GEMex

GEMex CONFERENCE

Potsdam, GFZ

18-19 February 2020

SUPERHOT GEOTHERMAL SYSTEMS AND THE DEVELOPMENT OF EGS

Final program & abstracts

GEMex Final Conference Proceedings

Deliverable 2.8

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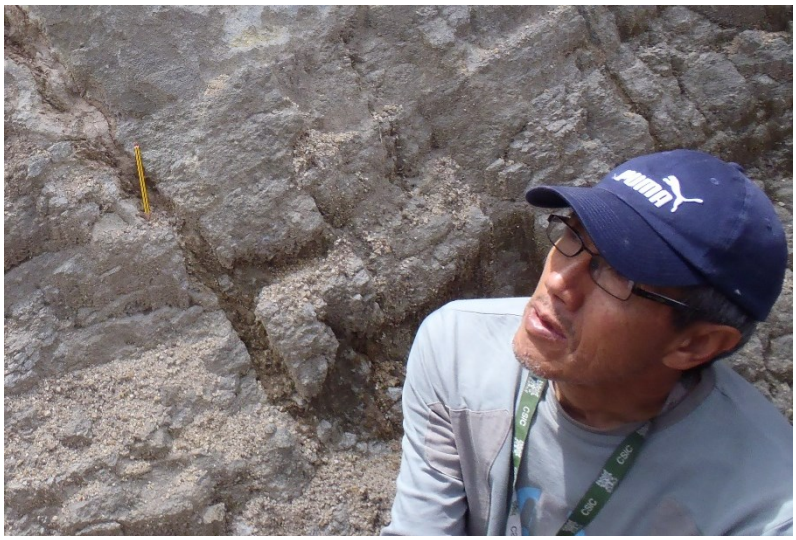


The final conference of the GEMex projects is dedicated to the memory of Víctor Hugo Garduño-Monroy, who was instrumental in the initiation of this project cooperation.

Program

17 February 2020

13:00 – 17:00	**General Assembly of the GEMex project, restricted to GEMex participants only**
13:00 – 13:15	David Bruhn: Welcome
13:15 – 14:00	Katrin Kieling: Final obligations and deadlines, Final reporting of EU project
14:00 – 14:20	Eugenio Trumpy: Presentation of the Paraview project for Acoculco
14:20 – 14:40	Emmanuel Gaucher: Presentation of the Paraview project for Los Humeros
14:40 – 15:00	Eugenio Trumpy: Presentation of Open Access Database
14:40 - 15:10:	**Break**
15:10 – 15:40	Ólafur G. Flóvenz: Current inflation and seismicity in the Svartsengi geothermal field, SW Iceland
15:40 – 16:00	Thomas Garabetian: Presentation of the Action Plan EU-Mexico on Development of EGS and Superhot Resources
16:00 – 17:00	Discussion: Continued collaboration between European and Mexican partners after the end of the GEMex project; including short pitches on collaboration ideas • Egbert Jolie • Luis Carlos Gutiérrez-Negrín
17:00 – 19:00	**Ice-breaker (building H, Foyer)**
18:00	**Executive Board meeting (building H, room V1, only for EB-members)**

18 February 2020

8:15 Registration

09:00 – 9:45 Opening ceremony

- Dr. Stefan Schwartze, Administrative Executive Director GFZ
- Ambassador HE Rogelio Granguillhome Morfin, Mexican Ambassador to Germany
- David Bruhn – Introduction to the GEMex' framework, facts and figures
- Aída López Hernández – Introduction to the scientific questions and the two geothermal sites considered within GEMex

09:50 – 10:35 Session 1: Studies covering Los Humeros and Acoculco (Chair: Luis C. Gutiérrez-Negrín)

1. Zayre González: Importance of social informed communication to the acceptance of geothermal project
2. Philippe Calcagno: 3D geomodels of Los Humeros and Acoculco geothermal systems (Mexico) - H2020 GEMex Project: Methodology, products and feedback
3. Marco Bonini: Collapsed calderas and resurgence vs inherited fabrics: insights from analogue modelling on the evolution of Los Humeros and Acoculco volcanic complexes

10:35 – 11:00 Coffee break

11:00 – 12:15

4. Bernard Sanjuan: Developments of auxiliary chemical geothermometers (Na-Li, Na-Cs) applied to the Los Humeros and Acoculco high-temperature geothermal fields (México)
5. Thomas Kretzschmar: Hydrogeological and hydrochemical characterization of surface and groundwater in the surroundings of Los Humeros and Acoculco
6. Natalia Cornejo: Towards visualization of the reservoir settings in the Los Humeros and Acoculco geothermal fields using gravity
7. Marco Perez Flores: Joint 3D inversion of regional gravity and magnetic data for Los Humeros and Acoculco geothermal fields with a petrophysical relation.
8. Eugenio Trumpy: Thermal signature and regional resource assessment in Los Humeros and Acoculco areas

12:15 – 13:15 Lunch

13:15 – 14:45 Session 2: Poster Presentations (Papers with odd numbers + Presentation of Paraview project from GEMex WP5 in Room 1)

14:45 – 15:00 Coffee Break

15:00 – 16:15 **Session 3: Development of Acoculco as an EGS Site (Chair: Domenico Liotta)**

9. Andrea Brogi: The structure of the Acoculco geothermal area (Mexico) and implications for enhanced geothermal system (EGS) development
10. Adrian Jiménez Haro: Neo-formed faulting and fracturing with conductive characteristics in the Acoculco geothermal system, Puebla, Mexico
11. Diego Ruiz-Aguilar: MT Data from the Acoculco geothermal area: 3D inversion and model assessment results
12. Abel Felipe Hernández Ochoa: Numerical Conductive-Heat Flow Analysis of the Natural-State Geothermal System of Acoculco
13. Michal Kruszewski: Integrated stress field estimation and implications for enhanced geothermal system development in Acoculco, Mexico

16:15 – 16:45 **Coffee break**

16:45 -17:45 **Development of Acoculco as an EGS Site (Chair: Aída López-Hernández)**

14. Paromita Deb: Hydraulic fracturing experiments in laboratory scale to generate benchmark datasets for verification of stimulation design tools
15. Baptiste Lepillier: A predictive mechanical model for hydraulic fracture stimulation in coculco geothermal reservoir system
16. Lies Peters: An integrated modelling approach for predictions of induced seismicity at the potential EGS site in Acoculco
17. Lies Peters: Simulation of potential production scenarios at Acoculco

19:00 – 22:00 **Conference Dinner** (Kutschstall, Am Neuen Markt 9A, Potsdam)

19 February 2020

09:00 – 10:15 **Session 4: Improving the understanding of the superhot geothermal site at Los Humeros (Chair: Egbert Jolie)**

18. Gianluca Norini: Structural model of the Los Humeros volcanic complex for the exploration of the deep Super-Hot Geothermal System
19. Leandra Weydt: Petrophysical reservoir characterization of the Los Humeros geothermal field: comparison of outcrop analogues and reservoir formations
20. Guido Giordano: Implications of an updated volcanological conceptual model at Los Humeros for geothermal exploration and modelling
21. Matteo Lelli: Novelties on water and gas geochemistry in Los Humeros geothermal field (LHGF)
22. Ingolfur Thorbjornsson: Material testing downhole at well H-64 at the Los Humeros geothermal field in Mexico

10:15 – 10:45 **Coffee break**

10:45 – 12:45 **Session 5: Poster Presentations (Papers with even numbers) + Presentation of Paraview project from GEMex WP5 in Room 1)**

12:45 – 13:45 **Lunch**

13:45 – 15:15 **Session 6: Geophysical results in Los Humeros (Chair: Gylfi Páll Hersir)**

23. Ásdís Benediktsdóttir: The Los Humeros superhot geothermal resource in Mexico: Results from an extensive resistivity survey
24. Flavio Poletto: Active seismic for exploration of SHGS geothermal systems
25. Tania Toledo: Local earthquake tomography at the Los Humeros geothermal field
26. Iván Granados: On the structure of the Los Humeros caldera using seismic multi-method modelling
27. Katrin Löer: Imaging the brittle-ductile transition zone at the Los Humeros geothermal field using ambient seismic noise
28. Svenn Tveit: Ensemble-based Bayesian joint utilization of information from multiple data types for Los Humeros

15:15 – 15:45 **Coffee break**

15:45 - 17:45 **Final Session: Synthesis and Conclusion (Chair: David Bruhn)**

29. Gianluca Gola: Extraction of regional and local geophysical features by cluster analysis and classification learning methods in Los Humeros and Acoculco volcano-geothermal fields (Mexico)
30. Gylfi Páll Hersir: Detection of deep structures: An overview of what has been achieved in WP5 within GEMex and joint visualisation in Paraview
31. Egbert Jolie & Aída López Hernández: Improvement of the conceptual model of Los Humeros: Beyond the GEMex Project
32. Domenico Liotta: Data integration to constrain the geological structures in the Acoculco area

David Bruhn: Closing remarks

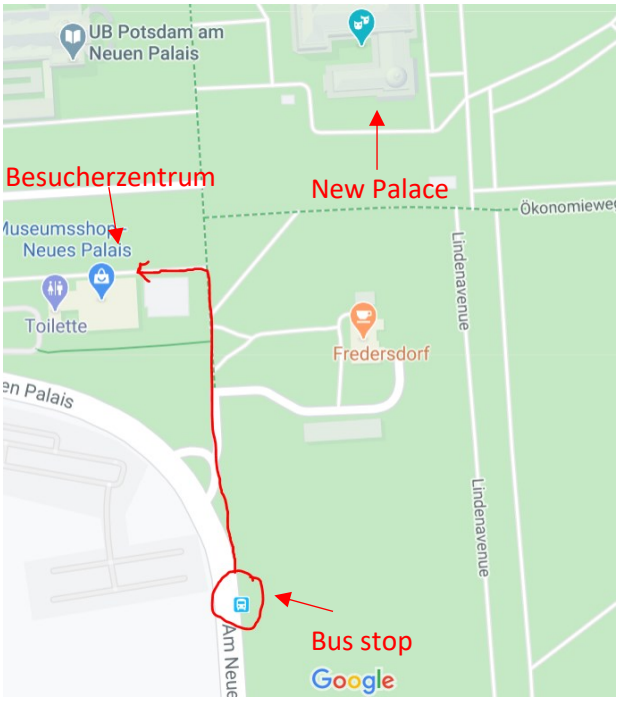
Venue

The conference takes place on the premises of GFZ German research Centre for Geoscience, Building H, on the historical science campus on Telegrafenberg in Potsdam.

20 February 2020

Field trip: Sightseeing tour in Potsdam Sanssouci Parc

- Meeting Point: 9:45 am at Besucherzentrum Neues Palais
- How to get there: From Potsdam city centre to bus stop “Neues Palais”
    - Bus 605 to “Wissenschaftspark Golm“
    - Bus 606 to “Alt Golm”
    - Bus 695 to “Bahnhof Pirschheide” With all three buses , you should exit at the bus station “Neues Palais”



We will take a 2 hours walk through the parc. Please bring warm clothes and comfortable shoes.

Poster Presentations

33. Michele Contini: Developing public engagement: a conceptual model
34. Héctor González García: Estimation of depression well cones in Los Humeros.
35. Dimitrios Mendrinos: Thermal loop design aspects in Ultra Hot Geothermal Systems
36. Dimitrios Mendrinos: Monitoring methods for Los Humeros super-hot geothermal system: state-of-the-art
37. Michal Kruszewski: Improving wellbore sealing integrity in deep high-temperature well applications
38. Francesco Parisio: Modelling fault reactivation and induced seismicity in supercritical geothermal systems
39. Sæunn Halldorsdóttir: Modelling enhanced fluid convection and heat transfer in superhot geothermal systems in Iceland
40. Claudia Finger (born Werner): Locating and characterizing seismic events in Los Humeros using time-reverse imaging
41. Claudia Finger (born Werner): Sensitivity maps for Los Humeros: Enhance localization results using time-reverse imaging to locate and characterize seismic events
42. Eszter Bekesi: Active deformation of the Los Humeros caldera floor inferred from Envisat and Sentinel-1 InSAR
43. Anna Jentsch: The exsolution of magmatic volatiles in the Los Humeros volcanic-geothermal system
44. Diego Ruiz-Aguilar: MT Data from Los Humeros geothermal area: 3D Inversion and model assessment results
45. Alessandro Santilano: Computational intelligence-based approaches to the integrated study of the Acoculco Caldera (Mexico): Particle swarm optimization of Magnetotelluric, Transient Electromagnetic and Vertical Electrical Sounding data
46. Ariel Almendral Vázquez: An automated workflow to study parameter sensitivities in a geothermal reservoir
47. Gylfi Páll Hersir: The Acoculco high temperature area in Mexico: resistivity surveying, data acquisition, processing and inversion
48. Baptiste Lepillier: How to evaluate Enhanced Geothermal System feasibility? A simple workflow applied to the Acoculco Geothermal case study
49. Zayre González-Acevedo: Characterization of soils in the geothermal zone of Acoculco, Puebla, Mexico
50. Massimo Angelone: Geochemical characteristic of the Acoculco geothermal soils
51. Massimo Angelone: Geochemical assessment of the Acoculco geothermal area's groundwater and their potential impact on population
52. Jacopo Cabassi: Novelties from fluid geochemistry of the Acoculco Enhanced Geothermal System
53. Giovanni Bongiovanni: Some aspect of seismic risks in Acoculco
54. Mathieu Perton: Seismic characterization of the Acoculco caldera
55. Biancamaria Farina: Seismic modelling including temperature in SHGS and EGS geothermal systems

56. Dimitrios Mendrinos: Los Humeros superhot and Acoculco EGS: distribution of rock modulus and correlation with temperature
57. Antonio Pola: Geomechanical and hydric characteristics of the Cretaceous sedimentary rocks, part of the basement of the Acoculco Caldera Complex
58. Federico Lucci: The Los Humeros caldera: unravelling the anatomy of the Holocene magmatic plumbing system through a petrological approach
59. Daniele Maestrelli: Interplay between rift propagation and inherited crustal fabrics: insights into the Los Humeros and Acoculco volcanic complexes
60. Roberto Sulpizio: Insights on caldera collapse as effect of clustering of large explosive eruptions: the example of the Faby Tuff eruptions at Los Humeros Volcanic Complex (Mexico)
61. Emmanuel Olvera Garcia: Faults controlling ore deposits distribution in the Las Minas area (Mexico)
62. Wiesław Kozdrój: Geochronological and paleomagnetic constraints on evolution of Palaeozoic plutonic basement and Miocene-Pleistocene volcanic succession of the Las Minas mining area (E-part of the Trans-Mexican Volcanic Belt)
63. Eivind Bastesen: Geological structures and analogue permeability studies in the Los Humeros and Acoculco geothermal systems
64. Walter Wheeler: Fault models of the Acoculco borehole area for 3D architecture and fluid flow appraisal
65. Gerardo Carrasco-Núñez: Understanding the complex volcanological evolution of Los Humeros Caldera Complex, as a key to improving our understanding of Superhot Geothermal Systems
66. Giuseppe Mandrone: Faults characterization aimed at geothermal fluid path identification and quantification
67. Giovanni Ruggieri: Insight into the fluids occurring in the super-hot reservoir of the Los Humeros geothermal system from fluid inclusions and isotopic data of the Las Minas exhumed system (Mexico)
68. Juliane Kummerow: The impact of reactive flow on electrical and hydraulic rock properties in supercritical geothermal settings
69. Alicja M. Lacinska: Evidence for fracture-hosted fluid-rock reactions within geothermal reservoirs of the eastern Trans-Mexican Volcanic Belt
70. Paromita Deb: Thermal modelling of Los Humeros superhot geothermal field
71. Giordano Montegrossi: Reservoir modelling and calibration for the superhot reservoir at Los Humeros
72. Rosa María Prol-Ledesma: Research work for shallow well siting and first drilling results

ABSTRACTS (PANEL SESSIONS)

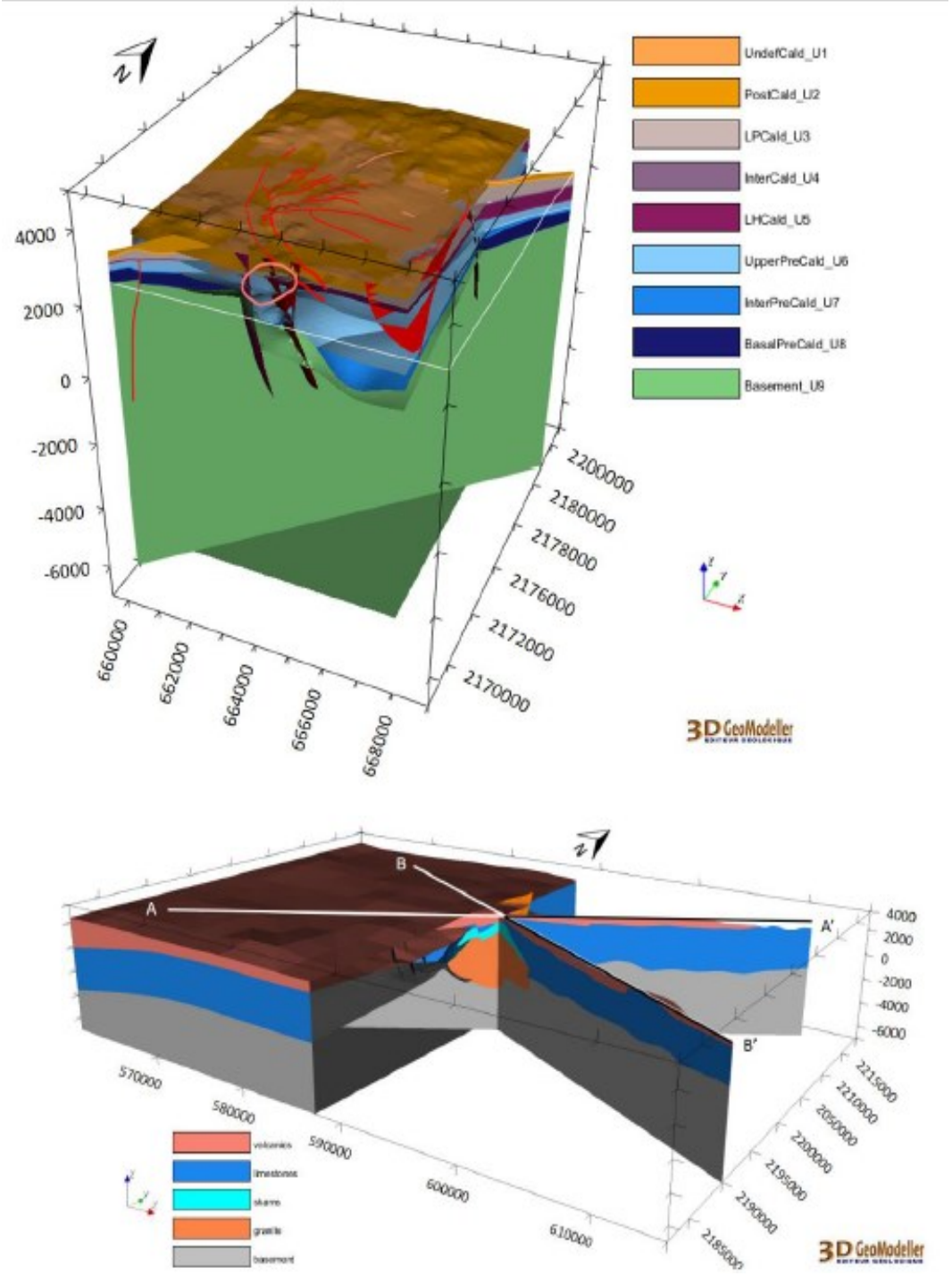
1. Importance of social informed communication to the acceptance of geothermal projects

González-Acevedo Zayre I., Leyva-Aguilera J. Claudia, García-Zarate Marco A., Sánchez-Vázquez M. Alejandra

The main applications of geothermal energy can be divided into two: indirect use to generate electricity and direct use in various domestic or industrial applications. This implies the generation and execution of good environmental practices and the consideration of a social process to implement initiatives, programs and promotion plans. Where the management of benefits and opportunities propitiates beneficial advantages and impacts for all actors. Many efforts must be made to achieve social acceptance of geothermal power plants, in the face of a complex Mexican reality. Finding a balance between energy development, community interest and environmental protection implies applying a sustainable development model that considers geothermal technology, the environment and society. There are several cases of social acceptance in countries such as Iceland, New Zealand, the Philippines and Kenya, where direct uses of geothermal energy, along with social commitment and social inclusion have been the key to success. In this work three principal aspects were evaluated: 1. Whether informed communication at all levels (government, stakeholders and communities) and at all stages of project development leads to social acceptance. 2. To what extent socially responsible industries foster harmonious relationships between local communities in the geothermal business. 3. Finally, whether minimizing potential environmental impacts and informed communication alone are sufficient for social acceptance. This evaluation was made in two sites in Mexico, one on exploration and one with a geothermal power plant that started commercial activities in year 1991. Resulting that the three evaluated factors are important to achieve social acceptance. Informed communication at all steps of the geothermal development. The corporate social responsibility is limited by the law and the personal compromise of the leadership of the geothermal developer. If the environmental impacts are informed to the communities and they are part of the environmental monitoring, it results in a social acceptance of the geothermal project. The social context is very important to be able to communicate correctly. The transparency of the facts and information is very important to develop a trust relationship between the developer and the nearby communities. This work was made as part of the WP9 of GEMex project, supported by CONACYT-SENER fund.

2. 3D Geomodels of Los Humeros and Acoculco geothermal systems (Mexico) - H2020 GEMex Project: Methodology, products and feedback

Philippe Calcagno, Eugenio Trumpy, Luis Carlos Gutiérrez-Negrín, Domenico Liotta, Gerardo Carrasco-Núñez, Gianluca Norini, Andrea Brogi, Víctor Hugo Garduño-Monroy†, Ásdís Benediktsdóttir, Emmanuel Gaucher, Tania Andrea Toledo Zambrano, Gylfi Páll Hersir, Adele Manzella, Alessandro Santilano, Gianluca Gola, José Luis Macías, Loes Vaessen, Gwladys Evanno, Claudia Arango Galván



3D geomodels of (top) Los Humeros at local scale, and (bottom) Acoculco at regional scale. Coordinate system is WGS84/UTM zone 14N.

The European-Mexican geothermal GEMex project aims at developing geothermal energy in the easternmost region of the Trans-Mexican Volcanic Belt. Two sites under development by the Comisión Federal de Electricidad (CFE, Mexican National Power Company) are investigated to assess possible superhot resources and to develop an Enhanced Geothermal System, respectively in Los Humeros and Acoculco. European and Mexican partners constructed 3D geomodels in a collaborative way on both sites. In a preliminary step, these models were set up using data available at the beginning of the project, including geological maps, cross-sections and well logs. In a second phase, they were updated thanks to the results from geological and geochemical field campaigns conducted by GEMex partners. The models are finally improved via the integration of geophysical data to strengthen the geological structures and infer the geothermal interpretation. The methodology deployed during the three main geomodelling phases and the evolution of the results will be described. In Los Humeros, the structures were modelled from the geological map, additional field work, and volcanoes alignment study. The geological formations were described in four groups at regional scale, and nine units at local and integration scales. The CFE provided records of fifty-six wells to constrain the Los Humeros area at depth. Geophysical data such as resitivity from MT survey, Vp/Vs computation, 3D seismic events, and gravity were used in the integration process. For Acoculco, the data core to build the 3D geomodels were made by the newer available geological map for the area, two geological cross-sections and about 50 structural stations acquired in the field works performed during the GEMex project. The structural asset and groups of formation were set-up for regional and local scale. In addition, 3D geomodels were constrained with the two deep boreholes drilled by the CFE, resistivity from MT and density from gravity surveys. The 3D geomodels of Los Humeros and Acoculco were used by partners along the course of the project as input for computations and simulations based on the geometry of the geological structures. In addition to the knowledge produced, the outcomes of the geomodelling work include the geomodels themselves that are shared in open access, and scientific presentations and papers. To conclude, the lessons learned during this interdisciplinary action will be discussed. The authors wish to thank the Comisión Federal de Electricidad (CFE, Mexico) for their assistance and support.

3. Collapsed calderas and resurgence vs inherited fabrics: insights from analogue modelling on the evolution of Los Humeros and Acoculco volcanic complexes

Marco Bonini, Daniele Maestrelli, Giacomo Corti, Domenico Montanari, Giovanna Moratti

Caldera collapse is a complex geological process that, due to its quasi-instantaneous nature, remains difficult and elusive to investigate. Several numerical and analogue modelling experiments have been performed during the last decades to investigate this process (e.g., Geyer et al., 2014, and reference therein), these approaches being effective for monitoring at reduced time and length scale the progressive evolution and the deformation architecture of caldera collapse. Analogue models available in literature show different processes for ring-fault formation and propagation, especially focusing on the interaction between outward-dipping reverse faults and inward-dipping normal faults. If a general agreement is shared regarding the first-order processes leading to collapsed edifices (e.g. Acocella, 2007), some aspects are still barely known and need to be investigated more in depth, such as the role of inherited structures and their interaction with caldera collapse processes, as well the interplay between inherited fabrics and caldera resurgence. In the frame of the GEMex Europe-Mexico cooperation project (Horizon 2020 Programme, grant agreement No. 727550), we have performed analogue models to investigate the influence of pre-existing faults on caldera formation, and afterward the possible caldera resurgence at the Los Humeros volcanic complex. In our modelling, we have induced caldera collapse by draining out an analogue magma emplaced below a brittle sedimentary cover. Pre-existing faults have been placed either at the caldera margin(s) and/or above the caldera depression. In particular, the shape of the magma chamber was varied by imposing straight sides, simulating pre-existing fault discontinuities. In some models, the sand pack was pre-deformed by introducing artificial dilation zones in different positions to simulate inherited fabrics within the brittle crust. Caldera resurgence was obtained by re-injecting analogue magma at various depths inside the collapsed caldera. Our models show that discontinuities may induce caldera ring-faults to deviate from standard evolution (i.e., initial inward dipping reverse-faults followed by outward-dipping normal faults). Specifically, the inherited fabric is able to influence significantly the deformation pattern, by modifying and/or inhibiting the formation of specific caldera collapse structures. The depth of re-injection strongly affects the type intrusion and interacts with the caldera fault pattern. The experimental results show some similarity with the ring fault pattern of the Los Humeros and Acoculco volcanic complexes, as well as with the deformation pattern of caldera resurgence observed at the Los Humeros volcanic complex.
Acocella, V. (2007). Understanding caldera structure and development: An overview of analogue models compared to natural calderas. *Earth-Science Reviews*, 85(3-4), 125-160. Geyer, A., & Martí, J. (2014). A short review of our current understanding of the development of ring faults during collapse caldera formation. *Frontiers in Earth Science*, 2, 22.

4. Developments of auxiliary chemical geothermometers (Na-Li, Na-Cs) applied to the Los Humeros and Acoculco high-temperature geothermal fields (Mexico)

Bernard Sanjuan

The knowledge of the temperature of the deep geothermal fluids, rock permeability and water reservoir capacity are three key parameters for developing deep geothermal energy. Since 1965, one of the major applications of fluid geochemistry in the exploration of the potential geothermal reservoirs involves estimation of their temperature, using classical chemical, isotope and gas geothermometers on fluids collected from geothermal wells and thermal springs. The classical Na-K-Mg ternary diagram and main geothermometers such as Silica-quartz, Na-K, Na-K-Ca, K-Ca, and 18-Oxygen (H_2O-SO_4), indicate that full chemical equilibrium is reached at about 290 ± 30°C for most of the geothermal waters discharged from the Los Humeros field (Fig. 1). This temperature range is concordant with the presence of an upper liquid-dominated reservoir area, with neutral pH at 290-330°C, located in augite and hornblende andesites, or in deeper basalts, as suggested in numerous studies. Among the different Na-Li geothermometric relationships existing in the literature, only the Na-Li auxiliary geothermometer defined for North-Icelandic high-temperature basaltic geothermal dilute waters give concordant temperature values (320 ± 30°C). The Na-Cs auxiliary geothermometer also yields similar temperature values (300 ± 30°C). The classical Na-K-Mg ternary plot indicates that all the thermal waters discharged from the Los Humeros and Acoculco areas (Fig. 1) are immature, having not reached full chemical equilibrium with the host rocks. In addition, solute geothermometry cannot be applied to acidic waters. Despite their common meteoric origin indicated by the Deuterium and 18-Oxygen isotopes, the Cl/Br mass ratios of these thermal waters are much lower (from 70 to 700) than those of the Los Humeros

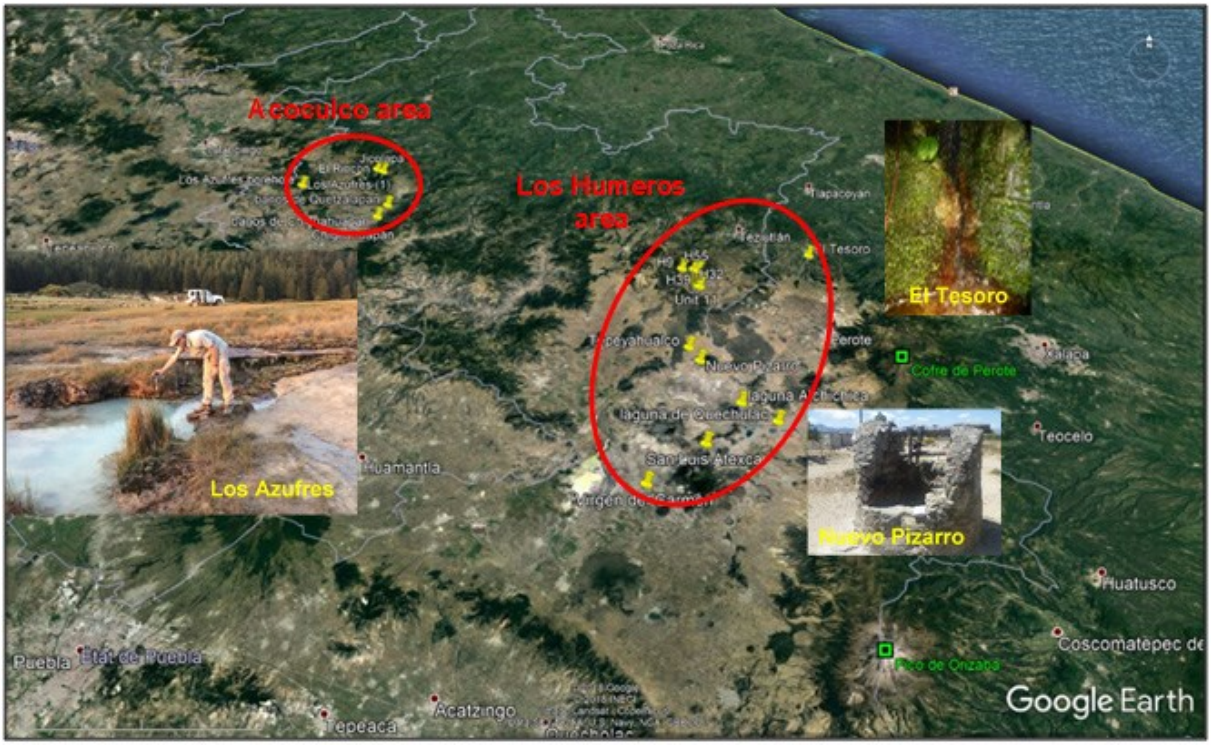


Figure 1: Location of the Los Humeros and Acoculco geothermal wells and hot springs.

geothermal fluids (from 1200 to 1700). The Ca-HCO_3 diagram shows that most of these thermal waters have interacted with calcium carbonates. They have high Ca, Mg and Sr concentrations compared with the Los Humeros geothermal waters, which are depleted in these elements. Their $^{86}Sr/^{87}Sr$ ratios, ranging from 0.706272 to 0.707262, suggest that they are interacting with marine carbonates formed during the Mesozoic period. Nevertheless, it appears that the Na/K and Na/Li ratios, for numerous thermal waters, are close to those of the Los Humeros geothermal fluids. Associated with δ^7Li values ranging from 4.7 to 6.5‰ and relatively high B concentrations, and some escapes of deep reservoir hot gases which reach the surface, these ratios suggest that small fluxes of deep waters, despite their low-permeability environment, could be able to preserve, more or less, their original Na/K and Na/Li ratios (and to a lesser extent, their Na/Rb and Na/Cs ratios), resulting from the temperature of their deep reservoir, even after significant mixing with cold waters and chemical changes, during their ascent up to the surface. In such a context of low-permeability, these ratios may be useful tools for high-temperature geothermal exploration. Classical geothermometers such as Silica, K-Mg and K-Ca, based on fluid equilibration with chalcedony, muscovite, clinochlore, K-felspar and calcite, which can re-equilibrate relatively fast, as well as the $\delta^{18}OH_2O$-SO_4, and the K-Sr and K-F geothermometers, indicate subsurface temperature estimations for these thermal waters, which vary from 60 to 100°C.

5. Hydrogeological and hydrochemical characterization of surface and groundwater in the surroundings of Los Humeros and Acoculco

Thomas Kretzschmar, Matteo Lelli, Juan Ignacio Sánchez Ávila, Francisco del Toro Guerrero, Rubén Campos Gaytán, Julio Cañas Ramírez, Yann René Ramos Arroyo, Victor Rodríguez Moreno, José Alonso Aguilar Ojeda

The development of hydrogeological and hydrogeochemical models for the Acoculco, Puebla/Hidalgo region and the Los Humeros, Puebla region were carried out in two phases. On the one side, the hydrogeological part was done by using different tools (satellite images, ArcGis, existing available information) to determine the size of watersheds for the two sites as well as the necessary parameters for establishing a surface water budget within these watersheds. The study areas consists in four different hydrological basins for Acoculco (AC) and six watersheds for Los Humeros (LH) covering areas of around 8,000 km^2 and 15,000 km^2, respectively. For each watershed the water budget was calculated by estimating potential and real evapotranspiration, runoff, infiltration as well as total precipitation in the area, using the data reported in the surrounding meteorological stations. Furthermore, areas where mountain front and mountain block recharge is possible were determined by combining geological and morphological features of the watersheds. The second part of the study consisted in an extensive fieldwork, which was carried out in four sampling periods in AC, from October 2017 to September 2019, with a total of more than 180 springs, wells and streams sampled during that period. For LH there were five sampling periods with a total of around 250 samples. Furthermore, runoff estimates, infiltration tests as well as soil profiles were carried out to get more data on the hydrologic properties of the areas. Anions (Cl, NO_3, SO_4, PO_4 and F), major cations (Na, Ca, K, Mg, Si), minor (Fe, Mn, Sr, Li) and trace elements (Al, Ni, Cu, Cd, As, Se, Ti, among others) were determined in all samples. In addition, stable isotopes of ^{18}O and deuterium at both sites were analyzed. Organic compounds and ^{11}B isotopes were determined only for LH. In all cases, pH, electrical conductivity (EC), alkalinity and dissolved oxygen were determined in the field. Most of the samples were taken in duplicate; one set was analyzed in the laboratories of the CeMIE-Geo in Ensenada, Mexico, and the second one in the CNR laboratories in Pisa, Italy. The field results showed for the cold springs (T up to 15°C) that EC varied between 29 and more than 2000 µS/cm, pH between 2.08 and 7.87 and dissolved oxygen between 3.23 and 8.2 mg/L. Hot springs with T between 32 and 48.3°C showed higher CE values of 1500 and 1600 µS/cm. In the wells EC ranged from 170 to 940 µS/cm, but most of them presented EC of less than 700 µS/cm. The pH of these wells varies between 6.4 and 7.9 and the dissolved oxygen between 1.7 and 6.4 mg/L. The most probable recharge areas within the watersheds cover relatively small areas, totaling around 20 to 25% of the total areas. The surface water budget calculations indicate significant amounts of infiltration at least into the subsurface zones. Connecting these amounts to a possible deeper recharge is still in process.

6. Towards visualization of the reservoir settings in the Los Humeros and Acoculco geothermal fields using gravity

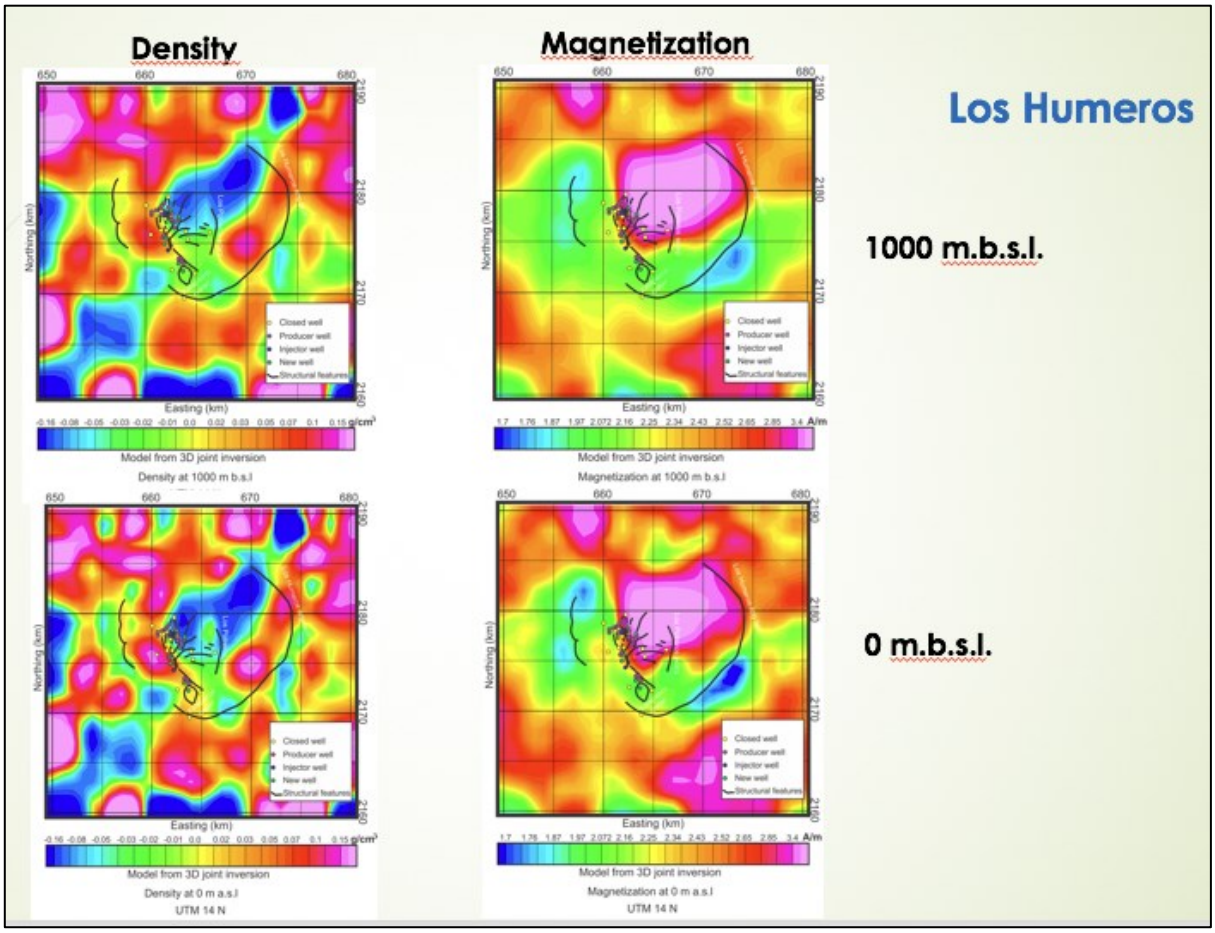
Natalia Cornejo

The GEMex project addresses different challenges in the development of Enhanced Geothermal Systems (EGS) and Superhot Geothermal Systems (SHGS) in the Trans-Mexican Volcanic Belt. Although they are located in similar tectonic settings, the geothermal conditions in Acoculco and Los Humeros differ and they can be categorized as an EGS and a SHGS system, respectively. The Los Humeros field is currently under conventional exploitation. North of the current production area, temperatures higher than 380°C are expected. The Acoculco site presents temperatures ~300°C at a depth of 2 km, but a reservoir has not been identified. The main goal of this work is to visualize and characterize the reservoir conditions using gravity data. To accomplish this, we processed data from a total of 344 gravity stations at Los Humeros and 84 stations at Acoculco. In Los Humeros, the Bouguer anomaly shows a clear trend of decreasing gravity from the NE to the SW, fitting with the Bouguer anomaly of the regional gravity data, where a minimum gravity anomaly was found in the center of the caldera. At the reservoir level in Acoculco, an area with a high-density anomaly coincides with an area of low permeability, revealed by the absence of water at depth were two non-productive exploration wells were drilled (Peiffer et al., 2014b).

7. Joint 3D inversion of regional gravity and magnetic data for Los Humeros and Acoculco geothermal fields with a petrophysical relation

Marco Antonio Pérez-Flores, Jonathan Carrillo-López, Luis A. Gallardo, Eva Schill

We have developed an inversion algorithm for getting simultaneously density and magnetization from three-dimensional structures assuming a petrophysical relation. This petrophysical relation between density and magnetization can be lineal, polynomial or parabolic and it is assumed as unknown and therefore it must be included in the Objective Function. This algorithm was used for processing the Los Humeros and Acoculco regional gravity data obtained from the National Hydrocarbon Commission (CNH) and the magnetic data from the Mexican Geological Survey (SGM). In Los Humeros, the three-dimensional density model reveal a circular feature that match with the larger caldera. The magnetization model shows a caldera centered high magnetization body that correspond with a low-density body (see figure below). The 3D magnetization model for Acoculco reveals a very deep circular feature perhaps related with the oldest caldera. A high magnetization body is located where the superhot drilled holes are.



8. Thermal signature and regional resource assessment in Los Humeros and Acoculco areas

Damien Bonté, Jon Limberger, Eugenio Trumpy, Gianluca Gola, Jan Diederik van Wees

The thermal behavior in the surface at regional scale and therefore the resource available was investigated in the two GEMex areas Los Humeros and Acoculco. The regional understanding of the considered sites is of great importance as it (1) provides boundary condition for the more local thermal investigation and (2) allows to understand what makes the specificities of the area under investigation both from and heat source and heat transfer perspective. The numerical modelling strategy differs for the two sites but the resource method is similar. The temperature in Los Humeros is constrained by 65 deep wells drilled to explore or exploit the geothermal system. Because of an unsteady formation temperature measurements a correction method was performed on the Bottom Hole Temperature (BHT). In particular the Instant Cylinder Source (ICS) method allowed to obtain a close to equilibrium temperatures. By looking at the thermal gradient, it is noticeable that the highest temperatures are in the northern part of the inner caldera and follow the main SW-NE faults. The thermal state of the lithosphere is estimated, assuming steady-state conditions and conductive heat transfer only. To study the effect of non-steady-state and/or advective effects, we used inverse modelling on a selection of temperature measurements to find a suitable range for the magma chamber emplacement depth, regional groundwater fluxes, and local advection. Our numerical approach solves the transient heat and mass transport equations to estimate the present-day temperature distribution around a single magmatic heat source, associated with the ~0.164 Ma ignimbrite eruption. On the two boreholes of Acoculco temperature time-series were acquired and used to extrapolate static temperature by the application of the well-known Horner Plot method. In both wells, the resulting static profiles show common features: i) a mainly conductive heat transport dominates in the underground and ii) the geothermal gradients show an increase nearby 1.75–1.80 km depth from 106–117 °C/km in the upper section to 275–355 °C/km in the deeper one. The regional thermal model was set up with the aim to test the hypothesis about the existence of a recent and relatively shallow magmatic intrusion that induced in the overlaying formations a transient thermal signal. Our numerical approach consisted in solving the transient heat and mass transport equations in order to forecast the present-day temperature distribution around a hypothetic and recent magmatic intrusion. Eventually a volumetric heat-in-place resource assessment was conducted for both Los Humeros and Acoculco. The main output is the theoretical capacity or heat in place H (J), which is the amount of thermal energy physically present in the reservoir rocks of a certain area or prospect. Most of the potential in Los Humeros is associated with the high temperatures observed within the caldera zone as well as for Acoculco the inner part of the caldera where the two boreholes exist has the higher potential.

9. The structure of the Acoculco geothermal area (Mexico) and implications for enhanced geothermal system (EGS) development

Andrea Brogi, Domenico Liotta, Walter Wheleer, Eivind Bastesen, Eugenio Trumpy, Fidel Gómez Álvarez, Adrián Jiménez Haro, Caterina Bianco, Víctor Hugo Garduño†, Baptiste Lepillier

The Acoculco geothermal area is located in the eastern sector of the Trans-Mexican Volcanic Belt (TMVB) at the border between the States of Hidalgo and Puebla (Mexico). It consists of a Neogene-Quaternary caldera complex developed in the 2.7–0.06 Ma time span, through emission of domes, cinder cones, fissure lava flows and ignimbrite eruptions. The volcanic evolution produced a pyroclastics and lava flows pre-dating and post-dating the caldera development. The volcanic succession rests on the Jurassic-Cretaceous carbonate succession, deformed during the Laramide Orogeny (i.e. Oligocene). The Acoculco caldera has been investigated by the Comisión Federal de Electricidad (CFE) for geothermal exploitation through deep boreholes drilled within the caldera adjacent to surface geothermal manifestations. The boreholes did not find productive geothermal fluids even though temperature exceeding 300°C was measured at about 2 km. Nevertheless, boreholes encountered skarn levels and rock volumes affected by hydrothermal alteration, therefore suggesting a geothermal system active in the past, within the caldera. Consistent with the cooling history the drilled rock volumes are now characterized by low permeability, even though the whole caldera is cut by faults with regional relevance. These faults, of NW- and NE-striking, are characterized by superposed kinematics and are framed in a NW-SE trending regional extension. Structural and kinematic analyses carried out through structural stations, generally located along the main regional faults affecting the volcanic and fluvial-lacustrine sediments, indicate that: i) the NW-striking fault system shows two superposed movements: the first movement is defined by right-lateral strike-slip to oblique-slip movements, while the second movement is characterized by a dominant vertical component; ii) the NE-striking faults are characterized by multiple movements with a dominant vertical component. The focal mechanisms from both NW- and NE-striking faults clearly show that the paleo-stress tensors for both datasets are compatible with the regional stress map. In this picture, we interpret the NW-trending structures as transfer faults associated with the NE-trending normal faults. The regional uplift is taken into account for explaining the normal kinematics documented in both the fault trends. The caldera sits at the northern edge of the plateau, hence erosion and the steep topographic gradient may affect the local stress field. Kinematics of faults is therefore a consequence of the competition between crustal stretching and regional and/or local (magma induced) uplift. In conclusion, the different kinematics and geometry of faults can be explained in the same tectonic extensional context, under the same regional stress field, characterized by a dominant NW-trending extensional direction. Rock volumes at the intersection of the two fault systems represent broad damaged volumes, presently sealed at the surface, where the lithotypes involved in the deformation cannot guarantee an appropriate permeability for channeling geothermal fluids. Reactivation of both fault systems at their intersection, and especially the NW-trending one, could offer significant fluid pathways for geothermal fluids stored at depth. EGS experiments should be addressed following such a result.

10. Neo-formed faulting and fracturing with conductive characteristics in the Acoculco geothermal system, Puebla, Mexico

Adrián Jiménez-Haro, Fidel Gómez-Álvarez, María Félix Gaitán-Ramírez, Víctor Hugo Garduño-Monroy†, Óscar García-Hernández, Monserrat Magaña, Alejandro Ávila-Olivera, Arturo Muñiz-Jáuregui, Sergio Nájera, Isabel Israde-Alcántara, Domenico Liotta, Andrea Brogi, Walter Wheeler, Eivind Bastesen

The Acoculco caldera is the zone selected within the framework of the GEMex project to be studied in order to develop an enhanced geothermal system (EGS). Starting in the 1980's, the Comisión Federal de Electricidad (CFE) carried out several studies including the drilling of two exploratory wells, EAC-1 and EAC-2, which resulted in temperatures up to 300 °C but with zero permeability. The results obtained in the Work Package 4.2 of the GEMex project show the existence of two main fault systems of regional extent that have been active from the Pliocene to the present, and are currently interacting with each other. The first system dominantly consists of right lateral strike slip to oblique faults of NW-SE direction, while the second one is NE-SW direction and consists of oblique to normal faults with a dominant vertical component. The first system is also characterized by a second kinematic event, with a dominantly vertical component. This structural scheme has been developed under a NW50°SE ± 7° extensional regime with evidence that suggests that it is still active during the Holocene, determining both crustal extension and uplift. The most important evidence is the existence of intra-caldera faults of NE-SW and NW-SE direction cutting Pleistocene and Holocene soils. Additionally, the results from a 2-year monitoring campaign of a precision geodetic GPS network consisting of 18 points strategically located within and surrounding the Acoculco caldera, documents movements of 6 to 36 mm in the NW-SE direction. The difference in the magnitude of NW-directed station velocity components indicates NW-directed extension in a region dominated by NE-trending normal faults and NW-trending transfer faults. Fracturing analyses were done through field measurements in outcrops and supported with statistical methods based on fractal theory. Measurements were made in the sedimentary and volcanic units that constitute the basement in which the geothermal system of Acoculco is housed. A discretization of the fractures was carried out taking into account their genesis. This was done by rotating planes of faults and fractures, using the stereographic network, in which the fracturing and faulting linked to the Laramide deformation were separated from those related to Quaternary deformation. This discretization was made based on folds-fracture models. To further characterize the fracturing, alteration minerals in faults and fractures were strategically sampled in order to constrain the chronology of tectonic activity and their relationship with the geothermal system. The characterization of the fracturing and faulting of the rocks where the Acoculco geothermal system is housed plays a very important role for the design of the hydraulic stimulation, necessary in the development of an EGS. However, the results obtained suggest that the area presents structural conditions favorable to be explored in order to develop a conventional geothermal system.

11. MT Data from the Acoculco geothermal area: 3D inversion and model assessment results

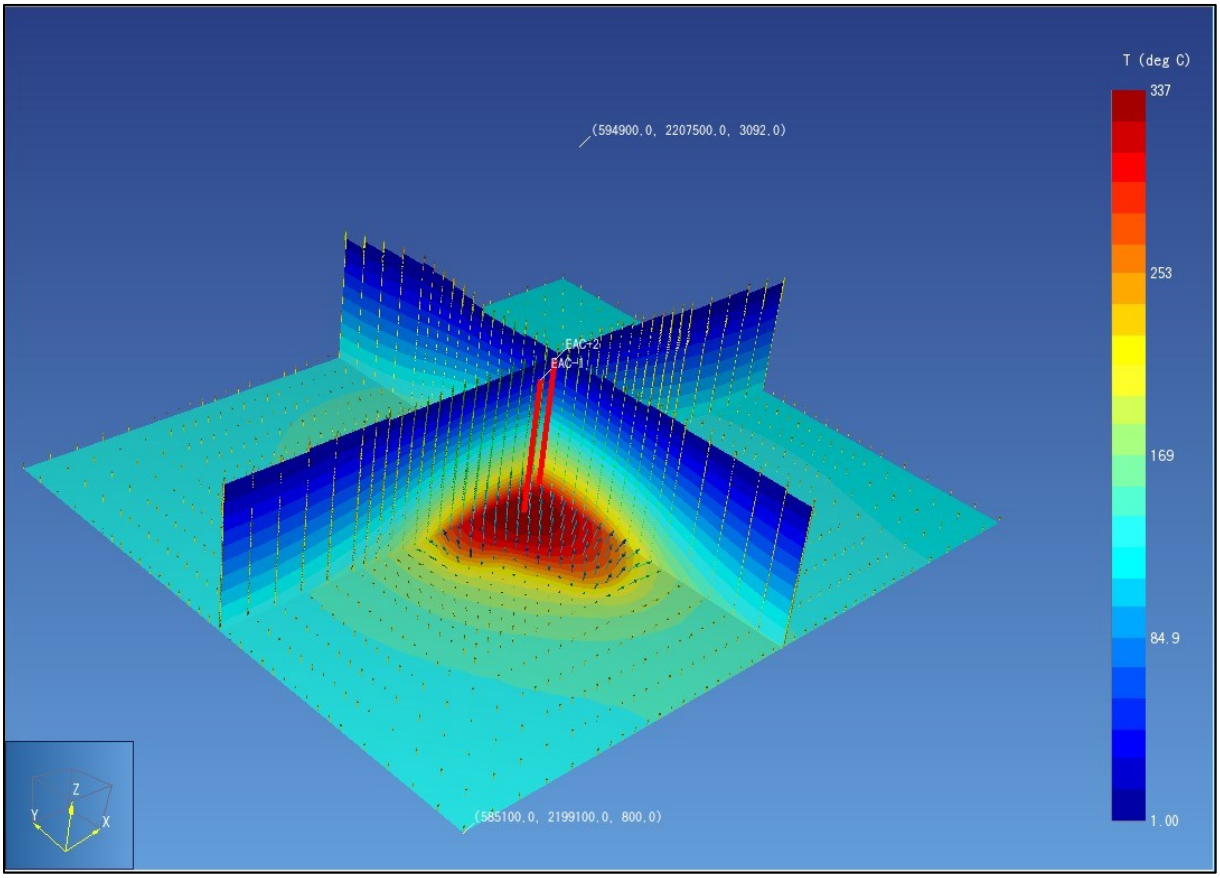
Diego Ruiz-Aguilar, José Manuel Romo-Jones, Claudia Arango-Galván, Ásdís Benediktsdóttir, Gylfi Páll Hersir

A total of 68 Magnetotelluric (MT) and 65 Transient Electromagnetic (TEM) soundings were acquired in Acoculco, which is a high-temperature geothermal area proposed to develop an Enhanced Geothermal System (EGS) within the framework of the GEMex project. Both techniques were applied at the same spots to use TEM information for static-shift correction of the MT data. Transient responses were measured from 0.1 to 90 ms with a TerraTEM device and using a 100 x 100 m^2 single-loop configuration. MT signals were recorded with Metronix systems in the period range from 0.001 to 1000 s. We used BIRRP (Bounded Influence Remote-Reference Processing) robust processing algorithm to estimate the MT transfer functions (i.e., apparent resistivity, phase, vertical magnetic transfer function). Three-dimensional inversion of MT data was performed using ModEM software. We explored starting the inversion process with different initial models and their results were evaluated. Before interpretation, we applied sensitivity tests to seek for artifacts derived by inversion and for defining the depth of investigation. The preferred inversion model shows a conductive clay cap over a more resistive structure.

12. Numerical conductive-heat flow analysis of the natural-state geothermal system of Acoculco

Abel Felipe Hernández Ochoa, Adriana Paredes Soberanes, Siomara López Blanco, Alfonso Aragón Aguilar, Georgina Izquierdo Montalvo, Joaquín Torres Rodríguez, Ismael González Reyes, Neftalí Reyes Picasso, Miguel Ángel Ramírez Montes

The geothermal system of Acoculco has been characterized as a Hot Dry Rock system, where a potential Enhanced Geothermal System (EGS) might be developed; temperatures close to 300 °C have been recorded in two exploratory wells at depths close to 2 km. Efforts have been undertaken by both the GEMex European and Mexican researcher teams to elaborate technical concepts aimed at developing an EGS in Acoculco. Recent re-assessment of the well rock samples and cuttings carried out by the Mexican geology group has led them presume that the granite unit might be just a continuation of the overlying skarn layer. This leads us to re-affirm the possibility of having several likely conceptual models as originally considered in the GEMex work plan. Thus, we have made independent numerical models that describe the spatial conductive heat flow distribution of this system at its natural state with the scope of reproducing measured pressure and temperature data and predicting the system's response under different working conditions; each numerical model corresponds to one of the possible conceptual (geological) models. All numerical models of Acoculco extend over a surface area of about 80 km^2 and depth of 2 km (see figure). Our results are expected to help better lay out the stimulation plan in one of the exploratory wells that should be designed taking into account the technical and economical input from the geothermal field owner.



13. Integrated stress field estimation and implications for enhanced geothermal system development in Acoculco, Mexico

Michal Kruszewski, Hannes Hofmann, Fidel Gómez Álvarez, Caterina Bianco, Adrián Jiménez Haro, Víctor Hugo Garduño†, Domenico Liotta, Eugenio Trumpy, Andrea Brogi, Walter Wheeler, Eivind Bastesen, Francesco Parisio

The Acoculco Caldera located within the Trans-Mexican Volcanic Belt in central-southern Mexico has been subjected to geothermal development attempts in recent years. The two deep exploratory wells, EAC-1 and EAC-2, encountered high temperatures, but scarce permeability and insufficient flow of reservoir fluids prevented commercial geothermal production. Therefore, heat exploitation in the Acoculco field may only be possible through the development of an Enhanced Geothermal System (EGS). In order to evaluate the potential concepts of EGS development a wide range of exploration and research activities have been carried out within the framework of the trans-Atlantic research project GEMex. One of the most important, but also the least defined, parameters for the planning of the stimulation operations, which is the best estimate of the in-situ stress field conditions, is presented in this work. The investigation is based on various types of geological and drilling data as well as results from the borehole logging campaign, which were acquired throughout the GEMex project. The resultant stress regime of the Acoculco field can be described as normal to strike-slip faulting with an average direction of S_{Hmax} of N56°E ± 5°, pore pressure gradient of 8.73 MPa/km, linearized minimum horizontal stress gradient of 12.5 ± 1.2 MPa/km and linearized vertical and maximum horizontal stress gradient of 22.7 ± 1.2 MPa/km. Based on the results from the in-situ stress estimation study, the maximum formation breakdown pressures, required to stimulate the reservoir rock, and potential EGS development methods are proposed.

14. Hydraulic fracturing experiments in laboratory scale to generate benchmark datasets for verification of stimulation design tools

Paromita Deb, Stephan Düber, Christoph Clauser

Enhanced Geothermal System (EGS) techniques are used to create permeability in hot, dry and impermeable formations by creating new fractures or by connecting existing fractures. These fractures form heat exchangers in which cold water is circulated and heated up for generating electricity at the surface. For a successful EGS design, it is fundamental to understand the propagation of fracture under different stress conditions. Codes for designing stimulation techniques and predicting fracture growth and propagation exist for several decades. However, verification of the constitutive relationships and model assumptions of these codes against real field data are generally lacking. This is due to the nature of the dataset obtained through field experiments where obtaining accurate information of all subsurface parameters and conditions are essentially impossible. With an aim to produce sets of hydraulic fracturing data, which could be utilized as benchmark to verify different numerical hydraulic stimulation design tools, we conduct hydraulic fracturing experiments in the laboratory. The experiments are conducted under well-controlled conditions and consists of all information, which are generally lacking when experiments are performed in the field. Within the framework of GEMex, we performed four experiments in the granite and marble samples collected from Las Minas, which is considered as an exhumed system for Los Humeros and Acoculco. These samples are considered to be representative of the subsurface rocks of our study area. Samples of size 30 cm × 30 cm × 45 cm are hydraulically fractured by injecting high-pressure fluid through a 20 mm diameter borehole drilled through the center of the sample. During the experiments, the sample is subjected to a confining pressure of around $\sigma x = \sigma y =$ 15 Mpa and $\sigma z =$ 5 Mpa. The experimental data set (flow-rate, pressure, injection volume) along with the boundary conditions, the rock and the fluid parameters are then distributed to the different simulation groups for verification of their stimulation design codes. This work is performed within the GEMex project, funded by the European Union's H2020 research and innovation programme under Grant Agreement No. 727550.

15. A predictive mechanical model for hydraulic fracture stimulation in Acoculco geothermal reservoir system

Baptiste Lepillier, Alex Daniilidis, Anita Torabi, David Bruhn, Eivind Bastesen, Francesco Parisio, Hannes Hofmann, Juliane Kummerow, Keita Yoshioka, Nima Doonechaly Gholizadeh, Oscar García, Pierre-Olivier Bruna, Richard Bakker, Walter Wheeler, and the GEMex consortium

The development of an EGS is one of the goals of the GEMex project, an international collaboration of two consortia, one from Europe and one from Mexico. The research is based on exploration, characterization and assessment of two geothermal systems located in the Trans-Mexican volcanic belt, Los Humeros and Acoculco. Los Humeros has been a producing field for several years, but Acoculco is yet to be developed. Thanks to surface manifestations of hydrothermal activities, the existence of a geothermal system is evident. However, two wells reached very high temperatures, but did not find any fluids. For that reason, the Acoculco Caldera is foreseen as EGS development site, hoping to connect existing wells to a productive zone. In this study, we develop a workflow that aims at assessing the feasibility of this EGS. The approach aims at generating a realistic predictive mechanical model for fracture stimulation from the borehole. The strength of the method stands in the combination of reliable data obtained from field work and experimental measurements on mechanical properties of the target rocks, used together to populate a numerical model. The workflow starts with the identification and description of the surface discontinuities using the scanline survey method. These surveys are interpolated and extrapolated using the multiple point statistics method to generate geological discrete fracture networks (DFNs). Using these DFNs together with the mechanical properties measured in the rock physics laboratory, the fracture propagation and its interaction with the pre-existing fracture network are simulated using the phase field in OpenGeoSys open-source FEM software. The results of these simulations are then evaluated in Comsol Multiphysics finite element software to model fluid and thermal flow through the fractured reservoir. The method offers a physically sound prediction of the reservoir flow characteristics as well as an accurate mechanical model of the fracture propagation and the pressure distribution for borehole stimulation. Because the workflow is based on easily accessible data and thanks to its simplicity, this approach could be applied in most EGS case studies.

16. An integrated modelling approach for predictions of induced seismicity at the potential EGS site in Acoculco

Thibault Candela, Elisabeth Peters, Jan Diederik van Wees

In case of EGS heat production, human-induced earthquakes might be triggered during both the hydraulic stimulation phase and the subsequent long-term production. For both instances, two dedicated models have been newly developed to capture the key ingredients which could potentially cause induced seismicity. These models will be demonstrated in the potential EGS site of Acoculco in the trans-Mexican volcanic belt. During the first phase of hydraulic stimulation, the focus is on modelling flow during a single or couple of close-well faults thought to be stimulated. An analytical injection model through faults is coupled with our newly developed physics-based block-spring type rupture model. In doing so, each single induced event potentially triggered by the cold-injection at the faults and/or inter-events stress transfer can be modelled. A special attention is given to the relative contribution between tensile opening events and shear events; this is particularly important since tensile opening events are generally more difficult to monitor even if they can contribute significantly to the flow enhancement. During the long-term production phase, a field-scale numerical flow and heat simulation is used as input for the modelling of induced seismicity. This flow simulation models the fracture-character of the Acoculco geothermal field including explicit faults embedded in a dual-porosity medium. Induced stress changes caused by both the changes in pressure and temperature during long-term production are modelled by our recently developed fast semi-analytical modelling approach (coined as MACRIS). The specificity of this novel geomechanical approach is that it is mesh-free, meaning that it can directly take as input the complex topology of the reservoir flow grid and thus simulating the geometrical complexity of the geothermal reservoir. The simulated stress changes are combined with the rate-and-state frictional response of the pre-existing faults in order to compute the potential rate of induced events. Finally, assuming pre-stress scenarios, we derive the instantaneous distribution of earthquake magnitudes given a volume-averaged seismicity rate, grow rate of the perturbed region, and background fault-size distribution. The combination of these two modelling strategies provides an integrated approach for prediction of earthquakes by geothermal operations at Acoculco, both during the stimulation phase and the long-term phase of production. A key element is that in both cases, the computation time is highly optimized, enabling to run an ensemble of seismicity simulations varying the specific range of each uncertain physical model parameters. This provides an efficient approach for a probabilistic prediction of induced seismicity based on physics-based models.

17. Simulation of potential production scenarios at Acoculco

Elisabeth Peters, Baptiste Lepillier, Hannes Hofmann

The site of Acoculco in the Trans-Mexican Volcanic Belt in Central Mexico has been identified as a potential geothermal site since at least the early 1980's (López-Hernández et al., 2009). Two exploratory wells were drilled measuring high temperatures (up to 300 °C), but little permeability making the site a candidate for an EGS development. Within the GEMex project, a feasibility study of how the site could be developed as an EGS is conducted. To this end, an extensive assessment has been done on the structural settings of the area and the rock properties based on existing and newly gathered information. This information is combined with data from the two exploration wells to develop stimulation scenarios (Lepillier and Hofmann, 2019) for one of the two exploration wells: EAC-1. Stimulation scenarios at different depths and with differing hydraulic fracturing treatments were developed. The next step is to evaluate the performance of such a stimulation, which is the focus of this paper. Based on the updated geological model created within the GEMex project and the characterization of the rock properties, a reservoir flow model of the area surrounding the EAC-1 well was created. Because of the high level of uncertainty, in particular for the deeper subsurface, a stochastic approach is required to arrive at meaningful production estimates. A fast model approach was therefore favored over a very detailed model. Simplifications used in the model approach are a reduction in the number of faults included in the model, relatively coarse gridding (25 x 25 m) and flow and heat modelling only. The latter means that the impact of geomechanical and chemical processes on the flow and heat transport are not accounted for. As the first step, production scenarios were developed based on the existing hydraulic fracturing stimulation scenarios (Lepillier and Hofmann, 2019). The hydraulic fracture scenarios were supplemented with two alternative stimulation concepts: one in which a pre-existing fracture network is re-activated resulting in a stimulated area around the well rather than a single main hydraulic fracture, and one in which a fault crossing or near the well path is reactivated (if there is a fault sufficiently close to the well). These scenarios were also applied at three different depths, which resulted in nine different scenarios. For each scenario, height, length, permeability and porosity of the stimulated zone are varied stochastically. The mean and variation of the probability distributions are based on the simulated stimulation scenarios whenever possible. For each stimulation scenario, it is assumed that the production occurs via a doublet, since natural recharge is assumed not to occur due to the low permeability. The placement of the second well is adjusted to the stimulated zone of the first well and the same stimulation is assumed. For each doublet, production rate and temperature are simulated for 30 years in order to estimate the overall performance of the doublet system. In a second step, the impact of geological uncertainty will be evaluated.

18. Structural model of the Los Humeros volcanic complex for the exploration of the deep Super-Hot Geothermal System

Gianluca Norini, Gerardo Carrasco-Núñez

The Los Humeros Volcanic Complex (LHVC) is an important geothermal target in Mexico, hosting a geothermal field currently producing ca. 94 MW of electric power. The geothermal field is located in a Quaternary collapse caldera where resurgence occurs since ca. ~50 ka. The analysis of the LHVC structure and its influence on secondary permeability and occurrence of thermal anomalies is important to get insights into the interplay between the volcano-tectonic setting and the characteristics of the geothermal resources in the area. In this study, we present a structural and morphostructural analysis of the caldera complex and geothermal field, integrated with thermal remote sensing and new and archive subsurface/geophysical data, like well logs, seismological data and magnetotelluric imaging. The structural analysis suggests that inherited regional tectonic structures recognized in the basement played an important role in the evolution of the magma feeding system, caldera collapses and post-caldera deformations (Fig. 1a). These inherited weak planes have been reactivated by field resurgence faults and post-caldera magma-driven hydrofractures under a local radial stress generated by the shallow LHVC magmatic and hydrothermal systems (Fig. 1b). Indeed, the displacement of Holocene pyroclastic deposits provides clear evidence of major neotectonic deformations of the caldera floor. The lack of continuity of this deformation beyond the caldera complex, the sharp decrease of the fault scarps height toward the periphery, and the semi-radial displacement vectors of the dip-slip fault system are all lines of evidence suggesting that the origin of the caldera floor faulting is the recent/active resurgence induced by the local stress field (Fig. 1c). The volcanotectonic stress field and resurgence faults influence the distribution of secondary permeability, with the expected geometry of faults and fractures producing geothermal fluids varying with location and depth. The results of this study constitute a volcano-tectonic model guide useful for the geothermal exploration of the LHVC Super-Hot Geothermal System and other resurgent calderas. The research leading to these results has received funding from the GEMex Project, funded by the European Union's Horizon 2020 research and innovation program under grant agreement No. 727550. The research also received support by Comisión Federal de Electricidad (CFE) of Mexico.

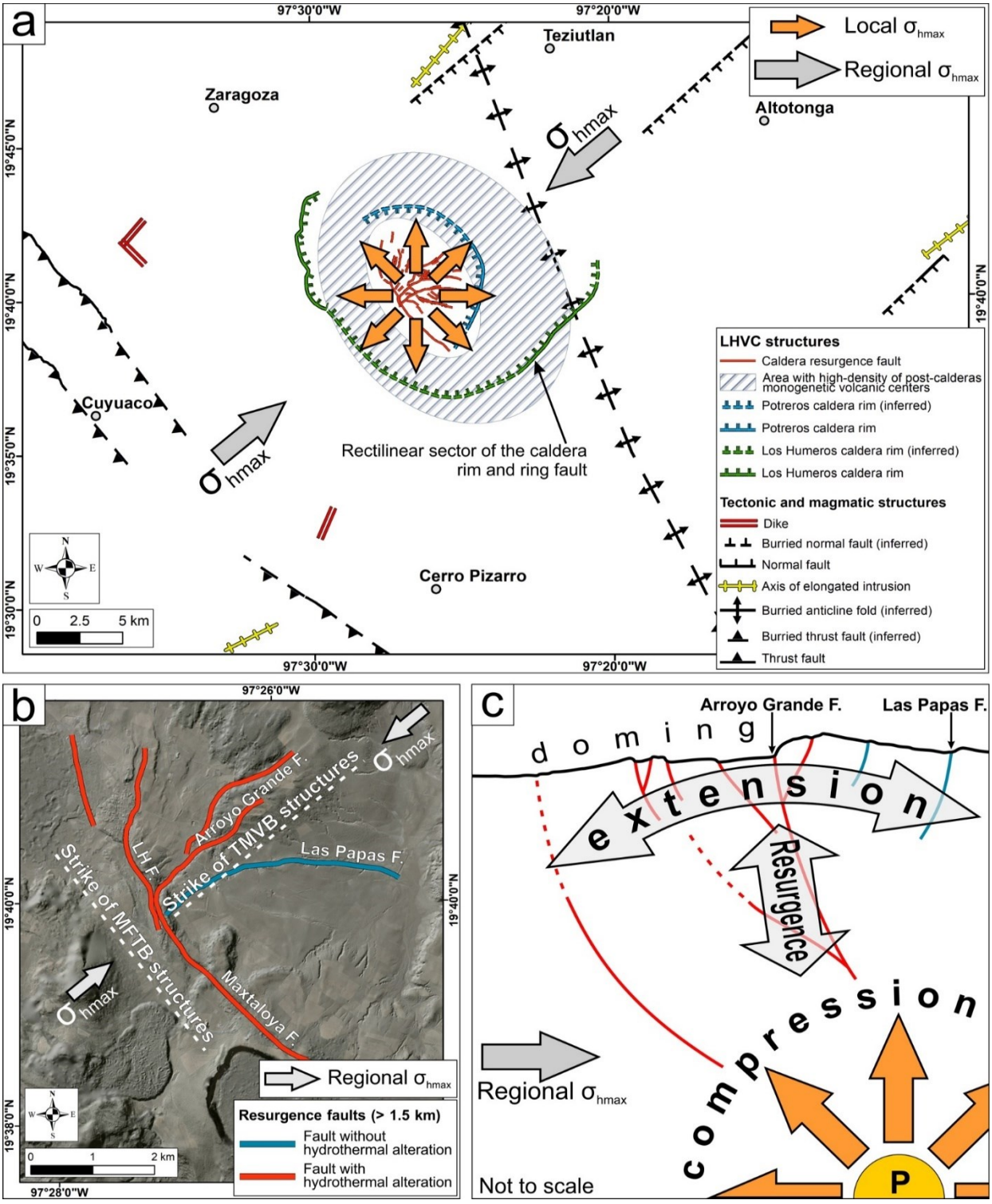


Figure 1: (a) Schematic structural interpretation of the LHVC and its basement. The orientations of the regional maximum horizontal stress and the local radial stress field are shown. (b) Simplified volcanotectonic map of the Los Humeros geothermal field, showing resurgence faults longer than 1.5 km and orientation of the regional inherited Mexican Fold and Thrust Belt (MFTB) and TMVB tectonic structures. Resurgence faults depicted in red are parallel to the regional inherited tectonic structures. LH F.: Los Humeros Fault. (c) Schematic not to scale structural cross-section of the central sector of LHVC. P: inferred pressure source inducing caldera resurgence. Color of faults as in Fig. 1b.

19. Petrophysical reservoir characterization of the Los Humeros geothermal field (Mexico): comparison of outcrop analogues and reservoir formations

Leandra Weydt, Kristian Bär, Ingo Sass and the GEMex team

The Los Humeros th temperatures above 380 °C, the system is characterized as a super-hot geothermal system (SHGS). The development of such systems is still challenging due to the high temperatures and aggressive reservoir fluids, which lead to corrosion and scaling problems. For better reservoir understanding and prospective modeling of the Los Humeros caldera complex, extensive geological, geochemical, geophysical and technical investigations are performed within the scope of the GEMex project (EU-H2020, GA No. 727550). Relatively little is known about the petrophysical and thermophysical rock properties in the study area. This data is critical for processing and interpreting geophysical data, and for 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 caprock. This also allow to identify geological heterogeneities on different scales (outcrop analysis, representative rock samples, thin sections and chemical analysis) enabling reservoir property prediction. More than 200 rock samples were taken from representative outcrops inside of the Los Humeros caldera, the surrounding area and from the exhumed 'fossil system' in Las Minas. Additionally, 66 borehole core samples covering 16 wells of the Los Humeros geothermal field were obtained. The samples 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. 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 20 parameters analyzed on more than 1400 samples altogether. The results enabled the classification of different lithofacies types with distinct properties, which is essential to define geothermal model units within a 3D geological model. Based on statistical analyses, 19 lithostratigraphic units were defined for the Los Humeros geothermal field. Hydrothermal alteration of different intensities was observed on the borehole core samples resulting in high heterogeneity in terms of sample appearance, chemical composition and rock properties. Detailed petrographic and chemical analyses (XRF, XRD and ICP-MS analyses) were applied to identify alteration facies and to relate the borehole core samples to different volcanic events. Previous lithostratigraphic classifications were updated allowing the adjustment of the local model units of the preliminary geological model provided by Calcagno et al. (2018). References: Calcagno, P., Evanno, G., Trumpy, E., Gutiérrez-Negrín, L.C., Macías, J.L., Carrasco-Núñez, G., and Liotta, D., 2018: Preliminary geothermal system is an operating steam dominated field with 65 wells (23 producing). Wi 3-D geological models of Los Humeros and Acoculco geothermal fields (Mexico) – H2020 GEMex Project, *Adv. Geosci.*, 45, 321-333, https://doi.org/10.5194/adgeo-45-321-2018

20. Implications of an updated volcanological conceptual model at Los Humeros for geothermal exploration and modelling

Guido Giordano, Gerardo Carrasco, Federico Lucci, Federico Rossetti, Stefano Urbani

The GEMEX project has prompted renewed volcanological studies in the Los Humeros geothermal area that have allowed significant improvements of the volcanological conceptual model bearing very relevant implications for the geothermal model, in some cases drastically changing the previous understandings. The main results that will be discussed in this contribution are: i) the improved understanding and quantification of the active magmatic plumbing system and its geometrical and compositional evolution over time implies the need to change the view and modeling of the heat source, from a single, deep and large source active at all times, to the superposition of several heat sources short lived, at various depths, temperatures and with variable volumes and thermal properties. ii) According to the previous point, also the volcanotectonic deformations observed within the active geothermal field, which control the secondary permeability, should be considered polyphased, nucleated and grown as a result of variable pressure sources at various depths associated with the interplay between magma related, evolving near field stress tensors that generated the caldera collapse structures and the intrusions deformations, and the regional far field stress tensor.

21. Novelties on water and gas geochemistry in Los Humeros geothermal field (LHGF)

Matteo Lelli, Thomas G. Kretzschmar, Jacopo Cabassi, Marco Doveri, Fabrizio Gherardi, Gabriella Magro, Francesco Norelli, Juan Sánchez-Ávila, Francisco del Toro, Yann René Ramos, Ruth Alfaro Cuevas Villanueva, Julio C. Cañas Ramírez, Eduardo González Manzano

During 2017 and 2018, in LHGF many samples from natural manifestations (e.g. cold and thermal waters and fumaroles) and also from re-injection wells were collected during field samplings. The study of chemical and isotopic characteristics allows to better understand the interaction processes between rocks and water, also providing precious information on the main recharge areas, the thermodynamic conditions and the fluid flow-paths. Two sampling trips were performed (the first on 03-16 June 2017 and the second on 16-31 March 2018, respectively), in which 55 and 99 samples were collected (among hot and cold springs, waters from wells, re-injection wells and gases from fumaroles). Chemical and isotopic analyses were performed on the collected samples, contributing to set-up a new robust dataset. In particular, several samples (cold springs, but also the Loma Blanca fumaroles inside the Los Humeros producing area) were collected and characterized for the first time, giving the opportunity to perform a very detailed hydro-geochemical study at regional scale. Main results concerned the recharge mechanism of LHGF. Fluid analysis (in particular stable isotope analysis, i.e. δD and $\delta^{18}O$) of natural manifestations (cold and thermal springs and fumaroles) in the area around and inside the caldera indicates that regional recharge cannot be ruled out and that it may represent an important percentage of the total amount. Water-rock interaction model reproduce precisely the isotopic composition of the natural gas emissions (e.g. fumarolic condensates), but also that of geothermal fluids and local andesites. Stable isotopic composition (in particular $\delta^{18}O‰$ and $\delta D‰$) of a cluster of cold springs collected in the Sierra Madre Oriental (on the west side of LHGF) is compatible with that of an hypothetical meteoric component, which can infiltrate in limestone outcroppings and then seep down toward the hottest part of LHGF. This hypothesis would also be satisfied by geological and hydrogeological points of view, since the limestone formations present in outcroppings in the Sierra Madre Oriental belong to the same geological formation present at the bottom of the productive levels of LHGF. Other possible contributions (i.e. from deep fluids and local infiltration) cannot be ruled out at priori, but their percentages seems to be subordinated to the regional one. Therefore, these findings indicate a more significant regional recharge contribution in LHGF than previously assumed.

22. Material testing downhole at well H-64 at the Los Humeros geothermal field in Mexico

Ingolfur O. Thorbjornsson, Luis Eduardo González, Miguel Ramírez, Lilibeth Morales, Heber Diez, Sigurdur S. Jonsson, Gunnar S. Kaldal, Larus Gudmundsson

Selection of materials for high-temperature geothermal wells follows oil and gas (O&G) standards and recommendations and the same applies for wellhead design, well design and drilling. Geothermal wells differ from O&G wells in chemistry of steam/brine and higher amount of non-condensable gases such as H_2S and CO_2, having higher temperatures and often low pH level. These are all parameters that have corrosive effect on the well materials and often more complicated forms of corrosion are observed in geothermal use than in common O&G wells. It is therefore of high importance for long life of geothermal wells to select casing materials that can both withstand the high temperature and the corrosive nature of the geothermal fluid. The goal of the work presented, was to test the corrosive nature of geothermal environment against candidate materials to be used in Los Humeros geothermal field in Mexico and to compare that with previous tests in Icelandic geothermal fields. For comparison with older results a selection of “stand alone” materials were tested but some are also prime candidate materials for cladding. Testing was done as downhole testing where the testing material was attached to a hexagonal bar acting as a sample holder and lowered down to 1290 m depth in the superheated well H-64 in Los Humeros. Duration of the test was two weeks inside the well.

23. The Los Humeros superhot geothermal resource in Mexico: Results from an extensive resistivity survey

Ásdís Benediktsdóttir, Claudia Arango Galván, Gylfi Páll Hersir, Sebastian Held, José Manuel Romo Jones, José Luis Salas, Thalia Avilés, Diego Ruiz Aguilar, Arnar Már Vilhjálmsson

GEMex, a joint geothermal project of two European and Mexican consortia, respectively, began in late 2016 with the purpose to develop geothermal energy utilization in the easternmost region of the Trans-Mexican Volcanic Belt. Los Humeros superhot geothermal area, granted to the Comisión Federal de Electricidad (CFE), was chosen as a test site for a superhot geothermal system. Extensive geological, geochemical, and geophysical studies were carried out to gain a better knowledge of the subsurface physical conditions. We present the results of the 3D inversion of static shift corrected MT data using the WSINV3DMT code. The inversion was performed for the full impedance tensor with different initial models. In the final model a spatially small and deep low-resistivity anomaly was identified underneath the village of Los Humeros. After exploring the extent of the anomaly and including the granitic basement in an additional inversion, it was concluded that the anomaly is most likely an artifact. Having data up to 1000 s might shed a better light on whether the deep conductive anomaly is truly an artefact. The resistivity model has been compared with the main geological structure in Los Humeros revealing the geothermal significance of the area and its most important location. Interpretation with other geoscientific results, such as gravity, passive and active seismics, and geology, is ongoing within the GEMex project. This abstract presents results of the GEMex Project, funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No. 727550, and by the Mexican Energy Sustainability Fund CONACYT-SENER, Project 2015-04-268074. More information can be found on the GEMex Website: http://www.gemex-h2020.eu.

24. Active seismic for exploration of SHGS geothermal systems

Flavio Poletto, Erika Barison, Gualtiero Böhm, Biancamaria Farina

Los Humeros is situated in the eastern sector of the Trans Mexican Volcanic Belt (TMVB), forming the northern boundary of the Serdán-Oriental basin. The field is a superhot geothermal system (SHGS) operated by the Comisión Federal de Electricidad (CFE), and is one of most important geothermal fields in Mexico, geologically characterized by a caldera complex with a complicated evolution. In the framework of the collaborative GEMex project, CFE provided OGS with legacy active-seismic data of Los Humeros, and UNAM supported with the collection and transfer of data. The contribution of active seismic data is relevant to provide detailed information on deep seismic structures, to be integrated with the other geological and geophysical measurements in the local model of Los Humeros. This presentation describes the work and the results of reprocessing of the active seismic data of Los Humeros performed by OGS in the framework of WP5 Task 5.2 'Seismic imaging'. This reflection survey consists in four 2D seismic lines: L2, L3, L4, L5, acquired with Vibroseis source in the Los Humeros Caldera by the Compañía Mexicana de Exploraciones, S.A. (COMESA), for CFE in 1998. The position map of the seismic lines in the local model of the faulted caldera is shown in Figure 1a (below). Figure 1b shows pre-stack-depth migration (PSDM) first-stage results, with a 3D view of the crossing lines observed from the corner between L5 and L3. The superimposed color maps represent the P-velocity model obtained by common-image-gather (CIG) horizon-driven interpretative velocity analysis of the active seismic lines. These initial results have been then reprocessed by iterative procedure, and used to update the Los Humeros velocity model in depth, compared with geological results (from WP3, Calcagno et al., 2018), integrated with geophysical results from other tasks and work packages (seismological and gravimetric data, in the framework of WP 5.4 within deliverables D5.9, D5.11, and also WP3.1), as well as reservoir modelling (WP6) and for the purposes of the geothermal model simulation with temperature (D5.5). We thank all the GEMex partners who

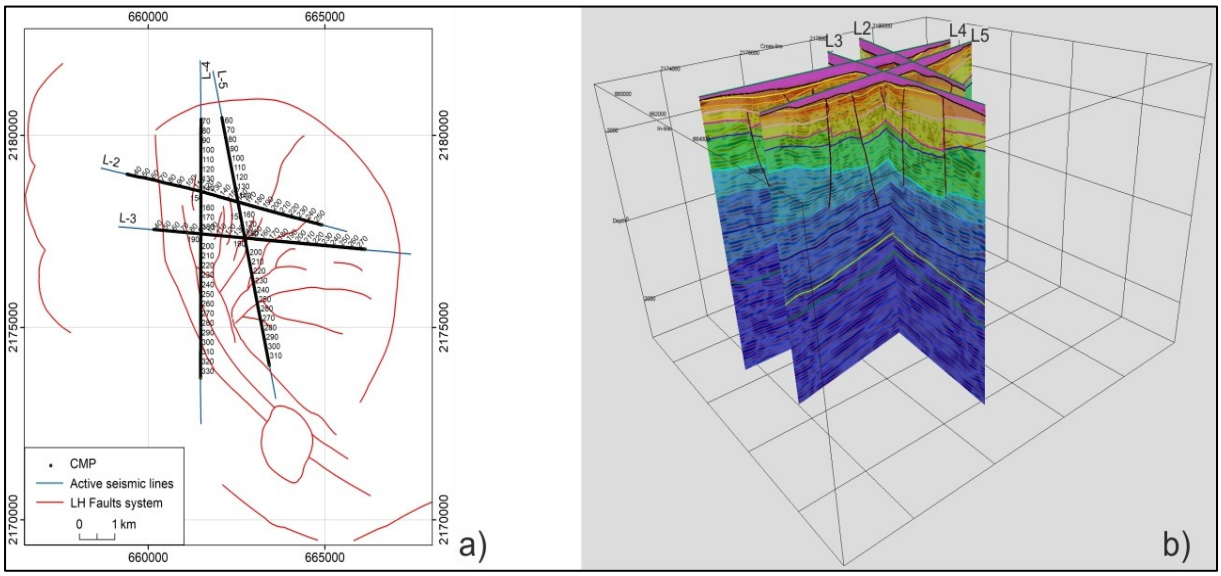


Figure: Position map of the active seismic lines in the local model of the faulted caldera (Figure 1, to the left) and pre-stack-depth migration (PSDM) first-stage results, with a 3D view of the crossing lines observed from the corner between L5 and L3 (Figure B, to the right).

contributed to provide information for this joint analysis. In addition to processing of deep reflections for imaging purposes, in this work we investigate the joint use of active-seismic data to improve the seismic modelling of the caldera of the super-hot geothermal system (SHGS) of Los Humeros with external constraint. The contribution on inversion of active-source seismic data with constraints is achieved by means of full-waveform elastic modelling, by comparison with passive results coming from seismological inversion and with density data from gravity inversion performed in the framework of GEMex (GEMex Deliverable D5.9). The analysis shows differences in the results obtained by different active and passive methods and resolutions in the local and regional models utilized for the geophysical and geological characterization of the Los Humeros Caldera deep and also shallower structures. The results lead to the recommendation to use the full-waveform active-seismic signals together with passive seismic data, and indicate a procedure to be followed for data integration in geothermal exploration of SHSG and also EGS, thus contributing to feed GEMex Deliverable D5.12.

25. Local earthquake tomography at the Los Humeros geothermal field

Tania Toledo, Emmanuel Gaucher, Philippe Jousset, Hansruedi Maurer, Charlotte Krawczyk, Marco Calò, Ángel Figueroa

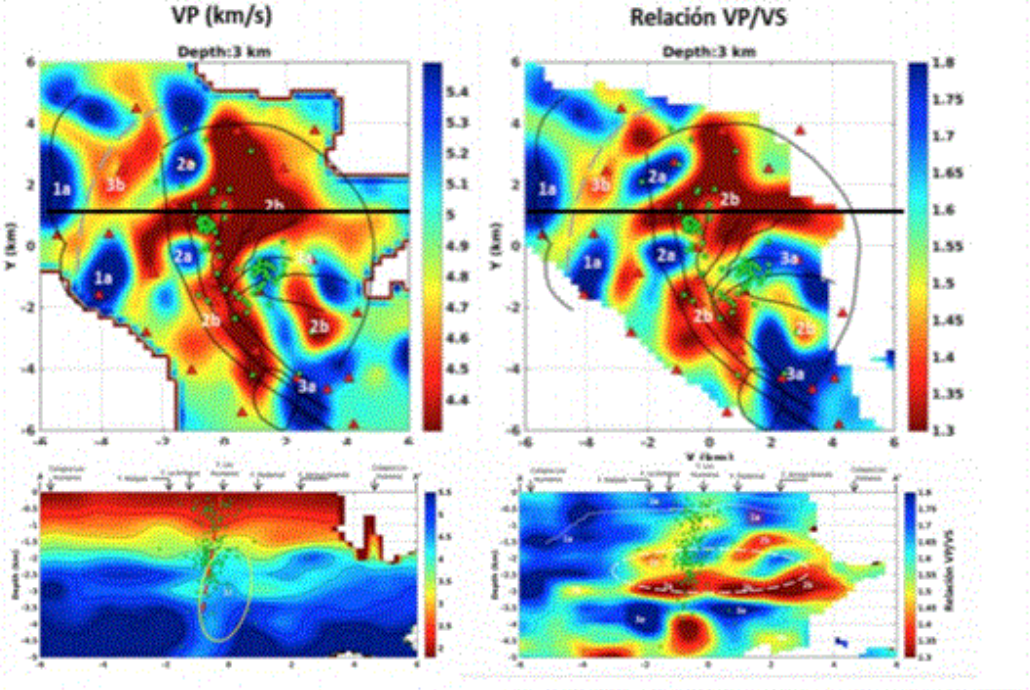
The Los Humeros Volcanic Complex (LHVC) is a super-hot geothermal system (SHGS) located in the Trans-Mexican Volcanic Belt (TMVB). It is presently one of Mexico's main geothermal fields with an installed electric power capacity of ~95MW. Although a large number of studies have highlighted several aspects of the shallow subsurface, a thorough knowledge of structures and behavior of the geothermal field at depths greater than 2 km is still rather sparse. In this context, within the framework of the European H2020 GEMex project several geochemical, geological, and geophysical surveys have been carried out to investigate the geothermal field properties at depth. In a broader sense, the study of the LHVC plays a major role in understanding the characteristics of the local geothermal system for further development. From September 2017 to September 2018, a seismic network comprising 23 broadband and 20 short period stations was deployed and maintained to monitor the geothermal field. In this work, we analyzed the continuous seismic data to detect seismic events mainly related to exploitation activities. We applied a recursive STA-LTA detection algorithm followed by manual review of the detected events and assembled a catalog of around 500 local earthquakes mainly clustered around injection wells. Focal depths range between 1 km and 4 km depth. Then, from the observed earthquakes at the stations, travel-time tomography was performed to derive minimum 1D velocity models, both for the P- and S-waves. The 1D velocity models were later used as initial models for 3D tomography, which led to optimized 3D velocity models and hypocenter relocations.

26. On the structure of the Los Humeros caldera using seismic multi-method modelling

Iván Granados, Marco Calò, Ángel Figueroa Soto, Stephani Cruz, Brenda de la Rosa, Joel Angulo, Mathieu Perton, Tania Toledo, Philippe Jousset

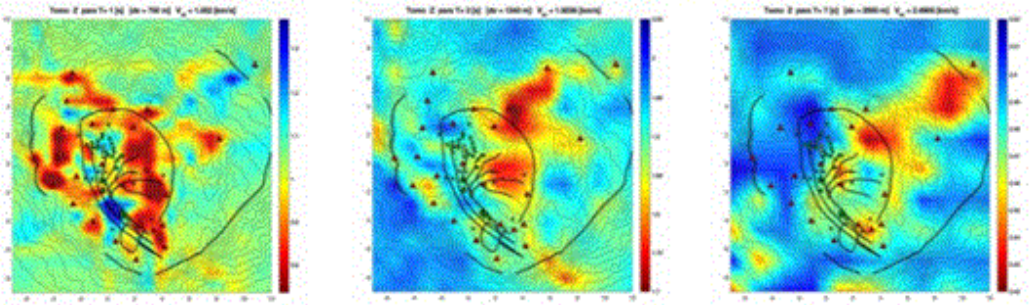
In the framework of the GEMEX project (cooperation between Europe and Mexico for geothermal development), a dense network of 45 stations was installed in 2017-2018 in the Los Humeros caldera, Mexico. The dense seismic network was deployed with the aim of: i) monitoring the seismic activity related to the power plant, and ii) reconstructing the shallow and deep structure using passive methods. Thanks to this network, an intense local seismic activity has been recorded in the geothermal field and surroundings, from which it has been possible to identify high frequency events (VT, 10 Hz) and low frequency seismicity (LP, 1-8 Hz). The first set of events is mainly associated with the local tectonics and power plant activities, while the second one has been generally recorded after strong earthquakes (Mw 7) occurred in Mexico. Consequently we adapted and applied two tomographic techniques to generate highly resolved seismic models. One was the Enhanced Seismic Tomography (EST) method (see figure below) that uses the travel times of the local seismicity. This method incorporates the Double Difference tomography (Zhang and Thurber, 2003) and the post processing Weighted Average Method (Calò et al., 2013) to generate Vp and Vs models. The second method was the surface wave tomography based on the ambient noise analysis (see figure below). In this case, we generated 3D anisotropic models of phase and group velocities of the Rayleigh and Love waves from Green functions retrieved by cross-correlation of the continuous records. Thanks to the severe pre-processing of the whole seismic database we were able to obtain reliable and highly resolved models with both techniques. Earthquake based models provided a detailed reconstruction of the Vp and Vp/Vs distributions near to the power plant. The dominant structures and the presence of the anomalous bodies are well imaged down to 3-4 km of depth allowing the first detailed description of the patterns associated with the geothermal reservoir at these depths. The surface wave ambient noise based models provided a larger view of the caldera and its main anisotropic pattern down to 7-8 km of depth. In these models, we were able to define the depth extension of the caldera rim, some important features of the internal part of the caldera and two anomalous bodies in the NE sector of the study region that result well correlated with the patterns described with other geophysical techniques. Finally, the two sets of events (VT and LP) have been relocated using the 3D seismic velocity models of the region in order to better characterize the structure of the geothermal field and identify regions where the fluids could have a role on the triggering of the seismicity observed. This work was performed in the framework of the Mexican-European consortia GeMex (Cooperation in Geothermal energy research Europe-Mexico, WP 5.2 No. 267084, funded by CONACyT-SENER S0019, 2015-04, and Horizon 2020, grant agreement No. 727550).

Enhanced Seismic Tomography

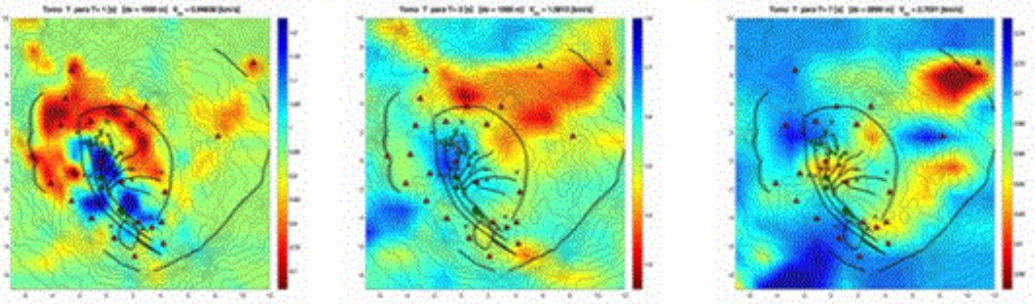


Surface waves ambient noise Tomography

Vertical component dispersion maps of group velocities at 1, 3 and 7s



Transverse component Dispersion maps of group velocities at 1, 3 and 7s



27. Imaging the brittle-ductile transition zone at the Los Humeros geothermal field using ambient seismic noise

Katrin Löer, Tania Toledo, Gianluca Norini, Xin Zhang, Andrew Curtis, Erik H. Saenger

The Los Humeros Volcanic Complex (LHVC) in the Trans-Mexican volcanic belt has been identified by the GEMex interdisciplinary European-Mexican collaboration as an important natural laboratory for the understanding of Super-Hot Geothermal Systems (SHGSs) in volcanic calderas. One of the aims of GEMex is to characterize the deeper structure (~2-3 km) of the active geothermal field hosted by the LHVC. At depth, rocks become progressively more ductile because of the increasing temperature, until the brittle-ductile (BD) transition is reached. The identification of this transition, which limits the extent at depth where brittle structures acting as hydrothermal fluids channel may exist, is of paramount importance for the exploration and thermodynamic modelling of geothermal areas. Here, we present results from ambient noise beamforming identifying for the first time the BD transition zone below the LHVC. Beamforming provides Rayleigh wave dispersion curves, which are then inverted

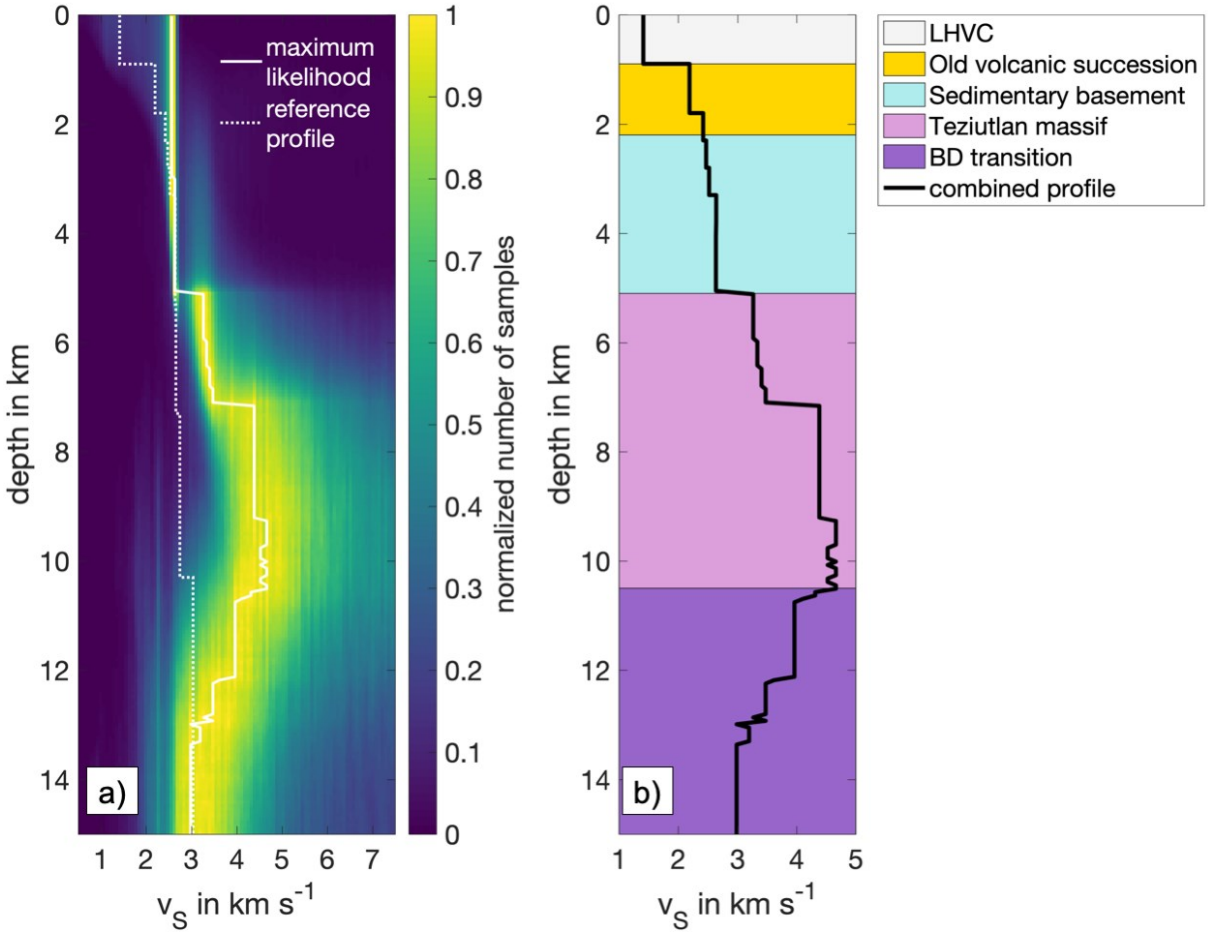


Figure 1: (a) PDF of shear-velocity distribution as retrieved from rj-McMC inversion of Rayleigh waves dispersion curves, normalized for depth level. The solid curve indicates maximum likelihood of the PDF, the dotted curve represents the profile retrieved from the analysis of earthquake data and is plotted for comparison. (b) Combined shear-velocity profile (black) from the analysis of earthquake data (dotted curve in (a), down to 4 km depth) and ambient noise beamforming (solid curve in (a), below 4 km); background colors indicate geological structure (see legend). Transition depths are derived from well data for the two upper sections and from the shear-velocity PDF for the deeper structures.

using a Markov chain Monte Carlo algorithm. From the inversion we obtain a probability density function (PDF) of the shear-velocity distribution at depth. This distribution is in good agreement with a shear-velocity profile from local seismicity analysis, which exists, however, only for the upper 4 km. By combining noise-based and earthquake-based models, we obtain a shear-velocity profile down to 15 km depth (Fig. 1), which is much deeper than any other method applied in the area so far. Matching our profile with well log and outcrop data, we identify different geological sections such as the top of the crystalline basement (Teziutlán massif) at ~5 km depth. The decline of shear-wave velocity at ~10 km depth marks the onset of the BD transition zone. Our findings suggest that SHGSs can exhibit brittle rheology at large depth despite positive thermal anomalies, increasing the rock volume available for geothermal exploitation. Based on ambient seismic noise, the beamforming algorithm is also applicable in aseismic regions where other methods are infeasible altogether.

28. Ensemble-based Bayesian joint utilization of information from multiple data types for Los Humeros

Svenn Tveit, Trond Mannseth

We consider the joint utilization of different geophysical data types and uncertainty quantification of the resulting earth-property estimates for the Los Humeros geothermal field. The joint utilization of data types and uncertainty quantification are done in a cooperative manner using a sequential Bayesian approach. Specifically, the posterior probability density function (PDF) obtained after assimilation of one data type is used as the prior PDF for assimilation of the next data type, and this sequence proceeds until the last data type is assimilated. From the final posterior PDF one may extract a best estimate (the mean), and quantify uncertainty utilizing the covariance matrix. For the Los Humeros field we investigated two ways of combining the different data types with our sequential approach: 1) We started with a seismic P-wave velocity model, then we assimilated gravity data, and lastly we assimilated of electromagnetic data (TEM and MT). 2) We started with a seismic P-wave velocity model and lastly we assimilated electromagnetic data (TEM and MT). Both procedures require cross-property relations to convert a posterior PDF for one data type to a prior PDF for the next data assimilation. Specific cross-property relations determined for Los Humeros were not available at the time of our study, thus generic relations with large associated uncertainty had to be used. To perform the assimilation of each data type we used ensemble-based methods. Such methods allow for approximate sampling of the posterior PDF in cases where accurate sampling methods are computationally prohibitively expensive, which is generally the case in 3-D subsurface problems. In both (1) and (2), the assimilation of MT data were performed last. The MT inversion results from the two approaches yielded different resistivity models, although some general trends were similar. The assimilation results showed that the uncertainty in the upper parts of the resistivity models is reduced more than in the deeper parts.

29. Extraction of regional and local geophysical features by cluster analysis and classification learning methods in Los Humeros and Acoculco volcano-geothermal fields (Mexico)

Gianluca Gola, Adele Manzella, Philippe Jousset, Tania A. Toledo Zambrano, Emmanuel Gaucher, Eva Schill, Natalia Cornejo, Gylfi Páll Hersir, Knútur Árnason, Ásdís Benediktsdóttir, Jan Diederik van Wees, Flavio Poletto, Jonathan Carrillo, Marco A. Pérez

Geophysical methods are largely applied in geothermal exploration to investigate buried structures as well as to detect and characterize deep-seated reservoirs. Although a single petrophysical parameter should image interesting relations with lithology, fluid saturation and underground physical conditions, a multivariate approach, i.e. integrating multiple datasets, may provide additional unequivocal information. In this framework, partitioning procedures of high-dimensional data into homogeneous subgroups are considered. We critically explored the pre-processing actions and the applicability of partitioning techniques tacking advantage of the availability of multiple geophysical dataset, e.g. resistivity, density, magnetization and velocity models, of Los Humeros and Acoculco geothermal fields. The analysis is performed using two separate survey scales enabling the extraction of regional and local geophysical features. Some pre-processing actions are needed. This result particularly true considering the intrinsic difference in resolution existing between the different geophysical models and the mandatory requirement that input data have to be defined on a common grid. For this purpose, data interpolation on a regularly-spaced grid without introducing artifacts is required. We applied quantile-quantile (Q-Q) plots for similarity check between initial and interpolated distributions. Moreover, we tested additional actions, e.g. typical tasks include removing outliers and trends, imputing missing data, and normalizing the data. Finally, we explored few partitioning procedures. Broadly speaking, they can be categorized into two main groups: 1) unsupervised clustering and 2) supervised classification methods. Unsupervised clustering methods recognize patterns in the dataset and they are useful when we don't know the number of clusters. Unsupervised clustering methods can be divided into two further subgroups: 1a) hard clustering, in which each data point either belongs to a cluster completely or not (e.g. K-mean algorithm); and 1b) soft clustering, in which instead of putting each data point into a separate cluster, a probability or likelihood of that data point to be in those clusters is assigned (e.g. Gaussian Mixture Model). In supervised classification methods, predefined classes by properties are assigned. It is a two-step process, comprised of a learning step and a classification step. In the learning step, a classification model is constructed (e.g. Decision Tree learning method) and, subsequently, the latter is used to predict the classes for a given multivariate dataset. The application of the above-mentioned partition procedures has shown that clustering and classification approaches can be used as effective methods to characterize buried structures in presence of complex geological settings and to retrieve local relationships between distinct physical parameters. Moreover, this work put the basis for the implementation of a protocol for data integration in geothermal exploration of Enhanced and Super-Hot Geothermal Systems.

30. Detection of deep structures: An overview of what has been achieved in WP5 within GEMex and joint visualisation in Paraview

Gylfi Páll Hersir, Claudia Arango Galván, Ásdís Benediktsdóttir, Philippe Jousset, Marco Caló, Eva Schill, Marco Antonio Pérez Flores, Eszter Békési, Flavio Poletto, Adele Manzella, Emmanuel Gaucher, Tania Andrea Toledo Zambrano, Sebastian Held, Joel Angulo Carrillo, José Manuel Romo Jones, Natalia Cornejo, Ángel Figueroa Soto, Jonathan Carrillo

The development of seismic and resistivity methods for high temperature geothermal fields has been the subject of the former and ongoing FP-6 supported projects I-GET and IMAGE. The objective of WP5 within the GEMex project was to further advance the methodology and test it by application to two high temperature systems in Mexico: the superhot conditions at depth in the Los Humeros field and the Acoculco high-temperature geothermal area proposed to develop an Enhanced Geothermal System (EGS). To accomplish this, extensive geological, geochemical and geophysical studies were carried out as well as analysing already existing data. In geophysics within WP5, resistivity and gravity surveys were carried out, micro-seismic stations were set up collecting data for about a year and InSAR data were studied. In Los Humeros 122 Magnetotelluric (MT) and 120 co-located Transient Electromagnetic (TEM) soundings were performed, and 68 MT and 65 co-located TEM soundings in Acoculco. The location of the soundings took advantage of previous geoscientific results. The MT and TEM resistivity data sets for the two areas have been jointly 1D inverted and the static shift corrected. MT data were 3D inverted using two different inversion codes –resulting in resistivity models for the two areas. Strike analysis was carried out for the two areas, adding structural information to both areas. Finally, a 3D inversion of the MT data was done using constraints from other geoscientific results. Already existing gravity and magnetic data from the two areas have been studied and 3D regional models re-sampled for both areas. Additionally, a gravity survey was performed on a regular grid in Los Humeros where gravity was measured at 341 sites, and at 84 sites in Acoculco. For both areas a density model for the subsurface was calculated based on the Bouguer gravity maps. In Los Humeros 45 seismic stations were deployed, and 18 stations in Acoculco, which collected data for about one year. The seismic activity in Los Humeros was substantial while it was minimal in Acoculco. The seismic data have been processed and analysed giving valuable information on the subsurface structure in Los Humeros. Active seismic profiles from a previous survey have been analysed. InSAR data from Los Humeros have been studied giving information on the deformation of the area. All of these geophysical data plus geological data have been inserted into Paraview for 3D visualization to facilitate a joint interpretation of all the information gathered. This abstract presents results of the GEMex Project, funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No. 727550, and by the Mexican Energy Sustainability Fund CONACYT-SENER, Project 2015-04-268074. More information can be found on the GEMex Website: http://www.gemex-h2020.eu.

31. Improvement of the conceptual model of Los Humeros: Beyond the GEMex Project

Aída López-Hernández, Egbert Jolie, Luis Carlos Gutiérrez-Negrín, Georgina Izquierdo-Montalvo, Domenico Liotta, Eduardo González-Partida, Gylfi Páll Hersir, Claudia Arango-Galván, José Manuel Romo-Jones, Miguel Ramírez-Montes

The analysis of information provided by the Comisión Federal de Electricidad (CFE) and coming from the Los Humeros geothermal wells, integrated and contrasted with new data obtained by the several GEMex teams, have leaded to a new and updated conceptual model of the geothermal system. This new model seems to better explain the part of the current system that has been exploited by the CFE in the last 25 years, i.e. the conventional geothermal resources, but also offers important clues for a better location and eventual exploitation of the superhot resources located at the deeper portions of the system –which was the main target of the GEMex Project in Los Humeros. Some of the most important features of that updated conceptual model include the confirmation and role of the two main structural systems, NNW-SSE and NW-SE, based not only on their current superficial expression inside the Los Humeros Caldera, but also on the findings revealed by the exhumed system in the nearby former mining site of Las Minas, by the processing of the new geophysical data and by the results of the analog modelling. Another important feature was provided by the thermo-barometric models applied on recent geochemical and geochronologic analyses of volcanic samples outcropping inside the Los Humeros Caldera and formed in the last 10 ka, which indicate several, isolate and distinct magma sources coming from different depths, instead of a single and massive magma chamber. An independent support to this multi-source model is that the current alteration mineralogy identified in the wells is typical of interactions between the underground rocks with fluids of neutral to alkaline pH, different to the acidic pH fluids of deeper, and probably more recent, origin. This probably doesn't impact the strategy for the current exploitation of the conventional fluids, but it must be take into account when searching for superhot geothermal fluids. An additional feature is that the isotopic composition of the current geothermal fluids is lighter than the present meteoric water, which could suggest an increasing share of ancient meteoric and magmatic water of deeper origin. Based on those features, and some other else, it is suggested a possible location and general design of a future exploration well aimed to find and produce superhot fluids in Los Humeros, whose development could give place to a sort of Project GEMex II between the UE and Mexico.

32. Data integration to constrain the geological structures in the Acoculco area

Eugenio Trumpy, Domenico Liotta, Andrea Brogi, Adele Manzella, Alessandro Santilano, Gianluca Gola, Eva Schill, Sebastian Held, Natalia Cornejo, Claudia Arango, Ásdís Benediktsdóttir, Gylfi Páll Hersir, Luis Carlos Gutiérrez-Negrín, Walter Wheeler, Eivind Bastesen

An integrated 3D geological model is proposed in the area surrounding the two exploration wells, which are considered for EGS investigations. The model derives from an integration of geophysical and geological 3D models. The 8 x 10 km 3D geological model was built including all the outcomes from the fieldwork regarding the fault systems, setting and lithologies. In particular, two systems of faults, striking almost normal to each other, and five different formations were modelled. In agreement with the regional knowledge, the kinematic analysis indicated that the NNW-SSE striking faults display a mainly oblique to strike-slip right-lateral movement, while the NE-SW striking faults are characterized by a dominant normal component. A later almost normal kinematic event is locally recorded on the NNW-SSE fault surfaces, thus indicating that this fault system also accommodated vertical movements. The activity of both fault-systems is contemporaneous and occurred from the Miocene to the Present, in the frame of the regional NNW-trending crustal stretching. Fracture distribution and paleostress analyses suggest that the NNW-striking fault system is characterized by significant permeability. On the basis of the mapped outcroppings and the litho-stratigraphic profiles from the two CFE boreholes, the modeled formations are, from top to bottom: i) volcanites (i.e., pre, sin, post-caldera) grouped with the extra-caldera and alluvial units; ii) limestones (cropping out in eastern part of the geological map and reported in the two boreholes) that locally include marbles; iii) skarns (observed in the two boreholes); iv) granite, consisting of an old, probably fractured, cold Tertiary granite, later crosscut by younger magmatic events, hosted in the limestone and in the (v) basement, mainly made up of Paleozoic phyllites (not encountered in the study area). By using the Paraview platform, the faults and bottom surfaces of the formations extracted from the 3D geo-model were visualized together with the local 3D density and 3D resistivity models. Different vertical and horizontal sections were constructed. The MT resistivity T-strike analysis indicates preferential conductivity trends in agreement with the NNW-SSE fault zone at the intermediate depth (frequency Range 0.1 – 1s). From this we infer that hydrothermal circulation deposited clays (conductive) in the fault-related rock volumes, and that these clay-filled fault-related rock volumes are likely wide and/or frequent; both are observed in outcroppings. Similarly, vertical and horizontal sections from MT-3D analysis indicate that the lowest values of resistivity are concentrated along almost horizontal levels, parallel to the stratigraphic layers. This is explained as a consequence of lateral migration of paleo-fluids through the volcanic strata, today recorded as hydrothermal alteration. Gravity analysis indicates relative low- and high-density bodies, with a general map distribution suggesting the presence of NNW- and NE-striking bounding structures and possible warm (or more fractured) otherwise cold (or less damaged) geological bodies. In this way the geological structures deriving from integration of geophysical and geological data were constrained.

ABSTRACTS (POSTER PRESENTATIONS)

33. Developing public engagement: a conceptual model

Michele Contini, Eleonora Annunziata, Francesco Rizzi, Marco Frey, Spyridon Karytsas, Alessandro Sciullo, Adele Manzella, Carlos Montalvo

The theme of public engagement is particularly relevant when, as in the case of geothermal technologies, switching the energy system to renewable sources may produce relevant economic, environmental and social impacts. A multidisciplinary approach to deal with public engagement in geothermal development was adopted following several steps. First of all a preliminary investigation was carried out on local public perception of (geothermal) energy and on the overall boundary conditions (e.g. social, environmental, economic, etc.), in order to take into account all the socio-economic and environmental issues related to the project. Second, a quali-quantitative investigation was conducted on different stakeholders to discover their interpretations and perspectives on geothermal energy development issues. Questionnaires and open ended interviews were conducted with citizens, companies, public authorities and local communities both in Mexico, Europe and a selection of developing countries. Suitable variables and indicators/quantitative models were defined to monitor, ex-ante, the possible sustainability-related consequences, thus representing an integrative part of the work. Based on the above, a conceptual model was built to combine public authorities' and private companies' efforts in fostering sustainable energy transition by taking into account local communities' socio-economic characteristics (Figure 1). The *Information level* relies entirely on the information provided to the public about the project's details and potential impacts on the local and wider community. It corresponds to a minimal level of relations between companies and local communities, which are considered as an actor without any active role. Public authorities are mainly involved in defining the boundaries of

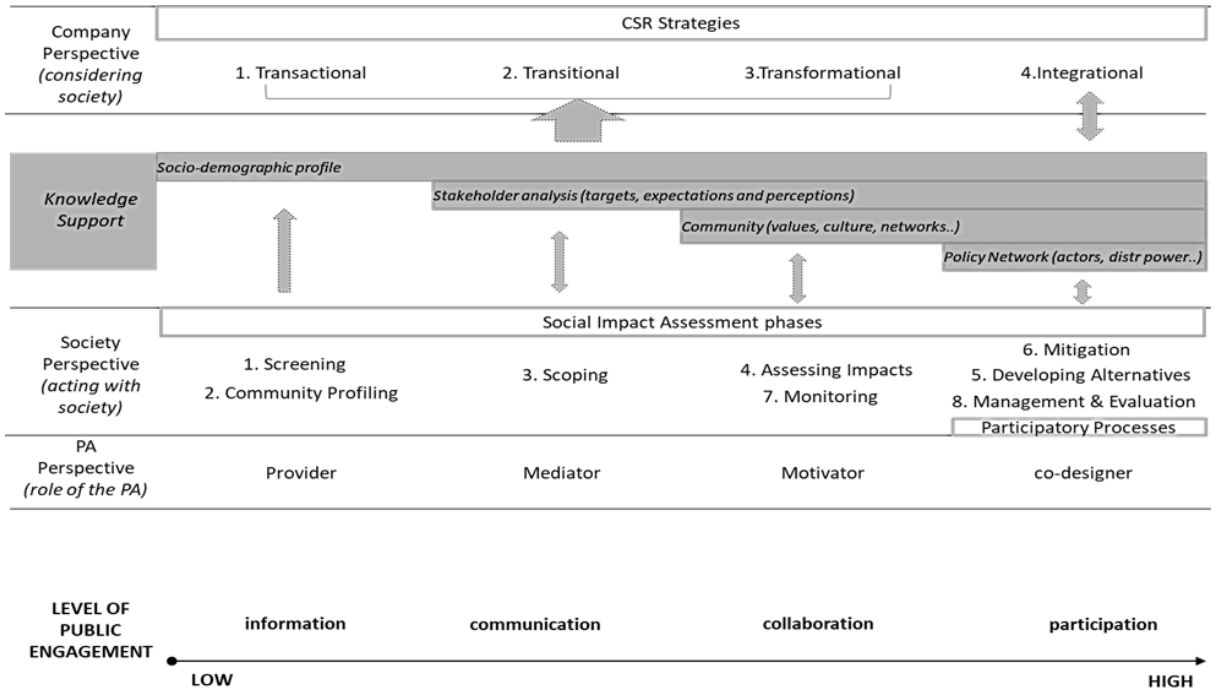


Figure shows the conceptual model, which identifies four levels of public engagement.

the community to be investigated. The *Communication level* includes active engagement of the public, and it is contingent upon the company's willingness to engage in conversation with communities. The flow of information and knowledge is bi-directional and the community is surveyed to contribute to the definition of the impacts. Public authorities are crucial in identifying the stakeholders and, more generally, in facilitating the engagement of the public. The *Collaboration level* considers the public as being part of the project development, while the project and its impacts' evaluation need to be adapted to the specific local/social needs. It is characterized by a high level of relations between companies and local communities, in which a continuing dialogue with no imbalances is present. Public authorities facilitate the process by providing the right arenas where the diverse actors could meet and collaborate. The *Participation level* consists in the actual engagement of the public in the design of the project. Companies adopt the set of engagement practices based on the diversity of expectations while public authorities are co-designers of the initiative, providing the institutional environment where the process takes place. These four levels are structured according to an increasing public engagement, from the information to the participation level. The conceptual model enables to simultaneously provide an integrated framework of three different perspectives from actors, and serves as a guideline on how to balance them, according to the level of engagement desirable and really achievable.

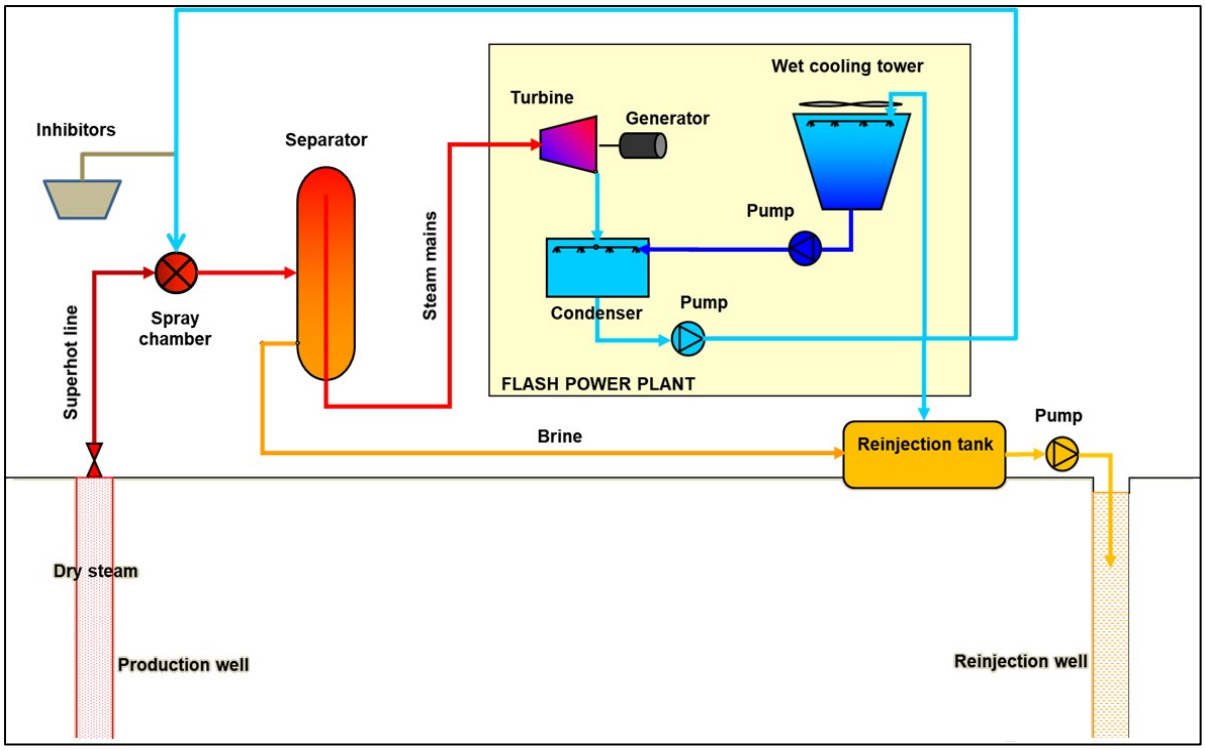
34. Estimation of depression well cones in Los Humeros

Héctor González García, Ernst Huenges, Henning Francke, Francesco Parisio

Sustainable development means to meet the needs of the present generation without compromising the ability of future generations to meet their needs (UN, 1987). Geothermal projects are usually planned to not only meet energy-generation needs, which means to maintain the production rate of the field, but also to be profitable. As the production rate is involved with the sustainability use, this study aims to detect if the proximity of the wells and their rate of production has a negative impact on the performance of the electric generation in Los Humeros geothermal field. We analyzed the productivity data from three wells on the southern part of the reservoir area (H-6, H-12, and H-39) to calculate the productivity index for each one. We used the Craft and Hawkins' (1959) definition of the productivity index (PI), as the fraction rate between the mass extraction rate and the pressure drop of the system. The resulting PI trends changed three times in the entire production period. The first notable change appeared after 10 years of production, when the PI of the wells H-6 and H-12 fell simultaneously. Furthermore, we calculated the equivalent area corresponding to the mass and heat extracted considering the effective thickness of the reservoir (Limberger et al., 2018) and applying the Heat in Place linear model (Muffler and Cataldi, 1978; Garg and Combs, 2015). These results could be an appealing baseline for profitability and sustainability.

35. Thermal loop design aspects in Ultra Hot Geothermal Systems

Dimitrios Mendrinos, Constantine Karytsas



The objective of this work is to make recommendations for the surface thermal loop of a deeper exploratory well to be drilled in Los Humeros, which is expected to tap a supercritical geothermal reservoir of pressures and temperatures much higher than the ones recorded in existing wells. Such a well should deliver highly more corrosive and abrasive fluids than standard high enthalpy wells, due to entrained acid gases (HCl and HF) and silica. Non condensable gases (CO_2 and H_2S) should be in much less concentration. Very few such wells are available worldwide, the most important of which are IDDP-1 and IDDP-2.

The thermal loop configurations for the exploitation of ultra-hot geothermal wells proposed in the literature are (i) central heat exchanger with binary plant, (ii) steam purification by wet scrubbing and condensing power plant and (iii) steam purification by dry scrubbing and condensing power plant, of which only wet scrubbing has been tested in IDDP-1 well and for limited time only. In Los Humeros geothermal system, the average well produces two phase fluid of 2600 kJ/kg specific enthalpy at 20 bar wellhead pressure, delivering 8 kg/s of steam with 3.86% non-condensable gasses (3.26% CO_2 and 0.37% H_2S) and steam condensate pH of 7.2. The hottest well integrated in the power plant, delivers superheated steam of 283 ^oC temperature, 40 bar pressure and 2900 kJ/kg specific enthalpy. The steam condensate has a pH of 4.47, compared to 2.62 of IDDP-1. Continuous Injection of K_2CO_3 with Amine based inhibitor at the two phase pipeline, upstream of well line connection, has been successful, resulting in reliable operation with zero scaling and zero measured corrosion.At present, there is no metal or alloy that can guarantee corrosion free operation with the aggressive superhot geothermal fluids. Aluminum is subject to intense pitting corrosion, copper and its alloys are attacked by H_2S, nickel is also attacked by H_2S and metal chlorides, while even the most exotic iron/steel stainless alloys are subject to corrosion above 150 ^oC. Titanium shows the highest

resistance and corrosion free operation up to 300 ^{o}C. Plastic claddings are not stable at such temperatures. Therefore, development and testing of high temperature (>450 ^{o}C) corrosion inhibitors and/or cladding is compulsory.

As the ultimate goal is to achieve reliable electricity generation from stand-alone superhot geothermal wells, key challenges for the new superhot well are to demonstrate reliable long term fluid treatment and steam purification methods and surface equipment. Suggested field experiments and tests should include optimizing wet scrubbing method for higher conversion efficiency, downhole wet scrubbing, dry scrubbing, as well as new corrosion resistant materials and equipment for operation at extreme temperatures & pressures.

36. Monitoring methods for Los Humeros super-hot geothermal system: state-of-the-art

Dimitrios Mendrinos, Christos Kalantzis, Constantine Karytsas

This work reviews reservoir monitoring methods currently practiced in the 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 and 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/Ar, U/Th, 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 morphostructural 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, and 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 aim to evaluate the 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.

37. Improving wellbore sealing integrity in deep high-temperature well applications

Michal Kruszewski, Giordano Montegrossi, Volker Wittig

The research work carried out in this study proposes methods for securing long-term wellbore sealing integrity in deep high-temperature applications. The analytical model developed in this study, accounting for mechanical properties of a coupled casing-cement-rock system with the influence of temperature changes, applied internal pressures, and isotropic far-field stresses, can be used to evaluate wellbore sealing integrity during various stages of a geothermal well life cycle and help to optimize and design drilling, production, and maintenance operations. Additionally, a potential replacement for the commonly used Portland-based cement mixtures with an alternative type of non-Portland sealing system is proposed. The laboratory research was focused on alkali-activated alumina-silicates, which proved to be good candidates for the future completions of high-temperature geothermal wells. This type of polymer-based sealing system exhibits more stable and higher compressive and flexural strength than conventional Ordinary Portland Cement, better resistance towards thermal cyclic loading, improved ductility with lower static and dynamic elastic modulus, acid insensitivity as well as improved water permeability, while its self-induced shrinkage remains marginal. Additionally, alkali-activated alumina-silicates sealing systems are economically feasible and their CO_2 emission during the manufacturing process is significantly lower, making them an environmentally friendly option for a wellbore sealing system in high-temperature geothermal systems, even in scenarios where reservoir temperatures exceed the critical point of reservoir fluids.

38. Modelling fault reactivation and induced seismicity in supercritical geothermal systems

Francesco Parisio, Victor Vilarrasa, Wenqing Wang, Olaf Koldit, Thomas Nagel

Understanding the geomechanical features of supercritical geothermal systems is a great challenge that involves coupled process in the solid skeleton: changes in temperature and pore water pressure influence both the stress redistribution and porosity change, which in turn can have an effect on permeability. Such changes can be induced by operation of deep geothermal wells involving fluid production/reinjection, both during drilling, permeability enhancement or long-term operations. The current lack of experience and the extraordinary challenges posed by accessing in-situ information make numerical modelling a viable exploratory method to understand coupled processes and assess geomechanical risks. We have performed finite element analyses including temperature, pore pressure, deformation and porosity/permeability changes of fluid extraction and reinjection in an idealized supercritical geothermal doublet. We have investigated the long-term fault stability during 25 years of reinjection/production and found that seismicity increase is dominated by rock cooling during cold fluid reinjection. The microseismicity is expected to increase its frequency by several orders of magnitude in a relatively short time (within 5 years), while the timing of greater magnitude events depends essentially on the heat diffusion characteristics of the system and the distance of major faults from the injection wellbore. In the case considered, the fault is expected to slip after roughly 10 years of operation and the slip front grows as a logarithmic function of time. While it is difficult to predict magnitudes of the largest events, our model provides precious insights on the fault stability of supercritical geothermal systems and proves to be a useful tool for safely managing site operations.

39. Modelling enhanced fluid convection and heat transfer in superhot geothermal systems in Iceland

Sæunn Halldorsdóttir

For decades it has been generally assumed that the main mechanism that transfers heat from heat sources of volcanic geothermal systems is driven by a Convective Downward Migration (CDM) process: a cooling front, driven by convecting water, migrates into hot rock through fractures that open up due to thermoelastic contraction induced by cooling of the rock. The heat sources are believed to be cooling magma chambers or intrusions and this process transports thermal energy, derived from the cooling intrusions, upwards to the geothermal systems by convection. The CDM process has been implemented in numerical models by increasing the model-permeability near the heat sources. The resulting heat transport could explain the existence of geothermal systems above magmatic sources, supporting the assumed role of CDM in geothermal systems. A new collaboration project between UiB, ISOR, Equinor, Reykjavik Energy, Landsvirkjun and HS Orka, aims to study these proposed conditions that enhance permeability and favor convection by opening of fractures in superhot conditions near crustal heat sources. Field data from two deep drilling sites, IDDP-1 in Krafla NE Iceland and IDDP-2 in Reykjanes SW Iceland, will be used to constrain coupled THM models to simulate effect of CDM on heat transfer deep in the geothermal systems.

40. Locating and characterizing seismic events in Los Humeros using time-reverse imaging

Claudia Finger (born Werner), Erik H. Saenger

Time-reverse imaging (TRI) is a migration-based method for locating and characterizing seismic events. TRI uses the whole time-reversed waveform and a seismic wave propagation solver to locate and characterize events. Therefore, it does not rely on the identification of seismic events and their onsets in the traces. This study is the first attempt at a complete analysis of the seismicity of a geothermal reservoir using TRI. An automatized tool is presented to locate and characterize seismic events using TRI, which may enable the mapping of existing fault networks, the estimation of local stress regimes and the distinction between tectonic and induced events. In contrast to common tools that provide hypocenters and focal mechanism solutions for seismic events, TRI does not assume any a priori knowledge about the sources. Since events are not picked in the seismic traces, no assumption is made about the number of sources recorded in a certain time window. Similarly, the characterization of events does not exclude any source type or put any constraints or assumptions on the sources such as them being only of double-couple nature. Therefore, TRI may be especially well-suited when the overall type of sources is not known or if it is suspected that common localization tools are not adequately depicting the physical processes in the subsurface. In the first part of this study, seismic events are located in the geothermal field of Los Humeros in Mexico. Sensitivity maps are used to enhance the localization capabilities and to determine the source-location accuracy. In the second part of this study, the located events are characterized by determining the full time-dependent moment tensor. Since no assumption about the source type is made, these moment tensors reveal new insights into the processes in the subsurface. The moment tensors are plotted in source-type plots and in focal sphere diagrams to compare them to results from other methods.

41. Sensitivity maps for Los Humeros: Enhance localization results using time-reverse imaging to locate and characterize seismic events

Claudia Finger (born Werner), Erik H. Saenger

Locating and characterizing seismic events is a crucial step in any reservoir characterization and monitoring scheme. The location of events may reveal the fault network and the brittle-ductile transition zone, while the characterization permits to estimate the local and regional stress regime and may allow for a distinction between tectonic and anthropogenically induced events. Time-reverse imaging (TRI) is a migration-based localization method that uses the whole time-reversed waveform. Therefore, even smaller events occurring close in space and time may be located using TRI. Previous studies have shown that the station network influences the obtainable source-location accuracy significantly using TRI. In this study, a workflow is developed to create sensitivity maps that reveal the spatial variability of the source-location accuracy for the temporary passive seismic network installed above the geothermal field of Los Humeros, Mexico. To create these sensitivity maps, numerous synthetic sources are distributed in the model and excited simultaneously during a forward simulation. Afterwards, TRI is used to locate these events. An automatic and user-independent workflow is proposed for the identification and accuracy determination of convergence spots. In general, sensitivity maps report on the source-location accuracy in the model and may be used to assess existing networks for their location capabilities or help to improve the design of future networks. Additionally, they provide an uncertainty estimation for real-life located events and thus, allow the distinction between artificial convergence of the wave field and actual source localizations. The sensitivity maps for Los Humeros reveal a non-linear influence of the station distribution and the velocity model on the source location accuracy. Additionally, different source types show drastically different patterns of the location accuracy. The sensitivity maps may be directly used during the localization of real-life events in Los Humeros by eliminating areas of the model that were revealed to be not locatable.

42. Active deformation of the Los Humeros caldera floor inferred from Envisat and Sentinel-1 InSAR

Eszter Bekesi

Interferometric Synthetic Aperture Radar (InSAR) can be a high-resolution cost-effective monitoring tool of geothermal fields, capable of detecting ground movements with millimeter accuracy. In most cases, surface deformation at geothermal areas occurs due to production, however, in high-enthalpy geothermal areas (volcano-) tectonic activity may also contribute to the deformation signal. We present ground deformations estimated at the Los Humeros Geothermal Field by InSAR. We performed Persistent Scatterer Interferometry (PSI) using acquisitions from Envisat and Sentinel-1 satellites covering the periods of 2004-2007 and 2016-2019, respectively. Results of the Envisat PSI time series analysis indicate that the local ground deformation up to 8 mm/year may exclusively originate from field operations. The Sentinel-1 data suggest that apart from the movements observed in the vicinity of the active geothermal wells, deformation of the central part of the Los Potreros caldera exists. The deforming area is also marked by natural seismicity, and the subsidence of the caldera floor is most likely caused by volcano-tectonic activity. Additionally, we mapped and modelled the surface movements induced by the 8 February 2016, Mw=4.2 earthquake, observed at the geothermal field, inside the Los Potreros caldera. Surface movements due to the 8 February 2019 earthquake indicate reverse movement along the trace of the Los Humeros fault, consistent with the focal mechanism solutions. Modeling results suggest that the seismic event was originated at a shallower depth, in the top of the reservoir. The co-seismic deformation of the Eastern block of the NNW-SSE-striking Los Humeros fault is in agreement with the long-term subsidence of the Los Potreros caldera floor. Our results demonstrate that InSAR can significantly contribute to study the interplay between field operations and active volcano-tectonics. It is especially relevant for the understanding of superhot geothermal systems, which are in most cases marked by volcano-tectonic activity.

43. The exsolution of magmatic volatiles in the Los Humeros volcanic-geothermal system

Anna Jentsch, Egbert Jolie, Dave G. Jones, Helen-Taylor Corran, Loic Peiffer, Martin Zimmer

The spatial variability of gas emissions at Earth's surface is a proxy for structural discontinuities in the subsurface of volcanic systems. The Los Humeros geothermal reservoir is characterized by a low to medium matrix permeability where fluid flow is mainly controlled by a dense fault/fracture network resulting from different periods of volcano-tectonic activity. This study focuses on different soil gas measurements to identify areas of increased gas emissions and relate them to (un)known volcano-tectonic structures. We developed an optimal sampling approach and network covering the main production zone of the geothermal field measuring different soil gases in order to understand their spatial variability. CO_2 efflux measurements were performed by the accumulation chamber technique where elevated emissions were measured along known faults as well as in areas of unknown fault related permeability. This was complemented by alpha spectroscopy for ^{222}Rn and ^{220}Rn emissions as well as soil temperature measurements at 50 cm depth. The results show a positive correlation with CO_2 efflux although in some parts negative correlations were observed indicating further structural permeability. Additional work focused on the origin of geothermal gases by analysing $\delta^{13}C$ of degassing CO_2 and $^3He/^4He$ ratios. Carbon isotopic data cover a broad spectrum from biogenic to geogenic sources showing typical values of an active magmatic system. Determined $^3He/^4He$ ratios indicate a mantle component of up to 65% being most evident in the northwestern and southwestern part of the study area. Our results suggest that especially the combination of different soil gas measurements is a useful approach to identify structural discontinuities in the subsurface that act as migration pathways of hydrothermal fluids. The combined processing of CO_2 efflux and $\delta^{13}C$-CO_2 facilitated the detection of permeable structural segments with a connection to the deep, high-temperature geothermal reservoir, also in areas with low to intermediate CO_2 emissions. Furthermore, the deployment of a permanent monitoring station measuring soil CO_2 efflux over a five-month period is used to understand the influence of environmental parameters (e.g. air temperature, pressure), seismic and/or volcanic activity as well as geothermal production/injection rates on soil CO_2 degassing.

44. MT Data from Los Humeros geothermal area: 3D Inversion and model assessment results

Diego Ruiz-Aguilar, José Manuel Romo-Jones, Claudia Arango-Galván, Ásdís Benediktsdóttir, Gylfi Páll Hersir

Within the framework of the European-Mexican project GEMex, 122 Magnetotelluric (MT), and 120 Transient Electromagnetic (TEM) soundings were acquired in Los Humeros volcanic complex (Mexico), which is considered a superhot geothermal system. We collected both datasets at the same locations, so that we were able to use the TEM data for static-shift correction of the MT data. Transient responses were measured from 0.1 to 90 ms with a TerraTEM device and using a 100 x 100 m^2 single-loop configuration. MT signals were recorded with Metronix systems in the period range from 0.001 to 1000 s. We estimated MT transfer functions with BIRRP (Bounded Influence Remote-Reference Processing), a robust processing algorithm. Dimensionality analysis of MT data suggests 1D and 3D subsurface resistivity structure. We performed three-dimensional inversion of MT data with ModEM software. We applied different 3D inversion schemes to the MT data, and evaluated their results. Before interpretation, a model assessment (i.e., squeeze tests and feasibility studies) was carried out to analyze whether or not the structures derived from the 3D MT inversion are reliable. In the preferred 3D inversion model, typical high enthalpy geothermal anomaly can be distinguished a conductive clay cap over a more resistive core.

45. Computational intelligence-based approaches to the integrated study of the Acoculco Caldera (Mexico): Particle swarm optimization of Magnetotelluric, Transient Electromagnetic and Vertical Electrical Sounding data

Alessandro Santilano, Adele Manzella, Alberto Godio, Francesca Pace, Gylfi Páll Hersir, Ásdís Benediktsdóttir, Sebastian Held, Claudia Arango Galván, José Manuel Romo Jones

We present the results of an innovative approach applied to geophysical data available in the Acoculco geothermal field. We exploit computational intelligence (CI) methods for the quantitative data integration of different datasets, by jointly solving the inverse problem of transient electromagnetic (TEM), vertical electrical sounding (VES) and magnetotellurics (MT). Data integration is extremely important in complex geological systems such as the Acoculco Caldera. The methods for solving the inverse problem are classified into deterministic and probabilistic ones. Deterministic methods are the conventional approaches to estimate the resistivity models from TEM, VES and MT data, by minimizing a functional operator according to a derivative approach. The solution of the procedure is heavily influenced by the choice of the starting model; moreover the procedure could be trapped into a local minimum of the functional. Probabilistic methods analyze different resistivity models retrieving the best-fit model(s) by directly estimating the minimization functional. The philosophy of the probabilistic approach, which can be considered as an optimization procedure, is to explore a wider space solution to seek for the global solution to the problem. The need for an accurate integration of multiple geophysical data comes from the possibility to overcome specific problems or limitations of a single method, such as the static shift effect in MT or the weak sensitivity to resistors for TEM or to conductors for VES. The limitation of an unconstrained starting model for the geophysical inversion was overcome by using computational intelligence. Subsoil data from geothermal wells have been used to test an innovative procedure that produces only a slight influence of a-priori information on the optimization. We adopted the particle swarm optimization (PSO), a metaheuristic algorithm that has been successfully tested in the frame of the FP7 IMAGE Project. We took advantage from the software package based on PSO and already developed for the 1D inversion of MT and TEM data. Furthermore, we have implemented new modules for the 1D inversion of VES data and the joint inversion of TEM and VES data. The possibility to apply computational intelligence metaheuristics for the geophysical study of geothermal fields was successfully demonstrated. We have interpreted a dataset of 59 MT and TEM coupled soundings and 20 VES acquired in the Acoculco Caldera. Different approaches were tested, and the results contributed to the understanding of the Acoculco geothermal field. The main results are: i) the identification of the static shift of MT curves by means of joint optimization of TEM and MT data; ii) the computation of a 2D laterally-constrained resistivity profile from VES with external information; iii) the computation of 1D resistivity models from the joint optimization of VES and TEM data. *Acknowledgements:* We thank CFE (Comisión Federal de Electricidad) for providing the VES and TEM data acquired in different geophysical surveys for exploration purposes. We have also analyzed MT and TEM data recently acquired in the frame of the GEMex Project.

46. An automated workflow to study parameter sensitivities in a geothermal reservoir

Ariel Almendral Vázquez, Ingrid Aarnes, Gerd Winterleitner

During the last two decades, a considerable effort has been made by the Oil and Gas industry to develop automated workflows to describe the uncertainty in the subsurface. The Ensemble Reservoir Tool, developed by the state-owned Norwegian company Equinor, has been a key tool to characterize and history-match real hydrocarbon reservoirs. The modelling goal has been to create repeatable, updatable and consistent reservoir models that capture the important uncertain parameters. Our objective is to demonstrate how these same tools used for uncertainty characterization can be adapted to automate a sensitivity analysis of a geothermal reservoir. As an example, we consider a synthetic aquifer located at about 2000 meter depth. A simplified facies-belt model of three sands with their static properties (porosity, permeability and thermal conductivity) has been set up. The forward thermal simulations are carried out with Eclipse's thermal functionality. We address the sensitivity of the energy production in a production well after 50 years of production, as a function of well placement, injection-production rates and heterogeneous thermal properties. Due to the versatility of this workflow, it can be readily used on producing geothermal reservoirs to help history match complex production histories and forecast future production.

47. The Acoculco high temperature area in Mexico: resistivity surveying, data acquisition, processing and inversion

Gylfi Páll Hersir, Claudia Arango Galván, Ásdís Benediktsdóttir, Sebastian Held, José Manuel Romo Jones, José Luis Salas, Thalia Avilés, Diego Ruiz Aguilar, Arnar Már Vilhjálmsson

The Acoculco high-temperature geothermal area in the easternmost region of the Trans-Mexican Volcanic Belt was proposed to develop an Enhanced Geothermal System (EGS) within GEMex. Therefore, extensive geological, geochemical and geophysical studies were carried out in the area. These included 68 co-located MT and TEM soundings which were measured in 2017-2019 through a joint effort by the European and Mexican partners. The TEM was measured using a TerraTEM equipment and the MT data were collected using instruments from the Metronix manufacturer. The Bounded Influence Remote Reference Processing method (BIRRP) was used for processing the MT time-series. A resistivity model of the Acoculco survey area has been compiled from the results of 1D joint inversion of the TEM and MT data. It is based on inversion of the TEM data and the apparent resistivity and phase calculated from the determinant value of the MT impedance tensor. During the inversion process the MT data were static shift corrected using the TEM data. Electrical strike analysis of the MT data was carried out through a study of the Tipper and induction arrows for different frequencies. In the Acoculco survey area, the "pseudo" 3D resistivity model from 1D inversion exhibits mostly one-dimensional resistivity structure. The area can be divided into two sub-areas that are distinguished from one another; the boundary could well be a buried fault. The low resistivity cap (presumably reflecting smectite hydrothermal alteration) becomes thinner close to the western well. It is in this area where the resistive core (presumably reflecting chlorite/epidote hydrothermal alteration) is the shallowest in a very confined area, suggesting the existence of a zone of geothermal interest. A 3D inversion has been performed for the full impedance tensor of the static shift corrected MT data using different initial models. Two codes were applied for comparison, the WSINV3DMT code was run in Europe and ModEM in Mexico. This abstract presents results of the GEMex Project, funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No. 727550, and by the Mexican Energy Sustainability Fund CONACYT-SENER, Project 2015-04-268074. More information can be found on the GEMex Website: http://www.gemex-h2020.eu.

48. How to evaluate Enhanced Geothermal System feasibility? A simple workflow applied to the Acoculco Geothermal case study

Baptiste Lepillier, Alex Daniilidis, Anita Torabi, David Bruhn, Eivind Bastesen, Francesco Parisio, Hannes Hofmann, Juliane Kummerow, Keita Yoshioka, Nima Doonechaly Gholizadeh, Oscar García, Pierre-Olivier Bruna, Richard Bakker, Walter Wheeler, and the GEMex consortium

The development of an EGS is one of the goals of the GEMex project, an international collaboration of two consortia, one from Europe and one from Mexico. The research is based on exploration, characterization and assessment of two geothermal systems located in the Trans-Mexican Volcanic Belt, Los Humeros and Acoculco. Los Humeros has been a producing field for several years, but Acoculco is yet to be developed. Thanks to surface manifestations of hydrothermal activities, the existence of a geothermal system is evident. However, two wells reached very high temperatures, but did not find any fluids. For that reason, the Acoculco Caldera is foreseen as EGS development site, hoping to connect existing wells to a productive zone. In this study, we develop a workflow that aims at assessing the feasibility of this EGS. The approach aims at generating a realistic predictive mechanical model for fracture stimulation from the well borehole. The strength of the method stands in the combination of reliable data obtained from field work and experimental measurements on mechanical properties of the target rocks, used together to populate a numerical model. The workflow starts with the identification and description of the surface discontinuities using the scanline survey method. These surveys are interpolated and extrapolated using the multiple point statistics method to generate geological discrete fracture networks (DFNs). Using these DFNs together with the mechanical properties measured in the rock physics laboratory, the fracture propagation and its interaction with the pre-existing fracture network are simulated using the phase field in OpenGeoSys open-source FEM software. The results of these simulations are then evaluated in Comsol Multiphysics finite element software to model fluid and thermal flow through the fractured reservoir. The method offers a physically sound prediction of the reservoir flow characteristics as well as an accurate mechanical model of the fracture propagation and the pressure distribution for well borehole stimulation. Because the workflow is based on easily accessible data and thanks to its simplicity, this approach could be applied in most EGS case studies.

49. Characterization of soils in the geothermal zone of Acoculco, Puebla, Mexico

González-Acevedo Zayre I., Peralta-De Hoyos Rolando, García-Zarate Marco A., González-Arqueros M. Lourdes

Soil is one of the dynamic and living natural entities that plays a very important role in terrestrial ecosystems. The problem of soil pollution is not only specific to rural areas of the world or industrialized or densely populated areas, sometimes due to natural phenomena or human impacts. Evaluating the physicochemical characteristics and chemical composition of soils allows us to identify processes that are affecting their quality. In the case of areas with natural hydrothermal activity, it is of great importance to characterize the soils. This, due to the potential presence of chemical elements that can be transported or inserted in the food chain, without losing sight of the human impacts of the region. To characterize the soil, texture is a parameter to know the distribution of particle sizes and classify the soils. Together with this, pH, electrical conductivity and the amount of organic matter give an idea of the possible processes that follow the chemical elements. The geothermal zone studied is located in Acoculco, Puebla, where the hydrothermal activity is characterized by temperatures of 25 °C and acid pH with bubbling hydrogen sulfide. Calculations of the enrichment factor, the geoaccumulation index and the anthropogenic factor allowed the identification of elements of geothermal origin (As, Ba, Fe, Mn and S), geological origin (Nb, Rb, Y) and anthropogenic origin (Br, Cl, Cr, V and K). Concentrations of trace elements such as Ho, Mo, Sb, Sc and Se were notable. Rain plays a very important role, as the concentrations of most of the chemical elements in the soil increased and a greater number of correlations were identified. Barium was detected in an order of thousands of parts per million, Cl, Mn, Rb, Sr, V and Zn in hundreds of parts per million. The site studied, as said before, shows specific characteristics of low-temperature hydrothermalism on the surface, with acidic conditions that can promote the mobility of trace elements. Having sandy loam soils, it promotes water infiltration and chemical reactions in the deep fraction between 40 and 50 cm. Chemical elements of anthropogenic and geological origin were also identified. This work was made as part of the WP9 of GEMex project, supported by the Mexican CONACYT-SENER fund and the European Horizon 2020.

50. Geochemical characteristic of the Acoculco geothermal soils

Massimo Angelone, Fabio Spaziani, Vladimiro Verrubbi

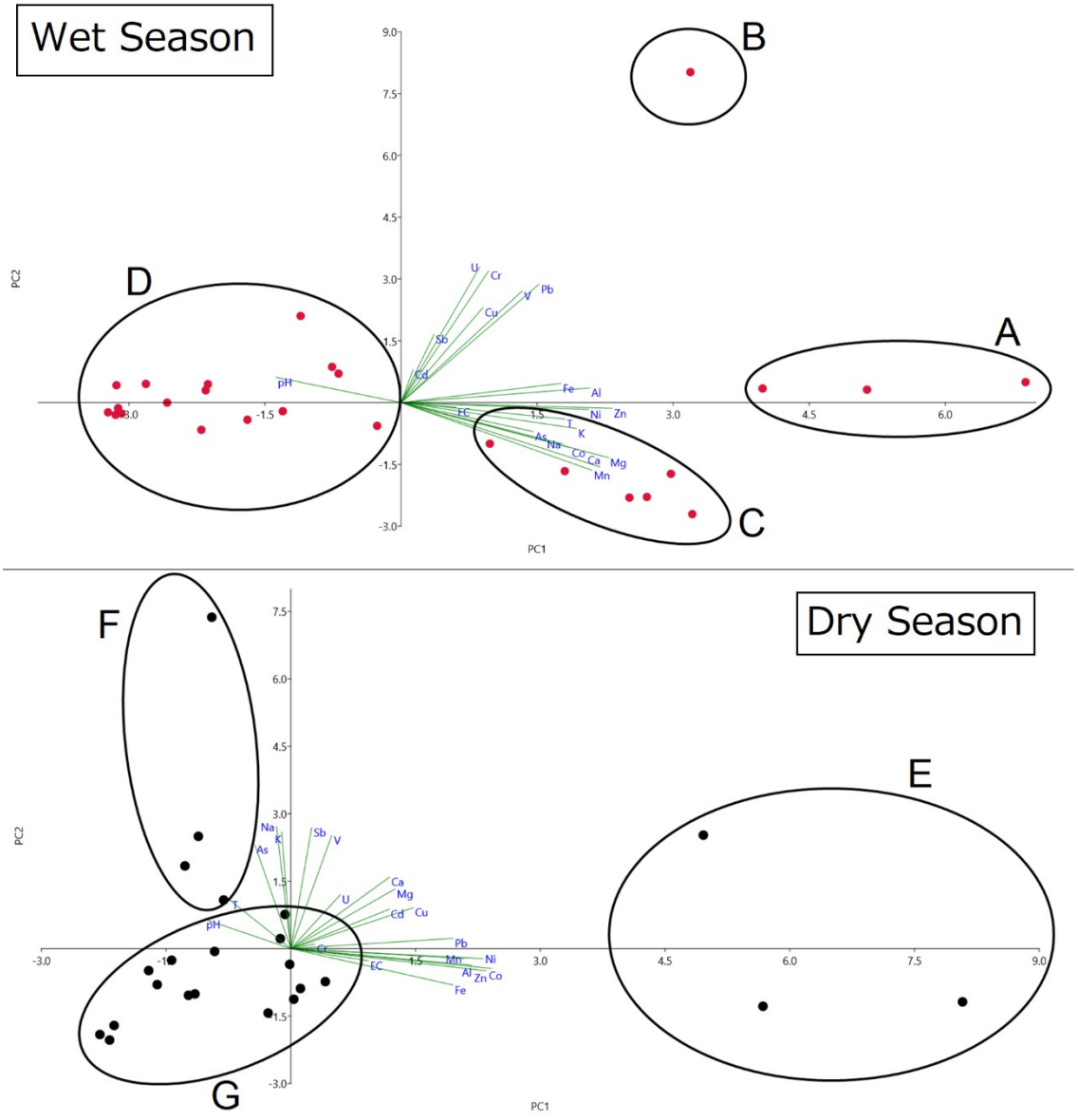
In the Acoculco geothermal area (255 km^2), characterized by high rainfall (annual average 727 mm), seven pedological units have been described. These units are characterized by the presence of superficial horizons rich in organic substances with fine to medium textures and clay accumulations in the underlying horizons. Andosols and Lovisols are the most common soils distributed on the 48% and 45% of the territory, respectively. From 2016-18, on behalf the GEMex project and in collaboration with CICESE, 18 soils, for a total of 60 different horizons selected between superficial (0-10 cm), intermediate (20-30 cm) and deep (30-40 cm) levels, were sampled in this area. Analytical data relating to minor and trace elements show, for some of them, a large concentration range linked to the wide compositional heterogeneity which is typical of geothermal areas. This applies mainly to S and As, while the Mn variability can be related to the redox conditions' variability. The correlation matrix calculated for all the variables shows high r values especially for some pairs of elements associated with hydrothermalism as As/S (r=0.82). Among the metals the greatest correlation is for Fe/V (r=0.85) and Fe/Zn (r=0.81), as far V/Zn (r=0.76) and Fe/Zn (r=0.80). The correlation between Ca and Zn (r=0.75) is the consequence of the ionic rays' similarity which leads them to participate in the same geochemical processes. The application of the PCA (Principal Component Analysis) evidences a wide sample dispersion and discriminates four groups: Group A includes the samples most enriched in Al, Fe, V and Zn; Group B contains samples with the highest concentrations of Ca, Mg and Mn; Group C holds the samples most strongly conditioned by geothermal activity as evidenced by the presence of elements such as As and S. Finally, group D includes a set of samples characterized by a wide dispersion in the PCA graph (this group includes soils with the highest concentrations of Na, K, Si, Ba and Zr). The Cluster Analysis also shows that Ba, in particular, and to a lesser extent, As, are the elements characterized by a marked distance with respect to the other geochemical parameters. This probably depends on the Ba greater geochemical mobility triggered by the particular redox conditions. The concentration levels for some trace elements from Acoculco soils do not show any particular critical concern considering the peculiarity of the environment. Arsenic is certainly an exception, whose values (range 0.80-2200; mean 309 mg/kg) are almost always above the typical ones found in natural soils. Such levels, may entail a hazard, in terms of its enrichment in local water and agriculture products. Critical, among the heavy metals, is the Zn: having an average of 111 mg/kg, exceeds the values usually found in world natural soils. Levels of attention occur also for Ni (range 15.1-212; mean 73 mg/kg) and, to a lesser extent, for Cr (range 0.84-96; mean 56 mg/kg) considering that values of 200 and 100 mg/kg are respectively suggested as concentration levels deemed excessive for global soils.

51. Geochemical assessment of the Acoculco geothermal area's groundwater and their potential impact on population

Massimo Angelone, Fabio Spaziani, Vladimiro Verrubbi

A study of selected shallow waters sampled in Acoculco was conducted to evaluate their geochemistry and potential impact on the local population. The waters, sampled in 2016-18 within the GEMex project in collaboration with CICESE, were analyzed for major and minor elements, also focusing on some trace metals of environmental concern. In order to assess the seasonality impact on the chemistry, samples from dry and wet seasons were examined. The results showed concentration for some elements, both major and minor ones, sensibly higher than the values defined by WHO and the Mexican legislation. For major elements, Al and Fe, respectively, reached values up of 17.4 and 40.0 mg/L in the wet season and 31.7 and 17.9 mg/L in the dry season (WHO guidelines: 0.2 and 0.3 mg/L). Even if these elements may not be necessarily toxic, they can affect the quality of farming products. More attention, instead, is necessary for As (WHO guideline: 10 µg/L), which hazard to human health is well known, since concentration up to 651 (wet season) and 1933 µg/L (dry season) were found. Such very high contents highlight the effect of the deep-rising hydrothermal fluids and the water rock interaction on the water hydrochemistry. A parameter that also exhibits peculiar values is the pH, since the waters showed on the whole acidic values, mean of 5.21 in wet season and 5.24 in dry season, with lower ones that fell to about 3 and therefore far from the guideline range of 6.5-8.5. In order to discuss the data in their entirety, various statistical approaches were applied. Al and Fe are the elements that revealed the greatest number of significant correlations as they are the main constituents of both minerals of primary and secondary formation. Among the minor elements, Zn is the one with the most significant correlations with all other variables, such as with Ni, Co and Mn. A remarkable correlation has also been found between Pb and Cr. The lower occurrence of significant correlations in the dry season water is probably related to the strong rain seasonality, since during the wet season the rainwater promotes the solubilization of the elements from volcanic rocks minerals and hydrothermal deposits. The PCA (Principal Component Analysis) calculated on the wet season highlighted four groups (see figure below): "A" includes the waters characterized by the highest concentrations in Fe, Al, Ni and Zn; "B", with only a sample, is characterized by the highest concentrations of Pb, V, Cr, U and Cu; "C", with the highest concentrations in major elements (Ca, Mg, Na, K, Mn) and As; and "D" is characterized by the lowest pH. The PCA of the dry season, instead, distinguished three groups: "E", characterized by the highest concentrations in Fe, Pb, Ni, Co and Zn; "F", whose samples have the highest concentrations in Na, K and, above all, As (the waters of this group were sampled close to an active

hydrothermal area, affecting the values of As); “G”, with the samples characterized by intermediate concentration values between the ones of the groups E and F.



PCA in Acoculco with four groups defined in the wet season and three in the dry season.

52. Novelties from fluid geochemistry of the Acoculco Enhanced Geothermal System

Jacopo Cabassi, Barbara Nisi, Orlando Vaselli, Matteo Lelli, Francesco Norelli, Franco Tassi, Juan Sánchez-Ávila, Thomas Gunter Kretzschmar, Belinda Sandoval Rangel, Ruth Alfaro Cuevas Villanueva, Eduardo González Manzano, Yann René Ramos

For the task 4.3 – Geochemical characterization and origin of cold and thermal fluids, a field campaign was carried out from 25th January to 5th February 2018 at the Acoculco zone, to measure diffuse soil CO2 fluxes and perform water and gas sampling. The main purposes were to: 1) identify the distribution of the CO2 soil fluxes and their correlation with the main fault/fracture systems; 2) geochemically and isotopically characterize the cold and thermal springs and gas emissions (Los Azufres and Alcaparrosa). Based on previous investigations regarding both regional and local geostructural features, some areas of the Acoculco Caldera were selected to perform 418 CO2 flux measurements using the accumulation chamber method. The φCO2 resulted to be characterized by low values (between 0.12 and 48.9 g m2/ day−1), implying that most CO2 flux data were associated with soil respiration, reflecting a low permeability of the geothermal system. Relatively higher values were only recorded close to the CO2 (H2S)-rich gas emissions of Los Azufres and Alcaparrosa. No univocal correlations between CO2 flux anomalies and fault systems were observed. The low CO2 flux values are likely due to the presence of: 1) a very thick grass cover associated with large swamping areas and 2) water-saturated soils related to the climatic conditions. However, flux measurements performed in dry conditions (Peiffer et al., 2014) did not show significant variations with respect to those registered in this study. The 45 studied waters, located inside and outside the Acoculco area, are fed by meteoric waters according to the δD-δ18O values, although for few samples evaporation and slightly positive δ18O-shift due to water-rock interaction and isotopic exchanges with CO2 cannot be excluded. A hydrothermal input within the Acoculco Caldera is testified by: 1) the acidic-SO4-rich waters located at Los Azufres and Alcaparrosa, also characterized by the highest contents of B and NH4; 2) the δ13C-CO2 values (from -4.5 to -4.1 ‰ vs. V-PDB) of the free gas samples. The δ13C-CH4 values (from -40.5 to -33.8 ‰ vs. V-PDB) of Los Azufres and Alcaparrosa are consistent with thermogenic processes involving organic matter. Distal waters (e.g. those from Tulancingo and Chignahuapan areas) are nearly neutral and Ca(Na)-HCO3 in composition. Nevertheless, the Ca-HCO3 thermal waters from Chignahuapan showed some features typical of hydrothermal fluids: 1) relatively high TDS; 2) relatively high temperature; 3) high NH4, B and Li. The origin of Na(Ca)-HCO3 and Ca(Na)-HCO3 waters is probably due to water-rock interactions involving Na(Ca)-silicates of volcanic rocks. For some samples (e.g. from Tulancingo area), dissolved Ca and HCO3 are also originated by interaction with limestones, extensively outcropping around the area. Deep contributions for this kind of water are negligible. These findings regarding fluid geochemistry allow to deeply characterize the Acoculco system and represent a novelty, since a detailed investigation at regional scale was not done before. Reference: Peiffer et al., 2014: Fluid geochemistry and soil gas fluxes (CO2–CH4–H2S) at a promissory Hot Dry Rock Geothermal System: The Acoculco caldera, Mexico. J. Volcanol. Geoth. Res., 284, 122–137.

53. Some aspect of seismic risks in Acoculco

Giovanni Bongiovanni, Massimo Angelone, Vladimiro Verrubbi

This presentation concerns some relevant aspects that could affect seismic risk in Acoculco, namely the complexity of geology and the potential amplification of surface seismic motion. Geological complexity affects the travel of seismic waves and, in the vicinity of the surface, can substantially modify the seismic field through geometric and mechanic interaction producing motion amplification; the aspects related to hypocenter determination are beyond the scope of this presentation. Seismic amplification can arise too from the presence of surface soil layers with mechanical characteristics lower than those of the underlying soil. The 2006 Basel seismic sequence, induced by EGS stimulation, produced minor nonstructural damage with an M=3.4 earthquake. The area is characterized by the presence of significant lateral discontinuities due to faults. Ripperger et al. (2009) studied the records and the comparison between the response spectra of the recorded motion and of the output of a 3D model of the Basel region enhanced a mismatch for short periods. The authors associate this fact both to closeness to faults and/or surface geology. In Italy, in a geological situation characterized by strong lateral discontinuities and faults system, an earthquake, MW=4.0 and epicentral distance of 2 km, produced, at a location a few hundred meters far each from the other, PGAs (Peak Ground Acceleration) ranging from 23 cm/s^2 to 221 cm/s^2. To date, the only possible explanation is related to multiple reflections from the discontinuities and constructive interference of the seismic waves (Sanò et al., 2015). Considering this background, the analysis of recordings from 18 seismic stations located in the Acoculco zone has been analyzed. A few days of continuous recording of 16 stations, obtained from UNAM, some with only noise and some containing far earthquakes, were analyzed looking at time histories, frequency content and HVSR technique (Horizontal to Vertical Spectral Ratio). Noise is very low and the frequency content is largely dominated by low frequencies: 0.13 Hz – 7.6 s, typical of oceans waves propagation. The rest of frequency content, very low amplitudes, shows a shape of one or more peaks surmounted by a ripple, that resemble that originated by echoes/reflection. Spectral ratios show, generally, wide frequency range with values over 2, which cannot be explained by stratigraphic amplification but could be related to the effect of multiple reflections, the same reason of the previous examples. Spectral ratios show too, in few cases, sharp peaks that could be related to soil deposit amplification. The same considerations are valid for the selected earthquakes analysis. With respect to the site that will host the geothermal test, it is suggested to install a very dense seismic network both in surface and downhole and to detail also the knowledge of surface geology. References: Ripperger J. et al., 2009. Ground motion and macroseismic intensities of a seismic event related to geothermal reservoir stimulation below the city of Basel—Observations and modelling. *Geophys. J. Int.* 179, 1757–1771. Sanò T. et al., 2015. Modellazione dei Fenomeni di Amplificazione Locale Basata su Registrazioni Accelerometriche al Sito. Convegno Anidis, L'Aquila, 2015.

54. Seismic characterization of the Acoculco caldera

Mathieu Perton, Ángel Figueroa-Soto, Luis Maldonado Hernández, Marco Calò, Philippe Jousset

In the framework of the working package (WP) 5.2, we installed a network of 18 seismic broadband stations of 3 components for characterizing the Acoculco caldera. We focus on two objectives: to obtain a 3D velocity model under the Acoculco area by using ambient noise surface wave tomography, and to characterize the seismicity. The ambient noise surface wave tomography results from a recently developed technique that combines the inversion of multi modal surface waves and H/V spectral ratio (ratio of Horizontal to Vertical ambient noise energies). The ambient noise processing allows to retrieve stable correlations up to 30 s and we used these results to obtain a velocity structure until 10 km depth. The 3D result shows a clear location of the reservoir location and of the magma paths and promotes the idea of a greater area for volcanic activities. The one year long seismic signal records were also used to detect and locate earthquake activity. Despite the high level of noise due to human local activities, we detected about ten earthquakes inside the extended area around the caldera. The earthquakes were located using an averaged velocity structure from the precedent 3D model. As the V_P/V_S ratio changed strongly in the area, we developed an ad hoc nonlinear location technique. Results show some relations with the NE and NW fault systems described by geologists as well as with some clusters occurring outside of the Acoculco caldera. This work was made in the framework of the Mexican-European Project GEMex (Cooperation in geothermal energy research Europe-Mexico, WP5.2 No. 267084 funded by CONACyT-SENER, and Horizon 2020 grant agreement No. 727550.

55. Seismic modelling including temperature in SHGS and EGS geothermal systems

Biancamaria Farina, Flavio Poletto, José M. Carcione, Dimitris Mendrinos

Seismic-wave modelling including temperature is an improved tool for the geophysical characterization of deep structures in geothermal and volcanic-caldera areas, where the presence of high temperatures can cause the existence of supercritical fluids and partial melting. The modelling is applied following different approaches to evaluate and improve geophysical imaging and detection of the deep reservoir structures in the Los Humeros super-hot geothermal system (SHGS) and Acoculco potential enhanced geothermal system (EGS), which are the two target Mexican geothermal fields of the collaboration study in the GEMex project. Seismic properties, velocity and attenuation, depend on the pressure and temperature conditions, which are closely related to the properties of the rock frame and geothermal fluids. We present the theory used to calculate the seismic properties of hot porous rocks in the presence of geothermal fluids based on the Burgers mechanical model to describe the an-elastic behavior at the brittle-to-ductile transition (BDT) due to shear deformation and plastic flow induced by temperature through the Arrhenius equation, and on the Gassmann equation to account for the fluid properties. As a first result, a sensitivity analysis is performed to understand how temperature and pressure variations can affect the seismic-wave propagation. The analysis is applied at seismic frequencies and compares the sensitivity effects for different typical seismic elastic quantities, showing the different performance in relation to physical effects, including melting, supercritical conditions, and their seismic observability obtained in different temperature regions. As a second result, seismic velocities and attenuation are calculated in terms of the subsurface distribution of the confining and pore pressures and temperature, assuming that the heat transfer from below is convective or conductive. The pore pressure is assumed hydrostatic. For the Los Humeros super-hot geothermal system the temperature is calculated assuming the boiling-point condition at the specific pore pressure down to the reservoir. Beneath the reservoir the temperature is assumed constant in convectively heated systems, and following a constant temperature gradient in conductively heated systems. In the Acoculco enhanced geothermal systems we assume conductive heat transfer and constant temperature gradient. Finally, full-waveform synthetic seismic propagation is computed in geothermal reservoirs as a function of temperature and confining pressure. In the application to hot and superhot systems, we introduced the concept of characteristic melting depth point (for selected signal frequency), based on the melting rate observed in the seismic velocity, showing that this point is different for P and S waves. The analysis is applied for full-waveform simulation in heterogeneous media, specifically in the Los Humeros superhot Mexican caldera (Figure 1) and Acoculco enhanced geothermal system. The simulation provides a novel analysis tool and makes it possible to detect differences in the seismic wavefields due to temperature effects, in surface and borehole seismic measurements.

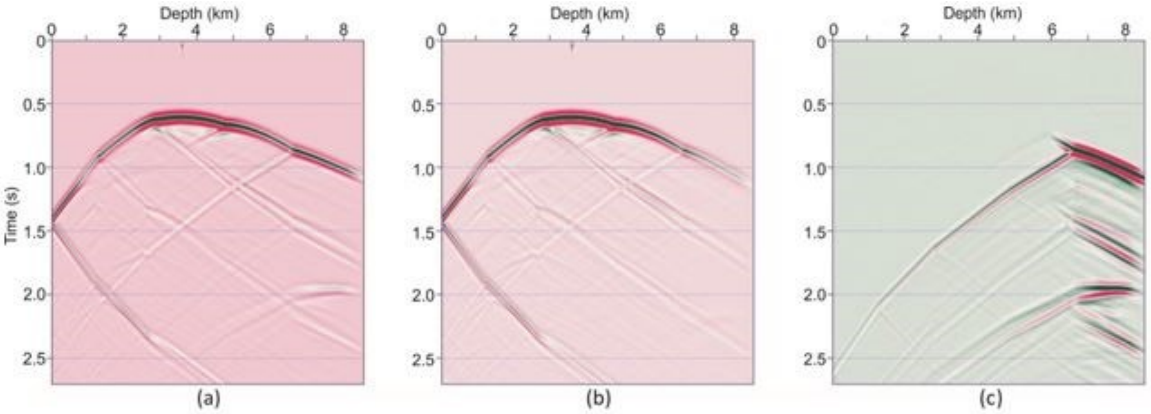
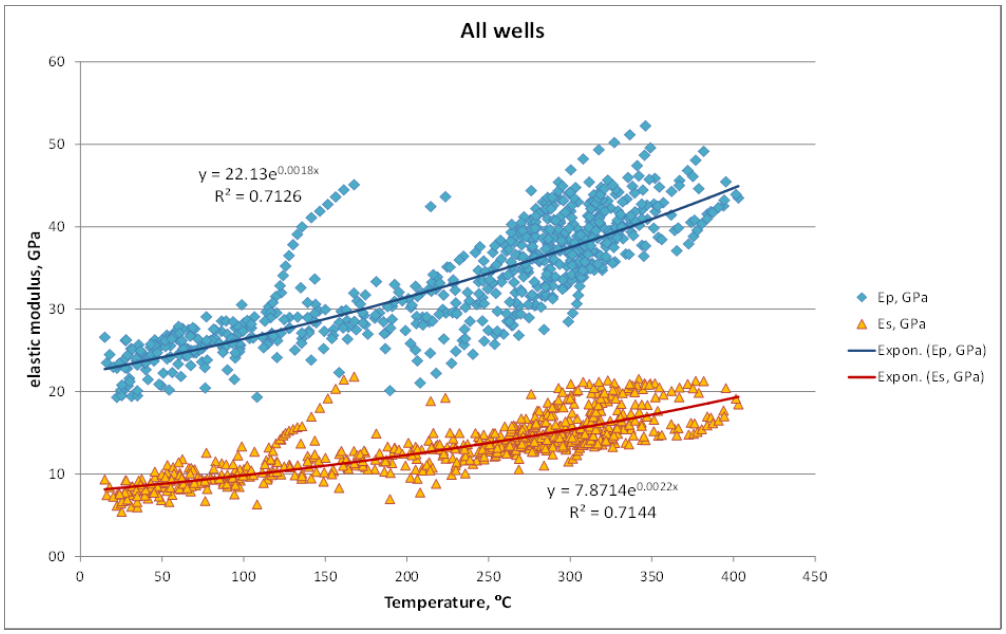


Fig. 1: Modeled synthetic VSP simulated assuming a source at depth at Los Humeros. a) In the absence of melting, b) with melting, and c) difference.

56. Los Humeros superhot and Acoculco EGS: distribution of rock modulus and correlation with temperature

Dimitrios Mendrinos, Spyros Karytsas, Constantine Karytsas, Flavio Poletto, Biancamaria Farina

Temperature measurements are available within geothermal wells down to circa 2 km depth or ~800 masl elevation in the Acoculco enhanced geothermal system (EGS), and down to circa 3 km depth or ~300 mbsl elevation in Los Humeros super-hot geothermal system. A constant temperature gradient is evident in Acoculco and a close to boiling-point-to-depth temperature pattern in Los Humeros. In Acoculco, one dimensional S-wave elastic modulus, calculated from ambient seismic noise analysis and local gravity survey, is related to measured temperature with a logarithmic function. This relationship may be also valid at deeper elevations below well bottom, down to the elevation where a local maximum elastic modulus is observed, as indicated when comparing S-wave modulus with extrapolated temperature calculated by the reservoir computer model of the field, which was developed within the GEMex project. As an approximation, in Los Humeros super-hot geothermal system, P-wave elastic modulus, which was estimated from both legacy active and recent passive seismic 3-D surveys coupled to a regional gravity survey, increases almost linearly with depth down to 100 m above sea level. S-wave elastic modulus, which was estimated by 1-D ambient seismic noise analysis and 3-D passive seismic survey coupled to a regional gravity survey, follows a similar pattern down to 500 masl approximately, where its value stabilizes with depth. At deeper levels, S-wave modulus shows variations not shown by P-wave modulus. In Los Humeros super-hot geothermal system, where 3-D data are available, seismic velocities and elastic moduli are correlated to temperature in the vertical direction by exponential functions (see attached figure), while no such statistically significant correlation is evident in the horizontal direction. This implies that an indirect relation may exist between seismic velocities and elastic moduli with temperature, e.g., through their dependence on common independent variables such as rock matrix pressure and/or pore pressure and fluid saturation. The weak correlations observed indicate that local anisotropy is also important.



57. Geomechanical and hydric characteristics of the Cretaceous sedimentary rocks, part of the basement of the Acoculco Caldera Complex

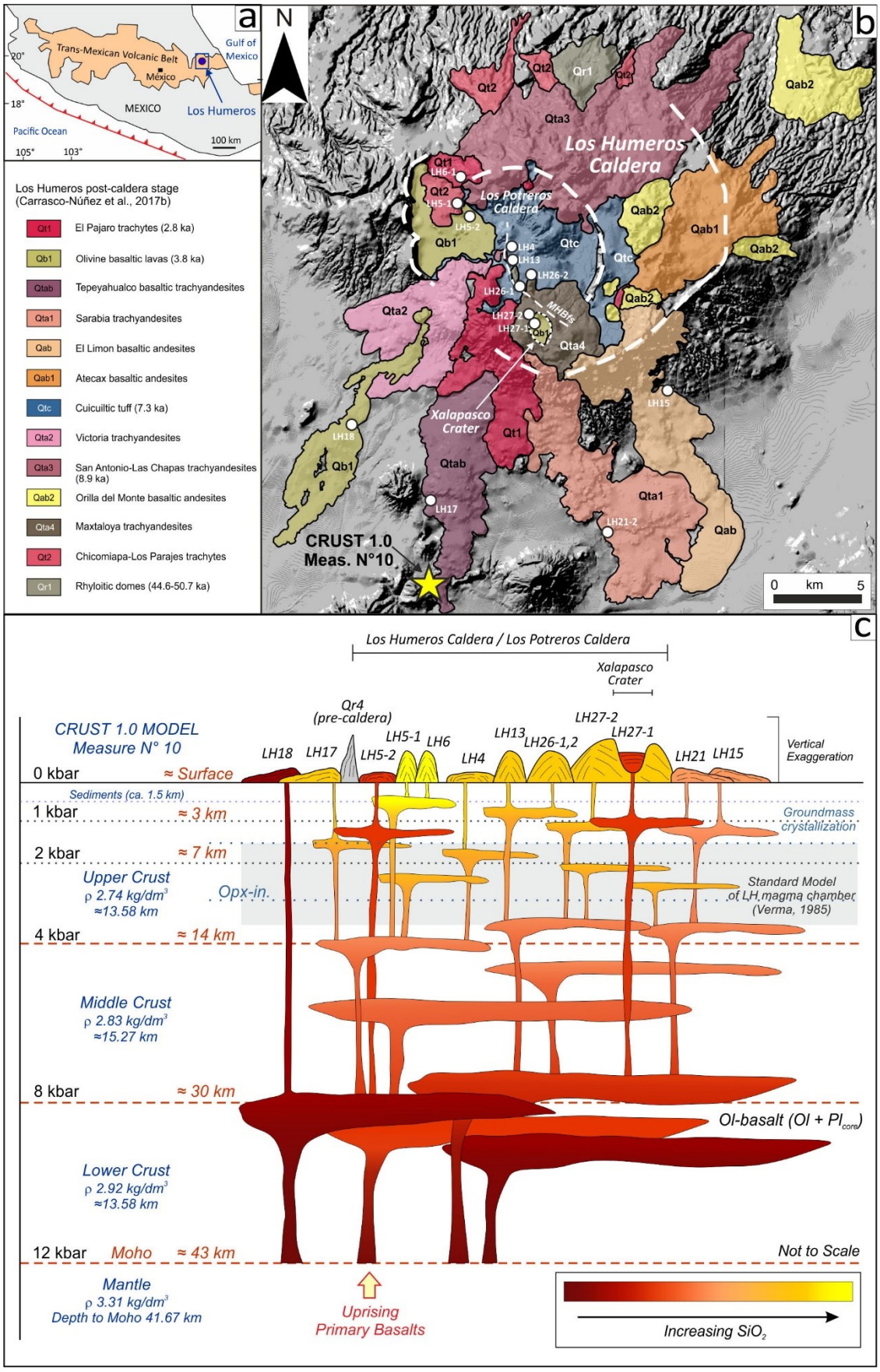
Antonio Pola, Ángel Andrés Ramírez Guzmán, José Luis Macías Vázquez, Andrés Mauricio Soto Herrera

General geomechanical and hydric characteristics of part of the basement of the Acoculco Caldera Complex were assigned by a series of laboratory measurements. The basement in the region is composed by a sequence of Jurassic to Cretaceous sedimentary rocks, including highly folded sandstones, limestones, conglomeratic beds, and intrusive granitic bodies. One of the main purpose of the study is to highlight the interaction between properties, particularly how the values of the permeability change in small range of different confining pressures and in fractured and not fractured specimens. The relationship of the pore system, microfracturing characteristics and permeability was explored by mercury porosimeter, helium pycnometer and nitrogen permeameter, respectively. In general, the matrix characteristics together with the characteristics of the architecture of the connectivity of the rock porous structure and fractures have important implications for fluid transfer. In this way, the knowledge of all these characteristics will be useful and needed to construct different conceptual models (e.g. fluid and heat transfer trough rock medium), which in turn, and together with other studies like geophysical and structural geology, will help to identify new zones of geothermal interest. Preliminary data shows that matrix permeability is very low even if the data of some specimens shows an increment due to particular characteristics (e.g. microfracturing). Permeability values of fractures seems to be higher and is strongly related to the particular physical and morphological characteristics of the fractures (e.g. filling, aperture, recrystallization of secondary minerals). Finally, this work also provides equations to describe the permeability behavior of different rocks including those altered collected inside the caldera complex.

58. The Los Humeros caldera: unravelling the anatomy of the Holocene magmatic plumbing system through a petrological approach

Federico Lucci, Guido Giordano, Gerardo Carrasco-Núñez, Federico Rossetti, Stefano Urbani

Understanding the anatomy of magmatic plumbing systems of active volcanoes is essential not only for unraveling the magma dynamics and eruptive behaviors, but also to define the geometry, depth and temperature of the heat sources for geothermal exploration. With the aim to decipher the anatomy of the current magmatic plumbing system feeding the geothermal system at Los Humeros caldera (Fig. 1a), we carried out a field-based petrological study of the exposed Holocene lavas (Fig. 1b). Textural analysis, mineral chemistry and whole-rock major elements geochemistry are integrated with (i) major-elements mass balance modeling and (ii) a suite of mineral-liquid thermos-barometric models (Lucci et al., 2019). The results obtained are: 1) a scenario (Fig. 1c) characterized by a heterogeneous polybaric multilayered system, comprising a deep (depth of ca. 30 km) basaltic reservoir feeding progressively shallower and smaller discrete magma stagnation layers and batches, up to shallow-crust conditions (depth of ca. 3km); 2) a magmatic system where evolution of melts is mainly controlled by differentiation processes through fractional crystallization (plagioclase + clinopyroxene + olivine + spinel); 3) the main outcome for the modelling of the magmatic heat source of the LHVC geothermal system is the inadequacy of conservative conceptual models based on the classical melt-dominated, single, long-lived and voluminous magma chamber, favoring a more realistic vision of the magmatic plumbing system composed of multiple, more or less interconnected, magma transport and storage layers within the crust, feeding small (ephemeral) magma pockets at shallow-crust conditions (Fig. 1c). These new findings must be considered into the new developing conceptual geothermal models to improve strategies for exploration and exploitation of the geothermal system within the LHVC. The results and approach presented in this work have also a general value and could represent an efficient strategy to explore and reconstruct the pre-eruptive geometry and the anatomy of active magmatic feeding systems. Reference: Lucci, F., Carrasco-Núñez, G., Rossetti, F., Theye, T., White, J. C., Urbani, S., Azizi, H., Asahara, Y., and Giordano, G. (2020): Anatomy of the magmatic plumbing system of Los Humeros Caldera (Mexico): implications for geothermal systems, *Solid Earth*, 11, 125–159, 2020 https://doi.org/10.5194/se-11-125-2020. Caption of Figure 1 (next page): (a) The Los Humeros volcanic complex (LHVC, blue dot) with respect to the Trans-Mexican Volcanic Belt (TMVB). (b) Shaded relief image obtained from 15 m resolution digital elevation model (DEM) of the LHVC. Volcanic products of the Los Humeros post-caldera stage are redrawn from Carrasco-Núñez et al. (2017). The map shows location (white dots) and volcanological significance of the samples used in this study. The yellow star indicates the locality of the measure No. 10 of the Crust 1.0 global model (see Lucci et al., 2019). (c) Schematic representation (not to scale) of the magmatic plumbing system feeding LHPCS activity, beneath Los Humeros caldera as derived by pressure-temperature estimates obtained from mineral-liquid thermo-barometry models (All figures taken from Lucci et al., 2020).


a
Trans-Mexican Volcanic Belt
Mexico
Gulf of Mexico
MEXICO
Los Humeros
Pacific Ocean
100 km
20°
18°
105°
103°
Los Humeros post-caldera stage
(Carrasco-Núñez et al., 2017b)
Qt1 El Pajaro trachytes (2.8 ka)
Qb1 Olivine basaltic lavas (3.8 ka)
Qtab Tepeyahualco basaltic trachyandesites
Qta1 Sarabia trachyandesites
Qab El Limon basaltic andesites
Qab1 Atecax basaltic andesites
Qtc Cuicuiltic tuff (7.3 ka)
Qta2 Victoria trachyandesites
Qta3 San Antonio-Las Chapas trachyandesites (8.9 ka)
Qab2 Orilla del Monte basaltic andesites
Qta4 Maxtaloya trachyandesites
Qt2 Chicomiapa-Los Parajes trachytes
Qr1 Rhyloitic domes (44.6-50.7 ka)
b
N
Los Humeros Caldera
Los Potreros Caldera
Xalapasco Crater
CRUST 1.0
Meas. N°10
LH6-1
LH5-1
LH5-2
LH4
LH13
LH26-2
LH26-1
LH27-2
LH27-1
LH18
LH17
LH21-2
LH15
MHBEs
0 km 5
c
Los Humeros Caldera / Los Potreros Caldera
Xalapasco Crater
CRUST 1.0 MODEL
Measure N° 10
Qr4 (pre-caldera)
LH18 LH17 LH5-2 LH5-1 LH6 LH4 LH13 LH26-1,2 LH27-2 LH27-1 LH21 LH15
Vertical Exaggeration
0 kbar ≈ Surface
Sediments (ca. 1.5 km)
1 kbar ≈ 3 km
Groundmass crystallization
2 kbar ≈ 7 km
Upper Crust
ρ 2.74 kg/dm³
≈13.58 km
Opx-in
Standard Model of LH magma chamber (Verma, 1985)
4 kbar ≈ 14 km
Middle Crust
ρ 2.83 kg/dm³
≈15.27 km
8 kbar ≈ 30 km
Ol-basalt (Ol + Pl$_{core}$)
Lower Crust
ρ 2.92 kg/dm³
≈13.58 km
12 kbar Moho ≈ 43 km
Not to Scale
Mantle
ρ 3.31 kg/dm³
Depth to Moho 41.67 km
Uprising Primary Basalts
Increasing SiO$_2$

59. Interplay between rift propagation and inherited crustal fabrics: insights into the Los Humeros and Acoculco volcanic complexes

Daniele Maestrelli, Marco Bonini, Giacomo Corti, Domenico Montanari, Giovanna Moratti

The Trans-Mexican Volcanic Belt (TMVB) is a large-scale, NW to SE trending volcano-tectonic feature extending through central Mexico for a length of more than 1000 km. Its genesis is strictly related to the interaction between the subducting Rivera and Cocos plates beneath the North America plate, as the eastward propagation of volcanism is considered to be associated with slab detachment, and consequent asthenospheric upwelling (e.g., Ferrari, 2004). The progressive SE-directed tearing of the slab and the consequent detachment are hypothesized to cause crustal extension propagating in the same direction. In this context, the TMVB developed several large scale volcanoes and calderas, some of which are the target of geothermal exploration. Noteworthy, these volcanic features are often controlled by pre-existing crustal weakness zones, which have the ability to localize volcanic centers, and thus being important elements in geothermal exploration. In the frame of the GEMex Europe-Mexico cooperation project (Horizon 2020 Programme, grant agreement No. 727550), we have investigated the interplay between the hypothesized propagating rift and inherited crustal fabrics, to get insights into the structural controls on the Los Humeros and Acoculco volcanic systems. In these areas, the inherited fabric is represented by ca. NE-SW and NW-SE regional faults (Campos-Enríquez and Garduño-Monroy, 1987). We have addressed the interplay between inherited structures and rifting through analogue models, which have reproduced continental-scale rift propagation in order to evaluate if and how the pre-existing fabrics may interact or reactivate during the rifting. In our models, rift propagation was simulated using a deformation apparatus represented by two basal moving plates hinged at their topmost side, allowing for rotational opening and consequent rift propagation. Extensional deformation was distributed using a rubber sheet overlain by a PDMS-corundum mixture reproducing the lower crust. The upper crust was instead simulated by a quartz and K-feldspar sand mixture. Artificial dilation zones trending at various angles to the rift axis (which coincides with the direction of rift propagation) have been introduced within the analogue brittle crust to simulate inherited fabrics. Our modelling results highlight that a propagating rift may reactivate the inherited fabrics as extensional structures or transfer zones (depending on their orientation) for angles ≤45° to the rift axis. Analysis of model fault pattern reveals that the reactivated features may have an important dilatational component, which may favor the ascent of magmatic fluids, especially at the intersection between rift faults and reactivated structures. The experimental results provide some important hints about the structural controls on the Los Humeros and Acoculco volcanic complexes. The understanding of fracture zone geometry is in fact a crucial information for the development of both SHGS and EGS. References: Campos-Enríquez, J., and Garduño-Monroy, V.H. (1987). The shallow structure of Los Humeros and Las Derrumbadas geothermal fields, Mexico. *Geothermics*, 16(5-6), 539-554. Ferrari, L. (2004). Slab detachment control on mafic volcanic pulse and mantle heterogeneity in central Mexico. *Geology*, 32(1), 77-80.

60. Insights on caldera collapse as effect of clustering of large explosive eruptions: the example of the Faby Tuff eruptions at Los Humeros Volcanic Complex (Mexico)

Roberto Sulpizio, Silvia Massaro, Antonio Costa, Gianluca Groppelli, Alessandro Vona, Guido Giordano, Claudia Romano, Gerardo Carrasco-Núñez, Gianluca Norini

Investigations on products of the activity precursory to caldera-forming events are essential in revealing how caldera systems evolve prior to climactic eruptions. Here, we investigate the deposits formed by Faby Tuff eruptions, which preceded the youngest caldera forming eruption (Zaragoza ignimbrite), at Los Humeros Volcanic Complex (Mexico). There is compelling evidence that caldera-forming eruptions are characterized by extremely large intensities. Estimations of Mass Eruption Rates (MERs) obtained with different independent methods indicate MERs of the orders 10^9–10^{11} kg/s (e.g., Bishop Tuff, Campanian Ignimbrite, Oruanui eruption, Taupo eruption, Peach Spring Tuff, Young Toba Tuff), implying durations of few to several hours only to evacuate even thousands of km^3 of magma. These huge MERs and erupted volumes imply relevant changes in crustal stress field during or before the inception of caldera collapse, having a significant influence on the way the magma is channeled through the crust and erupted explosively at the surface. However, changes of local stress driving to caldera-forming eruptions may be also induced by clustering of large (but not caldera forming) explosive eruptions in a time span of few centuries. This is the case of the Faby Tuff eruptions at Los Humeros caldera (Mexico), which form a cluster of seven large explosive eruptions immediately preceding the caldera-forming Zaragoza ignimbrite. We present here geological, volcanological, petrological and numerical simulations of Faby Tuff eruptions, aimed at better constrain the formation of the second caldera collapse at Los Humeros. The volcanological model has strong implications on the assessment to the geothermal resource.

61. Faults controlling ore deposits distribution in the Las Minas area (Mexico)

E. Olvera García, E. Bastesen, C. Bianco, A. Brogi, A. Caggianelli, V.H. Garduño Monroy†, D. Liotta, A. Torabi , W.H. Wheeler, M. Zucchi

In the Las Minas area (Central Mexico), hydrothermal mineralization is quite diffuse at the boundary between crystalline and sedimentary rocks and in fault zones. This is a consequence of the interaction between the cooling of Miocene felsic magmas and coeval fault activity. We investigated the role of the faults in channeling the hydrothermal fluids by fieldwork and analysis of fractures at outcrops. The field mapping was carried out at 1:10,000 scale (60 km^2). When possible, kinematic data on recent fault planes influencing the permeability and geothermal fluid paths were collected. This includes information on the main structural trends and the orientation of the intermediate kinematic axis. Six main units can be recognized in the map: 1) Jurassic-Cretaceous limestone and marble hosting Neogene magmatic rocks; 2) intrusive magmatic complex (Miocene); 3) skarn (Miocene); 4) lacustrine sediments (Miocene?-Pleistocene); 5) magmatic effusive deposits (Pleistocene-Holocene); 6) magmatic dykes (Neogene-Quaternary). The Jurassic-Cretaceous limestone is affected by contact metamorphism. In detail, the skarn is mainly located (i) along the boundary between the magmatic rocks and the Jurassic-Cretaceous limestone, (ii) along the main cataclastic fault zones, (iii) along the principal foliations affecting the limestone. Two families of faults have been recognized, NNW-SSE and NE-SW oriented, respectively. The NE-SW trending faults often controlled the emplacement of dykes, indicating that the magmatic fluid was channeled and driven by the faults induced permeability. Nevertheless, fault activity continued even after the emplacement of dykes, as indicated by the cataclastic zones also involving the magmatic dykes (Miocene). Since faults dissect Pleistocene lacustrine and volcanic units, their activity is at least encompassed between Miocene and Quaternary. The kinematics of the NNW-SSE trending faults is represented by oblique movement and normal component, the latter always overlapping the former. Whereas, the NE-SW oriented faults encompass a dominant normal component. The kinematic relation between these two fault systems could be explained in an extensional framework, assuming that the NNW-SSE fault system acted as transfer faults. Contemporaneously, the NE-SW faults acted as normal faults, although with a lateral component. The last kinematic event is however characterized by a dominant normal component in both fault systems. This could be explained as a consequence of regional uplift in the Trans Mexican Volcanic Belt (TMVB), where the preexisting fractured rock-volume, representing weakened sectors, was reactivated as normal faults, in the frame of the NW-SE striking regional extension that is conserved up to the present in the TMVB.

62. Geochronological and paleomagnetic constraints on evolution of Palaeozoic plutonic basement and Miocene-Pleistocene volcanic succession of the Las Minas mining area (E-part of the Trans-Mexican Volcanic Belt)

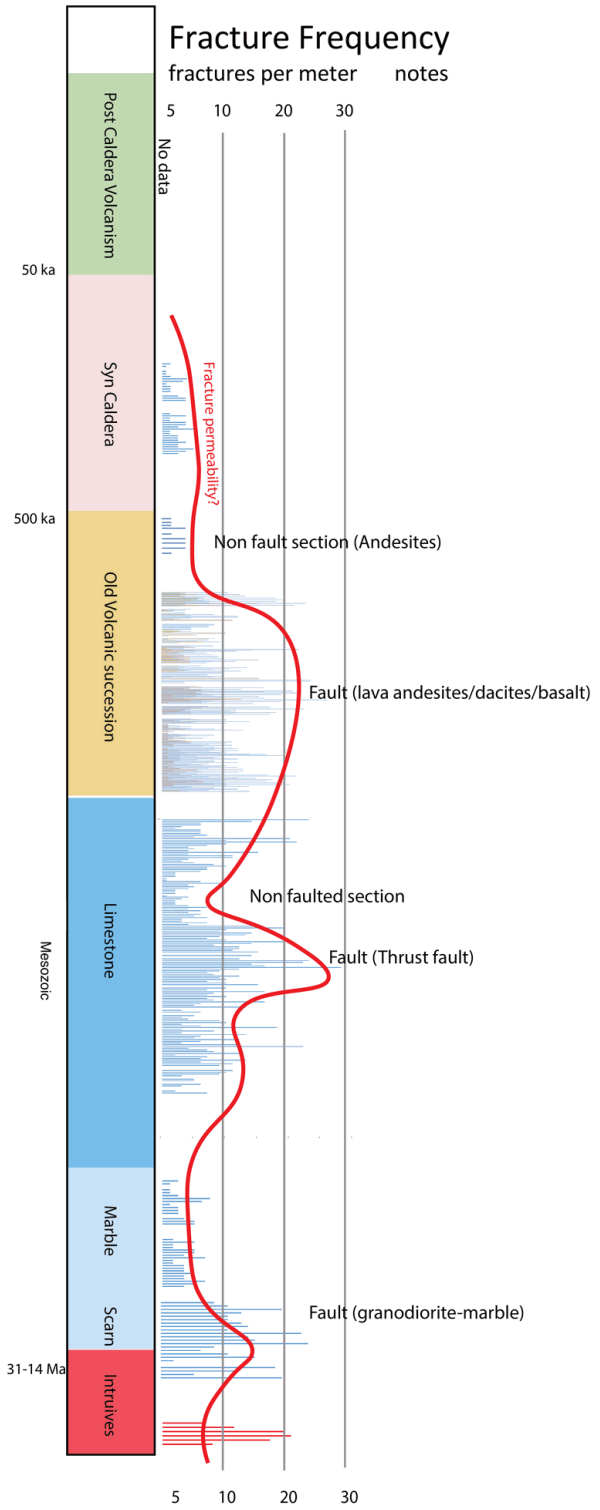
Wiesław Kozdrój, Magdalena Pańczyk-Nawrocka, Jerzy Nawrocki, Małgorzata Ziółkowska-Kozdrój, Krystian Wójcik

The Los Humeros Quaternary caldera represents a super-hot geothermal field studied within the framework of the GEMex project (Horizon 2020). This geothermal system is located in the eastern part of the latitudinal Trans-Mexican Volcanic Belt (TNVB) active from Neogene to recent times. Equivalents of the oldest, "pre-caldera" part of the Los Humeros volcanic succession and basement rocks outcrop in the Las Minas mining area where Miocene-Pleistocene volcanics lay unconformably on Jurassic and Cretaceous carbonates, underlain by the Chililis metamorphic shales and granitoids of the Teziutlán Massif. The latter units presumably constitute small fragments of a much larger, NNW-SSE oriented volcanic arc zone of Late Paleozoic-Triassic age, stretched along the eastern part of Mexico, and containing Permo-Carboniferous volcanics and Permo-Triassic granitoids. Considering present spatial terrane reconstructions, this arc was built on much older, deeply hidden substrate known as the Oaxaquia microcontinent composed of Meso- and Neo-Proterozoic gneisses and anorthosites covered with scarce Lower Paleozoic sediments. Two samples of granites from the Teziutlán Massif contain very similar populations of zircons: one cluster of Late Carboniferous age (U-Pb Concordia ages: 321 ± 3.6 Ma, 320 ± 4.8 Ma) and the second of Early Permian (U-Pb Concordia ages: 289 ± 5.3 Ma, 285.4 ± 3.2 Ma). These data may indicate (i) primary Late Carboniferous granite intrusion affected later by high-T processes forming new zircons in the Early Permian, or alternatively, (ii) very long, protracted life-span of magma chamber with initial zircon crystallization in Carboniferous and final cooling in Early Permian. Both samples of granites contain several inherited zircons with significant population dated from 936 to 1244 Ma suggesting assimilated source rocks of Grenvillian affinities. Mesozoic sediments are locally intruded by younger Miocene granitoids and in some places cut by mafic and felsic dykes. Quartz-diorite yielded U-Pb age of 16.97 ± 0.86 Ma and a mafic dyke a bit younger U-Pb age of 15.41 ± 0.36 Ma. The dyke contains also few inherited zircons of 302 Ma, 412 Ma and 1321 Ma. All these rocks and overlying basalts are exclusively of normal magnetic polarity and because of this, it cannot be excluded that they represent a very narrow time interval when the Miocene magmatic activity took place. Younger part of the Las Minas succession, including volcanics interbedded in lacustrine sediments, dacites and andesites yielded inaccurate U-Pb ages, bracketed within 2.34 ± 0.26 Ma to 1.39 ± 0.09 Ma. They often contain numerous inherited zircons grouped in two clusters: Carboniferous-Permian (335-275 Ma) and Neo-Mesoproterozoic age (948-1044 Ma). All the "pre-caldera" rocks are magnetized in reversed polarity direction what allow to constrain their emplacement to the Matuyama reversed polarity chron and even to more narrow time interval enclosed between 1.26 and 1.5 Ma. Isotopic studies of rocks from the Las Minas area emphasize complex story of magma formation before their final emplacement. Detection of remnants of high-grade Grenvillian rocks in the upper/middle crustal level beneath Las Minas area is particularly important for advanced modelling of the Los Humeros geothermal site geometry.

63. Geological structures and analogue permeability studies in the Los Humeros and Acoculco geothermal systems

Eivind Bastesen, Walter Wheeler, Andrea Brogi, Domenico Liotta, Anita Torabi, Baptiste Lepillier, Emmanuel Olvera Garcia, Oscar García Hernández, Víctor Hugo Garduño†

Caldera-related superhot geothermal reservoirs are in many cases underexploited. The primary exploration and production challenges, closely tied to investment risk, are predicting the reservoir and targeting the drilling. This contribution assesses the process of applying outcrop-based fracture observations in the Las Minas exhumed area to the Acoculco and Los Humeros reservoirs. The Los Humeros and Acoculco calderas are characterized by high heat-flow related to granitoids intruded into the Jurassic-Cretaceous limestone basement. Los Humeros produces from reservoirs below about 1300 m depth which consist of fractured lavas and ignimbrites and underlying limestone. The present caldera surface is composed of volcanic edifices, tuffs and lavas, the basement and analogue reservoir units are exposed on caldera flanks and in valleys such as Las Minas. Although the two exploration boreholes at Acoculco failed to produce, Holocene fault activity near the boreholes suggests a fractured reservoir could be developed. The main results of our study are a fracture database for most of the lithological units present in the reservoir, and workflows for applying these. Data were acquired using fracture scanlines and 3D quantitative outcrop models. From these we infer relative fracture permeability based on fracture size, orientation, connectivity and spatial frequency. For application to reservoir fluid-flow modelling, we distinguish fracture systems related to fault damage zones from background fracture systems (far from faults). We further attempt to differentiate fracture systems formed at shallow burial (near surface, e.g. between volcanic and sedimentary rocks that were fractured at surface and then buried) from fracture systems that formed under higher P/T conditions (deeper burial, e.g. present geothermal reservoir). We investigated damage zones along faults, in relays, and near fault intersections in regional faults trending NE-SW or NW-SE. We studied fracture (damage) zones ranging in width from 10 to 500 m, larger at intersections and overlap zones. Examples of major faults in andesites, limestones, basalt and skarn equivalent to deeper units of the Acoculco and Los Humeros geothermal systems, shows typically a 1 m thick cataclasite layer surrounded by a wide network of dominantly fault-parallel clustered joints and veins with alteration and iron oxide mineralization. Fracture frequencies range from 5-35 fractures per meter (see figure) with frequent intersections indicating high conductivity from which we infer high permeability in these zones. Permeability increases in fault intersections, due to higher fracture connectivity. On the other hand, hydrothermal veining, occasionally observed along the regional fault zones, significantly alters permeability. Background fracture systems, i.e rock



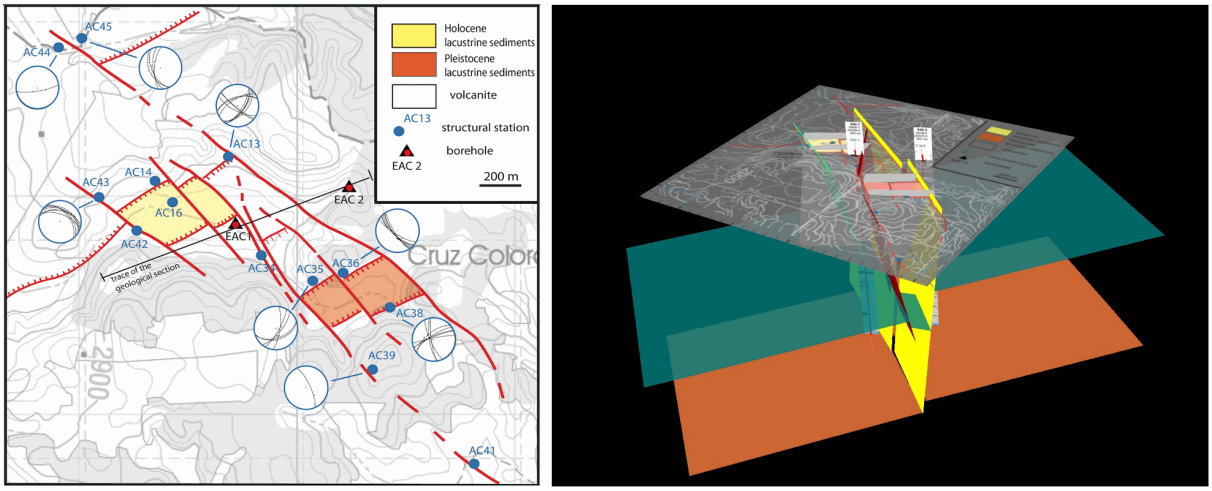
One-dimensional fracture frequency from representative outcrops, displayed as a pseudo borehole log with a lithological sequence typical of the Acoculco boreholes. Red line indicates variation of relative fracture permeability with depth, not considering fracture length, orientation, connectivity and matrix permeability. The outcrop data is from studies in Las Minas, Los Humeros and Acoculco.

volumes far away from faults, typically consist of orthogonal regularly-spaced joints, including shallow joints (horizontal and vertical, formed in the near-subsurface), cooling joints and hydrothermal veins. The low fracture frequency (0.1-0.3 f/m) and connectivity indicate low permeability. We discuss a geological model of the inferred fracture permeability including regional faults and background network. Furthermore, we discuss the value and limitations of using surface analogues to characterize the subsurface. For example, a syn- to post-caldera deposit will have a set of fractures formed near the surface before burial at reservoir depths. Thus these rocks carry an early, shallow-burial fracture network locally modified by deeper burial post-caldera deformation. How does this control fluid flow in the productive reservoir setting?

64. Fault models of the Acoculco borehole area for 3D architecture and fluid flow appraisal

Walter Wheeler, Eivind Bastesen, Domenico Liotta, Andrea Brogi, Víctor Hugo Garduño Monroy†, Adrian Jiménez Haro, Fidel Gómez Álvarez, Eduardo González Partida

Three-dimensional understanding of fractured reservoir properties is critical to modern evaluation of geothermal targets and drilling risk. In this contribution we present 3D models of the Acoculco borehole-area fault geometry with particular focus on fault-related fluid pathways for the case of active extension. Detailed models would typically be built from surface mapping, borehole image logs and high-resolution geophysical data, of which for Acoculco only the first is fully available. The structural and stratigraphic evolution of the Acoculco caldera, near the northeastern end of the Trans-Mexican Volcanic Belt, has been a particular focus of the GEMex project to better understand the exploration challenges and, in the well area, to apply methodologies of analysis for Enhanced Geothermal Systems. The two, 2-km-deep vertical CFE geothermal exploration boreholes, 500 m apart, demonstrate a temperature gradient of nearly 150°C per km and, albeit small fluid losses during drilling, tested a tight reservoir. The stratigraphy indicated by the boreholes consists of about 700 m thickness of volcanic deposits underlain by about 1000 m thickness of limestone and skarn, in turn underlain by granite. Between the wells there is an apparent 200 m offset of pre-caldera and older strata. Detailed geological mapping indicates the borehole area is cut by a system of NE-trending normal faults and NW- to NNW-trending strike- to oblique-slip transfer faults, with kinematic indicators consistent with the regional NW-directed extension (see figure below). This fault system is inferred active based on deformation of dated (Holocene) sedimentary deposits and gas seeps along many fault traces. The geologic map and the stratigraphy documented by the boreholes forms the basis for the 3D models, which focus on testing the implications of fault geometries projected from the surface traces in the kilometer surrounding the boreholes to a depth below the boreholes. The fault exposures are typically in lava and highly-compact welded tuff and characterized by damage zones estimated to be three to 10 meters wide with fracture frequencies of up to 10/m. Several of the steep NNW-



Left: Tectonic map of the Acoculco borehole area after the Liotta et al. 2019 D4.1 report. Right: Oblique view of 3D model looking NW. Strata are based on the EAC borehole interpretations of González-Partida et al. 2019: green indicates top carbonate-skarn sequence; Orange indicated top of granite; Stratal dip is not constrained. Synoptic fault geometry is based on surface relations constrained not to cut boreholes.

trending faults are projected to pass between or near the boreholes. Whereas the fault spacing and damage zone width is expected to change with depth and location in the fault network, the fault pattern and displacement indicates that the fault system cuts through the volcanic and underlying carbonate strata into the granite. Of particular interest are elements of the fault architecture that can be inferred to be particularly favorable as fluid pathways such as intersection and cross-cutting relations. These carry the implication of larger volumes of more intense fracturing and, given active fault slip, resistance to sealing. We include fault and fracture examples from outcrops, considering the application burial depth, burial history and lithology. We consider this to be important for reducing the risk in drilling strategies and stimulation design. Cross sections and depth slices prepared from the 3D architecture show model fault and strata relations which are not otherwise obvious in the interpretation of high-resolution geophysical data. Through forward modeling these can contribute to planning new acquisition.

65. Understanding the complex volcanological evolution of Los Humeros Caldera Complex, as a key to improving our understanding of Superhot Geothermal Systems

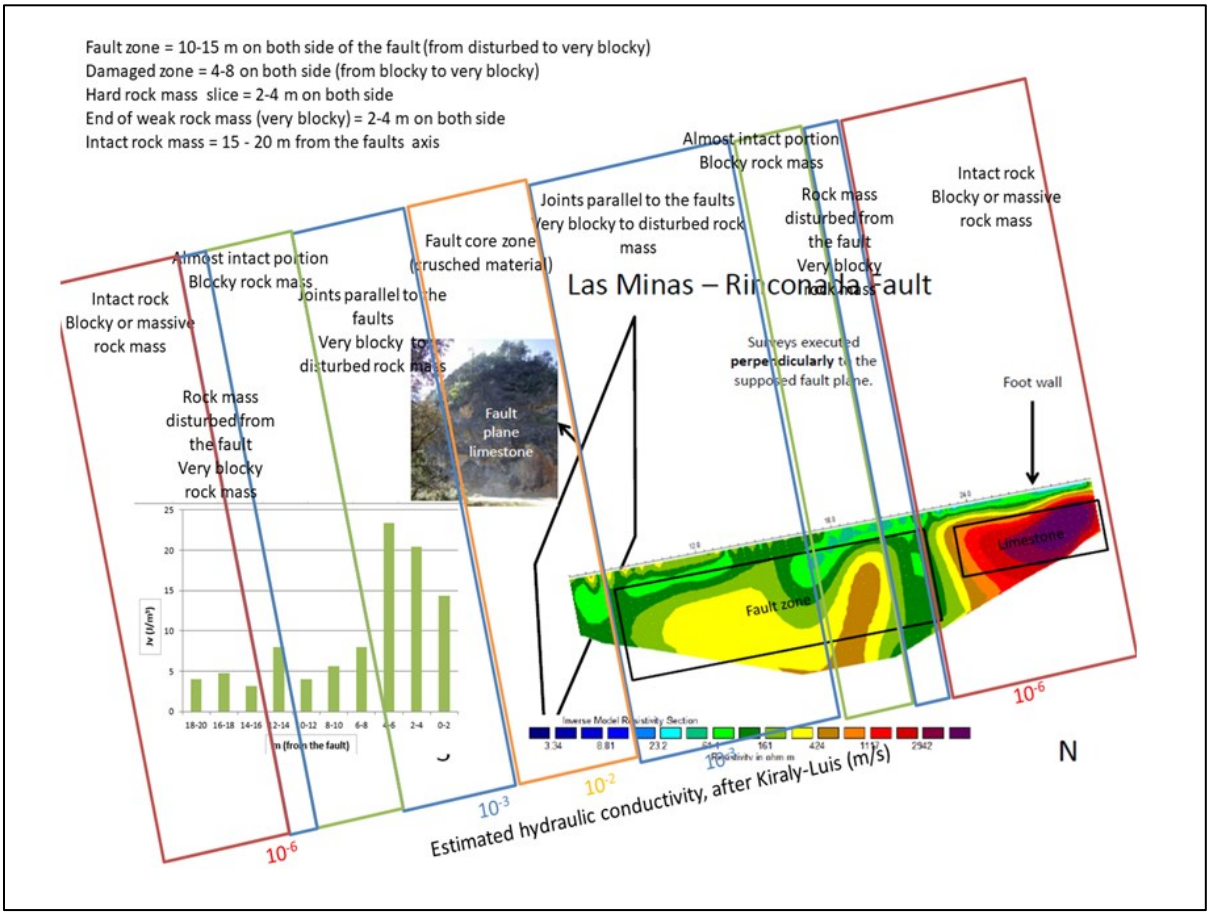
Carrasco-Núñez, G., Arzate, J., Barrios, S., Bernal, J.P., Cavazos, J., Cid, H., Corbo, F., Creòn, L., Dávila, P., Fernández, F., Arteaga, D., Giordano, G., Hernández, J., Jicha, B., López, P., Lucci, F., Norini, G., Peña, D., Rossetti, F., Urbani, S., Vega, S.

New strategies for geothermal exploration are focused now on Superhot Geothermal Systems (SHGS). A full understanding of these systems requires a comprehensive knowledge of volcano-tectonic behavior as a basis to explain how the geothermal system develops through time. Los Humeros volcanic complex (LHVC) hosts a geothermal system producing ca. 90 MW. It is located in the northernmost area of the eastern sector of Mexico and represents a classic example of SHGS. Recent findings obtained during the development of the GEMex project resulted from the integration of volcanological, structural, geophysical and petrological information, which provide a better understanding of the internal structure of the LHVC and help to explain how the magmatic system works and which are the conditions favoring the operation of the geothermal reservoir. The main outputs of this collaboration are: a) a reappraisal of the chronology for the LHVC showing that the main caldera-forming event is much younger (164 ka) and most voluminous (ca. 290 km^3) than previously reported, indicating more favorable thermal conditions for geothermal development; b) the internal structure is related to the superposition of three primary sources of stress and deformation including a regional dominantly extensional pre-caldera regime (NE-SW), a volcano-tectonic framework related to the caldera and resurgence stages and a most recent (Holocene) post-caldera framework associated with the intrusion of small magma batches from different depths and compositions; c) the magmatic plumbing system evolved from a large single magma chamber to a post-caldera multilayered configuration, and the heat source is due to the superposition of both systems; d) the complex fault and fracture-derived patterns mainly controls the circulation of fluids; however, heterogeneous lithology changes, lateral lithofacies variations, and microporosity play also an essential role in the permeability of the geothermal reservoir. Understanding the complexity of the volcanological and structural evolution of the episodic caldera-forming system, the resurgent stage, and recent monogenetic volcanism, together with the pre-caldera tectonic setting is crucial to contribute to a better understanding of the irregular and complex geothermal conditions that characterize the LHVC.
This work show results of the GEMex Project and was funded by the Mexican Energy Sustainability Fund CONACYT-SENER, Project 2015-04-268074, and by the European Union's Horizon 2020 research and innovation program under grant agreement No. 727550.

66. Faults characterization aimed at geothermal fluid path identification and quantification

Giuseppe Mandrone, Cesare Comina, Damiano Vacha

The fluids path in geothermal fields is by now demonstrated that are preferably set along bands of greater hydraulic transmissivity associated with phenomena of fragile tectonic. Faults and associated cataclastic bands are therefore objects of great interest in most productive or potential geothermal fields. The interest in the characterization of these entities is therefore of primary importance. Faults, and their most productive connected structures, very often barely outcrop on the surface due to their greater erodibility with respect to the surrounding rock masses. So, classic detection techniques are often difficult to apply to these cases. Mixed techniques, which integrate classic geological-structural observations, geomechanic characterization methods of rock masses, structure from motion photogrammetric techniques and geophysical prospecting have been applied to the geothermal fields covered by the GEMex project. Where it was possible to study a well-developed discontinuity and the related damage zone, it was possible to measure discontinuities on one side of the fault while the other part was investigated by geoelecrical survey. Studies highlight that there is an evident decrease in the fracturing intensity moving away from the fault core (see figure): from more than 20 joints/m near the fault to less than 5 j/m in the country rock mass. This passage was not progressive but there was a core of about 5 m of the fault characterized with more than 10 j/m, then a slightly deformed zone (about 5 j/m) of 6-8 m followed by a more fractured one that passes again to a less jointed rock mass. Strong emphasis we would like to give also to



the very good agreement between physical and geophysical results: geoelectric surveys, even if qualitative, couple very well direct observation and can be used when field observation is not possible. Due to these differences, also hydraulic conductivity changed from very high in the core (about 10^{-2} m/s) to a less permeable zone (10^{-5}) to an increase for a couple of m (see figure) to the permeability typical for intact rock mass (usually very low, 10^{-6} m/s). From a geothermal point of view, this situation depicts a damaged zone by a meaningful fault of about 30-40 m in which the permeability is definitely higher (orders of magnitude) than the rest of the rock mass. Where there were only indirect observation of subsoil fluids emissions (like nearby the Acoculco wells), surface geophysics is also able to give information about the origin of gas and/or brines: in that case, gas emission alignments fit well the resistivity anomaly highlighted by electrical tomography. Interpretation seems to give the idea that fluids came through a fault with strong dipping towards SW.

67. Insight into the fluids occurring in the super-hot reservoir of the Los Humeros geothermal system from fluid inclusions and isotopic data of the Las Minas exhumed system (Mexico)

Giovanni Ruggieri, Guia Morelli, Martina Zucchi, Eleonora Braschi, Samuele Agostini, Gennaro Ventruti, Andrea Brogi, Domenico Liotta, Chiara Boschi, Eduardo Gonzalez Partida

The skarn-hydrothermal exhumed system of Las Minas is thought to be analogue of the super-hot system located below the present exploited zones of the Los Humeros geothermal system. Structural studies coupled with mine-petrographic, fluid inclusion and isotope analyses have been carried out on skarn-hydrothermal mineral assemblages collected in the Las Minas area in order to: i) obtain information on the physic-chemical features and the origin of the fluids that circulated in the paleo-super-hot reservoir; ii) define the fluid-rock interaction processes promoted by the fluids circulating through the paleo-reservoir; iii) characterize the structural control on the fluids circulation in the exhumed system. This information was used to predict the features of the deep fluids in the active system of Los Humeros. Structural data showed that the two main fault systems NNW- and NE-trending acted as main conduits favoring the uprising of the fluids from deep to shallow structural levels at Las Minas. Fluid inclusions analyses revealed that at least five fluid-types were trapped into the inclusions: 1) magmatic-derived, high-temperature, hypersaline fluid; 2) high-temperature saline fluid, also exsolved from a magma; 3) aqueous-carbonic fluid with low to moderate salinities released during the contact metamorphism of carbonate rocks; 4) aqueous fluid with variable salinities produced by mixing of saline magmatic-derived fluid with meteoric fluid and boiling meteoric fluid; 5) vapors formed during fluid immiscibility. Radiogenic isotope (Sr, Nd, Pb) analyses on skarn minerals and magmatic and carbonate rocks, representing the two main isotope source end-members, suggest that generally the isotopic signature of the skarn is close to those of the magmatic rocks, although in some instances mixing between fluids deriving from the two sources occurred. Stable (O) isotopic temperatures are coherent with the high-temperature indicated by fluid inclusions. The integration of all data suggests a three-stage evolution of the system. The first stage was characterized by a very high-temperature (up to 650 °C), saline (18-20 wt% NaCl equiv.) magmatic-derived fluids that reacted with carbonate rocks, forming early skarn assemblages at lithostatic pressure. Nearly contemporaneous aqueous-carbonic fluids, produced during contact-metamorphism, were also present and eventually mixed with the saline fluids. During the second stage decompression (to hydrostatic value) triggered fluid immiscibility producing a hypersaline (up to 70 wt% NaCl equiv.) fluid and low-salinity vapor. The ingress of meteoric fluids was responsible for salinity decrease and cooling. The latest stage was characterized by input of low-salinity fluid of meteoric origin in the system, which caused the dilution and cooling of the residual magmatic-derived fluid. However, during the early phase of the third stage temperature could be still relatively high (up to 450 °C). The above data suggest that the fluid features of the super-hot reservoir at Los Humeros can be comparable to those of the third stage at Las Minas or, less probably, to those of the second stage. The research leading to these results has received funding from the GEMex Project, funded by the European Union's Horizon 2020 research and innovation program under grant agreement No. 727550.

68. The impact of reactive flow on electrical and hydraulic rock properties in supercritical geothermal settings

Juliane Kummerow, Siegfried Raab, Erik Spangenberg

Electrolytes, dissolved in aqueous solutions, have the tendency to associate at near-critical temperature, which causes a removal of free charge carriers from the solution. This behavior becomes noticeable in a reduction of fluid conductivity from a maximum at 300-350 °C by an order of magnitude above 375 °C. This trend was also found in the very few petrophysical studies available for electrical properties of water saturated rocks at high temperatures (Glover and Vine, 1992; Violay et al., 2012; and Nono et al., 2018). Thus, deep resistivity surveys are regarded to provide a convenient means for detecting supercritical roots of geothermal high-enthalpy reservoirs. However, mass transfer and diffusion-controlled chemical reactions accelerate in supercritical electrolytic solutions, whereby the dissolution of minerals as well the formation of new ones changes the availability of charge carriers in the pore fluid. In consequence, resistivity contrasts between sub- and super-critical systems may be blurred by fluid-rock interactions in geological settings, what could reduce the spatial resolution of electrical measurements at field scale. As none of the set-ups used so far do offer the possibility of fluid flow, the effect of dynamic chemical conditions and the impact of high-temperature fluid-rock interactions on petrophysical parameters was not considered in measurements, yet. To study this effect, in the frame of the GEMex project we upgraded our high-temperature flow-through setup, which is now suitable to conduct long-term reactive flow experiments at temperatures up to 500 °C at a fluid pressure of 25-35 MPa. Our tests were run on equivalent material of key lithologies and brines (s_{fluid} = 0.2 to 1 S/m) of the Los Humeros reservoir. Dolerite and andesite samples represent the reservoir unit, and a limestone was studied as proxy for the carbonate basement. A high conductivity contrasts between sub- and super-critical conditions was observed for a volcanic breccia within a very narrow temperature range of ± 3 °K around the critical temperature. This was accompanied by a precipitation-induced reduction of permeability. However, further experiments show that the concomitant entry of new charge carriers during reactive flow weakens the conductivity gradient significantly and in case of the limestone sample, at supercritical conditions the conductivity increases by almost an order of magnitude. Our results show that for steep temperature gradients, as they are given in magmatic-related systems, the depth range covering the critical 350-400 °C temperature interval could be resolvable and anomalies with low conductivities should be identifiable, given that electrolytic conductance is the dominating contribution to bulk conductivity. However, the detectability of areas with supercritical fluids will mainly depend on the intensity of fluid-rock interactions, which besides lithological factors is affected by structural characteristics. Whereas low permeable zones with less fluid-rock interactions might be characterized by a negative conductivity anomaly, highly permeable areas with correspondingly extensive hydrothermal overprinting may be difficult to identify as supercritical, since a high load of extra charge carriers might lead to underestimated temperatures. References: Glover and Vine, 1992, *Nature*, 360; Nono et al., 2018, Doi:10.1016/j.volgeores.2018.04.021: Violay et al., 2012, *Transp. Porous Media*, 91.

69. Evidence for fracture-hosted fluid-rock reactions within geothermal reservoirs of the eastern Trans-Mexican Volcanic Belt

Alicja M. Lacinska, Chris Rochelle, Andrew Kilpatrick, Jeremy Rushton, Leandra M. Weydt, Kristian Bär, Ingo Sass

Fractures within hydrothermal systems represent major flow pathways facilitating the onset of natural convection[1] and subsequent maintenance of fluid flow. It is vital to understand processes occurring along such fractures as these will impact the productivity of hot fluids during geothermal exploitation. This is especially important where fluid movement crosses contrasting rock types, resulting in a range of fluid-rock reactions, mineral dissolution and precipitation, and changes in fracture permeability. Within the GEMex project we have studied changes in mineralogy and fluid-rock reactions in systems where igneous intrusions into basement carbonates of the eastern Trans-Mexican Volcanic Belt have driven fluid flow upwards into overlying volcanic units of mainly andesitic composition (similar to those that are the focus of current geothermal exploitation at Los Humeros). The basement calcic and dolomitic carbonates have been variably metamorphized close to contacts with the igneous intrusions, in some places forming periclase (now brucite) marble (host rock in Figure 1). Subsequent fracturing and ingress of very high-temperature (likely ~500 °C), granite-derived, H_2O-NaCl (+acidic gases) fluids, resulted in high temperature Si-metasomatism and the formation of skarn minerals such as wollastonite, garnet, diopside, forsterite and spinel. These metasomatic assemblages exhibit a large array of complex, neo-formed, pseudomorphic and replacement textures. Later lower temperature hydrothermal circulation resulted in the hydration of a number of the initially anhydrous phases, with serpentine and talc replacing the original Mg silicates. Ascent of the now Si-depleted hot fluids transported Ca from the basement carbonates into overlying andesitic units. This resulted in Ca-metasomatism along the walls of the fractures, together with bleaching of adjacent andesite through the acid-induced mobilisation of Fe. Understanding the interplay between mineral chemistry, rates of fluid-rock reaction and texture of a metasomatic assemblage within/and adjacent to fractures is essential to create viable models for the potential temporal evolution of fracture flow/sealing. Secondly, the presence of minerals such as serpentine and talc, both representing structurally-weak phases, might induce frictional sliding[2] along the fracture and thus govern the hydro-mechanical reservoir response during exploitation. This requires

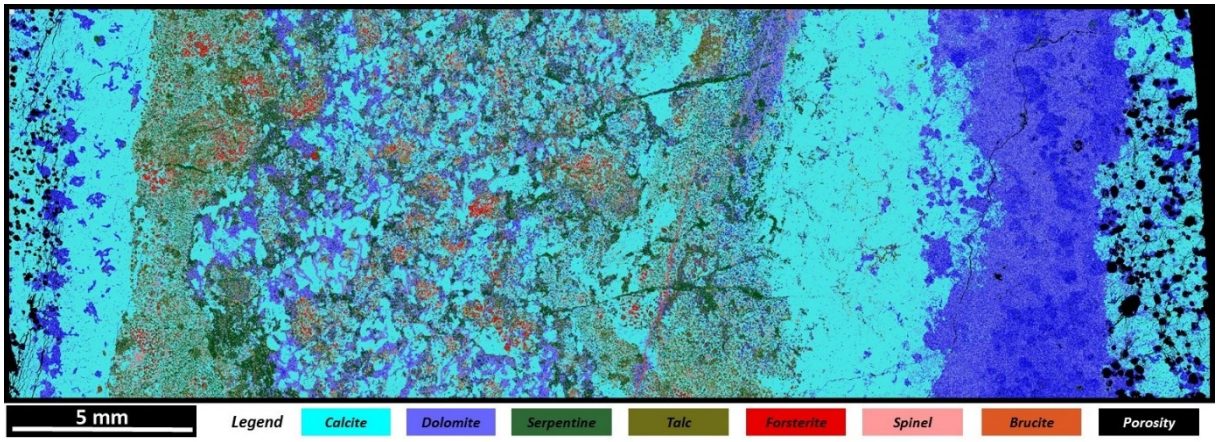


Fig. 1: Large scale mineralogical map of metasomatic vein in brucite marble, Las Minas.

further attention, in particular in Mg-rich basement/reservoir rocks such as those observed in the area of Las Minas. References: 1. Hanano M., 2002: Two different roles of fractures in geothermal development, *Proceedings World Geothermal Congress 2000*, Kyushu-Tohoku, Japan. 2. Richard, J. et al. 2014: Rock and mineral transformations in a fault zone leading to permanent creep: Interactions between brittle and viscous mechanism in the San Andreas Fault. *Journal of Geophysical Research*, 119, 8132-8153.

70. Thermal modelling of Los Humeros superhot geothermal field

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Los Humeros is the third largest geothermal field in Mexico in terms of its production capacity. It is operated by Comisión Federal de Electricidad (CFE) and has been under exploitation for more than three decades. In spite of its long production history, several fundamental processes driving this superhot geothermal system are still poorly understood. They are studied within the EU funded GEMex project. Our Work Package within GEMex aims to characterize the reservoir system in terms of its hydraulic and thermal properties in its initial conditions i.e., prior to the onset of production. We construct a 3D numerical model by using an existing geometrical structure created within GEMex to solve the Darcy and the heat transport equations with variable hydraulic and thermal properties. The modeling is performed for an area of 9.5km x 12.5 km x 6.5km comprising of 6 million numerical grids. The geological structure includes a limestone basement and several volcanic series on top and a number of caldera related fault systems. We analyze temperature and pressure data from more than 50 wells obtained during the drilling and completion stages and ancillary information owned by CFE to reconstruct the pseudo steady-state temperature and pressure conditions at depth. The output of the numerical model is validated against these data. Significant uncertainties exist regarding structural settings, dimension and depth of the heat source, and rock and fluid properties due to lack of sufficient field scale data. Therefore, different approaches were chosen for addressing this uncertainty in modeling the system and comparing the results. Several scenarios were simulated for quantifying the impact of uncertain basal heat flow conditions and fluid pathways on the temperature and pressure field. The simulated results of the initial state of the model and its validation against field data provides a better understanding of the distribution of the heat source and fluid pathways. We present results of different scenarios, which enabled us to identify the most sensitive parameters driving the superhot geothermal system. This work represent results of the joint activities performed by European and Mexican researchers within the GEMex project, funded by the European Union's H2020 research and innovation programme under Grant Agreement No. 727550, and by the Mexican Energy Sustainability Fund CONACYT-SENER, Project 2015-04-268074.

71. Reservoir modelling and calibration for the superhot reservoir at Los Humeros

Giordano Montegrossi

The aim of the present work is to have a calibrated 3D numerical model of the Los Humeros geothermal system. The process of collecting the available data related to reservoir engineering, consist of investigating the well temperature profile while heating up to obtain the formation temperatures, investigate on pressure build up during heating to identify the pivot point and the pressure controlling the feed zones as well as the pressure in the wellbore surroundings. Lastly, using the production data and dynamic wellbore modeling we were able to have the conditions at the bottom well. All these data provide a sounding thermodynamic basis to constrain the natural state model of the Los Humeros geothermal system. The simulation of the natural state 3D model was built using the TOUGH2 V.2.1 numerical reservoir simulator extended for water supercritical conditions by using IAPWS-IF97 formulation, managed by using the Petrasim pre- and post-processing software package. These extensions were needed to overcome the temperature limit (350 °C) of the commercial TOUGH2 version, to be able to model superhot and supercritical geothermal systems, such as those of Los Humeros at depth. The natural state model was obtained by computing a steady state model based on the boundary condition defined as atmospheric boundary, recharge zone and a deep hot source at constant temperature. The reservoir pressure gradient was obtained by using the pivot point data from the reservoir engineering study, while the recharge boundary conditions were obtained from geochemical and isotopic data provided by Task 4.3 (WP4) and other data provided by CFE, such as the hydraulic head in the Los Humeros area. In this stage, once obtained the feed zones geometry from well data and the average rock properties extrapolated from the geological model, the temperature calibration was performed by shifting up or down the bottom boundary condition (consisting of element at fixed temperature of 400 °C), until a match of the steady state temperature, obtained from the numerical model and the temperature for the corresponding feed zones, is obtained. Lastly, a dynamic model using the production data from CFE was computed to reconstruct the current state of the geothermal reservoir, and to provide an updated working model for possible future uses. The model and its results are available for the geothermal exploitation plan, and the obtained P, T, Sg distribution could be used for other computation, e.g. geomechanical study.

72. Research work for shallow well siting and first drilling results

Rosa María Prol-Ledesma

The main objective of the WP 5.3 is the construction of the Acoculco geothermal system thermal model. Geothermal gradient measurements in shallow wells will be the validation data, and the location of these wells is highly relevant to accurately define the heat transport mechanisms. The southern section of the caldera has been characterized by two deep wells that present a predominantly conductive thermal regime; therefore, new measurements were planned to depict the areas that lack geothermal gradient information. In order to define the best locations to provide key information on the heat transport within the geothermal system, the following work was accomplished: i) Remote sensing images and aeromagnetic data processing to define the main targets for field work. ii) Field work to verify the results obtained from multispectral images and aeromagnetic data processing to collect information on structures, surface geology, geochemical (fluids and whole rock geochemistry), reconnaissance K-Ar geochronology of dacite domes, land use, roads and social information about the local communities. iii) Mineral associations and textures were determined by optical petrography, infrared spectroscopy (SWIR), electron microscopy (SEM-EDS) and X-ray diffraction. iv) Collect information about the local flora and fauna to generate the environmental impact report to obtain the permits from the local Ministry of Environmental Protection for drilling. v) Information campaigns to the local population about the project to improve the mindset of the inhabitants of the Acoculco area towards geothermal projects. The results obtained include unreported surface manifestations that include warm springs, hydrothermal alteration zones, silico-calcareous sinter deposits, and fault outcrops. The hydrothermal precipitates are composed of opal (A and A/CT), quartz, alunite, kaolinite, montmorillonite, ammonium-smectite, buddingtonite, pyrite, cinnabar, barite, coquimbite, anatase and ferrhydrite. Detailed alteration suits (silicification, argillic, intermediate and advance argillic) were defined in all sampling sites that define the local conditions of water-rock interaction. The main faults: Apan-Tlaloc (NE-SW), Chignahuapan (NE-SW), Manzanito (NW-SE), Agua Caliente-Río Azul (NW-SE), and Atotonilco (E-W) in the Acoculco Caldera, represent the main fault systems: (a) NE-SW, (b) NW-SE, (c) E-W, and act as control structural arrangements. The most recent volcanism (<1 Ma) occurs in the north-central region and the eastern boundary of the caldera and is represented by cineritic cones, basalt, andesite and rhyolite lavas, and rhyolitic and dacitic domes. The geochemistry of the water and gas samples revealed high temperature at depth in the northern area of the caldera and the magmatic isotopic signature of the discharged fluids. CO_2, CH_4 and H_2S degassing indicates the location of permeable zones that would favor convective heat transport. The integration of this information was the basis for the drilling site location. The map includes the proposed sites for seven wells (see Fig. 1). The available information was included in a 3-D heat transport model to aid in well siting. The model will be improved as more information from the wells is obtained. The Environmental Impact Report was presented to the Ministry of Environment. The information campaign for the local population was successful and the drilling project has the support of the farmer organizations and general population.

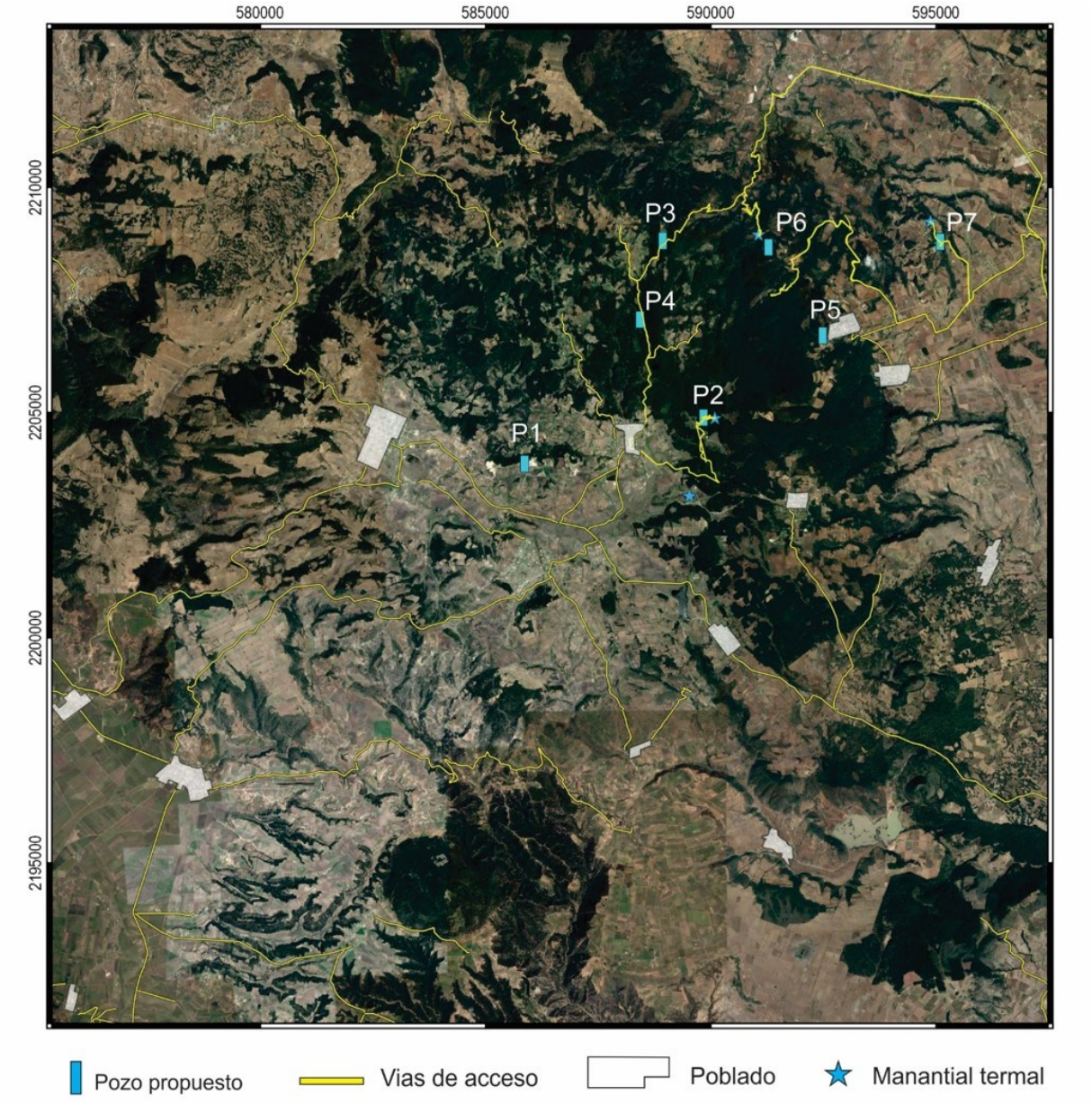

Fig. 1. Proposed location of seven shallow wells in Acoculco.

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More information can be found on the GEMex Website: http://www.gemex-h2020.eu.