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Petrophysical Reservoir Characterization of the Los Humeros and Acoculco Geothermal Fields, Mexico

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ABSTRACT

The Los Humeros (LH) geothermal system is steam dominated and has been exploited since the 1990's with 65 wellbores (23 still producing). With temperatures above 380°C, the system is characterized as a super-hot geothermal system. The geothermal system in Acoculco (AC, presently consisting of two exploration wells) is characterized by temperatures of approximately 300°C at a depth of about 2 km. It contains almost no fluids, even though a fracture network exists. Therefore the system serves as a demonstration site for the development of an enhanced geothermal system.

For better reservoir understanding and prospective modeling, extensive geological, geochemical, geophysical and technical investigations are performed within the scope of the GEMex project (EU-H2020, GA Nr. 727550). Relatively little is known about the petro- and thermophysical rock properties in the study area. However, this data is critical for i) processing and interpreting geophysical data and ii) parameterizing reservoir models. Therefore, outcrop analogue and reservoir sample studies have been carried out in order to define and characterize all key units from the basement to the cap rock. Thus to identify geological heterogeneities on different scales (outcrop analysis, representative rock samples, thin sections and chemical analysis) enabling reservoir property prediction.

More than 300 rock samples were taken from representative outcrops inside of the LH and AC calderas, the surrounding areas and from exhumed 'fossil systems' in Las Minas and Zacatlán. Additionally, 66 core samples from 16 wells of the LH geothermal field were obtained. Samples were analyzed for density, porosity, permeability, thermal conductivity, thermal diffusivity, heat capacity, as well as ultra-sonic wave velocities and magnetic susceptibility. Detailed complementary thin section analysis combined with XRD and XRF measurements provide information about the mineral assemblage, geochemistry and the intensity of hydrothermal alteration. Based on the outcrops and petrological analysis, the unit's geological heterogeneity, which controls the rock properties, can be addressed. An extensive rock property database was created comprising more than 34 parameters analyzed on more than 2160 plugs altogether. Based on statistical analysis (geostatistical analysis and stochastic modeling approaches) different thermofacies-units were identified to define geothermal model units of future TH(M) 3D models.

1. INTRODUCTION

Unconventional geothermal systems like Enhanced Geothermal Systems (EGS) or high temperature geothermal systems (> 350°C) have the worldwide largest potential for deep geothermal energy utilization (Huenges, 2010) and have raised the interest of the industry and scientific community in the last decades. The majority of previous deep and high temperature drilling projects encountered highly corrosive fluids, reaching or close to (super-) critical conditions (Reinsch et al., 2017). Several issues like corrosion and scaling effects, damage of the casing material, cementing operation or surface equipment occurred, which led to serious well failures and well abandonment (Kruszewski and Wittig, 2018). Comprehensive and detailed exploration is needed to improve reservoir understanding and -modeling and to develop new drilling technologies, which help to handle the extreme conditions in the reservoir. Therefore, the GEMex project (EU-H2020, GA Nr. 727550) focuses on the development of (hot) EGS and the investigation of high-temperature geothermal fields (SHGS) on two sites in the northeastern part of the Trans-Mexican Volcanic Belt (TMVB), the AC and LH caldera complexes (Puebla).

Over the last few decades both caldera complexes have been the focus of several research projects regarding geothermal exploration and exploitation. However, relatively little is known about the petrophysical and thermophysical rock properties in the study area. Other than recent updates on geological maps of the LH and AC area (Carrasco-Núñez et al., 2017a; Avellán et al., 2018), almost all previous studies focused on the caldera complexes itself. GEMex aims to create integrated reservoir models at a local, regional and superregional scale including the resulting data and models from different scientific disciplines (Jolie et al., 2018). This is the first time that the surrounding area of the caldera complexes is taken into account in a 3D geological model (Calcagno et al. 2018). As a consequence, further data is needed for processing and interpreting geophysical data and for parameterizing reservoir models. Therefore, outcrop analogue studies have been conducted in order to define and characterize all key units from the basement to the cap rock and to identify geological heterogeneities on different scales (outcrop analysis, representative rock samples, thin sections and chemical analysis), enabling reliable reservoir property prediction (Weydt et al., 2018, 2020).

This paper presents the first results of the 'reservoir characterization' work group within the GEMex project. Results briefly describe the workflow, data processing starting from outcrop analogue as well as reservoir sample analysis to parametrization of a 3D geological-geothermal model.

2. GEOLOGICAL SETTING

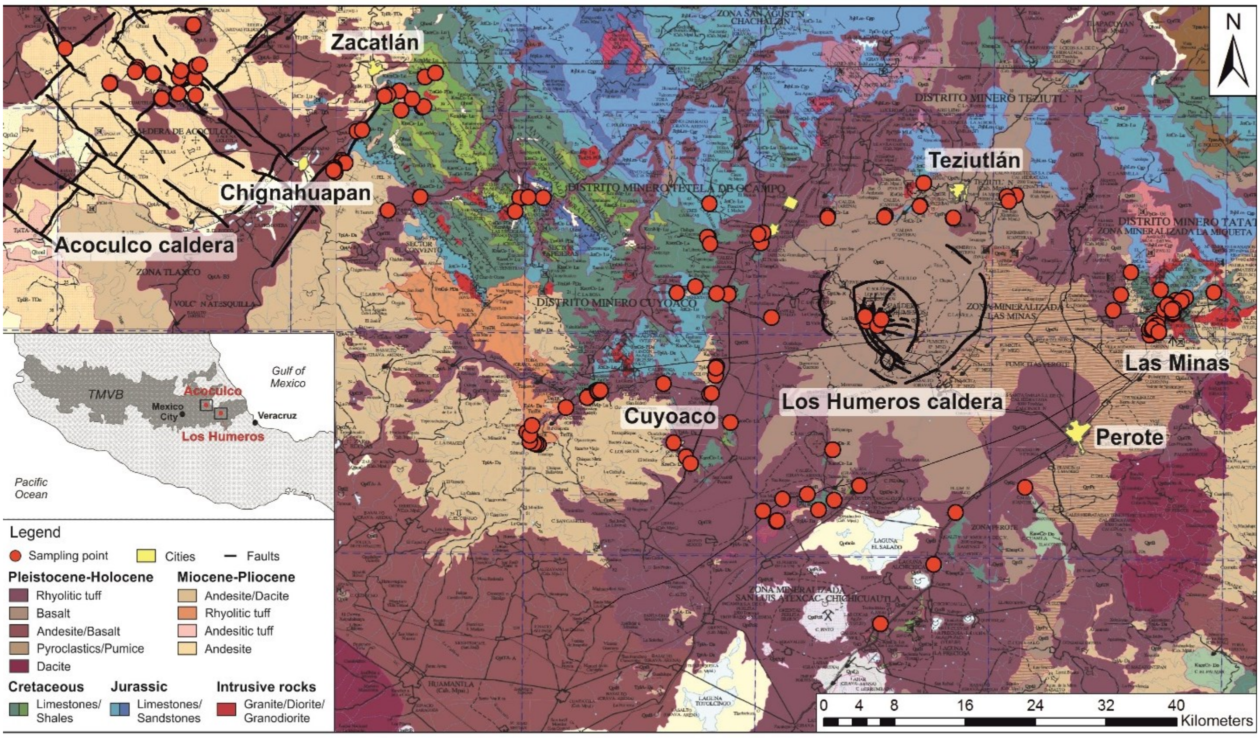

Figure 1: Geological map of the AC and LH area (SGM, 2002a and b). The red points mark the sampling points. The brown lines represent (regional) faults, which were recently mapped and characterized by Liotta et al. (2019) and Norini et al. (2019).

The AC and LH caldera complexes are located in the northeastern part of the TMVB, 125 km and 180 km east of Mexico City, respectively. The E-W trending TMVB is a ~ 1000 km long calc-alkaline volcanic arc which is directly linked to the subduction of the Rivera and Cocos plates beneath the North American plate along the Middle-American Trench (López-Hernández et al., 2009, Avellán et al., 2018).

The AC caldera complex has an 18 x 16 km asymmetric rhombohedral to sub-circular geometry and is defined by the Atotonilco scarp to the north, the Manzanito fault to the southwest and venting sites to the east and south (Avellán et al., 2018). Intersecting NE- and NW-striking normal fault systems create an orthogonal arrangement of grabens, half-grabens and horsts. The Acoculco caldera is located on the NE-SW Rosario-Acoculco horst and directly sits on Cretaceous limestones. Miocene volcanic rocks (predominantly andesitic and dacitic lava domes) in the study area were related to early stages of the TMVB, while the magmatic activity of the caldera began with the emplacement of the Acoculco ignimbrite (~2.7 Ma), followed by several early- (~2.7 – 2.0 Ma) and late-post caldera (~2.0 – 1.0 Ma) volcanic events producing basaltic to trachyandesitic lava flows and rhyolitic lava domes, respectively. The extra-caldera volcanism comprises several andesitic and basaltic lavas as well as scoria cones and is related to the volcanism of the Apan-Tezontepec Volcanic Field.

The younger LH caldera comprises Pleistocene to Holocene basaltic andesite-rhyolite volcanic rocks and has a 21 x 15 km irregularly circular shape (Carrasco-Núñez et al., 2018). The oldest volcanic activity in this area is represented by a thick sequence of andesites, dacites and basaltic lava flows (10.5 Ma, Cuyoaco and Alseseca andesites), and Teziutlán andesites (1.44-2.65 Ma). These andesites form the geothermal reservoir in the subsurface of the LH geothermal system (Carrasco-Núñez et al., 2018). The emplacement of the LH caldera is associated with two main caldera-forming eruptions, multiple voluminous plinian eruptions, as well as alternating episodes of dacitic and rhyodacitic dome-forming eruptions (Carrasco-Núñez et al., 2017a). The LH caldera collapse is associated with the emplacement of the high-silica rhyolite Xáltipan ignimbrite at ~160 ka (Carrasco-Núñez et al., 2017b). A second caldera forming eruption occurred at ~69 ka and is related to the Zaragoza ignimbrite emplacement forming the Los Potreros caldera within the LH caldera. Together with Tuffs, ash fall deposits and diverse pyroclastic flows, the ignimbrites form the cap rock of the reservoir. Overlying this are Holocene to recent basalt lava flows.

The volcanic rocks of the AC and LH geothermal fields are emplaced on intensively folded Mesozoic sedimentary rocks belonging to the Sierra Madre Oriental (López-Hernández et al., 2009) comprising Jurassic sandstones, shales, hydrocarbon-rich limestones and dolomites overlain by Cretaceous limestones and shales. Granitic and syenitic plutons of Cenozoic age and basaltic and andesitic dykes intruded into the sedimentary sequences and led to local metamorphism of marble, hornfels and skarn (Ferriz and Mahood, 1984).

The steam dominated LH geothermal system is exploited and operated by CFE since 1990. About 65 wells have been drilled so far (depths between 1500 m and 3100 m), while 23 are still productive (Romo-Jones et al., 2017). Produced power is about 68 MW with a possible total capacity of about 94 MW. Temperatures around 380°C were encountered at depths below 2 km in the northern parts of the caldera complex (Pinti et al., 2017).

Up to now, two exploration wells have been drilled by CFE in the AC geothermal field, which encountered temperatures of approximately 300°C at a depth of about 2 km (Canet et al., 2015). In both wells no geothermal fluids were found (Lopez-Hernandez et al., 2009), even though it was thought that a well-developed fracture network exists in the area. Therefore, a deep EGS is planned to be developed and enhance connections between networks of fractures in order to connect existing wells to proximal fluid bearing fracture zones (Jolie et al., 2018).

3. MATERIAL AND METHODS

3.1 Thermophysical and petrophysical properties

Outcrop analogue studies offer a cost-effective option to investigate and correlate facies, diagenetic processes and petrophysical properties at different scales (macro = outcrop analysis, meso = representative rock samples, micro = thin sections and chemical analysis). In order to create a dataset covering the whole area of interest, rock samples were taken from outcrops inside the caldera complexes, the surrounding areas and in the exhumed 'fossil systems' Zacatlán (east of AC) and Las Minas (east of LH). The exhumed systems expose almost all units from the basement to the cap rock and serve as proxies in order to understand fluid flow and the above-mentioned processes in the reservoirs.

More than 300 rock samples were taken for rock property measurements from about 130 outcrops covering all key lithologies. Furthermore, 66 core samples covering 16 wells of the LH geothermal field were obtained. Plugs with diameters from 25 to 64 mm were drilled from the samples and subsequently dried at 105°C for at least 24 hours until a constant mass was reached. Afterwards the plugs were cooled down to room temperature in a desiccator (20°C). The plugs were analyzed for petrophysical (e.g. density, porosity, permeability) and thermophysical properties (thermal conductivity, thermal diffusivity, heat capacity) as well as ultra-sonic wave velocities and magnetic susceptibility. Detailed complementary thin section analysis combined with XRD and XRF measurements provide information about the mineral assemblage, geochemistry and the intensity of hydrothermal alteration.

Grain- and bulk density measurements were performed with an AccuPyc 1330 gas pycnometer and a GeoPyc 1360 powder pycnometer (Micromeritics, 1997 and 1998). Porosities were calculated afterwards. Matrix permeability was determined with a column permeameter after Hornung and Aigner (2004). The plugs were measured using at least five air pressure levels ranging from 1 to 5 bar. Measurement accuracy varies from 5% for high permeable rocks ($K > 10^{-14}$ m²) to 400% for impermeable rocks ($K < 10^{-16}$ m²) (Bär, 2012). For the determination of thermal conductivity and thermal diffusivity, a thermal conductivity scanner was used after Popov et al. (1999, 2016). Here, the measurement accuracy is 3 % (Lippman and Rauen, 2009). Specific heat capacity was determined using a heat-flux differential scanning calorimeter (Setaram Instrumentation, 2009), where samples were heated at a steady rate from 20 up to 200 °C within a period of 24 h. Specific heat capacities were derived from the resulting temperature curves through heat flow differences. The measurement accuracy is 1 % (Setaram Instrumentation, 2009). Ultra sonic wave velocity was measured with pulse generators (UKS-D from Geotron-Elektronik, 2011) comprising point-source transmitter-receiver transducers. Polarized pulses at high voltage in a frequency range from 20 kHz to 1 MHz for the UKS-D were generated. The combined measurement of both P- and S-wave velocity offers the opportunity to retrieve elastic mechanical parameters like Poisson ratio, Young's modulus and G modulus (Mielke et al., 2017). Magnetic susceptibility was analyzed using a pocket size magnetic susceptibility meter (ZH Instruments, 2008), which consist of an oscillator with a pick-up coil. An interpolating mode was applied including two air reference measurements and one measurement directly on the sample surface. The frequency change of the oscillator is proportional to the magnetic susceptibility of the rock sample. To ensure optimal contact of the sensor on the sample surface and to reduce the impact of air while measuring, only the plane surfaces of the plugs were analyzed. Selected results of the thermophysical and petrophysical properties are shown in Fig. 2 and 3.

3.2 Sample classification and statistical analysis

The samples were associated to different geological units as described in Norini et al. (2015), Carrasco-Núñez et al. (2017a) and Avellán et al. (2018) which can be classified into 1) Post-caldera volcanism, 2) Caldera volcanism, 3) Pre-caldera volcanism and 4) Basement and Intrusive rocks. This classification was also used by Calcagno et al. (2018) to create regional model units within the preliminary 3D geological model of LH ("G1-Post-caldera" to "G4-Basement"; Fig 2). For the local model within the LH caldera, the volcanic sequences (caldera units) were distinguished further, resulting in nine model units ranging from "U9 Basement" to "U1 Undefined pyroclastics" (Fig 2). The preliminary 3D geological model of AC uses five regional units. Within this model all volcanic deposits were summarized into one unit "AC5-Volcanics", whereas the basement rocks were split into four separate units "AC4-Limestones", "AC3-Skarns", "AC2-Granites" and "AC1-Basement" (=metamorphic basement below the sedimentary rocks of the Sierra Madre Oriental).

With respect to the given model units and based on macroscopic, thin section and chemical analysis as well as dating techniques (Kozdrój et al., 2019), the outcrop samples were classified into lithostratigraphic units (Fig. 2 and 3). Taken the results of the petrophysical measurements and their statistical analysis into account, further subunits needed to be defined. Both standard statistical as well as geostatistical analyses were applied in order to assess the heterogeneity of the units, the relation between individual rock properties and the distribution and the predictability of the parameters. For example, the coefficient of variation C_v as presented in Figure 2 is a simple measure of heterogeneity (relation of standard deviation to its mean value; Fitch et al., 2015) and very useful for analyzing the variability within a data set. Thereby a homogenous formation will have a C_v of zero, with the value increasing with increasing heterogeneity in the given data set. However, it is worth mentioning that measures of variability are biased by the number of visited outcrops and collected samples for each unit.

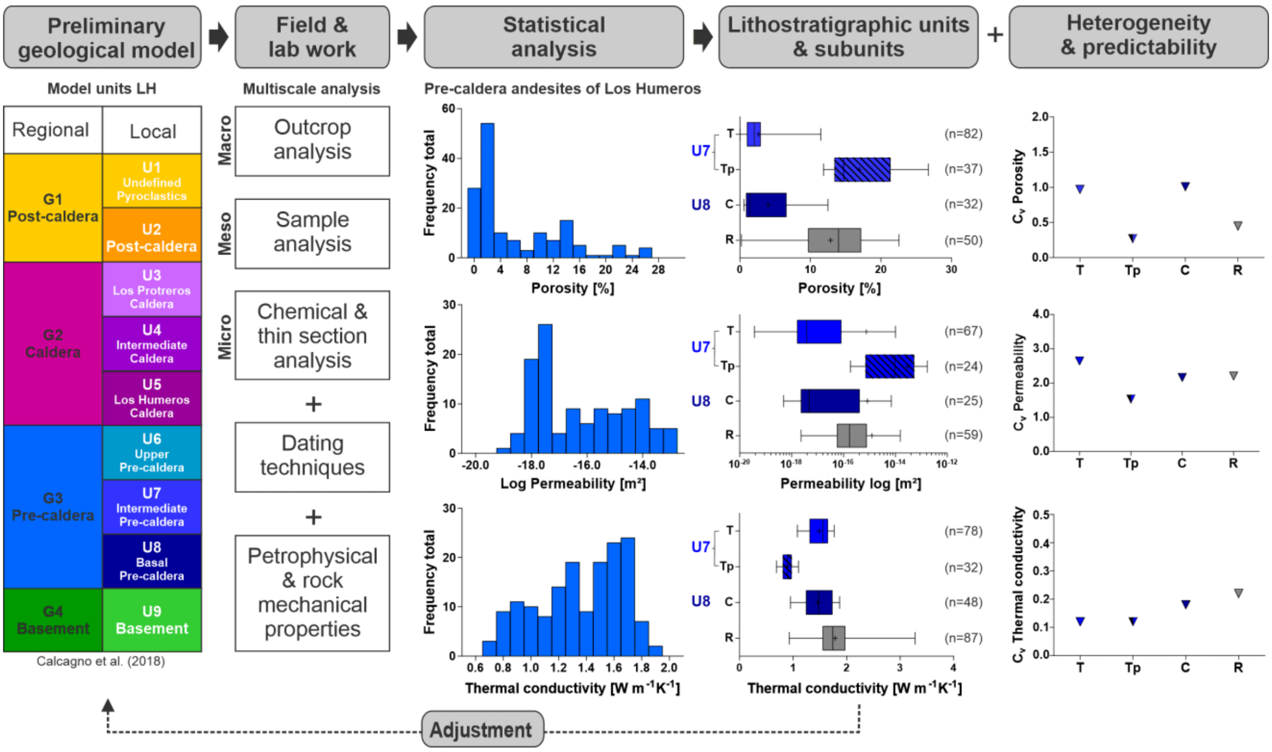

Figure 2: Schematic work flow using the example of the Miocene-Pleistocene andesitic lavas (Pre-caldera group) of the LH area. It represents the individual steps of the work-flow starting from field and lab work to definition of individual lithostratigraphic units with distinct thermophysical and petrophysical properties, which form the basis for parameterization of TH(M) models, processing and interpreting of geophysical data and further adjustment of the preliminary 3D geological model (Calcagno et al., 2018). N = number of analyzed plugs, T = Teziutlán andesite, Tp = Teziutlán andesite (porous), C = Cuyoaco andesite/Dacite and R = reservoir samples.

4. RESULTS

The field campaigns have shown the geological complexity within the study area. Detailed outcrop analysis is paramount to characterize and discover heterogeneities within the geological units. Composition, extension and distribution of the volcanic sequences are very variable within both sites. Furthermore, the basement rocks showed high heterogeneity comprising several different rock types. Thus, the results of the petrophysical and thermophysical properties of the outcrop samples reveal a high variability and a wide parameter range for individual units.

About 2160 plugs have been analyzed for petrophysical and thermophysical properties so far. With respect to the given model units provided by Calcagno et al. (2018), 18 lithostratigraphic units were defined for LH and 15 units for AC. In general, matrix permeability (< 10^{-16} m²) and porosity (< 5%) of the Jurassic and Cretaceous limestones as well as the Cenozoic (non-porous) andesite units in LH are very low. Thus, geothermal fluid flow has to be fracture controlled (Fig. 3), which also applies for AC. Exceptions to this are the porous Teziutlán andesite unit as well as the Jurassic sandstones in LH with matrix porosity and permeability values above 15% and 10^{-15} m², respectively. In contrast to limestones and andesite units, the Post-caldera and Caldera units in LH and AC have a generally higher matrix porosity (up to 50 %) and permeability (up to 10^{-13} m²). Thermal conductivity of the volcanic units in both reservoirs is rather low (<0.4 – 1.7 W m^{-1} K^{-1}), while thermal conductivity of limestones is variable but generally higher, and increases with decreasing clay content and increasing dolomitization and metamorphic overprint. The metamorphic rocks like marble, quartz and skarn taken from outcrops in Las Minas show the highest variability in rock properties, explained by their variable mineralogical composition. This results from the complex metamorphic processes in the contact zones as well as the type of protolith: carbonate (exoskarn) or igneous rock (endoskarn).

The reservoir samples provided by CFE were classified into lithological units based on the lithostratigraphic profiles, microscopic and chemical analyses. They predominantly comprise microcristalline to porphyritic basaltic andesites and andesites, but also basalt, rhyolite, trachyandesite, ignimbrite, marble and skarn (Fig. 3e and f). Hydrothermal alteration of different intensities was observed ranging from weak to strong. Thereby, different processes like calcite enrichment and argillic alteration in the upper part of the reservoir as well as silicification and intensive propylitic alteration with garnet precipitation in the lower part of the andesitic reservoir were identified (more details are described in Rochelle et al., 2020). The intensity of hydrothermal alteration is highly variable often within a cm-scale and hydrothermal alteration is often restricted to small fractures. This leads to high heterogeneity in terms of sample appearance, chemical composition and rock properties. As a consequence, each collected sample has unique features and it is challenging to correlate between individual wells. Matrix permeability and porosity varies from <10^{-17} to 10^{-14} m² and < 3% up to > 20%, while thermal conductivity ranges between 1.1 – 2.1 W m^{-1} K^{-1}.

Except for the Pedernal rhyolitic lavas collected within the AC caldera, the presented outcrop samples within this paper mainly show no or only a weak hydrothermal overprint. However, hydrothermal alteration of different intensities were also observed in the vicinity of dykes and fault zones in the outcrops, as well as in igneous bodies intruded into the sedimentary basement, which are spread over the LH area.

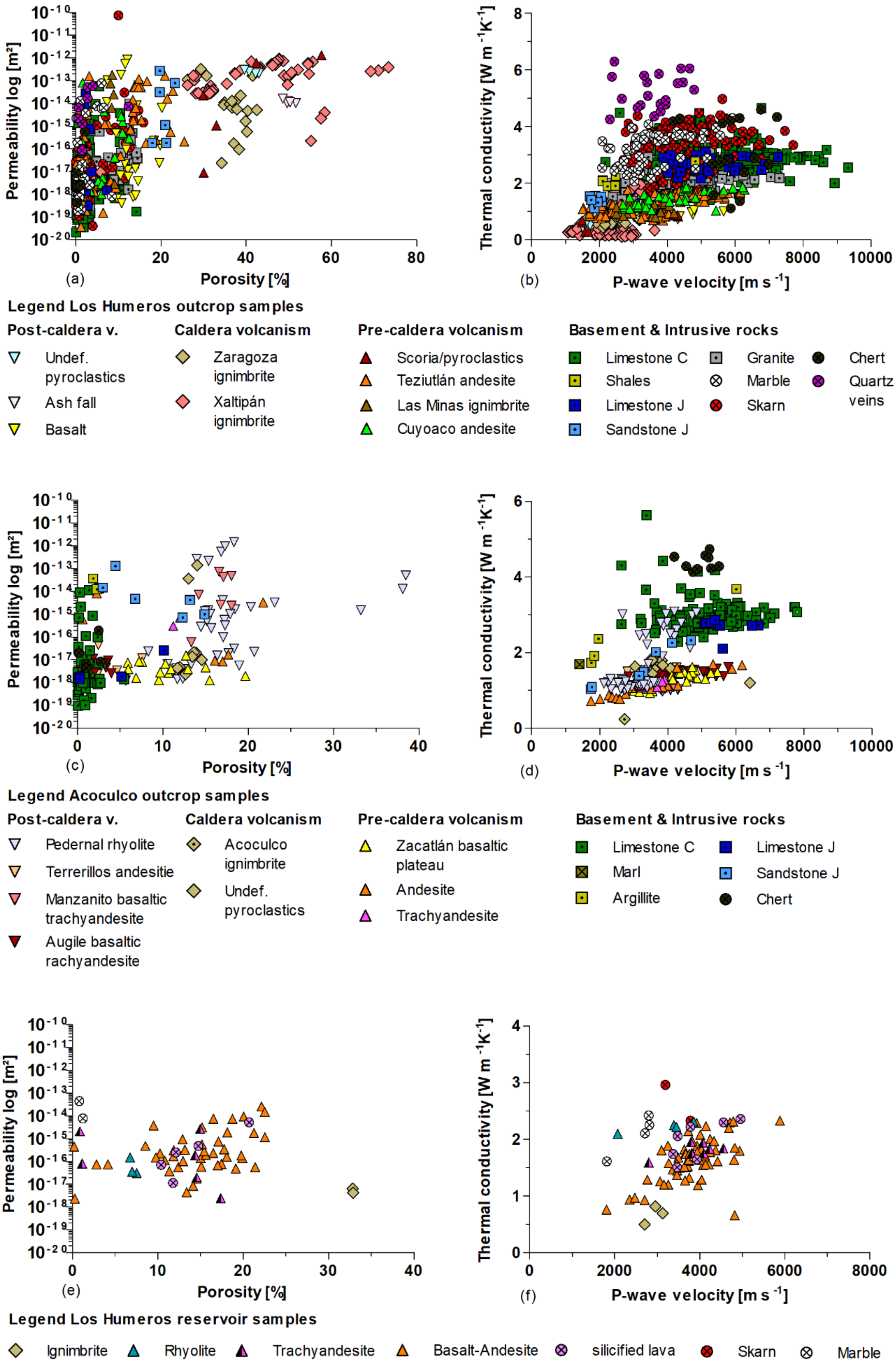

Figure 3: Thermophysical and petrophysical properties analyzed at dry conditions of the AC and LH geothermal field. For the number of analyzed plugs please see Weydt et al. (2020).

As the local and regional model units comprise different lithologies, the rock properties of the lithostratigraphic units were weighted with respect to their relative contribution (calculated from stratigraphic borehole profiles provided by CFE) for parameterization of TH models (Deb et al., 2019a and b). Depending on future applications of the 3D preliminary geological models and the results of processed geophysical data, it could be useful to adjust the model units at a local scale. For example, the results of the unaltered andesitic, basaltic and trachyandesitic lavas of AC have shown that a classification after stratigraphic levels is not useful, while the definition of subunits within the basement unit could be helpful to depict the unit's heterogeneity.

5. CONCLUSIONS AND OUTLOOK

The field campaigns and especially the results from the laboratory investigation of the rock properties revealed the complexity of the two reservoirs. Detailed outcrop analysis is paramount to characterize and discover large to medium scale heterogeneities within the geological units. An extensive rock property database was created (Weydt et al. 2020), comprising 34 parameters determined on more than 2160 plugs. More than 31,000 data entries were compiled covering volcanic, sedimentary, metamorphic and igneous rocks from different ages (Jurassi to Holocene). The results enable the classification of different lithofacies types with distinct properties. With respect to the given model units within the GEMex project, 18 and 15 lithostratigraphic units were defined for the LH and AC calderas, respectively. Hydrothermal alteration of different intensities was observed on borehole core samples of LH resulting in high heterogeneity in terms of sample appearance, chemical composition and rock properties. Compared to the Teziutlán and Cuyoaco andesite outcrop samples, the reservoir core samples show an increased average matrix porosity, thermal conductivity and permeability, but lower P- and S-wave velocities and magnetic susceptibility. Likewise, hydrothermal alteration can be observed in outcrops in the vicinity of dykes, igneous bodies and fault zones.

Upcoming studies will focus on quantifying the impact of hydrothermal alteration on the analyzed rock properties. Rock mechanical tests (uniaxial- and triaxial tests) are intended to evaluate the possibility of hydromechanical stimulations of the basement. Thermotriaxial tests and thermal conductivity measurements at temperatures of up to 180 °C will allow the transfer of the rock properties from laboratory to reservoir conditions.

This study forms the basis for definition and parameterization of geothermal model units within a TH(M) 3D model and for processing and interpreting geophysical data. It serves to improve the understanding and modeling of super-hot unconventional reservoirs with (super-) critical conditions.

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