of the fault zone. Same patterns have been observed at different faults but in less clear signals (Fig.3).

In summary, information from structural-geology, hydrogeology and borelogdata show, that fault zones can act as hydraulically conductive pathways parallel to the fault strike. Therefore, cold surface water can infiltrate along faults and parallel fractures.

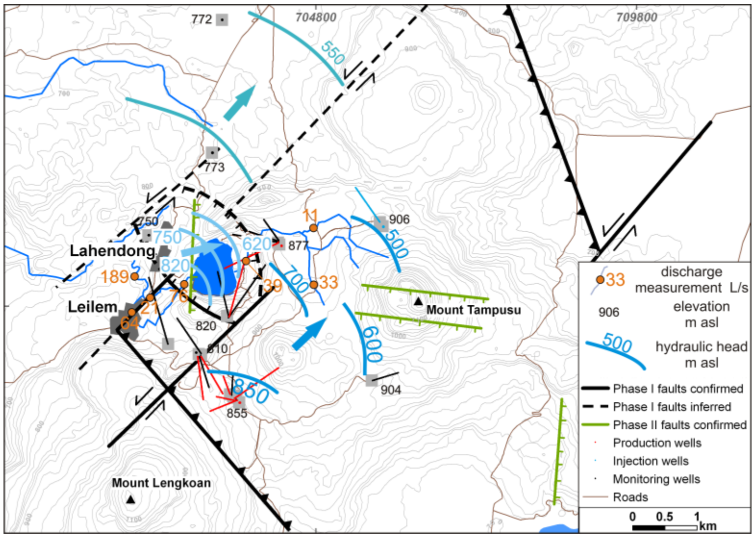

Figure 1: Different groundwater flow systems with hydraulic head distributions dominated by fault structures. Black numbers are elevations of wells where the hydraulic head was measured, to explain the location of artesian conditions. Discharge measurements in rivers with discharge in L/s show water losses in the river across normal faults.

2.2 By Geochemistry

Water samples have been collected from ten ~1800 m deep production wells targeting the reservoir and from eleven hot springs in the Lahendong area. After on-site pH, electric conductivity (EC), temperature (T), and bicarbonate (HCO3) tests, the brine was analyzed on major ions. In general, water from wells and hot springs was found to be either highly acidic (pH of 1.8–3.2) or noticeably closer to neutral (pH of 4.2–7.0). The reservoir waters can be classified as chloride or acid sulphate-chloride types, while hot springs are bicarbonate- or sulphate water types (Arnorsson et al., 2007; Ellis and Mahon, 1977; Nicholson, 1993; Utami, 2011 and White, 1957). Major ions in the acidic reservoir water are Cl, SO4, Na, Si and K, while neutral reservoir water additionally contains HCO3. Main gas phases are CO2 and H2S with up to 355 mmol/kg. At the surface major ions are SO4, Fe, Ca and Si for acid springs and HCO3, SO4, Cl, Na, Si and Ca for neutral springs (Brehme et al., 2016).

The geothermal field is subdivided by impermeable fault zones into two hydrochemical regimes mainly based on temperature, electrical conductivity, and pH of the fluids. High electrical conductivities and low pH characterize the acidic type of waters. On the other hand low electrical conductivities and moderate pH define a neutral type of water. The acidic type of water is found in the wells and hot springs around and beneath Lake Linau, the neutral type of water is observed in the south and northeast of Lake Linau (Fig.2).

Acidic water typically forms as a consequence of H2S degassing from a magma chamber. This takes place after the sulfide oxidizes to sulfate by O2 dissolved in the surface meteoric waters (Nicholson 1993). In the study area, the magma chamber is assumed to be located beneath Lake Linau (Brehme et al. 2014). Here, meteoric water infiltrates through faults and oxidizes the magmatic H2S. This lowers the pH-value and increases the SO4 content.

Rock samples were taken from wellbore-cores, outcrops and areas of hot springs in the Lahendong area. Surface rock samples from outcrops were analyzed by XRD and XRF for their chemical and mineral composition. Special attention was also paid to occurrence of fluid flow pathways in the form of fractures. Results show, that the Lahendong reservoir is predominantly composed of andesite and volcanic breccia with altered and unaltered plagioclase, quartz, epidote, pyroxene and olivine. Pores and fractures within the reservoir rocks can act as fluid pathways but are often filled by secondary minerals. The filling minerals are phyllosilicates (e.g. chlorite and clay minerals) and more abundant in rocks hosting acidic water (Fig.3).

Hydrochemical modeling predicted potential mineral precipitation depending on pressure and temperature conditions. After equilibrating the reservoir water with main gas phases at physical reservoir conditions, muscovite, kaolinite, pyrite, sulphur, chalcedony/quartz, alunite, and gibbsite were found to be supersaturated. When reservoir water was equilibrated with these minerals, only the acidic reservoir water (LHD23) still remained supersaturated with respect to phyllosilicates such as chlorite, chrysotile or talc. Furthermore, the modeling suggests that spring water forms by mixing of high temperature and saline reservoir waters with near-surface low temperature and saline waters.

In summary, rock alteration is mainly controlled by water-rock-interaction in highly fractured and permeable areas accommodating increased fluid flow. However, at a later stage, the alteration process of the host rock decreases permeability again by filling of fractures with secondary minerals. This effect has been indirectly observed in wellbore-core samples of the study area. In faulted areas with high fracture density, fewer cores were available because the reservoir rocks were highly damaged thus limiting core extraction. The few available cores showing alteration were of very low permeability. Secondary mineralization, which fills the fluid pathways in fractured areas, can also clog perforated casings. This may lead to a decrease of well productivity as observed in the Patuha geothermal field (Layman and Soemarinda 2003)—a major risk for geothermal plant operation.

The combination of different geochemical approaches allowed to exemplify the ability to trace fault zone permeability using geochemical "tracers". In areas of extensive fluid flow, such as along permeable fault zones, a distinct change of geochemistry can be observed. Turning this association around, geochemical properties can then be used to locate and characterize fault zones.

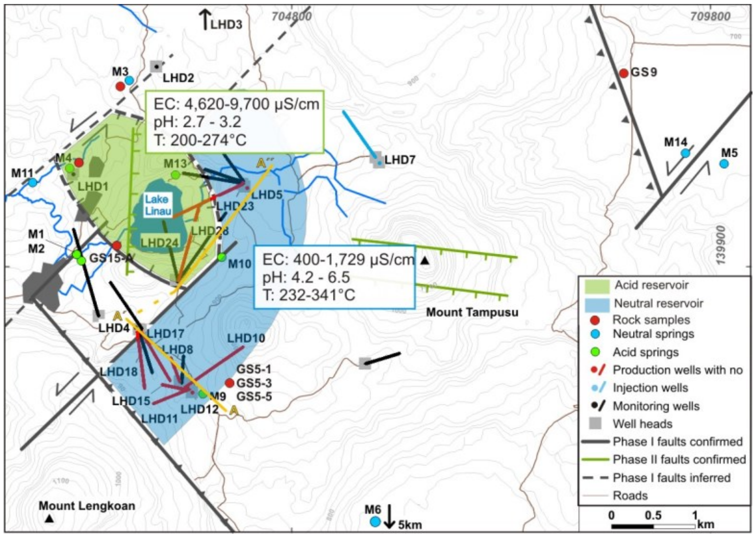

Figure 2: Map of the study area with main faults and hydrochemical characteristics (EC: electrical conductivity, T: temperature). Red, blue, and black lines indicate deviated wells. The yellow line shows the location of the cross section in Fig. 3 (modified from Brehme et al., 2014).

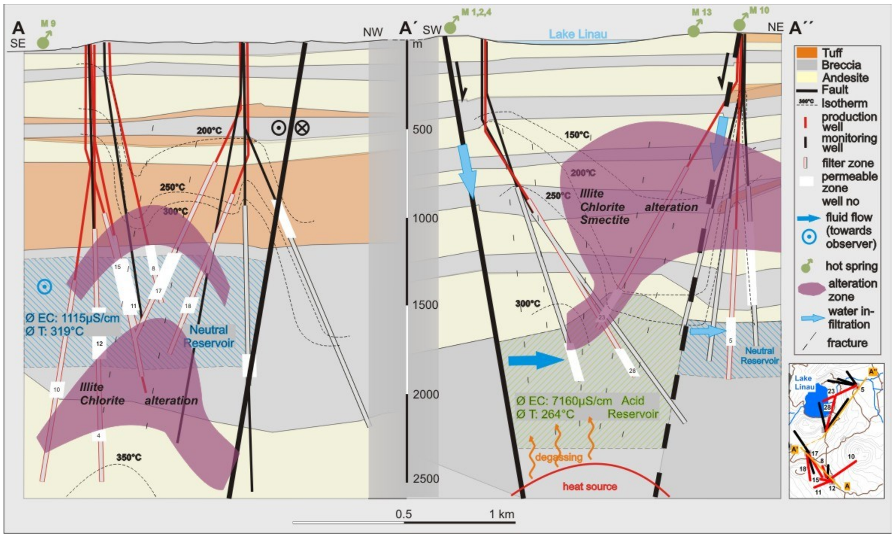

Figure 3: Conceptual geochemical model of the study area, described by cross-sections with geological layering, fault location, temperature distribution, sample points and alteration patterns. For cross section line see Fig. 2 (modified after Brehme et al., 2014 and Utami, 2011).

2.2 By thermal-hydraulic modeling

Thermal-hydraulic modeling of the Lahendong geothermal field aims at understanding the detailed subsurface permeability distribution. The model geometry is a 2D vertical SW-NE trending cross section extending 6 km in horizontal and 3 km in vertical direction. The profile parallel to the groundwater flow direction cuts major faults and wells, which are used for temperature and pressure comparison. Results show pressure-driven and thermally induced fluid flow (Brehme et al., 2016a).

Initial input for models is measured matrix permeability. With an average of 1.5E-14m^2 it remains within typical permeability range of fractured igneous rocks (Schön 2004). However, modeled permeability is generally higher than measured ones in the order of up to four magnitudes. This is due to fracture patterns, which are not detectable at core-sample scale. Furthermore, modeled permeability distribution in the Lahendong reservoir is direction-dependent and overprints the lithology. Permeability in the faults and surroundings is lowest in the study area. There the permeability is by a factor of 10 higher in the vertical direction than in the horizontal direction. In the areas between faults, permeability is in some parts by a factor of 10-100 lower in the vertical direction (Fig.4).

By adapting permeability patterns large-scale structures with high permeability anisotropy could have been located, which have not been known before modeling. Therefore, beneath Lake Linau another fault zone has been added between two known faults with vertical dip and NW strike. This fault has neither been seen in data from former studies nor in the field at surface, because it is covered by Lake Linau (Fig.4). Furthermore, simulated permeability distribution shows the shape of fault zones, which is not necessarily a straight line but actually can have bended shapes (i.e. NE of Lake Linau).

The resulting pressure distribution in the study area is controlled by groundwater flow in low permeable rocks and vertically high permeable fault zones. Isobars drop following the natural hydraulic gradient from SW to NE. Overpressure releases through high permeable zones beneath Lake Linau and discharges towards surface. Temperature distribution along the Lahendong geothermal reservoir suggests convective heat transport in the reservoir rocks. Therefore, isotherms generally follow the SW-NE oriented flow pattern, the rise and infiltration of fluids. Upwelling of isotherms between the faults verifies water rise towards Lake Linau. Infiltration of cold water causes down welling of isotherms particularly on the northeast section of the model (Fig.5).

Iterative matching of measured and simulated temperature and pressure resulted in a good agreement with an average deviation of 1%. Small deviations are caused by small-scale flow processes, especially in faulted and fractured areas not capable by the model. In summary, the most important factors influencing the reliability of numerical reservoir models are absolute and relative permeability. However, a permeability adaptation has been done for each geological layer, the vertical permeability anomalies are overprinting those layers and are constraining the regional groundwater flow. Those permeabilities of fractures directly influences the productivity of the reservoir (Cherubini et al., 2013) . Therefore, the permeability characteristics should be investigated in detail.

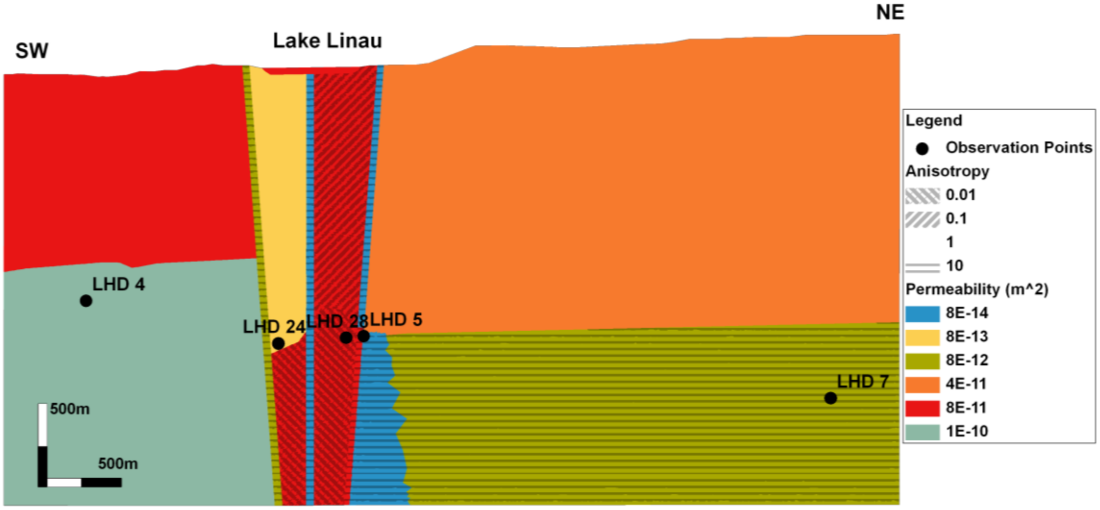

Figure 4: Final adapted permeability and anisotropy distribution throughout the model domain. Anisotropy shows the relation between vertical and horizontal permeability, when >1 vertical permeability is higher

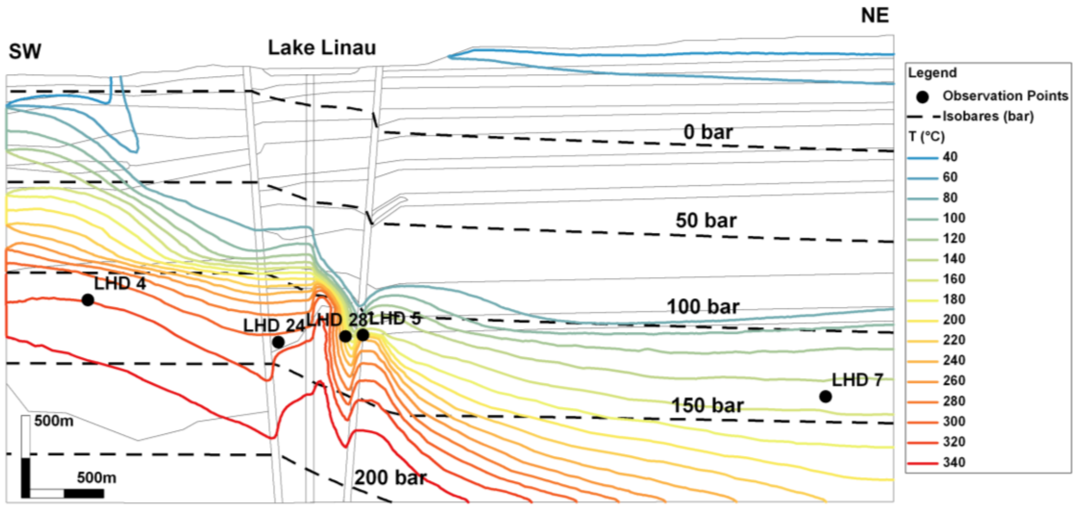

Figure 5: Modeled temperature and pressure distribution in the study area showing high pressure fields in the SW and convective heat transport with rising hot fluids and infiltration of cooler water through faults.

3. CONCLUSION

Results from structural-geological mapping, surface tracer experiments and well-log analysis were combined in a conceptual fault model, which shows that the Lahendong reservoir can be subdivided into different sections. The subdivision occurs at fault zones, which either act as fault-normal flow barriers due to sealing of the fault core, or as conductive pathways in the damage zone sub-parallel to the fault strike. The damage zone, especially in case of extensional faults, is characterized by fractures. Two fundamental phases of faulting have been identified by the structural investigations.

This contribution demonstrates that systematically performed structural analysis helps to understand the fluid flow in geothermal reservoirs. In that frame, present-day stress field analyses provides insights into the hydrogeological role of fault systems. The spatial distribution of structural elements and their temporal evolution has been combined with their hydraulic properties to explain subsurface fluid flow. It has been confirmed that the hydrotectonic concept combining the tectonic and hydrogeological information essentially improves the understanding of subsurface flow of thermal fluids.

Geohydrochemical methods used in this study consist of on-site physicochemical measurements, chemical analysis of fluid and rock samples and verification of those observations by hydrochemical modeling. Those investigations allow characterizing fluid- and rock-composition and the interaction between fluids and rocks. Measurements show that the two reservoir sections reflect different geohydrochemical properties suggesting an horizontally impermeable fault representing a boundary between the different chemical regimes. One section is characterized by acidic water, considerable gas discharge, high productivity and strongly altered and fractured rocks. The other section hosts neutral waters, high temperatures and less altered rocks. These reservoir conditions observed on-site have been confirmed by numerical models.

The results further show that the chemical reactions are mainly controlled by fluid flow through the faults/fractures. Fluid flow increases in fractured permeable areas and causes enhanced water-rock-interaction, which leads in a later phase to decrease of permeability. Hence, evidences for enhanced water-rock-interaction, such as alteration pattern or type and location of hot springs, allow characterizing the permeability distribution along the geothermal reservoirs.

Numerical analysis is performed built on the previously derived conceptual models in order to simulate local permeability distribution using temperature and pressure conditions for model calibration. The main outcome is, that numerical models are able to localize permeability patterns, which have not been known before and are only detectable by such simulations. Thus, a deep-seated fault, that has previously not been traced at the surface could be characterized by the thermal-hydraulic modeling. Furthermore, simulated permeability distribution shows the shape of fault zones, which is not necessarily a straight line but actually can have bended shapes. Generally, vertical and horizontal fluid flow is controlled by fault permeability. This characteristic behavior is used to simulate different reservoir sections with a general fluid flow in SW-NE direction. Recharge and discharge occurs along the faults, especially in the SE and near to Lake Linau.

The main conclusion of this study is that fault zones have an essential influence on geothermal reservoir behavior. Detailed investigation of these structures is a crucial step for site selection and smart drilling strategies. The hydraulic conductivity of fault zones controls the subsurface fluid flow. The proposed workflow is to characterize hydraulic conductivity of fault zones by combining structural geological mapping with hydrogeological investigations. Furthermore, geohydrochemical analysis of fluids and rocks broadens the understanding of flow directions and of quantity of fluid flow while numerical simulations allow predicting the permeability distribution in sparsely sampled spots of the target area. Although the target area is Lahendong, the general workflow is applicable for other geothermal sites consisting of similar constraints.

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