Petrophysical and mechanical rock property database of the Los Humeros and Acoculco geothermal fields (Mexico)

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Abstract

Petrophysical and rock mechanical rock properties are key parameters for reservoir characterization but also for the parameterization of numerical models to simulate subsurface processes and for the interpretation of geophysical well logs and exploration surveys. Rock properties are characteristic for specific rock types and lithologies and are easily affected by tectonic events, diagenetic or metamorphic processes and hydrothermal alteration leading to a high variability. Thus, the detailed knowledge of petrophysical and rock mechanical data determined for each target unit significantly governs the accuracy and quality of modeling approaches and interpretation of geophysical surveys. A sound understanding of the controlling factors is needed to identify statistical and causal relationships between the properties as basis for a profound reservoir assessment and modeling.

However, detailed information on rock properties for the area of interest are often scarce, inconsistent or spread over multiple publications. Thus, subsurface models are often populated with generalized or assumed values resulting in high uncertainty. To overcome this knowledge gap, a new workflow was applied within the scope of the GEMex project (EU-H2020, GA Nr. 727550), which aims to develop new transferable exploration and exploitation approaches for enhanced and super-hot unconventional geothermal systems on two sites in the northeastern part of the Trans-Mexican Volcanic Belt, the Acoculco and Los Humeros geothermal fields (Puebla). Both sites are caldera complexes comprising Pleistocene to Holocene basaltic to rhyolitc lavas, lava domes, scoria cones and ignimbrites emplaced on Miocene to Pleistocene basaltic and andesitic lavas (Pre-caldera volcanic basement) that are situated on top of intensively folded and thrusted Jurassic and Cretaceous limestones, sandstones and shales (Mesozoic sedimentary basement, Fitz-Díaz et al., 2017). The Los Humeros geothermal system is steam dominated and has been exploited since the 1990's with 65 wellbores of which 28 are still producing. With temperatures above 380 °C at about 2 km depth (Pinti et al., 2017), the field is characterized as a super-hot geothermal system.. Two exploration wells were drilled in the Acoculco geothermal field, which reached temperatures of approximately 300 °C at 2 km depth (Canet at al., 2015). Although a well-developed fracture network exist in the study area, no geothermal fluids were found in both wells (López-Hernández et al., 2009). Therefore the system serves as a demonstration site for the development of a deep enhanced geothermal system (EGS).

Over the last few decades both caldera complexes have been the focus of several research projects regarding geothermal exploration and exploitation. However, almost no information exists about petrophysical and rock mechanical properties in the study area. 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 3D geological models (Calcagno et al. 2018). As a consequence, further data is needed for processing and interpreting geophysical data and for parameterizing numerical reservoir models. Therefore, outcrop analogue studies were 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.

More than 300 rock samples were taken from about 140 representative outcrops inside of the Los Humeros and Acoculco calderas, the surrounding areas and from exhumed 'fossil systems' in Las Minas and Zacatlán. Additionally, 66 core samples from 16 wells of the Los Humeros geothermal field and 8 core samples from well EAC1 of the Acoculco geothermal field were obtained. Cylindrical plugs were drilled and prepared according to ASTM D4543-19. Subsequently, nondestructive tests were performed to determine particle and bulk density, porosity, permeability, thermal conductivity, thermal diffusivity, specific and volumetric heat capacity, as well as compression and shear wave velocities, dynamic Young's modulus and passion ratio, magnetic susceptibility and electric resistivity. Thereby, thermal conductivity, thermal diffusivity, electric resistivity, compression and shear wave velocities were measured at dry and saturated conditions. Afterwards destructive rock mechanical tests were performed to determine tensile strength, uniaxial compressive strength, static Young's modulus and Poisson ratio, bulk modulus, shear modulus, fracture toughness, cohesion and friction angle. Complementary thin section and chemical analyses (XRD and XRF) were performed to provide information about the mineral assemblage, bulk geochemistry and the intensity of hydrothermal alteration. Detailed information on the experimental set-up, applied methods and measurement conditions are described in Weydt et al. (2020).

An extensive rock property database was created comprising 34 properties analyzed on 2,169 plugs covering volcanic rocks (950 plugs), sedimentary rocks (716 plugs), igneous rocks (147 plugs) and metamorphic rocks (356 plugs) of Jurassic to Holocene age. In total, 80 outcrop samples were collected for Acoculco and 226 outcrop samples were collected for Los Humeros including 101 samples from the exhumed system Las Minas. Thereby, 563 and 1606 plugs were analyzed for each system, respectively. The samples were related to their stratigraphic unit (Table 1) and classified into 1) Post-caldera volcanism, 2) Caldera volcanism, 3) Pre-caldera volcanism and the 4) Pre-volcanic basement (Mesozoic sedimentary basement). The reservoir core samples from the Los Humeros geothermal field were predominantly retrieved from basaltic to andesitic as well as rhyolitic lavas belonging to the Pre-caldera group. Only a few core samples cover the cap rock (Xaltipán ignimbrite) and the Pre-volcanic basement below (marbe). The reservoir core samples from well EAC1 of the Acoculco geothermal field comprise ignimbrite (core 1), dacitic to rhyolitic lavas (core 2 and 3), skarn (core 4), marble (core 5) and granodiorite (core 5).

Table 1: Analyzed lithostratigraphic units of the Los Humeros and Acoculco geothermal fields

Unit	Los Humeros	Acoculco
Post-caldera group	Undefined pyroclastic deposits (n. d.) Basaltic lava (< 7 ka, n. d.) Ash fall deposits and basaltic lavas of the Xoxoctic member (n. d.)	Perdernal rhyolitic lava (1,600 ± 100 ka) Terrerillos andesitic lava (1,708 ± 54 ka) Manzanito basaltic trachyandesite (2,199 ± 24 ka) Augila basaltic trachyandesite (2,441 ± 234 ka)
Caldera group	Zaragoza ignimbrite (69 ± 16 ka) Xaltipán ignimbrite (164 ± 4.2 ka)	Acoculco andesitic ignimbrite (2,731.8 ± 185 ka)
Pre-caldera group	Teziutlán andesite (1.46 - 2.61 Ma) Cuyoaco andesite (8.9 - 10.5 Ma)	Miocene andesitic and basaltic trachyandesitic lava, Zacatlán basaltic plateau (n. d.)
Pre-volcanic basement	Miocene granite and granodiorite, marble and skarn, Cretaceous and Jurassic limestones, shales and sandstones	Cretaceous and Jurassic limestones, shales and sandstones

(n. d. = not dated so far), ages are retrieved from Carrasco-Núñez et al. (2017, 2018) and Avellán et al. (2018, 2019)

The database is provided as a flat file Excel format and as .csv format comprising a user friendly hierarchical structure to keep the handling as simple as possible and to allow for simple and fast filtering. The database is divided into two data-sheets. For each plug, the first data sheet comprises all 1) complementary sample information such as sample location, rock type, macroscopic description and plug dimensions, 2) results of non-destructive measurements including petrophysical, thermophysical and dynamic mechanical properties, as well as electric resistivity and magnetic susceptibility, and 3) results of destructive measurements. The second data sheet comprises all chemical data retrieved from XRF and XRD analyses performed on composite sample material obtained from 133 samples.

In total 31,350 data entries were generated (Table 2) allowing for detailed statistical and spatial geostatistical analyses on different scales, the population of 3D numerical models, the interpretation of geophysical data and the validation of different analytical methods. Furthermore, the data allows for the prediction of rock properties of target formations in the subsurface at early exploration stages or in case of low data density, which forms the basis for reservoir assessment and the estimation of uncertainties and related economic risks. Although the data base mainly provides information relevant for geothermal exploration and reservoir characterization related to two volcanic settings in the TMVB, it facilitates various applications in geo-scientific disciplines in comparable geological settings worldwide.

Table 2: Number of measurements for each parameter

Parameter	No. of measurements	Parameter	No. of measurements
Particle density	1,876	P-wave velocity (sat)	1,356
Bulk density	1,377	S-wave velocity (sat)	1,314
Porosity	1,351	Dynamic Young's modulus (dry)	1,738
Permeability	1,051	Dynamic Young's modulus (sat)	1,314
Thermal conductivity (dry)	1,668	Dynamic Poisson ratio (dry)	1,723
Thermal conductivity (sat)	1,464	Dynamic Poisson ratio (sat)	1,314
Thermal diffusivity (dry)	1,616	Dynamic Shear modulus (dry)	1,730
Thermal diffusivity (sat)	1,395	Dynamic Shear modulus (sat)	1,314
Specific heat capacity	188	UCS	392
Specific heat capacity (calculated)	1,091	Static Young's modulus	218
Volumetric heat capacity	188	Static Poisson ratio	220
Magnetic susceptibility	925	Shear modulus	186
Electric resistivity (dry)	31	Bulk modulus	186
Electric resistivity (sat)	50	Tensile strength	363
Formation factor	39	Fracture toughness	86
P-wave velocity (dry)	1,807	Friction angle	20
S-wave velocity (dry)	1,739	Coehsion	20
Total			**31,350**

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