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GEMex – Cooperation in Geothermal Energy Research Europe-Mexico for Development of Enhanced Geothermal Systems and Superhot Geothermal Systems

David F. Bruhn[1,2], Aída López Hernández[3], and the GEMex consortia (Europe, Mexico)

[1]Helmholtz Centre Potsdam German Research Centre for Geosciences GFZ, 14473 Potsdam, Germany
[2]Dept. of Geoscience&Engineering, TU Delft, The Netherlands

[3]Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Mich., México

dbruhn@gfz-potsdam.de

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ABSTRACT

The GEMex project is a complementary effort of a European consortium with a corresponding consortium from Mexico, who submitted an equivalent proposal for cooperation. The joint effort is based on three pillars: (1) Resource assessment at two unconventional geothermal sites, for EGS development at Acoculco and for a superhot resource near Los Humeros. This part is focused on understanding the tectonic evolution, the fracture distribution and hydrogeology of the respective region, and on predicting in-situ stresses and temperatures at depth. (2) Reservoir characterization using techniques and approaches developed at conventional geothermal sites, including novel geophysical and geological methods tested and refined for their application at the two project sites: passive seismic data were used to apply ambient noise correlation methods, and to study anisotropy by coupling surface and volume waves; electromagnetic data were collected in combination with gravity measurements. For the interpretation of these data, high-pressure/ high-temperature laboratory experiments will be performed to derive the parameters determined on rock samples from Mexico or equivalent materials. All these data will be integrated with the help of structural geological mapping, including analogue outcrop studies representing the deep subsurface targets. (3) Concepts for Site Development: all existing and newly collected information is applied to define drill paths, to recommend a design for well completion including suitable material selection for the superhot resource, and to investigate optimum stimulation and operation procedures for safe and economic exploitation with control of undesired side effects. These steps included appropriate measures and recommendations for public acceptance and outreach as well as for the monitoring and control of environmental impact. The projects end in May 2020, such that results will be presented in various individual contributions. This poster will provide the overview and link the different contributions on the specific research topics addressed. This paper presents a general overview of the projects which link the large number of individual contributions on specific project tasks and results.

1. INTRODUCTION

The international cooperation between Europe and Mexico GEMex (Cooperation in Geothermal energy research Europe-Mexico for development of Enhanced Geothermal Systems and Superhot Geothermal Systems) is an activity in the framework of the Bilateral Agreement on Science and Technology between the European Union and the United States of Mexico. The challenge is to increase knowledge and expertise to reduce technological and social risks associated with the development and exploitation of EGS and superhot geothermal fluids. The calls for proposals (Horizon 2020 Work Programme 2016 -2017, 10. 'Secure, Clean and Efficient Energy') asked for "scientific exchange of researches and capacity building … as an indirect project impact. Proposals should appropriately exploit the complementarities between the EU and Mexico, and pave the way for significant enhancement in the cooperation between researchers and research institutions".

The resulting cooperation encompasses two partner projects, one funded within H2020 and one by the government of Mexico through the National Council of Science and Technology CONACyT. The projects are designed to explore two specific sites to develop concepts for their utilization as Enhanced Geothermal System (EGS) and as Superhot Geothermal System (SHGS). The site for EGS development is the Acoculco crater, SHGS are investigated at Los Humeros, both in the eastern Trans-Mexican Volcanic Belt. Los Humeros is currently exploited with steam temperatures reaching up to 340°C. In some wells, temperatures higher than 380°C were inferred (e.g., Lorenzo Pulido, 2008), but these are not currently used for energy conversion. The system feeding these super-hot wells is the target of GEMex investigations on SHGS. Acoculco is not currently exploited, but was the target of two 2km deep and 300°C hot wells that did not encounter any fluids, despite some surface manifestations indicating the presence of a hydrothermal resource (e.g., Lopez-Hernandez et al., 2009).

The two consortia from Europe and from Mexico (see Table 1) formed previously existing networks: The European project was developed within the European Energy Research Alliance (see the WGC2020 contribution by Berre et al., 2020), while the Mexican consortium already cooperated in the Mexican Centre for Innovation in Geothermal Energy (CeMIEGeo, Centro Mexicano de Innovación en Energía Geotérmica; www.cemiegeo.org), funded by CONACyT. The project cooperation formally started in October 2016 with a joint kick-off meeting in Mexico. The European project will end in May 2020, while the Mexican project will continue until May 2021. Both projects received funding of nearly 10 Mio €.

Table 1: Consortium EU

Germany	Helmhotz Centre Potsdam German Research Centre for Geosciences - (GFZ)	Coordinator
Iceland	Iceland GeoSurvey- (ISOR)	
Netherlands	*Netherlands* Organisation for Applied Scientific Research- (TNO)	
Italy	University of Bari - (UNIBA)	
Netherlands	University of Utrecht - (UU)	
Germany	RWTH Aachen University- (RWTH)	
Italy	National Research Council of Italy - (CNR)	
Germany	Technical University of Darmstadt - (TUDA)	
France	French Geological Survey - (BRGM)	
Norway	Institute for Energy Technology - (IFE)	
Greece	Centre for Renewable Energy Sources and Saving - (CRES)	
Italy	National Institute of Oceanography and Applied Geophysics - (OGS)	
Norway	Centre for Integrated Petroleum Research, NORCE Bergen- (CIPR)	
Italy	Roma III University - (UROMA3)	
Italy	National Agency For New Technologies, Energy And Sustainable Economic Development - (ENEA)	
Italy	Sant'Anna School of Advanced Studies - (SSSA)	
Germany	Karlsruhe Institute of Technology - (KIT)	
United Kingdom	British Geological Survey - (NERC)	
Germany	Bochum University of Applied Sciences- (HBO)	
Italy	University of Turin - (UNITO)	
Poland	Polish Geological Institute – National Research Institute - (PIG)	
Belgium	European Geothermal Energy Council AISBL - (EGEC)	
Germany	Helmholtz-Centre for Environmental Research - (UFZ)	
Germany	IGA Service GmbH - (IGA)	

Consortium Mexico

Mexico	Universidad Michoacana de San Nicolás de Hidalgo - (UMSNH)	Coordinator
Mexico	UNAM: Instituto de Geofisica	
Mexico	UNAM: Escuela Nacional de Estudios Superiores	
Mexico	UNAM: Centro de Geociencias, Campus Juriquilla	
Mexico	Instituto Nacional de Electricidad y Energías Limpias - (INEEL)	
Mexico	Centro de Investigación Científica y de Estudios Superiores de Ensenada - (C.I.C.E.S.E.)	
Mexico	Geología, Minería y Consultoría, SA de CV - (Geominco)	
Mexico	JL Energía, S de RL de CV	
Mexico	CFE – Affiliated industry partner; owner of test sites at Los Humeros and Acoculco	

2. OBJECTIVES

GEMex is based on the assumption that the development of hot-EGS and SHGS resources carries an enormous potential to expand the known geothermal resource base and to multiply its energy output. Thus the overall objective of GEMex is to show a way how to better understand, explore and develop a) EGS in a hot geological environment and b) super-hot resources that cannot be explored and exploited by standard technologies.

The objectives for GEMex follow from the barriers and challenges identified for hot-EGS and SHGS resources. These include:

- Speeding up the geothermal development in Mexico and beyond, by leveraging the knowledge of European and Mexican researchers and industry
- Reduction of the pre-drill mining risk by in depth understanding of the geological context of the resource, in order to improve prediction of the occurrence of geothermal resources and their quality
- Improvement of geophysical imaging and detection of deep reservoir structures by novel approaches dedicated to HOT-EGS and SHGS, and targeted to improved imaging resolution
- Improvement of predictive models for reservoir characterization and simulation
- Provision of conceptual models for sustainable site development

3. PROJECT STRUCTURE

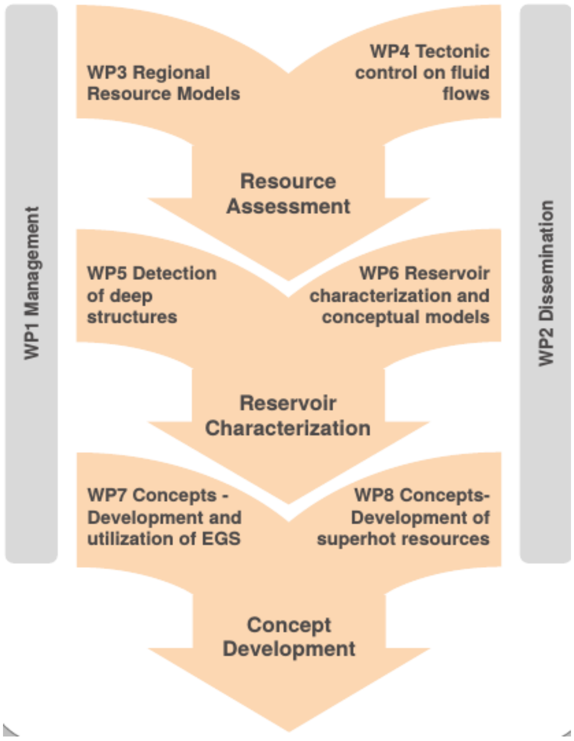

Figure 1: Project Structure

The projects are structured in 3 parts (Fig.1.): Resource Assessment, Reservoir Characterization and Concept Development. The actual work is performed in 8 (Mexico: 9) work packages.

3.1 WP3 Regional Resource Models

Work Package 3 is focused on modelling the resources at regional scale both in Acoculco and Los Humeros. The models are geological (conceptual, numerical, and analogical), thermal, and hydrogeological. These models have the objective to characterize the geological and geothermal system in close collaboration with the geological and geophysical work performed in WP4 and WP5 respectively. The understanding at regional scale on how the geological and geothermal systems have evolved and are structured will help the purpose of the other work packages.

Within WP3, 3 preliminary models, 2 for Los Humeros (local and regional) and a regional for Acoculco were created on the basis of all existing information available to the project, primarily provided by the site owners CFE. The development of these models is explained in Calcagno et al. (2020).

The work on the thermal and hydrogeological modelling included first a collection of data (both for temperature and hydrogeology) specifically for the purpose of the modelling. Then, by using the geological structure and knowledge provided by the preliminary geological model (Bonté et al., 2020a) and by the new information collected during the project a preliminary model has been built for the thermal structure in Los Humeros and Acoculco, and for the hydrogeology in Acoculco (Bonté et al., 2020b).

In addition, the relationships between regional tectonics and volcanoes were investigated and the surface deformation patterns related to the collapse of caldera and volcanic edifice were mapped and described by Carrasco-Núñez et al. (2020).

3.2 WP4 Tectonic Control on Fluid Flow

Work Package 4 addresses the understanding of the relationships among geological structures and physical and chemical properties of high temperature geothermal resources in volcanic systems. For this purpose relationships between brittle geological structures and fluid flow was studied in detail in fossil, analogue, geothermal systems at the old mining area of Las Minas, where the stratigraphic and volcanic successions are well exposed and represent a good analogy to both Los Humeros and Acoculco. The results produced more detailed stratigraphic knowledge and a new geological map (Liotta et al., 2020).

The relationship of geological structures, magmatism and the development of the volcano and the geothermal reservoirs at Los Humeros is described by Carrasco-Núñez et al. (2020). In addition, the chemical and physical characteristics of the paleo-fluids were investigated to better constrain geothermal processes in the subsurface. These investigations address the relationships between the brittle geological structures and the superhot fluids in Los Humeros, as expressed by the observed silicification processes (Izquierdo-Montalvo et al., 2020) and by soil gas emissions (Jentsch et al., 2020). At Acoculco, the relationships between brittle geological structures and fluid flow are investigated to better constrain the conditions at which EGS can be performed (Lepillier & Bruhn, 2020).

3.3 WP5 Detection of Deep Structures

The objective of this work package is to further advance integration of information acquired from different geophysical methods and test it by application to the two high temperature systems in Los Humeros and Acoculco. The existing models from two superhot fields in Iceland (Krafla and Reykjanes) will also be revised by applying improved methodology and results from the two first deep drilling projects in Iceland, IDDP-1 in Krafla and IDDP-2 in Reykjanes. The improved models from these fields will be compared to the Mexican fields.

Resistivity data, MT and co-located TEM, were collected during several campaigns in Los Humeros and Acoculco from early November 2017 until February 2019. Results of the campaigns at Los Humeros are presented by Benediktsdóttir et al. (2020) and by Romo-Jones et al. (2020). Results for Acoculco are shown by Hersir et al. (2020). Magnetotelluric phase tensor analysis and its significance for tectonic interpretation was shown at both sites by Held et al. (2020). Different strategies were applied to 3D Inversion Modeling of MT data at Los Humeros by Ruiz-Aguilar et al. (2020).

Existing active seismic data for Los Humeros were reprocessed to generate a velocity model for newly acquired passive seismic data. The network deployed in Los Humeros was operated until September 2018. The network in Acoculco was deployed in April and May 2018. The data from Los Humeros are used to analyze the seismic structure by tomographic methods (Toledo et al., 2020) and ambient noise analysis. Time dependent processes have been investigated by time-dependent tomography, time-reverse imaging (TRI is a method for locating and characterizing seismic events), analysis of seismic energy accumulation and a time-lapse study of passive seismic attributes caused by partially saturated rocks.

Other geophysical information used includes ENVISAT ASAR (2003 to 2007) and Sentinel-1 (2014-2019) data to analyse observed ground motions and relate the derived motions to production in Los Humeros (Békési et al., 2020). In addition, Gravity data were collected parallel to the electromagnetic survey profiles at both sites. These data are used to constrain fluid flow in Los Humeros and Acoculco by Cornejo et al. (2020) and for a joint inversion with magnetic data by Carillo et al. (2020). Integration of all geophysical data with the structural geology is ongoing.

3.4 WP6 Reservoir Characterisation and Conceptual Models

In Work Package 6, the reservoirs in Acoculco and Los Humeros are characterized with respect to rock and fluid properties and their variation with temperature and pressure. These are required, on the one hand, for setting up and parameterizing discretized structural models used in static and dynamic numerical simulations of fluid flow, heat transport, and phase behavior before and during geothermal exploitation. On the other hand, rock and fluid properties and their variation with temperature and pressure are required for interpreting geophysical seismic and electromagnetic measurements on the surface.

To analyze petrophysical and geomechanical properties of reservoir rock samples, reservoir fluid properties and outcrop analogues at different pressure and temperature conditions, a total of 333 samples were collected during various field trips in Mexico. 252 samples are from the Los Humeros area, outcrop analogues and exhumed systems of Las Minas, 70 plugs are from 41 core sections of 15 cored wells of the LH geothermal field; and 81 are from the Acoculco area, outcrop analogues and exhumed systems. The physical properties of the rocks were measured in great detail as input for reservoir models. In addition, reactive flow at supercritical conditions through some of the samples was investigated and it effect on electrical resistivity on the rock/fluid system was measured (Kummerow et al., 2020). Rock-fluid interactions were also investigated in fossil geothermal systems at exhumed outcrop analogues (Rochelle et al., 2020), which helps to better constrain, understand and interpret the alterations that have to be expected in the fractures of a reservoir and how they influence fluid flow and alteration of the rock properties.

The importance of geological and geophysical data for the development of a geothermal site like Acoculco is explained by Aguirre-Diaz et al. (2020). Combining all these data collected in the project WP3, 4 and 5 in combination with laboratory derived geomechanical analyses performed in various labs by the project partners, conceptual static reservoir models were created. The parametrized models are to be used for static (steady-state) regional simulations of fluid flow and heat transport in Los Humeros and Acoculco s (Deb et al., 2020). An approach for the characterization of the initial state in a geothermal reservoir is presented by Aragón-Aguilar et al. (2020) and by Hernández-Ochoa et al. (2020). In addition, the acquired data were used for a full petrophysical reservoir characterization of the two sites (Weydt et al., 2020).

3.5 WP7 Concepts for the Development of EGS

The goal of work package 7 is to develop EGS stimulation techniques capable of achieving sufficiently high and sustainable flow rates in such a way that the environmental effects are minor and acceptable and that the local community is consulted and engaged. This is achieved by developing a numerical model workflow and optimized stimulation scenarios for Acoculco, based on the collected data and models created in the other WPs of GEMex. Model approaches for EGS development by soft stimulation measures are presented by Hofmann et al. (2020). The resulting fracture propagation was investigated numerically by Parisio et al. (2020), while the stimulation and plasticity in the context of high temperature EGS development is presented by Fokker et al. (2020).

On the basis of the static models created in WP6, dynamic reservoir models for the potential EGS in Acoculco will be developed, together with development scenarios for stimulation and operations. Production scenarios for such an EGS at Acoculco are presented by Deb et al. (2020). The final tasks in the project include a detailed stimulation design and the analysis of induced seismicity and environmental hazards. Public engagement strategies are proposed within WP7 in the European project, while a separate work package has been in dedicated to this topic in the Mexican project (WP9).

3.5 WP8 Concepts for the Development and Utilization of SHGS

In WP8 the goal is the development and verification of concepts and technologies to access and exploit super-hot reservoirs (> 300°C, including conditions above the critical point of water in the reservoir) on the basis of the work and data derived in the projects combined with additional information provided by the operating site in Los Humeros. Main objectives are:

- To integrate the results obtained from the technical work packages 3-6 and use them in various model approaches in order to predict the reservoir properties
- To prepare a list of materials suitable for installation in super-hot conditions
- To prepare a best-practice guide for drilling and completion in super-hot setting
- To give recommendations for a thermal loop design
- To propose monitoring systems in order to avoid or mitigate potential threats for the environment

For the prediction of reservoir properties, geochemical analyses need to be performed to simulate the specific superhot reservoir conditions. These models will have to address the laboratory results provided on the electrical conductivity at supercritical conditions of the reservoir fluid (Kummerow et al., 2020). In addition, the will have to address the question of the brittle-ductile transition in the mechanical behavior (Fokker et al., 2020).

For downhole installations, the superhot conditions present a particular challenge. Materials have been tested at in-situ conditions in a deep well in Los Humeros for this purpose and compared to similar tests performed in Iceland. The results of these tests are presented by Thorbjornsson et al. (2020). Similarly, drilling and well completion at superhot conditions is a challenge, for which only limited experience exists. A study addressing this challenge is presented by Kruszewski,et al. (2020). A geologic-economic assessment of the reserves at Los Humeros is performed by González-García et al. (2020)

3.6 WP9 Environmental Impact and Public Engagement

In the European project, environmental impact and public engagement are addressed within WPs 7 and 8, while the Mexican project has a full workpackage devoted to it. Especially the public engagement at the local scale can only be conceptual for the European partners, while it has been an essential part of the Mexican work. As a way to assess environmental impact, Garcia et al. (2020)

propose an identification of environmental units for geothermal exploration areas using geographic information systems. The specific environmental impact addressed in the projects included the assessment of the mobility of potentially harmful elements in geothermal soils. Partners performed experimental work to develop a simple and fast tool to assess trace elements mobility in geothermal soils exposed to the thermal fluids. Soil samples were collected in Los Humeros for metal mobility assessment, and results were compared with those from the Campi Flegrei Field (Italy). Soil erosion was mapped to predict the transport of chemical elements in geothermal areas (Gonzalez et al., 2020a). Zarco et al. (2020) investigated the bacterial composition of thermal springs in the Acoculco area. In the context of stimulation and operations of a potential EGS, the seismic hazard was assessed and monitoring of seismic parameters & seismic risk mitigation measures were proposed.

The socio-economic analysis within GEMex defines a conceptual model for implementing a public engagement strategy to support and improve the local acceptance of geothermal developments. The analysis has used quali-quantitative methods focusing on relevant stakeholders involved in the geothermal energy development: consumers, local communities, public authorities and energy companies.

For the public engagement, European partners designed a conceptual model that requires the identification of suitable stakeholders who can assume an active and passive role in the development of geothermal energy projects. With a specially developed questionnaire survey consumers contribute to the model by informing the developer about their desired positive impact when geothermal energy is developed. The unstructured interviews with local communities and public authorities analyzed by the *Social Impact Assessment method* inform the model by identifying the type of contribution communities can provide, and the role public authorities can assume per each level of engagement across different strategies. Thus, the model presents a scheme in which energy companies, *local communities and public authorities* cooperate by sharing information and processes and build a shared and multi-perspective vision of the social aspects to be addressed and of the public engagement strategies to be implemented. The model identifies four levels of public engagement achievable: information, communication, collaboration and participation. Information relies entirely on the information provided to the public about the project details and potential impact on the local and wider community. Communication includes an active engagement of the public. Collaboration asks to actually engage the public in the project development by adapting to the specific local/social needs, both the project and the impact evaluation. Participation represents the highest level of public engagement and consists of the actual engagement of the public in the design of the project. Then, the analysis concludes by providing policy and managerial recommendations for supporting the implementation of public engagement strategies.

Mexican partners conducted a lot of surveys, public information events as well as environmental assessment in the field. As a result, Moreno et al. (2020) look at the situation in Acoculco to investigate the impact of geothermal projects in rural communities. From all the information collected, Gonzalez et al. (2020b) then develop scenarios for a sustainable development for geothermal projects.

4. DISSEMINATION

To communicate project results within and beyond the scientific geothermal community, several dissemination measures are applied. Two of the partners in the European consortium, EGEC and IGA, are specifically included to guarantee open and smoot communication with the international stakeholders. In addition, a strategic communication plan was developed and presented to the EC. The project websites (in English and in Spanish) are continuously updated and contain a lot of information (www.gemex-h2020.eu; www.gemex-h2020.mx) .An official poster, a flyer and presentation slides can e downloaded from the website for dissemination purposes. Interested parties can sign up for and receive a regular project Newsletter. The consortium also agreed to hold regular stakeholder information events.

4.1 Open Access Database

A special task is dedicated to the design, implementation and maintaining of an Open Access Data Base to collect and make available the datasets produced in the frame of GEMex project. The used software (GeoNode) allows to store and describe with metadata the collected datasets and even to organise them in aggregated maps (Figure 2).

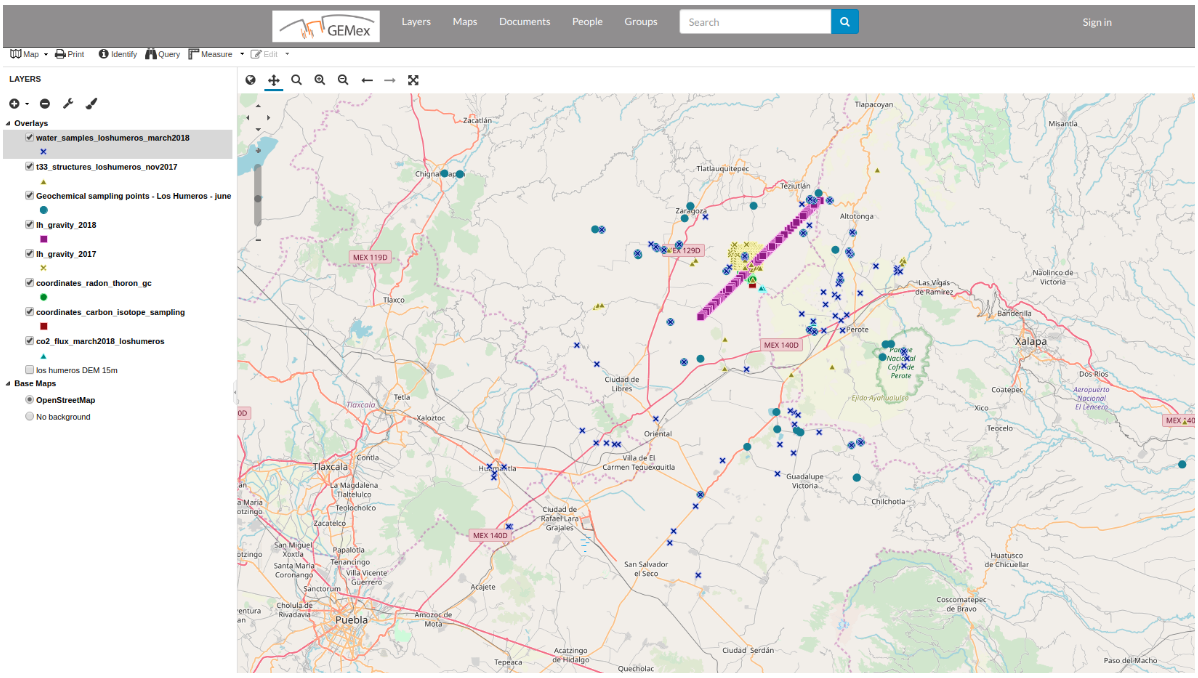

Figure 2: Map of the location of data collected in Los Humeros

The open Access Database is updated continuously with the datasets produced by each partner up to the end of the project.

5. CONCLUSIONS

While the GEMex projects are still ongoing, several of the project goals have been reached already. Most notably, the cooperation between European and Mexican researchers has been developed and deepened. And enormous amount of data have been collected and present a wealth of high quality information that can be combined to provide the basis for site characterization and development. These data will continue to be available and will enable advanced modelling, interpretation and a deeper understanding not only of the specific sites investigated in Mexico but in general. The approach to investigate an analogous site for the better interpretation of the reservoir processes and the hidden structures has shown to be very promising.

Whether or not these results will lead to further site development is not within the control of the project partners. The general approach and the comprehensive data, information and interpretation provide, however, go well beyond what is available for most conventional geothermal project developments. We therefore believe that GEMex has made great contribution to the progress of EGS and SHGS, not only in Mexico but all over the world.

ACKNOWLEDGEMENTS

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