PROCEEDINGS, 43rd Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 12-14, 2018
SGP-TR-213

Natural and Altered Physical Flow Structures in the Earth´s Crust with Applications for Geothermal Energy

Maren Brehme[1], Peter Leary[2], Harald Milsch[1], Sigitas Petrauskas[3], Robertas Valickas[3], Yustin Kamah[4] and Guido Blöcher[1]

[1]Helmholtz Centre Potsdam - GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany,

brehme@gfz-potsdam.de

[2]Advanced Seismic Instrument & Research, 1311 Waterside, Dallas, TX 75218-4475, USA

[3]UAB GEOTERMA, Lypkių g. 17, LT-94100 Klaipėda, Lithuania

[4]Upstream Technology Center Pertamina, Jl. Medan Merdeka Timur no. 6, Jakarta, Indonesia

Keywords: injectivity decline, permeability, field-productivity, well-core, well-logs, spatial correlation, pore clogging

ABSTRACT

Fluid flow in the Earth's crust is controlled by pore-connectivity over scales from mm to km. Micro-scale pore-connectivity structures can appear as fractures on the meso-scale, and at macro-scales they can appear as displacement faults. Whatever their appearance, however, pore-connectivity structures are characterized by a single spatial correlation process attested by well-log spatial fluctuation systematics over the cm to km scale range. The crustal spatial correlation process is seen as 1/k power-law scaling of well-log Fourier power-spectra, $S(k) \sim 1/k$, over five decades of spatial frequency k from 1/km to 1/cm. Because pore-connectivity structures are due to random processes, they are inhomogeneously distributed in space. Power-law scaling spatial correlation means that one cannot meaningfully average pore-connectivity and associated permeability structures within or across geological layers. The effect of spatial correlation from 1/k scaling is apparent in different data related to fluid flow: well-logs, well-productivity, and well-core. Relevant accessible datasets have been analysed from different geothermal fields in the world, e.g. Indonesia, New Zealand, Mexico, Germany and Lithuania.

Measurements of well-core samples show that porosity spatially correlates with the logarithm of permeability. Where porosity is greater, permeability is very much greater due to strongly increased pore-connectivity leading to increased fluid flow. The combined effect of increased porosity and very much increased permeability results in lognormally distributed well productivities, as observed in crustal fluid flow systems across the world. Lognormality is particularly important in convective geothermal fields, where only very few wells give the necessary high flow output while the better part yielding low to moderate outputs are commercially useless.

These natural fluid flow pathways can be altered by effects of field operations. Physical, chemical and biological processes can trigger blocking of natural flow structures and lead to exponentially declining injection curves. Small-scale changes in grain-scale pore-connectivity can lead to a huge negative influence on large-scale sustainability of geothermal systems. That is, strong negative effects caused by field operations flow can be based on the grain-scale connectivity nature of fluid flow in geological media. Such changes can be induced by chemical processes in the reservoir and the plant (precipitation, corrosion). Also, biological reactions can either directly affect the physical flow structure (biofilm) or interact with chemical reactions (triggered precipitation or corrosion). Therefore, it is important to consider the interaction of different processes that occur in geothermal reservoirs. These processes have been observed and analysed at field data from a geothermal plant in Lithuania.

In particular, the observed injectivity decline for a low enthalpy heating plant provides an example of pore-connectivity reduction mechanisms during standard geothermal operations. Both understanding of location and structure of natural fluid pathways and how they can be altered during field operations are of greatest interest for sustainable reservoir management.

1. INTRODUCTION

1.1 Rules for Spatial Correlation of Permeable Structures in the Earth´s Crust

Permeable structures in the Earth´s crust are of highest interest for any kind of reservoir exploitation where fluids are or were involved. Therefore, we have to understand physical rules controlling the interaction between the Earth´s crust and its fluids.

Rule 1) describes the spatial distribution of permeable structures. As permeable structures are void spaces for fluids, they can be easily observed in well-logs which record fluid characteristics. The spatial distribution is described by the expression $S(f) \sim 1/f^n$ where S(f) is the Fourier power-spectrum of a well log, f is the spatial frequency and varies over five decades from 1/km to 1/cm, and n is the scaling exponent. Exponent n would be 0 if permeable structures are uncorrelated and 2 if permeable structures are strongly linked to geological layering. For spatially correlated structures, as observed in the Earth´s crust, $n \sim 1$.

Rule 2) defines the relation between porosity and permeability in any type of rock. This relation can be easily measured in well-cores and is expressed by $\delta\varphi \sim \delta\log(k)$. More precisely, a change in porosity results in a logarithmic change of permeability.

Rule 3) relates the first two rules to fluid flow in permeable structures. Therefore, it can be observed in well-capacities all around the world. This rule describes a more detailed relation of porosity (φ) and permeability (k), $k \sim k_0 10^{\alpha(\varphi-\varphi_0)}$ says that the logarithmic change of permeability as answer to a change in porosity is controlled by a constant factor α. For spatially correlated permeable structures α is observed to range between 30 and 45 for crustal reservoirs with typical fractional porosities $0.1 < \varphi < 0.3$.

The above described phenomena are observed in oil/gas- as well as geothermal fields around the world. Geothermal fields can be further subdivided into Hydrothermal Systems, Geothermal Aquifers and Enhanced Geothermal Systems. This paper focuses on fluid flow characteristics of example sites for Hydrothermal Systems and Geothermal Aquifers.

1.2 Hydrothermal Systems

Hydrothermal Systems are middle to high enthalpy geothermal fields with high temperatures and pressures. Its permeable structures release high amounts of brine and/or steam. Characteristics of permeable structures and its relation to fluid flow in hydrothermal systems is of special interest in hydrothermal systems because porosities are generally low and few permeable structures transport the main flow volume. In such systems, it is important to drill at the right location in order to obtain sufficient production rates. Throughout this study, we introduce and analyze geothermal fields from Indonesia, the Philippines, Mexico and New Zealand.

1.3 Geothermal Aquifers

Geothermal Aquifers are shallow geological structures hosting elevated temperatures in highly porous environments. Compared to Hydrothermal Systems Geothermal Aquifers are characterized by higher porosities due to geological development. One can observe an overprinting effect of geological layers on spatially correlated permeabilities. Nevertheless, the characteristics of permeable structures and its relation to fluid flow is especially of interest for injection scenarios. In particular, if fine particles are injected into few highly permeable flow paths they clog the fluid pathways and force lowering of flow rates. In this study, we show data from a low enthalpy geothermal field in Lithuania.

2. OBSERVATIONS

2.1 Well-logs – Rule 1)

Well-logs provide valuable information of a geothermal field over a great depth range. If the scaling exponent of the Fourier power-spectra of the well-log is ~1, permeable zones are correlated within the spatial frequency of the log. This phenomenon has been observed in various well-logs of georeservoirs, e.g. in the Los Azufres hydrothermal field in central Mexico and in the geothermal aquifer in Klaipeda-Lithuania.

The Los Azufres geothermal field runs since 1982 and has nowadays an installed capacity of >220 MW_e (Negrin and Lippmann, 2016). 39 production wells tap a vapour-dominated reservoir at 240-320°C. Eight different well-logs from one well in the Los Azufres field have been analysed using the Fourier power-spectrum. The average scaling exponent is 1.24±0.2. Effective porosity and Δtime-P have the lowest values with 1.03 and 1.10 most clearly reflecting the spatial correlation of permeable zones. The highest values are seen in the Δtime-St and γ logs (1.41 and 1.57) showing the strongest sensitivity to geological layering (Fig.1). In summary, the well-logs indicate spatial correlation of permeable zones in the Los Azufres geothermal field over four decades from 1/km to 1/m.

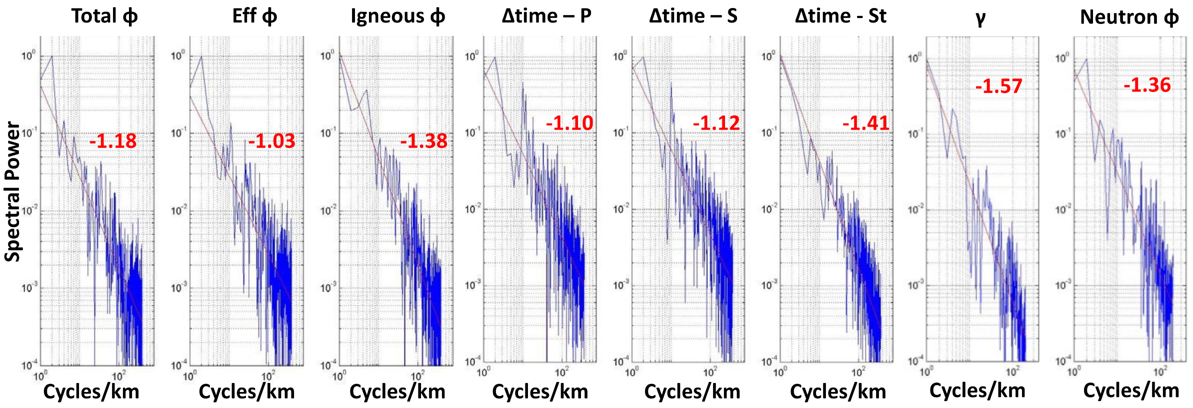

Figure 1: Spectral Power of well logs with scaling exponents from the Los Azufres well 01D. The average scaling exponent is 1.24±0.2 (Leary et al., 2013)

Well-logs from the geothermal aquifer in Klaipeda show similar behaviour in the Fourier power-spectrum analysis. Spectral power-law scaling exponents are determined for porosity-logs in three wells. n is observed to be 0.93 for the porosity-log of well 3P, for well 1I it is 1.2 and for well 4I it is 1.1 (Fig.2). The porosity sequences with 1/fn spatial fluctuation power-law scaling show the spatial correlation nature of the local crustal flow structures.

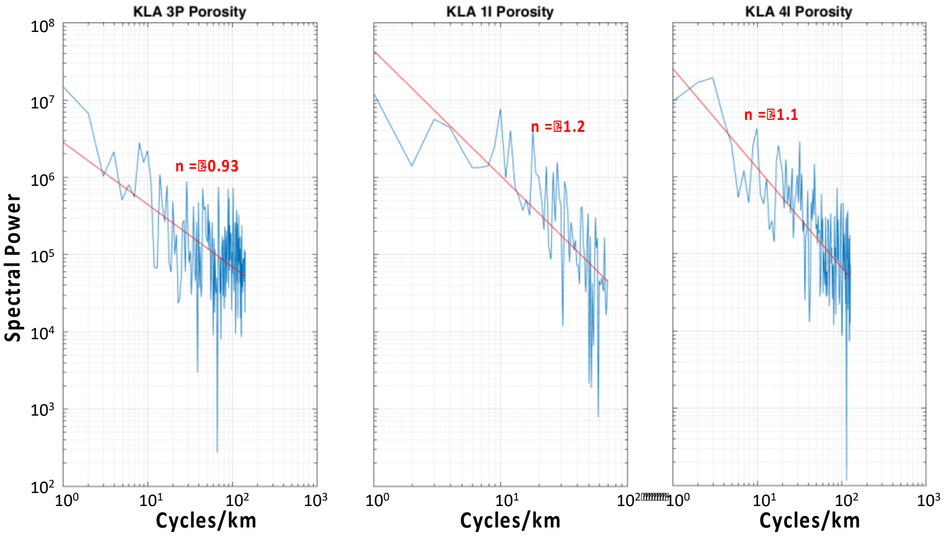

Figure 2: Fourier power spectra of porosity well logs for Klaipeda wells 3P, 1I and 4I

2.2 Well-cores – Rule 2)

Well-core data on porosity (φ) and permeability (k) as well as their relation have been analyzed in many oil/gas and geothermal fields. The general relation is described by $\delta\varphi \sim \delta\log(k)$. Hence, a plot of porosity over log-permeability values would show a strong correlation (Leary et al., 2018). Several examples from georeservoirs show also correlating porosity and log-permeability logs, e.g. in the Bulalo-Phillipines and Ohaaki-New Zealand geothermal field below.

The Bulalo geothermal field in the Philipines is located on the Luzon Island and provides 426 MW_e. Wells target a 260-340°C hot liquid-dominated reservoir at ~2 km depth (Stimac et al., 2006). The Ohaaki geothermal field in New Zealand provides >110 MW_e since 1989. More than 70 wells target a reservoir at 1.4 km depth with 300°C (Mroczek et al., 2016, Kortright, 2015). Porosity and permeability logs show a strong correlation in both fields. High porosity values show a similar peak in log-permeability (Fig.3). Absolute values of porosity range between 5 and 15% in the Bulalo field and 20 to 40% in the Ohaaki field (Fig.4). Porosity data are normally distributed while permeability values show a log-normal distribution. Permeabilities range between E^{-16} and E^{-17} m^2 for the Bulalo field and E^{-14} and E^{-15} m^2 for the Ohaaki field (Fig.4).

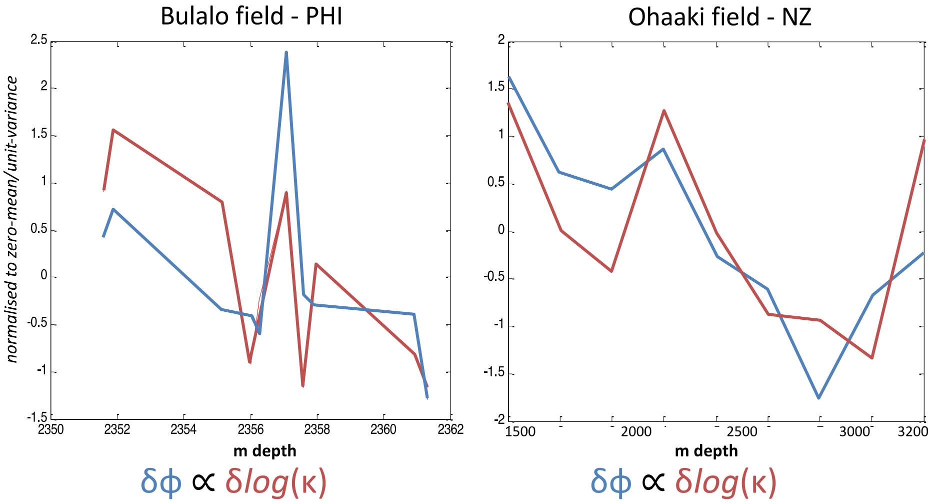

Figure 3: Porosity and permeability well-logs show a strong correlation in the Bulalo-PHI and Ohaaki-NZ field (Stimac, 2007)

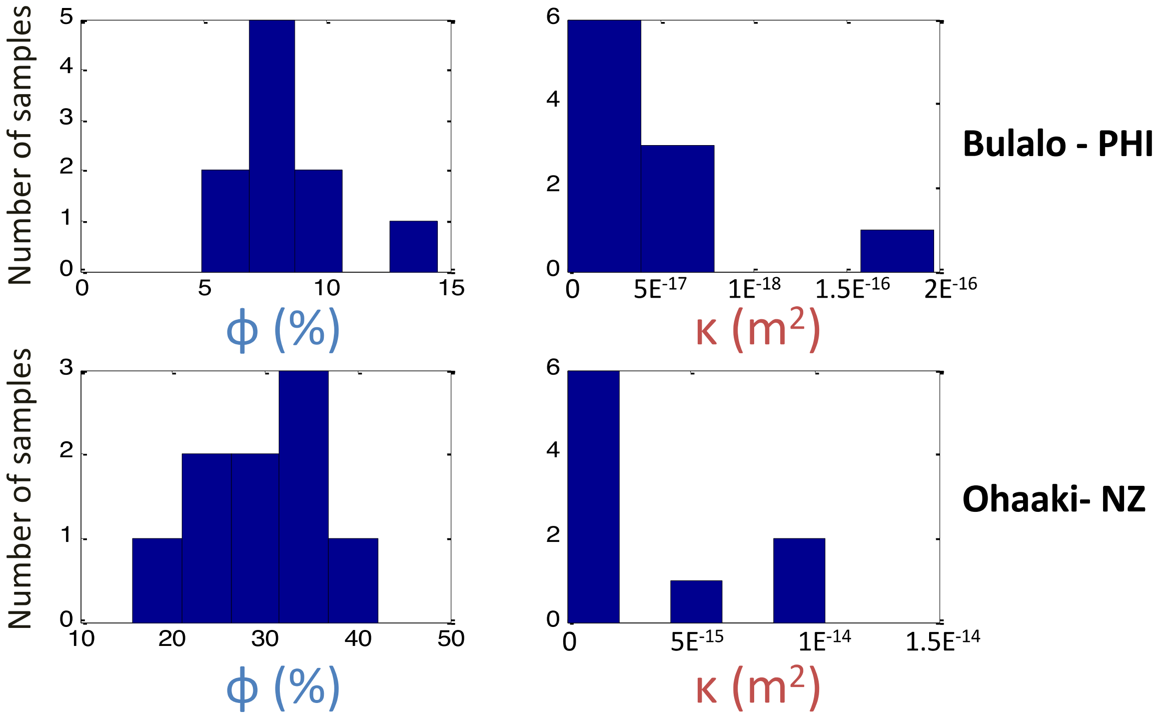

Figure 4: Absolute porosity and permeability values in the Bulalo-PHI and Ohaaki-NZ field

2.3 Well-capacities – Rule 3)

Well-capacities in geothermal fields around the world have been extensively analyzed by World-IFC report (IFC, 2013). Over 2600 geothermal wells are the database for studying successful drilling. Of special interest for this study are well capacities and its drilling history. Well capacities compiled from all studied fields show a lognormal distribution regardless of geological environment. This distribution suggests that most of the drilled wells have low-moderate capacity and only few wells have a high capacity (Fig.5).

Similar behavior is seen in single fields, e.g. the high-enthalpy geothermal field Lahendong in Indonesia. In Lahendong only two wells provide 50% of the total installed capacity (40 MWe). Ten wells were drilled to cover additional 40 MWe. Moreover, the two highly productive wells were drilled after completing nine wells with moderate capacity (5 MWe) and 13 non-productive wells (Brehme et al., 2014, Brehme et al., 2017a).

This statistical distribution of well capacities is a result of the relation between porosity (φ) and permeability (k): $k{\sim}k010\alpha(\varphi-\varphi0)$. Analysis of oil/gas and geothermal fields all around the world show an average α-factor of 30-45 for crustal reservoirs with typical fractional porosities $0.1 < \varphi < 0.3$ (Leary et al., 2018).

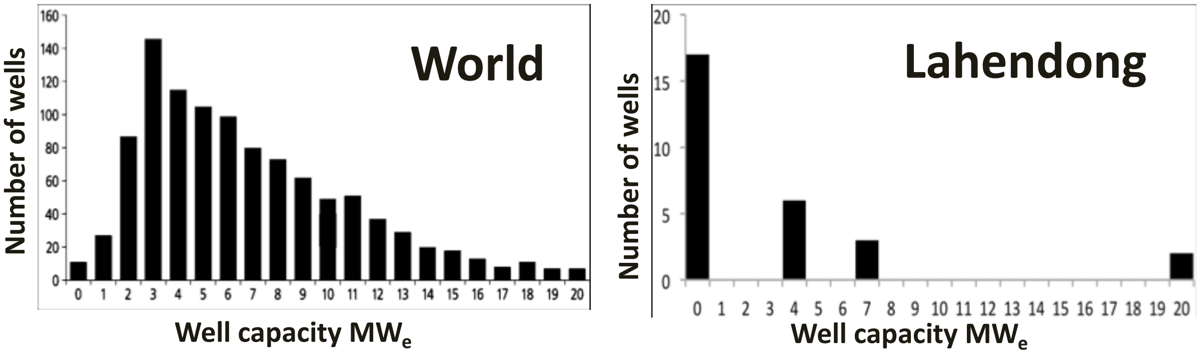

Figure 5: Distribution of well capacities in the world and in the Lahendong field Indonesia show a lognormal distribution regardless of geological environment (ICF, 2013)

2.4 Effect of Operation on Spatial Correlation

As seen in above presented examples, fluid flow in the Earth´s crust occurs in spatially-correlated poroperm structures. Presented rules are proper descriptions of deep hydrothermal systems and geothermal aquifers. In geothermal aquifers operators often have to deal with proper injection strategies to maintain reservoir pressure. During injection of cool fluid also fine particles enter the permeable horizons. These artificially injected particles can clog permeable zones. When these structures are clogged e.g. near an injection well fluid flow decreases quickly. This can have negative commercial implications for the site because also production has to be decreased.

Clogging processes are related to field operations and can be of physical, chemical or biological nature. Here, physical processes refer to the structure and hydraulic properties of the flow medium. Chemical processes represent mainly the composition of fluids and solids as well as chemical reactions between them, e.g. precipitation. Biological processes summarize reactions mainly driven by bacterial activity, e.g. coagulation. The process types might not only play an individual role but also be coupled interacting in the geological media.

In this frame we studied a low-enthalpy geothermal field in Lithuania. Wells in Klaipeda target one of the oldest groundwater on earth in 36°C warm Devonian sandstones. The geothermal plant was commissioned in 2000 and has a total capacity of 17 MW_{th}. Since 2002 the injection wells face decreasing injectivities while productivities from the same wells are remarkably higher (Brehme et al., 2017b).

Results show that chemical processes active onsite are precipitation and corrosion. Chemical reactions lead to the release of fines particles. These artificially generated particles mix with clay particles and are injected into the aquifer. These particles then clog pores in highly permeable sandstone layers. Additionally, biofilm has been found to cause blocking of pore space. Also, the interaction of physical, chemical and biological processes is important to consider, e.g. microbiologically triggered corrosion. The reasons for pore clogging should be understood as early as possible to avoid long-term aquifer degradation. The nature of spatial correlation of permeable zones is responsible for exponentially declining injectivity curves.

SUMMARY AND IMPLICATIONS

Examples presented in this study show that physical rules that describe spatial correlation of permeable zones in the Earth´s crust are valid both for hydrothermal systems and geothermal aquifers. The spatial correlation is described in well-capacities, well-logs and well-cores. Despite the description of geothermal reservoirs and aquifers, spatial correlation of permeable zones has direct implications on daily operation. During injection, e.g., the few highly permeable zones can be rapidly clogged by injection of fines particles (Brehme et al., 2017b). Thus, well-stimulation techniques have to be adapted appropriately. During drilling, the challenge is to target the high permeable areas. Therefore, a tool for mapping highly permeable zones in georeservoirs is strongly needed. However, structural characterization is important not only to ensure sustainable use of geothermal reservoirs but also to implement hazard mitigation measures (e.g. Bulut et al., 2018).

ACKNOWLEDGEMENTS

The authors sincerely thank the team of GEOTERMA and PGE for access to the site and providing numerous information. The DESTRESS project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 691728.

REFERENCES

Brehme M, Bauer K, Nukman M, Regenspurg S (2017a) Self-organizing maps in geothermal exploration–A new approach for understanding geochemical processes and fluid evolution. J Volcanol Geotherm Res 336:19–32.

Brehme M, Blöcher G, Regenspurg S, et al (2017b) Approach to develop a soft stimulation concept to overcome formation damage – A case study at Klaipeda , Lithuania. Proceedings, 42nd Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 2017

Brehme M, Moeck I, Kamah Y, et al (2014) A hydrotectonic model of a geothermal reservoir – A study in Lahendong, Indonesia. Geothermics 51:228–239. doi: 10.1016/j.geothermics.2014.01.010

Bulut, F., Havazlı, E., Yaltırak, C., Doğru, A., Sabuncu, A. and Özener, H. (2018) The 2017 Ayvacık Earthquake Sequence: A Listric Fault Activated Beneath Tuzla/Çanakkale Geothermal Reservoir (Western Turkey), Proceedings, 43rd Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 2018

IFC (2013) Success of geothermal wells: A global study. IFC, Int Financ Corp World Bank Gr 80.

Kortright NI (2015) Ohaaki Geothermal Power Station – Renewing Resource Consents Comparison with Greenfield Development. World Geotherm Congr 2015 19–25.

Leary P, Malin P, Saarno T, Kukkonen I, (2018) αφ ~ αφcrit – Basement Rock EGS as Extension of Reservoir Rock Flow Processes, Proceedings, 43rd Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 2018

Leary P, Malin P, Shalev E, et al (2013) Lognormally Distributed K / Th / U Concentrations – Evidence for GeoCritical Fracture Flow , Los Azufres Geothermal Field , MX. GRC Trans. pp 1–14

Mroczek EK, Milicich SD, Bixley PF, et al (2016) Ohaaki geothermal system: Refinement of a conceptual reservoir model. Geothermics 59:311–324. doi: 10.1016/j.geothermics.2015.09.002

Negrín, LCA. G., Lippmann, M. J. (2016) Mexico: Thirty-three years of production in the Los Azufres geothermal field. In: Geothermal Power Generation. S. 717-742.

Stimac JA (2007) Properties of the Bulalo Geothermal Reservoir Top based on Core Analysis. 29th NZ Geotherm. Work. 2007

Stimac J, Moore J, Latayan J (2006) Hydrothermal alteration and evolution of the Bulalo geothermal field, Philippines. GRC Trans. pp 959–964