Monitoring methods for Los Humeros superhot geothermal system: state-of-the-art

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Abstract

This work reviews reservoir monitoring methods currently practiced in Los Humeros superhot geothermal system. They aim at assessing geothermal resources in the reservoir, imaging subsurface structures, understanding the chronology of volcanic processes, quantifying fluid flow, heat transport and water-gas-rock interaction, monitoring fluid production parameters and defining reservoir flow patterns. Detailed achievement of the above will help in a deterministic approach and more accurate interpretation of the exploitation potential of the geothermal system. Methods for achieving these goals include geological & structural mapping, field geophysical surveys, field geochemistry, fluid production monitoring and tracer testing.

In the context of improving understanding of the geothermal and magmatic system, geological and structural mapping methods and techniques are applied. They are evaluation of pyroclastic stratigraphy, physical volcanology, which includes high-precision geochronological methods (C^{14}, Ar^{40}/Ar^{39}, U-Th/zircon, U-Th/He thermochronometry and paleomagnetic dating), electron probe microanalyzer and isotope ratio measurements, (which provide valuable information about the thermal and chemical evolution of the magma chamber), methods of morphostuctural mapping such as remote sensing & field verification, estimations of volcanic vents and heat flow and rainfall, also methods of X-ray micro-tomography, which gives us a picture of the permeability distribution, as well as visualization of surface and subsurface data (GIS 3-D).

Field geophysical surveys include magnetotellurics (MT) and microgravity surveys to locate and characterize shallow and deep structures, micro-seismicity surveys to locate active faults through which thermal fluids flow, thermal remote sensing, InSAR (Satellite Interferometric Synthetic Aperture Radar) techniques to detect anomalies at the ground surface associated with hydrothermal processes at depth.

Geochemical analyses include geochemical characterization of hydrothermal fluids including geothermometers, geobarometers and pH, geochemical and petrographic characterization of volcanic rocks and hydrothermal alteration, as well as x-ray tomography of reservoir rocks from core samples to determine the porosity and permeability. Tools to accomplish this are sample analysis by X-Ray diffraction (XRD), scanning electron microscopy (SEM), petrography (PETRO) and electron microprobe analyzer (EMPA).

Fluid production parameters monitored are wellhead temperature and pressure, production and reinjection mass flowrates, production specific enthalpy, separated liquid chemistry, gas content of the steam and $\delta^{18}O$ and δD isotopes.

Reservoir modelling employs numerical models of fluid flow and heat and mass transport (OpenGeoSys and FEFLOW) to quantify rates of heat transport from source to surface, thermophysical and chemical properties of produced fluids, as well as wellbore flow simulation (WELLSIM) to calculate reservoir parameters from surface production data.

Tracer testing applications have as an objective the evaluation of wells interconnectivity by tracer injections at one reinjection well and the return of tracer in production wells, which provides valuable insights of the geothermal system. High temperature resistant 2,6-NDS liquid-phase tracer has been used.

All these technologies, techniques and methods are greatly contributing to significantly improve our knowledge of the features and capabilities of the geothermal field and to make optimal decisions about its current and future exploitation.

Introduction

The Los Humeros superhot geothermal system is located in the eastern part of the volcanic zone of Mexico ca 180 km NEE from the city of Mexico, at an altitude of 2,750-3,000 m. Its first ca 2 km deep well was drilled in 1982 and the utilization of the upper 1.5-3.0 km of the system started in 1990 with the installation of the first 5 MWe geothermal power generating unit [1]. Since then, more than 60 wells were drilled and additional units of 5 and 25 MWe each were installed, reaching a total installed capacity of ca 95 MWe.

Existing deep wells tap the upper two geothermal reservoirs encountered at Los Humeros. The upper reservoir is liquid dominated with temperature 300-330 ^oC located in augite andesite at 1.2-1.8 km depth, while the deeper is vapour dominated with high steam saturation and 300-400 ^oC temperature located in basalts and hornblende andesite at 1.9-2.7 km depth [2]. According to the results of the GEMex project, these reservoirs are characterized by both matrix and fracture permeability. At deeper levels, within the carbonate basement, which comprises mainly of marbles of very low porosity and matrix permeability with intercalations of basaltic dykes and skarns, fluid movement of higher temperature is anticipated only within the fault zones, which form a third superhot reservoir of 400-500+ ^oC temperature [3].

Los Humeros

Geological & structural mapping has been implemented starting with surface data and followed by analysis of cuttings and cores from deep wells. The geologic and structural model of Los Humeros has been recently updated by the results of the GEMex project, according to which the superhot geothermal system includes the three main reservoirs mentioned above, which are confined within the Los Humeros caldera boundaries. Caldera boundary faults isolate these reservoirs from regional lateral recharge; therefore recharge is limited to local rainfall [2], reinjection and steam rising through deep basement structures.

Los Humeros

Concerning the geologic evolution of the system, after rhyolitic dominant volcanism with episodic dome formation during 693-270 thousands year ago, the 18 km in diameter Los Humeros caldera collapsed 164 thousands years ago. 69 thousand years ago the smaller Los Porteros caldera, 9 km in diameter, was formed inside the Los Humeros one. Since then there have been 6 volcanic eruptions, the last of which was dated as 2.8 thousand years old. [4], [5], [6]

The first **Schlumberger resistivity and MT surveys** carried out in Los Humeros were during field exploration in the early 1980's [7]. During the GEMex project, coupled Magnetotelluric (MT) and Transient Electro-Magnetic (TEM) soundings sharing the same locations were performed. TEM soundings were used to correct the MT data. They showed that Los Humeros is characterized by a three-dimensional resistivity structure controlled by the main faults including Los Porteros caldera boundaries. Considerable horizontal contrasts are evident. One of the most prominent features identified is a resistive core that domes up along one of the main faults in the region. [8]

A **gravity survey** was carried out in Los Humeros during the early stages of field development which showed the main features of the subsurface structure of the caldera [7]. Recent gravity surveys carried out during the GEMex project were a regional gravity survey coupled to a magnetic survey carried out by the Mexican team [9], [10] and a local gravity survey carried out by the European team. Both yielded the density distribution beneath the surface.

For the local gravity survey, a total of 344 gravity stations were measured in two different times, indicating a density distribution controlled by faults aligned in the NE-SW and NW-SE directions. In particular N-S oriented secondary faults in the northern part of the field coincide with relatively high-density distribution, whereas the NE-SW to E-W oriented secondary faults are characterized by low-density. [11] Furthermore a lower density body was identified extending to depth beneath the caldera surface.

The first **magnetic survey** was carried out by air during the early stages of field exploration, which identified a bipolar magnetic anomaly in the central part of the Los Humeros complex [7]. During the GEMex project the Mexican team carried out a magnetic survey in conjunction with the gravity one, a joint inversion of both yielded magnetism and density distribution at subsurface. A magnetised elongated ellipsoidal ball shape, ca 10 km in diameter, is evident extending beneath Los Humeros caldera from surface down to 7 km depth located between the wells and the east caldera boundary [10].

Only one **active seismic survey** has been carried out in Los Humeros. It was carried out by the Compañia Mexicana de Exploraciones S.A. (COMESA) on behalf of Comision General de Electricidad (CFE) in 1998. It comprised seismic data acquisition along four 2D reflection seismic lines using Vibro seismic sources. [12] This survey was reprocessed during the GEMex project, providing the P-wave and S-wave seismic velocities tomography, as well as the subsurface seismic structure of the geothermal system [13].

Monitoring micro-seismicity in Los Humeros has been carried out by CFE since 1994 with an installed permanent network of 6 seismographs. Most hypocentres of observed micro-seismic activity are located within the two upper permeable horizons of augite andesite and hornblende andesite and are associated with the reinjection fluid flow patterns due to fractures opening by contraction of cooling rock. That way, zones of high permeability have been identified, which were set as targets for subsequent production wells [14].

During the GEMex project, 20 short-period plus 25 broad-band three-component sensors were installed and local micro-seismicity was monitored for ca 1 year [13]. Location of hypocentres indicated strong association with reinjection practices. Travel-time tomography allowed the calculation of 3D P-wave and S-wave seismic velocity [13], [15] and rock moduli distribution [16], which was compared with synthetic models [17], in an effort to identify the seismic signature of a superhot geothermal system and examine potential relations to fluid properties of saturation, pore pressure and temperature. Ambient seismic noise correlation methods provided the 1-D seismic velocities profile to great depth.

The **InSAR remote sensing** synthetic aperture radar satellite images taken by the ENVISAT satellite of the European Space Agency (ESA) during 2003-2007 have used to generate digital maps of surface elevation and monitoring subsidence and structural stability of Los Humeros caldera [2].

Processing of these data during the GEMex project, identified subsidence of max 8 mm/y at the north part of Los Humeros caldera surface, which were related to fluid volume changes in the reservoir. Furthermore, C-Band radar images from Sentinal-1 ESA Copernicus satellite were used to map the deformation caused by the reinjection induced Mw 4.2 earthquake of 8 February 2016, which highlighted the activation of shallow faults (max 1.2 km depth) beneath the caldera. [18]

Differential GPS surveys carried out every six months identified horizontal ground displacements of 3 cm in NW-SE direction during a large earthquake, indicating that the caldera is tectonically active. The GPS surveys will continue for the next years. [18]

In Los Humeros, field-based **petrological and thermo-barometric analysis** of the post-caldera surface lavas was carried out during the GEMex project, which pointed to a revised deep system conceptual model comprising of multiple magma chambers within the carbonate basement at 3-30 km depths, where the main basaltic magma reservoir is expected. Thermo-barometer models indicated rock melting and mineral forming at 900-1250 ^oC. [19]

Los Humeros

Oxygen isotope data of skarn minerals and fluid inclusion analysis of rock samples from the Las Minas fossil geothermal system, which is adjacent to Los Humeros, highlighted the typical evolution of a magmatic-hydrothermal system characterized by an early hypersaline fluid (18-60 % NaCl equiv.) of very high temperature (500-650°C) circulating within fractures, which emanated from a crystalizing melted magma, and the presence of a vapor phase produced at hydrostatic pressure of 40-1000 bar. [20]

In Los Humeros, since production started in early 1980s, **fluid production parameters** monitored are wellhead and well-bottom temperature and pressure, production and reinjection mass flowrates, production specific enthalpy, steam saturation, separated liquid chlorides content and chemistry, gas content of the steam and $\delta^{18}O$ and δD isotopes. Since reinjection practice started, reinjection mass flow rate was recorded. During 1982-2012 ca 123 Mtons of fluid were produced comprising ca 84% steam and ca 16% liquid, only 5% of which was reinjected. This massive fluid extraction from the reservoir with very limited reinjection resulted in the following changes to occur within the reservoir: pressure decrease, enthalpy and vapour saturation increase, boiling with steam condensation, production of reinjection returns heated to reservoir temperature and deep steam recharge. [1]

Tracer testing applications have as an objective the evaluation of wells interconnectivity by tracer injections at one reinjection well and the return of tracer in production wells, which provides valuable insights of the geothermal system. High temperature resistant 2,6-NDS liquid-phase tracer has been practiced in Los Humeros, by adding it to the reinjected fluid. The results revealed reinjection returns in all monitored production wells, corresponding to 1% of injected fluid. The conclusion is that 99% of injected fluid flows to the deep part of the system and that no thermal interference is expected. [21]

Reservoir modelling practiced in Los Humeros employs numerical models of fluid flow and heat and mass transport (OpenGeoSys and FEFLOW) to quantify rates of heat transport from source to surface, as well as thermophysical and chemical properties of produced fluids [2]. When only wellhead production data are available, a wellbore simulator (e.g. WELLSIM) can be employed to calculate bottomhole transients.

During the GEMex project the SHEMAT and TOUGH-2 heat and mass transport reservoir simulators were used in order to model the natural state of the Los Humeros reservoir, using all data collected and the results produced by the project consortium. One of the simulation results was that temperatures of ca 400^{o}C are expected at 3 km and above 500 ^{o}C are expected at 4-7 km depth beneath the caldera. [22], [23]

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