Final technical report
Reporting period 3
Part B

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Project Number: [727550]

Project Acronym: [GEMex]

Project title: [Cooperation in Geothermal energy research Europe-Mexico for development of Enhanced Geothermal Systems and Superhot Geothermal Systems]

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Work package 1

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Website: http://www.gemex-h2020.eu

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Executive summary

This report gives an overview over the project activities performed in the third reporting period, which covers the period from 1st April 2019 to 31st May 2020. It provides a detailed description of the actions taken. Concerning the results, reference is given to the respective deliverables. Deviations from the Description of Action in the Grant Agreement are highlighted for each work package, as well as dissemination activities and publications. The status of all work packages is reported and the links to the milestones reached and deliverables submitted are shown. This report is the final project report. Therefore, for each work package, we also highlight the main results and the impact achieved.

GEMex is a joined effort of the European project (funded by the European Union's Horizon 2020 programme for Research and Innovation under Grant Agreement No 727550) and the Mexican partner project (funded by the Mexican Energy Sustainability Fund CONACYT-SENER, project 2015-04-268074). This project report focuses on the European part, but since the two projects are strongly connected, sometimes depending on each other and in all aspects collaborating, a strict distinction between activities performed by the Mexican or European colleagues is sometimes difficult. Consequently, this report will partly refer to the work performed by the Mexican team.

The general status of the project is: ***The project has delivered all deliverables. All tasks and work packages have been successfully concluded***.

Here below a short summary of the activities and results of GEMex is given:

The GEMex project was an international cooperation between a European and a Mexican consortium on deep geothermal energy, with the aim to speed up the development of unconventional geothermal systems. So far, the use of geothermal energy for electricity production in Mexico has been restricted to conventional geothermal systems indicated by surface manifestations such as hot springs and fumaroles, where high temperatures suitable for exploitation and electricity production are reached at relatively shallow depths. GEMex investigated two types of unconventional resources: 1) Enhanced Geothermal Systems (EGS), where sufficiently high temperatures are found but either the permeability of the rocks is too low or there are no geothermal fluids available at all; and 2) Superhot geothermal systems (SHGS), where temperatures above 350 °C require specific safety measures for drilling and materials to withstand the harsh conditions of the fluid.

The project was based on four pillars

1. **Resource assessment** for the EGS site near Acoculco and for a superhot resource near Los Humeros. The focus of this part was on understanding the tectonic evolution, the fracture distribution and hydrogeology of the respective region, and on predicting in-situ stresses and temperatures at depth.

   The resource assessment provides the basic geological knowledge on the two research sites. Fieldtrips were dedicated to collecting new data and take rock, fluid and gas samples. Integrated geological and volcanological models have been developed. The knowledge gained in this part of the project was subsequently used by the project partners as a-priori information for the models and inversions. The geological fieldwork as well as the modelling were both performed in collaboration with the Mexican team in an equal partnership.

2. **Reservoir characterization** using techniques and approaches developed at conventional geothermal sites, including novel geophysical and geological methods to be tested and refined for their application at the two project sites: passive seismic data were collected to apply seismic tomography and ambient noise correlation methods; newly collected electromagnetic data were inverted and used for joint interpretation with the seismic data. For the interpretation of these data, high-pressure/ high-temperature laboratory experiments were performed to derive the parameters determined on rock samples from Mexico or equivalent materials.

   Geophysical fieldwork in Los Humeros was finished within 2018 and data analysis was ongoing until the end of the project starting with preliminary and successively updated models with constraints from other methods. Sample analysis for physical rock properties contributed to the reservoir models. An extensive database of physical rock properties is published. Reservoir modelling was performed with different approaches. Geophysical fieldwork has benefitted from enormous support by the Mexican team, who did the major part of the geophysical surveys, even though survey planning and data analysis were carried out in an equal partnership.

3. **Concepts for Site Development**: all existing and newly collected information was applied to define drilling targets, to recommend a design for well completion including suitable material selection, and to investigate optimum stimulation and operation procedures for safe and economic exploitation with control of undesired side effects. These steps include appropriate measures and recommendations for public acceptance and outreach as well as for the monitoring and control of environmental impact.

   The concept development was mainly carried out in the final period of the project. For the potential EGS site, various stimulation approaches have been evaluated, based on the data collected and derived in the project. On the basis of these stimulation approaches, productivity scenarios were evaluated. A specific workflow for a stimulation test in one of the two existing wells in Acoculco was proposed. Furthermore, the environmental risks were evaluated (soil pollution and seismic risk). Finally, an in-depth study on social acceptance and public engagement strategies resulted in a conceptual model for public engagement. For the superhot site in Los Humeros, a number of different modelling approaches have been developed in order to select a suitable location and drill path for a superhot well. A downhole material test in Los Humeros was performed and suitable materials for the completion of a superhot well have been proposed. A review of failure modes of superhot drilling projects has been completed and laboratory experiments for non-Portland cement have been performed.

4. The work package for dissemination internal communication (WP2) has enabled and supported the dissemination of project results throughout the lifetime of the project. Internal communication has been supported by the Virtual Research Environment, which was used by both, the Mexican and the European consortia. 60 scientific papers have been published or are currently under review. 244 conference contributions have been presented

or are foreseen in the near future. Additionally, GEMex engaged with industry stakeholders through 2 stakeholder workshops, a series of three online-seminars and participation to two industry exhibitions. A patent has been filed on a high-temperature tracer.

The two GEMex partner projects brought together the extended Mexican know-how of discovering, developing, and deploying conventional geothermal energy systems with a variety of European expertise from superhot geothermal energy systems (Italy, Iceland etc.) and in developing EGS technology. The synergy of competencies was used to develop concepts for extended future deployment of geothermal energy in Europe and Mexico.

In particular, the relationship between recent volcanism, regional structures and the current geothermal potential were newly defined for Los Humeros. By using the strongly multidisciplinary approach the work performed in GEMex has defined new areas outside the currently exploited locations where superhot geothermal resources are likely. In addition, the material testing approach has clearly constrained the candidate steels and metal alloys for future well completion in such highly aggressive geothermal environments.

The lack of data for Acoculco was alleviated by extensive field campaigns to constrain the local fracture network and derive as much information as possible on the local stress field. In addition, the mechanical properties of the downhole rock types were well defined with sophisticated laboratory measurements. These new data provided a much more advanced and reliable basis for EGS development and for the decision where to place a new well.

The concepts for site development provided by GEMex present a major step forward for the regional geothermal operations and future deployment. Beyond the regional progress, the systematic approach applied by GEMex provides a blueprint for the investigation of superhot geothermal systems and their potential development in the future. Their exploitation would lead to a significantly higher electricity generation from drilled wells such that fewer wells would need to be drilled to produce even more geothermal energy than from conventional geothermal systems. Even though there is currently no installation producing energy from such resources in the world, international interest in exploiting such economically highly promising resources has grown significantly in the last years, leading to numerous projects investigating them, for example in the Iceland Deep Drilling Project IDDP. GEMex is a major contribution towards the development of these resources in the future.

Explanation of the work carried out by the beneficiaries and overview of the progress

This section describes shortly objectives of the project and gives a detailed insight into achievements and results from various activities implemented in individual tasks within all nine work packages of GEMex.

1. 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:

- To speed up the geothermal development in Mexico and beyond, by leveraging the knowledge of European and Mexican researchers and industry
- To reduce 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
- To improve geophysical imaging and detection of deep reservoir structures by novel approaches dedicated to HOT-EGS and SHGS, and targeted to improved imaging resolution
- To improve predictive models for reservoir characterisation and simulation
- To provide conceptual models for sustainable site development

2. Explanation of the work carried out per WP

2.1 Work Package 1: Project Management

Lead: GFZ
Partners: CNR, GFZ, ISOR, TNO, UNIBA
Duration: month 1-44
Status: completed

Objectives:

The main objective of this work package was to properly coordinate and manage the legal, financial and administrative issues associated with GEMex and to ensure effective communication between the partners, the European Commission and all interested parties. This WP also encompassed the coordination with the Mexican partner project as well as the management and monitoring of deliverables and the planning, organising and implementing of Executive Board meetings.

An additional objective of the work package was the adjustment of the projects efforts with regard to the scientific aims and the summary of the results from the technical work packages towards the overarching project results.

Table 1: Status quo of personal resources WP1.

Participant number	1	2	3	4	7	9	18	22	**Total**
Short name	GFZ	ISOR	TNO	UNIBA	CNR	BRGM	UKRI	EGEC	
PM foreseen in total GEMex	36	4	4	4	1	0	0	0	49
PM used	34.1	15.49	4.29	4.1	2	3.44	1.19	0.9	65.51

2.1.1 Task 1.1 Legal Issues

The coordinator has been providing comprehensive advice on the legally correct implementation of the action to the consortium on various occasions.

No specific legal task had to be addressed during this reporting period.

2.1.2 Task 1.2 Financial issues

The partners have been constantly informed on the financial issues and given advice when needed. A rough financial overview over the financial status has been achieved with the interim reports collected every 6 months and partners have been notified if their costs so far seem unusually high or low.

2.1.3 Task 1.3 Administrative issues

The coordinator has been in constant contact with the partners, providing them with administrative notifications via various mailing lists and exchanging individually on upcoming deadlines, activities or events.

The consortium agreed to submit interim reports in connection with (interim) project meetings. The coordinator has collected interim reports from all beneficiaries in February 2020 which include a rough description of actions performed, publications, dissemination activities, collected data and delays with respect to the description of action. Most of the beneficiaries have contributed to the interim report.

2.1.4 Task 1.4 Meetings

Project meetings are foreseen approximately every 6 months in order to encourage communication between the project partners and to facilitate the planning of joint tasks and the exchange of results. Table 2 details the project meetings.

Table 2: List of project meetings.

Event	Location	Planned Date	Organizer
1st project meeting: Kick-off meeting (Joint meeting with Mexican partners)	Morelia (Mich.), Mexico	15.-17.11.2016	UMSNH
2nd project meeting: European project meeting	Utrecht, The Netherlands	23.-24. 3.2017	TNO
3rd project meeting: General Assembly (Joint meeting with Mexican partners)	Akureyri, Iceland	2.-3. 10. 2017	ISOR / GFZ
4th project meeting: European project meeting	Bari, Italy	12.-13. March 2018	UNIBA
5th project meeting: General Assembly (Joint meeting with Mexican partners)	Morelia (Mich.), Mexico	18-20 October 2018	UMSNH
6th project meeting: European project meeting	Bochum, Germany	18-19 June 2019	HBO
Final conference and General Assembly (Joint meeting with Mexican partners)	Potsdam, Germany	17-20 February 2020	GFZ
Mexican final meeting	Mexico	May 2021 *tbc*	UMSNH

Most project partners participated in the project meeting in Bochum (Germany) in June 2019. All project partners participated in the GEMex final conference in Potsdam (Germany) in February 2020.

2.1.5 Task 1.5 Deliverables to the European Commission

All Deliverables to the European commission which were scheduled have been delivered. Some deliverables have been updated after the first submission in order to correct mistakes or add proper references. No significant change to the content has been made.

All public deliverables have been published on the project website once they have been accepted by the Project Officer of INEA.

2.1.6 Task 1.6 Coordination with Mexican Partners

The coordination team and the Executive Board members have been in close contact with the Mexican partners throughout the whole project. In this last reporting period, less coordination was necessary, since the beneficiaries and especially the task leaders have established regular and efficient ways of communication with their Mexican counterparts.

The Mexican partners have participated remotely to the project meeting in Bochum (Germany) in June 2019. 20 Mexican researchers have participated to the GEMex Final conference in Potsdam (Germany) in February 2020.

The fruitful cooperation between the European and the Mexican partners is shown by the numerous contributions of the Mexican partners to the projects deliverables and by the large number of joint publications and dissemination activities (see section 2.2.4 *Task 2.4 Promotion of project results*)

2.1.7 Deviations from the Description of Action

- No deviations in terms of actions to be performed
- Partner BRGM shifted 3.44 person months from WP4 to this work package for attending project meetings.
- Partner EGEC shifted costs for 0.9 person months from other direct costs to this work package for attending project meetings.
- Partner UKRI shifte 1.19 person months to WP1 in aorder to attend project meetings.
- GFZ shifted 6 person months to ISOR, since ISOR took over part of the scientific coordination of the project
- GFZ, ISOR and CNR report higher person months than anticipated due to the extension of the project and the higher than expected coordination with the Mexican partners

2.2 Work Package 2: Dissemination

Lead: CNR
Partners: CNR, EGEC, GFZ, IGA
Duration: month 1-44
Status: completed

Objectives:

WP2 set up the dissemination strategies and the tools to ensure a fruitful cooperation with Mexico on geothermal energy, to facilitate internal communication within the project consortium and externally with the interested stakeholders. The dissemination of the project results was conducted by means of different channels implemented in the 5 tasks. The objectives achieved in each task are reported in the next subsections and the activities are detailed in the task reports.

Table 3: Status quo of personal resources WP2.

Participant number	1	6	7	9	13	21	22	24	9	**Total**
Short name	GFZ	RWTH	CNR	BRGM	NORCE	PGI-NRI	EGEC	IGA	BRGM	
PM foreseen in total GEMex	4	0	13.5	0	0	0	5.5	2	0	25
PM used	3.8	0.52	16.07	1.92	1.56	6.64	6.55	3	1.92	40.06

Summary (incl. exploitable results and their exploitation):

The project website, whose activities were related to the activities of the Task 2.2, was launched in the third month of the project and it will continue to be online and available at least for two year after the end of the project. The website was equipped with a tracking tool able to reveal the interesting key parameters related to the use of the website. During the period where the tracker was operating (i.e., 36 months) we had 7227 connections, 30968 page views and on average (over the whole project lifetime) 59 users per week. The number of users per week has increased in the last months - probably due to more and more project deliverables being available on the website and all the information (i.e., registration page, event information, Agenda, presentations materials) related to the GEMex Final Conference being published. Most users, 1297 (17.64%), are from the US. Mexicans, Germans and Italians follow with 1025 (13.94%), 918 (12.48%) and 841 (11.44%) respectively. The 'home' page is the most visited page, followed by the 'GEMex Final Conference', 'Project reports' and 'Consortia' pages.

The Open Access DataBase (OADB) is the main result from Task 2.3. The OADB infrastructure is available since the beginning of the project (month 3) and was available during all the life time of the project. As for the website it will be maintained for at least two years after the end of GEMex. The aim of the OADB was to provide a repository to store all the datasets produced by the project. Most of the datasets arrived in the very last period of the project because most of the deliverables including project results were due for the last months of the project. About 100 different datasets were uploaded, stored and described with metadata in the OADB. Moreover, about 10 different maps were created to put together similar datasets (e.g., maps of the two geothermal areas, maps on similar dataset typology).

GEMex results promotion was carried out in Task 2.4. Two E-News were released and broadcast to the global geothermal community in September 2019 and March 2020 (i.e., GEMex scientists, EGEC and IGA networks, EERA-JPGE network, EU and MEX stakeholders (stakeholder board), the cluster of EU Geothermal projects on deep geothermal set-up by INEA and ETIP-DG). These two E-News were a compilation of the project results for the period between October 2018 - September 2019 and October 2019 - March 2020 respectively. In the last month of the project the Brochure summarising the principle results and the Action plan drafting possible future EU-MEX cooperation were accomplished and delivered.

GEMex events were organised in the frame of Task 2.5. In this last period (RP3), 3 webinars were set-up and scheduled for the 2019 autumn (i.e., 28th of November, the 5th of December and the 12th of December 2019). The webinars were dedicated to: i) how to involve citizens in geothermal projects; ii) developing geothermal markets in EU and MEX and iii) research and innovation in geothermal. In October 2019, the second informative GEMex event was organised as a side event of the European Geothermal Workshop (EGW) that was held in Karlsruhe. At the EGW, 13 contributions treated GEMex topics and one keynote talk was dedicated to the presentation of results from the project. In February 2020 the GEMex Final Conference took place in Potsdam, hosted by GFZ. More than 100 attendances were registered for the two-day conference with 32 technical oral presentations and 40 posters.

The scheduled activities and the used resources have been in line with the timing and effort/cost proposed in the Grant Agreement (GA). The personnel resources used in the WP are slightly higher than expected, mainly due to the extension of the project which resulted in a longer timespan in which dissemination activities had to be organised and coordinated. Deviations from the Description of Action are concerning some partners who initially had not planned any person months for WP2, but contributed to some tasks in this work package. Those deviations are reported in section 2.2.8

The collaboration between the work-package leader, task leaders, project coordinator, WP2 participants and the WP/task leaders of other work-packages was very fruitful. Since April 2018 16 monthly calls were organised to track the activities.

2.2.1 Task 2.1 Strategic Communication Plan and communication campaign

Task 2.1 has been concluded in the previous reporting period.

2.2.2 Task 2.2 Website

The Task 2.2 is dedicated to the design, implementation and maintaining of the project website and partner's corner.

In the third reporting period, the project website was continuously updated in the contents. No major changes were carried on to the website structure. Minor changes were made in the home page, where the highlights on main organised events as the webinars and the final conference were advertised (Figure 1). Consequently, dedicated pages for webinars and for the Final conference were set-up and links on the main menu were added accordingly. The results section was largely enriched with: i) two news E-News, ii) two new GEMex organised events (i.e., the second side event at the EGW and the GEMex Final Conference), iii) 19 interviews accordingly subtitled to our Mexican colleagues performed at the end of the third Mexican technical meeting (27-29 June 2018), iv) 3 dedicated pages to the organised webinars, v) an updated page of the GEMex publications and vi) an updated version of the delivered project reports.

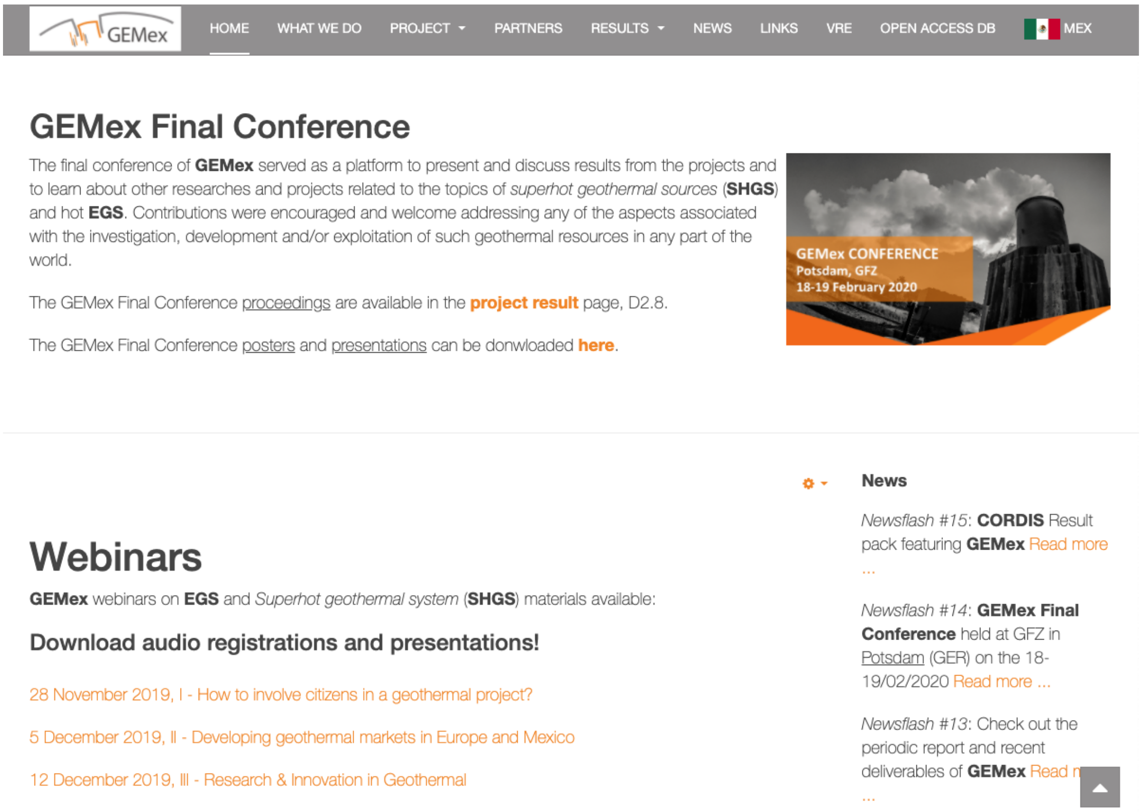

Figure 1 - Scrolled down home page with the two advertisements on the GEMex events close-up: Final conference and Webinars. On the right the last newsflashes.

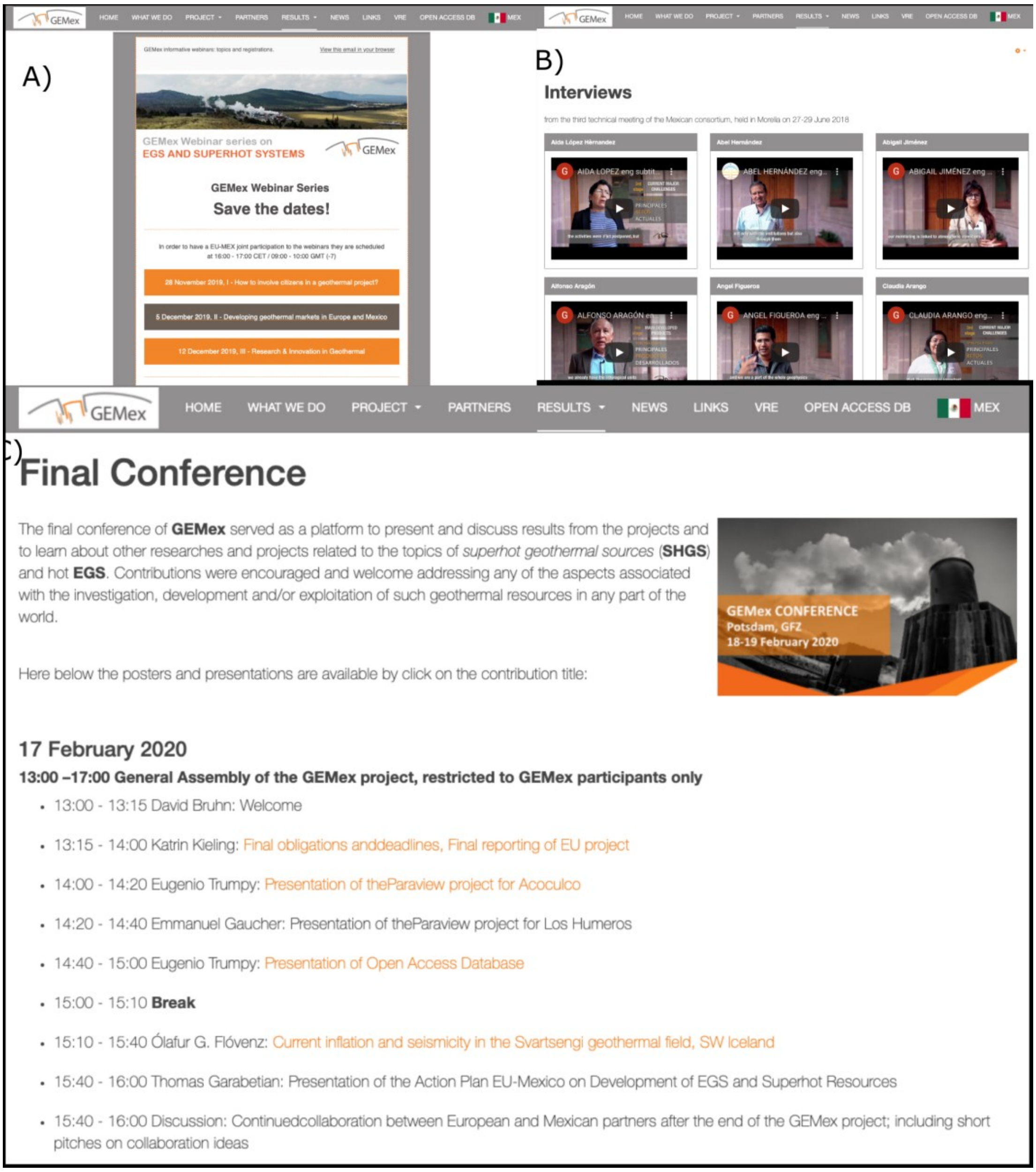

Figure 2 - A) Webinars page, B) Interviews page, C) Final Conference page with the available contributions (i.e., presentations and posters).

In the last 13 month (RP3) 4 newsflashes were prepared and published on the website. These newsflashes highlighted the GEMex general assembly, results, Final conference and advertised on the Geothermal pack, embedding GEMex info, released by CORDIS (European Commission).

The administration part of the website, equipped with a statistical tool, continuously recorded the website traffic as reported above in the summary.

The Mexican WP2 counterpart continued to update synchronously the Spanish version of the website (www.gemex-h2020.mx).

The private part of the project website, dedicated to the project consortium (Partner's Corner) and developed by using the Virtual Research Environment (VRE) technology, was very well used by the project community. About 221 users were registered to the GEMex VRE, where 167 and 52 are Europeans and Mexicans scientists respectively. The project's deliverables, publications, presentations together with the meeting minutes or any other relevant document were available for the GEMex consortia. The use of the social wall of the GEMex VRE was constant in the last months: 5 posts per month in average were used by the scientists for example to announce a congress participation, a result of an experiment, a paper publication, uploading of materials or datasets on the VRE (Figure 3). More than 1250 files were uploaded and stored for sharing on the VRE for a data volume of about 24GB.

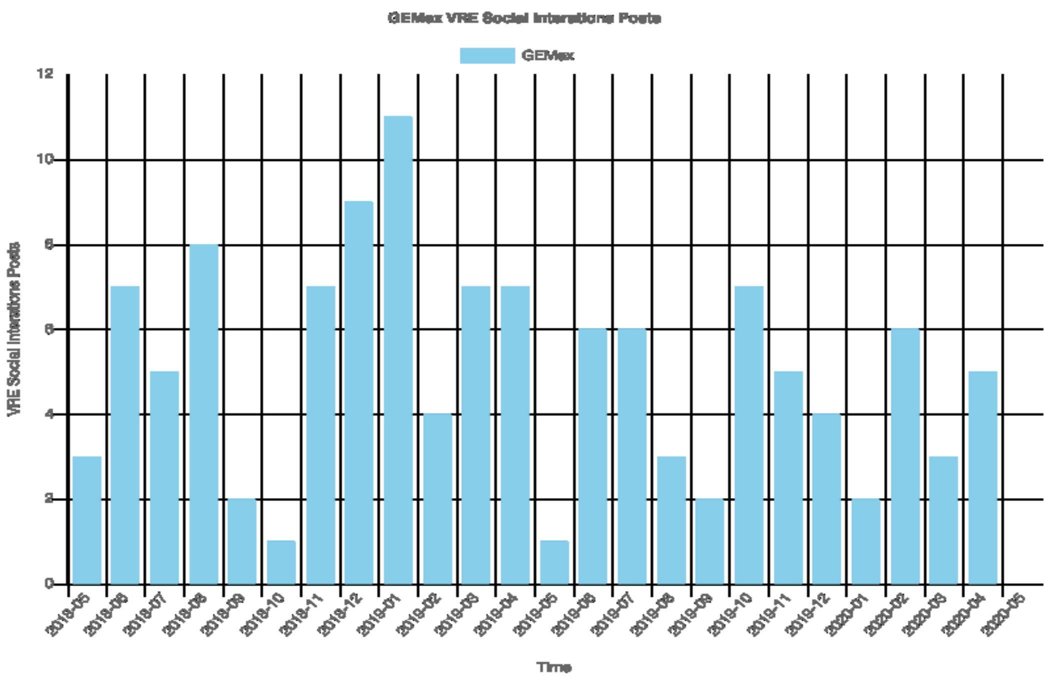

Figure 3 - GEMex VRE social interactions in terms of posts. The average number of monthly posts is ~5.

2.2.3 Task 2.3 Open access database

Task 2.3 was dedicated to the design, implementation and maintenance of an Open Access DataBase (OADB) to collect and make available the datasets produced in the frame of the GEMex project. The used software (GeoNode) allowed to store and describe with metadata the collected datasets and to organise them in aggregated maps.

At the end of the project, the OADB includes more than 100 spatial layers all available for download. The layers include some general datasets made freely available by the Mexican authorities (e.g., DEM, a vectorial geological map, some geological important sites, caldera points, ...) and the locations of the sampling sites recorded by the GEMex scientists during the field works performed as well as the complete datasets with data. 10 dedicated maps were created to aggregate the available datasets by location and typology. 2 maps include all the datasets available for the two GEMex areas (i.e., Los Humeros and Acoculco), while the other four group out the geological, geophysical, geochemical and sampling points datasets. Other maps were created to put together specific datasets for example Thermal models results and resources assessment, gravity and resistivity results from 3D models, analogue geological models results. In each map, the features are represented with a specific symbology and can be queried by using the dedicated tool of the WebGIS. All cross-sections traces (i.e., from resistivity 3D model, from density 3D model, from 3D thermal models, …) were linked to the cross-sections images (Figure 4).

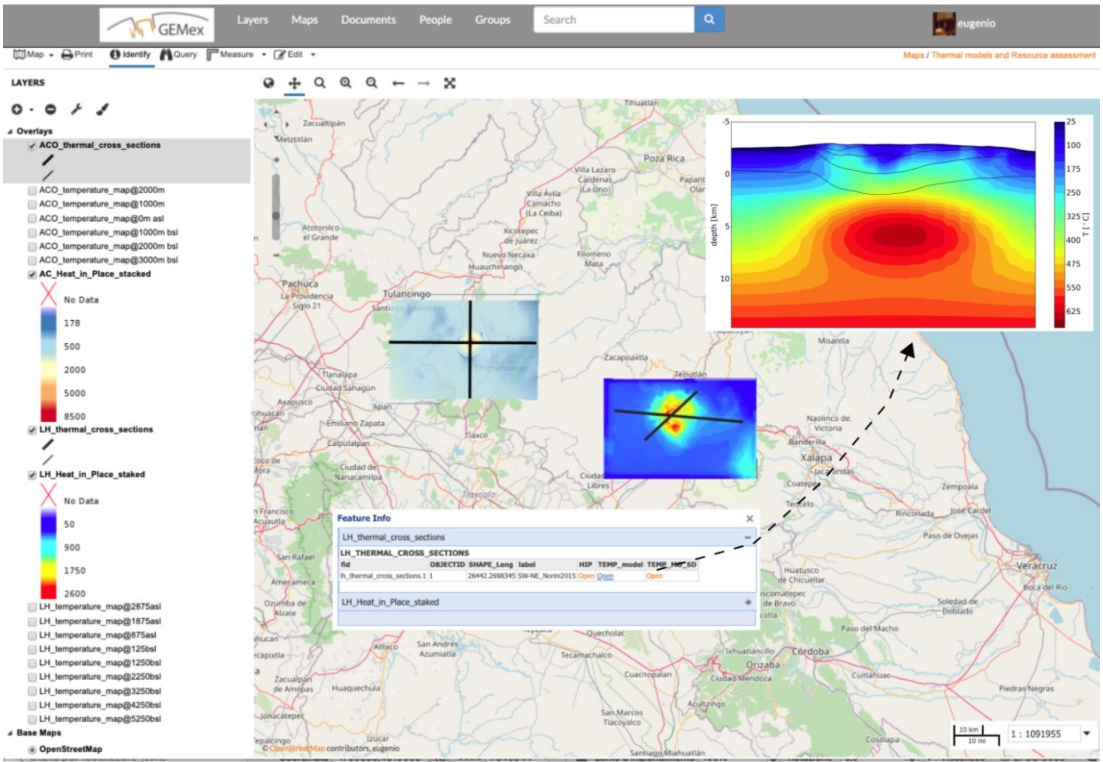

Figure 4 - The webGIS interface of the OADB. Here, we show the thermal models and resource assessment results of the two GEMex areas. In particular, the table results from a query on Los Humeros area performed with the 'Identity' tool button. From the resulting table, it is possible to 'Open' (see the dashed arrow) the related iconografic material, in this case the cross-section from the 3D thermal model.

2.2.4 Task 2.4 Promotion of project results

A **series of 3 GEMex e-news** were produced during the project. The first e-news was sent in October 2018 with 44 views. The second e-news was sent in October 2019 with 100 views. The third e-news was sent in March 2020 with 110 views. The 3 e-news summarized the main results of the project and the promotion of events like the GEMex Final Conference. The 3 e-news can be found on the GEMex website in the results section.

The GEMEX Action Plan was drafted by EGEC, through exchanges with the partners from the WP2 and building on the knowledge acquired in other project tasks, in particular task 7.4. Moreover, regular exchanges, discussions and feedback rounds with the GEMex stakeholder boards, which gathers representatives from the Geothermal industry interested in the prospects of a EU/Mexico cooperation on geothermal developments, have allowed to keep the GEMex action plan grounded into the priorities of the European Geothermal industry.

The GEMex Action Plan is structured as follow:

- Presentation of technologies and state of play in the European and Mexican geothermal sectors;
- Overview of the geothermal resources in Mexico and in Europe;
- SWOT analysis regarding the non-technical barriers to the market uptake of geothermal energy technologies, with a specific focus on EGS and superhot systems;
- Overview of the good practices on environmental impact and community engagement based on the results of the Task 7.4 of the GEMex Project;
- Conclusion including recommendations for future cooperation EU/Mexico on geothermal energy, notably Superhot and EGS systems.

The GEMex Action Plan is published in May 2020, and disseminated to the mailing lists of the GEMex project along the last GEMex e-news.

GEMex workshops for stakeholders/Stakeholders Board.

EGEC organised 2 Stakeholders workshops. The first one was organised on November 15th, 2017 in Brussels attended by more than 15 participants.

The second workshop was organised on January 10th, 2019, in Brussels. It was attended by 10 participants.

Presentation of project results

Finally, project activities and first results have been presented to the public in several conferences and meetings (Table 4) – altogether 244 contributions (however these include the 36 contributions which are foreseen in the WGC2021 which was shifted due to the Corona-pandemic.

Table 4: List of contributions to conferences.

Event	Location /Date	Who	Authors, Title
1° Simposio Ambiental, Economico y Social de Sistema Geotermicos Mejorados y Supercalientes	Morelia (Michoacan, Mexico) 27th February – 1st March 2017	Michele Contini (SSSA)	Socio-economic dimensions in geothermal energy project: three-years common thread
European Geothermal PhD Day 2017	Bochum, 1-3 March 2017	C. Colombero	C. Colombero, F. Vagnon, J. Chicco G. Mandrone: Field and lab characterization of fault zone in geothermal areas in central Mexico
ETIP-DG, Deep Drilling WG	Pisa, Italy, March 2017	Michal Kruszewski (HBO)	Kruszewski M., Drilling and Well Completion Technologies for Super (Hot) Geothermal Systems
EGU 2017	Vienna (Austria)	Cesare Comina (UNITO)	C. Comina et al.: "A multidisciplinary approach for the characterisation of fault zones in geothermal areas in central Mexico"

GeoEnergi2017 – Geothermal Conference	Bergen (Norway), 22-23 May 2017	Walter Wheeler (CIPR)	W. Wheeler et al.: “GEMex- Europe-Mexico collaboration for development of Enhanced Geothermal Systems and Superhot Geothermal Systems”
		Jiri Muller (IFE)	Muller, J., “Laboratory Studies of Geothermal Tracers at Supercritical Conditions.”
IAVCEI Conference	Portland (USA), 14-18 Aug 2017	G Gropelli	Groppelli, G., et al., “New geological, structural and volcanological data of the Los Humeros Volcanic Complex: implications for reconstruction of the 3D model volcanic structure and geothermal exploration.”
German Geothermal Congress; Keynote lecture	Munich (Germany), 12-14 Sept 2017	David Bruhn (GFZ)	GEMex: Cooperation Europe-Mexico for the development of unconventional geothermal systems
IMAGE Final Conference	Akureyri (Iceland), 4-6 Oct. 2017	Anna Jentsch (GFZ)	Structural-geological impact on soil gas composition at Los Humeros Volcanic Complex
		Tania Toledo (GFZ)	Seismic network survey design and performance
5th European Geothermal Workshop	Karlsruhe (Germany), 12-13 October 2017	Y. Qin (KIT)	Qin, Y., Schill, E., Weydt, L. M., Bär, K., Sass, I., and Pérez-Florez, M. A.: Concept of Gravimetric Exploration of Enhanced and Super-Hot Geothermal Systems in Acoculco and Los Humeros (Mexico),
		Michal Kruszewski (HBO)	Supercritical Drilling – Casing Design Review, Methodology and Case Studies
		Leandra Weydt (TUDA)	Weydt, L., Bär, K., Sass, I. (2017): Outcrop Analogue Study to Determine Petrophysical Properties of the Los Humeros and Acoculco Geothermal Systems, Mexico
CHPM2030 Geochemistry of Geothermal Fluids Workshop	University of Miskolc – Hungary, October 2017	Giordano Montegrossi (CNR)	Montegrossi G., Lelli M., 2017 Introduction and geochemical aspects of the GEMEX project
Society of Petroleum Engineers Student Technical Conference	Clausthal-Zellerfeld, Germany, November 2017	Michal Kruszewski (HBO)	Kruszewski M., Methods of Assessing Casing Setting Depths for High-Temperature Geothermal Wells in New Areas
Stanford Geothermal workshop, Presentation on GEMex	Standford (USA), Feb 2018	Egbert Jolie (GFZ)	E. Jolie et al.: GEMex –A Mexican-European Research Cooperation on Development of Superhot and Engineered Geothermal Systems

European Geothermal PhD Day	Zurich (Switzerland), 14-16 Mar 2018	Tania Toledo (GFZ)	T. Toledo et al.: “Experimental Network Design for Earthquake Location Problems: application to geothermal field seismic networks”
		Baptiste Lepillier (TU-Delft/GFZ)	B. Lepillier, R. Bakker, D. Bruhn: “Characterization of a fracture-Controlled Enhanced Geothermal System (EGS) in the Trans-Mexican-Volcanic-Belt (TMVB)”
		Emmanuel Olvera-García (UNIBA)	E. Olvera-Garcia: “The Las Minas exhumed geothermal system (Veracruz, Mexico): a proxy for Los Humeros geothermal field”
		Gergö Hutka (GFZ)	Hutka GA, Hofmann H, Farkas MP, Yoon JS, Zimmermann G, Zang A, “Benchmarking of hydro-mechanical coupled models against true-triaxial laboratory hydraulic fracturing experiments”
Energía geotérmica y sociedad: Aceptación y participación social en desarollos de energía geotérmica,	16 Apr 2018, Puebla, Mexico	Michele Contini (SSSA)	Contini, M., “How do consumers perceive corporate social responsibility (CSR) and business ethics actions from their energy providers? An international survey”
		Michele Contini (SSSA)	Contini, M., “Conceptual model for analysing corporate best practices and strategy to increase social acceptance of projects for exploiting natural resources”
		Karytsas S., CRES	Karytsas, S. “Actions from the companies’ side to increase social acceptance of geothermal energy projects”
		Karytsas S., CRES	Karytsas, S., Polyzou, O., and Karytsas, C., “Social aspects of geothermal development in Greece”
11th National Conference for Renewable Energy Sources	14 – 16 Mar 2018, Thessaloniki, Greece	Karytsas S., CRES	Karytsas, S., Polyzou, O., and Karytsas, C. “Evaluation of social acceptance of geothermal energy in Greece”
Seminar	Universidad Politecnica de Catalunya (UPC-IDAEA-CSIC), March 15th 2018	Francesco Parisio (UFZ)	Parisio, F., “Enhanced supercritical geothermal systems: toward stimulation design”
EGU 2018	Vienna (Austria), 9 -13 April 2018	Leandra Weydt (TUDA)	L. Weydt, K. Bär, I. Sass: “Outcrop analogue study to determine reservoir properties of the Los Humeros and Acoculco geothermal fields, Mexico” (EGU2018- 7228)
		Damien Bonté (UU)	D. Bonté et al.: “Preliminary estimation of the thermal structure of the Acoculco-Los Humeros area, Mexico” (EGU2018-16270)

		Philippe Calcagno (BRGM)	Calcagno, P., et al.: “3D preliminary geological models of Los Humeros and Acoculco (Mexico) - H2020 GEMex project” (EGU2018-12811)
		Eszter Békési (UU)	Békési, E., et al., “Active deformation of the eastern Trans-Mexican Volcanic Belt based on InSAR persistent scatterers” (EGU2018-15520)
		Tania Toledo (GFZ)	Toledo, T., “Optimized Experimental Network Design for Earthquake Location Problems: applications to geothermal fields seismic networks”, EGU 2018-15056
		Paromita Deb (RWTH)	Montegrossi, G., Deb, P., Clauser, C., Diez, H., Ramirez Montes, M. A., “Modeling of Los Humeros geothermal field: preliminary results” (EGU2018-17600)
		Juliane Kummerow (GFZ)	Kummerow, J., Raab, S., Schüssler, J., “Fluid-rock interactions at near- and supercritical conditions and their effect on physical properties of high-enthalpy hydrothermal systems” (EGU2018-7097)
		Paromita Deb (RWTH)	Deb et al., “Hydraulic-fracturing experiments on a laboratory scale for numerical codes verification” (EGU2018-16136)
		Francesco Parisio (UFZ)	Parisio F., Vinciguerra S., Kolditz O. and Nagel T., “The lithological control on the brittle-ductile transition in volcanic areas” (EGU2018-2429)
			Santos-Basurto R., Sarychikhina O., Lopez-Quiroz P., Norini G., Carrasco-Nuñez G. (2018). The Mw 4.2 (February 8th, 2016) earthquake detected inside of Los Humeros caldera,
80th EAGE Conference	Copenhagen, Denmark, June 2018	Paromita Deb (RWTH)	Deb et al., Laboratory fracking experiments for verifying numerical simulation codes, 1354, Hydro-Thermal-Mechanical Modelling in Tight Formations
Breaking the Rules! Energy Transitions as Social Innovations, International conference hosted by the Leibniz Research Alliance on Energy Transitions	Berlin (Germany), June 14-15, 2018	Alessandro Sciullo (UNITO)	Annunziata, E., Contini, M., Diaz, F., Karytsas, S., Manzella, A., Padovan, D., Sciullo, A., “Public engagement strategy: a conceptual model for enhancing the development of geothermal energy”

24th EM Induction Workshop	Helsingør, Denmark, August 12-19, 2018		Arango-Galván, C., Hersir, G. P., Benediktsdóttir, A., Romo-Jones, J. M., Salas-Corrales, J. L., Avilés-Esquivel, T., Held, S., Manzella, A., Santilano, A., Schill, E., “Electromagnetic exploration for unconventional geothermal systems in Mexico: The GEMex Project”
Goldschmidt Conference	Boston (USA), 12-17 August 2018		Carrasco-Núñez, G., Giordano, G., Dávila, P., Bernal, J.P., Jicha, B., “Short time scales and recent replenishment in large magmatic systems: case study of Los Humeros caldera complex“
Cities on volcanoes	Neaples (Italy), Sept. 2-7, 2018	Anna Jentsch (GFZ)	Jentsch, A., Jolie, E.,“Systematic soil gas studies for volcanio tectonic analyses of the Los Humeros Geothermal Field, Mexico”
		Marco Calo(UNAM , Mexico)	Granados, I., Caló, M., Soto, A. F., Oregel, L., Toledo Zambrano, T. A., Martins, J., Jousset, P., Perton, M. (2018): Structure of the Los Humeros geothermal field, Mexico, using seismic noise tomography - Abstracts, 10th Cities on Volcanoes Conference (Naples, Italy 2018)
		Philippe Jousset (GFZ)	Jousset, P., Toledo Zambrano, T. A., Soto, A. F., Calo, M., Metz, M., Hersir, G. P., Martin, J. E., Obermann, A., Gaucher, E., Saenger, E., Kieling, K., Bruhn, D. (2018): New passive seismology network deployed in Los Humeros caldera (Mexico): first results - Abstracts, 10th Cities on Volcanoes Conference (Naples, Italy 2018)
		Marco Calo (UNAM)	J. Angulo, M. Calò, A. Figueroa Soto, P.Jousset. “Induced and trigered events in geothermal fields following large earthquakes. The example of the Los Humeros Caldera, Mexico”, Cities on Volcanoes 10 meeting, Naples, Italy, 2-7 September 2018.
		Gerardo Carrasco (UNAM, Mexico)	Lucci F., Carrasco-Núñez G., Giordano G., Rossetti F., “Petrogenesis of the magmatic heat source of the Los Humeros caldera geothermal field”
		Ivan Granados (UNAM)	Granados, I., Caló, M., Soto, A. F., Oregel, L., Toledo Zambrano, T. A., Martins, J., Jousset, P., Perton, M. (2018): Structure of the Los Humeros geothermal field, Mexico, using seismic noise tomography
11. Sitzung DGMK-	Bochum, September 2018	Michal Kruszewski (HBO)	Kruszewski M., "Cementing Challenges in High Temperature Geothermal Wells"

Arbeitskreis Bohrspülung			
GeoMod 2018 conference	Barcelona, Spain, 2-4 October 2018	Maestrelli, D.,	Maestrelli, D., Bonini, M., Corti, G., Montanari, D., Moratti, G.: Exploring the role of inherited structures during caldera collapse: insights from analogue modelling
European Geothermal workshop	Strasbourg (France) 10-11 Oct 2018	Emmanuel Gaucher (KIT)	Gaucher, E., Toledo, T., Calo, M., Figueroa Soto, A., Jousset, P.: "Passive seismic monitoring of the Los Humeros (Mexico) geothermal field"
		Michele Contini (SSSA)	M. Contini, E. Annunziata, F. Rizzi, M. Frey, "Consumer's perception of company's corporate social responsibility in the context of a geothermal energy facility development"
		Baptiste Lepillier (TU Delft / GFZ)	Lepillier, B., Bakker, R., Bastesen, E., Bruhn, D., Bruna, P.-O., Daniilidis, A., Garcia, O., TTorabi, A., Wheeler, W., "Characterization of a Fracture-Controlled Enhanced Geothermal System (EGS) in the Trans-Mexican-Volcanic-Belt (TMVB) Predictive mechanical model for fracture stimulation in an Enhanced Geothermal System (EGS)"
		Leandra Weydt (TUDA)	Weydt, L., Bär, K., Sass, I. (2018): New insights on geothermal rock properties of the Los Humeros geothermal field, Mexico
GRC Geothermal Resources Council Annual Meeting	Reno, Nevada, USA 14 - 17 October 2018	David Bruhn (GFZ)	Bruhn, D., Jolie, E., Huenges, E., "European research efforts on engineered and superhot geothermal systems within Horizon2020"
		Michal Kruszewski (HBO)	Kruszewski, M., Ramírez, M.,Wittig, V., Sanchez, M., Bracke, R., "Drilling and well completion challenges in the Los Humeros Geothermal Field, Mexico"
SEG (Society of Exploration Geophsicists) Annual meeting	Anaheim, CA (USA), Oct. 14-19, 2018	Sven Tveit (CIPR)	Tveit, S., Mannseth, T., "Identification of geothermal reservoirs from ensemble-based Bayesian inversion of 3D MT data"
VI Polish Geothermal Congress	Zakopane, Poland, 23 – 25 October 2018	Michal Kruszewski (HBO)	Kruszewski M., Wittig W., "The Influence of Mechanical Material Properties of Cement and Rock Formations on Stresses in the Wellbore Cement Under Defined Reservoir Conditions of a Geothermal Well"
Society of Petroleum Engineers - Student Technical Conference (SPE STC)	Freiberg, Germany, 8-9 November 2018	Michal Kruszewski (HBO)	Kruszewski, M., Wittig, V., "The influence of elastic properties of cement and rock formation on cement sheat stresses in geothermal reservoirs"
		M. Glißner	Glißner M., Lefebvre M., Hahn S., Kruszewski M., Wittig V., Bracke R., "Alternative Cement

German Geothermal Congress	27 – 29 November 2018, Essen, Germany		for Deep High Temperature Wells based on Alkali-Activated Alumino-Silicates"
		Michal Kruszewski	Kruszewski M., "An Influence of Mechanical Properties of Cement and Rock Formations on Wellbore Cement Stresses in a Geothermal Well"
Minisymposium on Poroelasticity	Bochum, Germany, 19. February 2019	Michal Kruszewski	Kruszewski, M., Montegrossi, G., Ramírez Montes, M., Wittig, V., Gomez Garcia, A., Sánchez Luviano, M., Bracke, R “A Novel Approach on Crustal Stresses Prediction and Scientific - Basis for Geomechanical Modeling on the Example of The Los Humeros Geothermal Field, Mexico”
EGPD 2019	25-27 Feb 2019, Potsdam (Germany)	Anna Jentsch (GFZ)	Jentsch, A., Systematic soil gas survey at Los Humeros geothermal field, Mexico
		Héctor Gonzales-Garcia (GFZ)	Gonzalez-Garcia H., Estimation of energy reserve at Los Humeros geothermal power plant
		G. A. Hutka (GFZ)	Hutka GA, Hofmann H, Farkas MP, Yoon JS, Zimmermann G, Zang A, Benchmarking of hydro-mechanical coupled models against true-triaxial laboratory hydraulic fracturing experiments
		Baptiste Lepillier (GFZ/TU Delft)	Lepillier, B., Predictive mechanical model for fracture stimulation in an enhanced geothermal system (EGS) context
		Emmanuel Olvera-Garcia (UNIBA)	Olvera-Garcia E., Exhumed geothermal systems as the key for understanding active geothermal fields: The case of Las Minas (Mexico)
		Tania Toledo (GFZ)	Toledo Zambrano, T. A., Passive seismic monitoring at the Los Humeros geothermal field, Mexico: preliminary results
		Claudia Werner (HBO)	Werner, C., Is time reverse imaging suitable for locating microseismic events in geothermal reservoirs?
DGG Annual meeting	Braunschweig, Germany, 4-7 March 2019	Emmanuel Gaucher (KIT)	Gaucher, E., Toledo-Zambrano, T., “Local seismicity recorded at the geothermal field of Los Humeros (Mexico)”
		Katrin Löer (HBO)	Löer, K., Riahi, N., Saenger, E.: “Quantifying the composition of ambient seismic noise using three-component beamforming”
EGU	Vienna (Austria) 7-12 April 2019	Jon Limberger (UU)	Limberger, J., Bonté, D., Békési, E., Beekman, F., Kretzschmar, T., van Wees, J. D.: ”Studying the effects of magma chamber emplacement depth, groundwater flux, and local advection

			on the regional thermal structure of the Los Humeros Volcanic Complex, Mexico”
		Juliane Kummerow (GFZ)	Kummerow, J., Raab, S., Spangenberg, E. Schleicher, A.M., Schuessler, J.,: “Monitoring reactive flow in geothermal settings: A petro- and fluidphysical approach” (EGU-2019-11295)
		Michal Kruszewski (HBO)	Kruszewski, M., Montegrossi, G., Ramírez Montes, M., Wittig, V., Gomez Garcia, A., Sánchez Luviano, M., Bracke, "Wellbore Stability and Scientific Basis for Geomechanical Modeling on the Example of the Los Humeros Geothermal Field, Mexico
		Tania Toledo (GFZ)	Toledo, T., Gaucher, E., Malte, M., Jousset, P., Maurer, H., Krawczyk, C., Figueroa, A., Calo, M.,: Seismic earthquake tomography imaging of the Los Humeros geothermal field, Mexico: first results, EGU2019-15960-1
		Marco Calo (UNAM)	Marco Calò, Joel Angulo Carrillo, Brenda De la Rosa Espinosa, Ivan Granados Chavarria, Stephani Cruz Hernandez, Angel FIgueroa Soto, Philippe Jousset, Mathieu Perton, Tania Andrea Toledo Zambrano, and Emmanuel Gaucher. Triggered LP seismicity in geothermal fields and its implication on the characterization of the buried structures.
		Gerardo Carrasco-Núñez (UNAM)	Carrasco-Núñez, G et al. “Short time scales and recent replenishment in large magmatic systems: case study of Los Humeros caldera complex“
		Claudia Werner (HBO)	Werner, C., Saenger, E.,: Sensitivity maps for time-reverse imaging, EGU2019-7106
		Katrin Loeer	Löer, K., Riahi, N., Saenger, E.: “Investigating the deep structures of the Los Humeros geothermal field, Mexico, with three-component beamforming of ambient seismic noise”
AAPG 3rd Hydrocarbon - Geothermal Cross Over Technology Workshop	8-9 April 2019, Geneva, Switzerland	Gianluca Gola (CNR)	Gola, G., Santilano, A., Trumpy, E., Manzella, A. “Data Integration and Modelling of the Acoculco (Mexico) and Larderello-Travale (Italy) High-Temperature Geothermal Fields”
International Geothermal Association’s Board of	Budapest, Hungary, 12 May 2019	Michal Kruszewski (HBO)	Kruszewski, M., "Developments and Challenges of Deep (High-Temperature) Geothermal Drilling"

Directors meeting			
Seismology of the Americas	Miami, Florida, USA 14-17 May 2018	Luis Morales	Morales, L. A. O., Figueroa-Soto, A., Calo, M., Jousset, P., Ramírez, V. H. M. (2018): Analysis of the seismicity in the Los Humeros Mexican geothermal field within the framework of the GEMEX consortium
Ciclo di Seminari per studenti e dottorandi	Dip. Scienze Università Roma Tre, Maggio 2019	Federico Lucci (UNIROMA)	Lucci, F. Lectio Magistralis "Anatomy of the magmatic plumbing system of Los Humeros Caldera (Mexico): implications for geothermal systems
2019 EAGE Annual meeting	London, 3 June 2019	Jiri Muller (IFE)	Muller, J., Viig, S. O., Stray, H.: Laboratory Studies of Organic and Inorganic Geothermal Tracers at Superhot and Supercritical Conditions
		Gianluca Gola (CNR)	Gola, G., "Thermal modelling of magmatic geothermal systems: the role of deep-seated heat sources."
EGC 2019	De Haag, Netherlands, 11-14 June 2019	Eszter Békési (UU)	Békési, E., Fokker, P. A., Esteves Martins, J., van Wees, J.D.: "Inversion of coseismic deformation due to the 8th February 2016, Mw 4.2 earthquake at Los Humeros (Mexico) inferred from DInSAR"
		Arie Verdel (TNO)	Verdel, A., Martins, J., Obermann, A., Toledo, T., Jousset, P.: "Ambient noise seismic reflection interferometry at the Los Humeros geothermal field, Mexico"
		Spyros Karytsas (CRES)	S. Karytsas, O. Polyzou, D. Mendrinos, C. Karytsas. "Towards Social Acceptance of Geothermal Energy Power Plants"
		Emmanuel Gaucher (KIT)	Gaucher, E. "One year of passive seismic monitoring of the Los Humeros (Mexico) geothermal field"
		Flavio Poletto (OGS)	Poletto, F., Farina, B., Carcione, J. M., Pinna, G., "Analyis of seismic wave propagation in geothermal reservoirs"
		Michal Kruszewski (HBO)	Kruszewski, M. "Crustal Stress determination and wellbore stability analysis: Los Humeros geothermal field case study
		Paromita Deb (RWTH)	Laboratory experiments and numerical simulations of hydraulic fracturing for enhanced geothermal systems
		Paromita Deb (RWTH)	Modeling Natural Steady State of Super-Hot Geothermal Reservoir at Los Humeros, Mexico
		Peter Fokker (TNO)	Fokker, P.A. and Wassing, B.B.T., "A fast model for THM processes in geothermal applications"

81st EAGE Conference & Exhibition	3-6 June 2019, London, UK	Gianluca Gola (CNR)	Gola, G., Thermal modelling of magmatic geothermal systems: the role of deep-seated heat sources. Extended abstract
27th IUGG General Assembly	8-18 July 2019, Montreal, CA (Poster)	Gola, Santilano, Trumpy & Manzella	Gola, G., Santilano, A., Trumpy, E. & Manzella, A., "Numerical strategies on modelling deep seated heat sources in continental, magmatic geothermal systems."
16th International Symposium on Water-Rock Interaction	21-26 Jul 2019 – Tomsk, Russia	Thomas Kretzschmar (CICESE)	Kretzschmar T., Lelli M., Alfaro R, Ignacio Sanchez J., Rene Ramos Y. (2019). Chemical and stable isotope composition of surface and groundwater in the surroundings of the Los Humeros Caldera, Puebla, Mexico.
XIV European Sociological Association Conference	Manchester (UK), 20-23 August 2019	Alessandro Sciullo (UNITO)	Sciullo, A.,"Measuring the social impact of renewables infrastructure: the potential of integrating counterfactual approach and Social Impact Assessment methodology"
Celle Drilling 2019	Celle, Germany, 10-11 September 2019	Michal Kruszewski (HBO)	Montegrossi, G., Ramírez Montes, M., Wittig, V., Gomez Garcia, A., Sánchez Luviano, M., Bracke, R.: "A wellbore cement sheat damage prediction model with the integration of acoustic wellbore measurements"
EAGE Near Surface Conference: 1st Conference on Geophysics for Geothermal-Energy Utilization and Renewable-Energy Storage	8 - 12 September, 2019 in The Hague, The Netherlands	Erika Barison (OGS)	Barison, E., Poletto, F., Farina, B.: Offset-gap compensation by seismic interferometry for shallow signals of active-seismic lines acquired in a superhot geothermal field
		Gualtiero Böhm (OGS)	Böhm, G., Poletto, F., Barison, E.: Near-surface geophysical investigation for characterization of a volcanic geothermal reservoir by active-seismic-data tomography and attenuation analysis
		Katrin Kieling (GFZ)	Kieling, K. and the GEMex consortium "Searching for Superhot and EGS: an overview on geophysical approaches applied in the GEMex joint European - Mexican project"
3rd International Geothermal Conference GEOHEAT2019	Research Geotechnological Center of Far Eastern Branch of Russian Academy of Sciences, Petropavlovsk-Kamchatsky, Russia, 3-4 September 2019.		Norini, G., Carrasco–Núñez, G., Corbo-Camargo, F., Lermo, J., Hernández Rojas, J., Castro, C., "Volcano-tectonic model guide for the geothermal exploration of the Los Humeros Volcanic Complex, Mexico"

SGI-SIMP 2019	Parma (Italy), 17-19 September 2019	G. Morelli,	Morelli G., Ruggieri G., Zucchi M., Braschi E., Agostini S., Ventruti G., Brogi A., Liotta, D., Boschi C., González-Partida E., “Characterization and evolution of the paleo-fluids circulating in the exhumed geothermal system of Las Minas (Mexico)”
		Daniele Maestrelli (CNR)	Maestrelli D., Bonini M., Corti G., Montanari D., Moratti G., “Interplay between rift propagation and inherited crustal fabrics: a case study from the Trans-Mexican Volcanic Belt (Mexico).”
		Daniele Maestrelli (CNR)	Maestrelli D., Bonini M., Corti G., Montanari D., Moratti G. “Collapsed calderas vs inherited fabrics: insights from analogue modelling”
1st Setubal International Conference on Energy and Sustainability	17 Sept 2019, Setubal, Portugal	Karytsas S., CRES	Karytsas S., Mendrinos D., Annunziata E., Contini M., Sciullo A., Manzella A., and Montalvo C., “GEMEX European project: Public engagement strategy for enhancing the development of geothermal energy”
XL Aisre (Associazione Italiana di Scienze Regionali) Conference	L’Aquila (Italy), 16-18 September 2019	Allesandro Sciullo (UNITO)	Sciullo, A., “Evaluating the impact of energy renewable infrastructure on local communities: a case study on geothermal energy in Mexico”
Latin American Colloquium	Hamburg (Germany), September 19, 2019	Natalia Cornejo (KIT)	Cornejo, N., Schill, E., Held, S., Perez, M., Carillo, J., “Towards visualization of possible fluid pathways using gravity in Los Humeros and Acoculco geothermal fields”
Assolombarda working group on environmental communication for companies	Milan (Italy) 26th September 2019	Michele Contini (SSSA)	Community engagement: a model for practical application
EGW, European Geothermal workshop	9-10 October 2019, Karlsruhe (Germany)	Gianluca Norini (CNR)	Keynote: “Volcano-tectonic model guide for the geothermal exploration of the Los Humeros Volcanic Complex, Mexico”, Norini, G., Carrasco–Núñez, G.,
		Natalia Cornejo (KIT)	Cornejo, N., Liotta, D., Held, S., Schill, E., Piccardi, L., Brogi, A., Perez, M., Carrillo, J., Garduño, V. H., “Regional structures in the Los Humeros geothermal system: insights for superhot geothermal fluids location.”

		Leandra Weydt (TUDA)	Weydt, L., Bär, K., Sass, I.,“Thermo- and petrophysical rock properties of the Los Humeros geothermal field (Mexico): comparison of outcrop analogues and reservoir formations”
		Baptiste Lepillier (TU Delft /GFZ)	Lepillier, B., Bruhn, D., “Predictive Mechanical model for fracture stimulation in an enhanced geothermal system (EGS) context”
		Daniele Maestrelli (CNR)	Maestrelli, D., Bonini, M., Corti, G., Montanari, D., Moratti, G., “Constraining caldera structures to understand geothermal fluid migration: insights from analogue modelling, and implications for the Los Humeros Volcanic Complex”
		Giuseppe Mandrone (UNITO)	Mandrone, G., Comina, C., Vinciguerra, S., Ferrero, A.M., Vagnon, F., Colombero, C., “Effect of temperature on physical properties of carbonatic rocks.”
		Giuseppe Mandrone (UNITO)	Comina, C., Vacha, D., Mandrone, G., Chicco, J., “Field methodologies aimed at geomechanical and geophysical characterization of faults zones in geothermal areas”
		Walter Wheeler (NORCE)	Bastesen, E., Wheeler, W., Liotta, D., Garduño, V.H., Torabi, A., Lepillier, B., Olvera García, E., Brogi, A:, “Geological structures and analogue permeability studies in Los Humeros geothermal system”
		Walter Wheeler (NORCE)	Wheeler, W., Liotta, D., Brogi, A., Bastesen, E.,Garduño V. H., Geological structures in the Acoculco geothermal area, Mexico: a background for EGS development
		Tania Toledo (GFZ)	Toledo, T., Gaucher, E., Jousset, P., Maurer, H., Krawcyk, C., Calo, M., Figueroa, A., “Local earthquake tomography of Los Humeros geothermal field”
		Sebastian Held (KIT)	Held, S., Benediktsdóttir, A., Arango Galvan, C., Liotta, D., Hersir, G. P., Cornejo, N., Salas, J. L., Schill, E., “Magnetotelluric phase tensor analysis and its significance for tectonic interpretation: Case studies of the Los Humeros and Acoculco geothermal resources, Mexico”
		Ásdís Benediktsdóttir (ISOR)	Benediktsdóttir, A., Arango Galvan, C., Hersir, G. P., Held, S., Romo Jones, J. M., Salas, J. L., Ruíz Aguilar, D., Vilhjálmsson, A. M., Manzella, A., Santilano, A. “The Los Humeros Superhot Geothermal Resource in

			Mexico: Results from an Extensive Resistivity Survey”
		Gianluca Gola (CNR)	Gola, G., “Thermal modelling of magmatic geothermal systems: the role of deep-seated heat sources”
MFront User Meeting	17.–18. Oct. 2019, Paris, France	Thomas Nagel	Nagel, T., Parisio, F., Naumov, D., Lehmann, C., Kolditz, O.. MFront and OpenGeoSys. Connecting two open-source initiatives for simulations in environmental geosciences and energy geotechnics.
Herbsttagung AG Induzierte Seismizität (DGG)	Hannover, 2019	Claudia Finger (HBO)	Finger, C., Saenger, E.H. (2019), Abschätzung der Genauigkeit von Erdbebenlokalisierungen im geothermischen Reservoir Los Humeros (Mexiko): Sensitivitätskarten für Time-Reverse Imaging
SBE19 Thessaloniki Conference - Sustainability in the built environment for climate change mitigation	Thessaloniki (Greek), 22-25 October 2019	S. Karytsas (CRES)	S. Karytsas, D. Mendrinos, C. Karytsas. “Methods for measuring social impacts of renewable energy projects”
26th Meeting of Petrology Group of the Mineralogical Society Of Poland	24-27 October 2019, Chęciny, Poland	Pańczyk-Nawrocka Magdalena (PIG-PIB)	Pańczyk-Nawrocka M., Nawrocki J., Kozdrój W., Ziółkowska-Kozdrój M., Wójcik K.."New U-Pb ages of magmatic succession from Los Humeros Geothermal Field (E Mexico)", https://konferencje.pgi.gov.pl/ images/ptmin2019/mineralogia _special_papers_49_v8.pdf
Decovalex 2019 Symposium. Coupled Processes in Radioactive Waste Disposal and Other Subsurface Engineering Applications	4–5 Nov, 2019, Brugg, Switzerland.	Thomas Nagel (UFZ)	Parisio, F., Vilarrasa, V., Wang, W., Kolditz, O., Nagel., T., Coupled thermo-hydro-mechanical simulations of a supercritical geothermal system. In
38° Convegno Nazionale GNGTS	12-14 November 2019, Roma	Gianluca Gola (CNR)	Gola, G., Relationship between reservoir permeability, magmatism and the development of geothermal resources in continental settings
Der Geothermiekongress 2019	19-21 November 2019, Munich (Germany)	Leandra Weydt (TUDA)	Weydt, L. M., Bär, K., and Sass, I.: Thermo- and petrophysical rock properties of the Los Humeros geothermal field (Mexico): from outcrop analogue analysis to parametrization of a 3D geological-geothermal model

Assolombarda working group on environmental communication for companies	26 Nov 2019, Milan, Italy.	Michele Contini (SSSA)	Contini, M., (2019), “Community engagement: a model for practical application”
AGU 2019, Annual meeting of the American Geophysical Union (AGU)	9 – 13 December 2019, in San Francisco (USA)	Claudia Finger (HBO)	Finger, C., Saenger, E., “Estimating the source-location accuracy in the geothermal site of Los Humeros(Mexico) using sensitivity maps for time-reverse imaging”
		Daniel Maestrelli (CNR-IGG)	Maestrelli D., Bonini M., Corti G., Montanari D. and Moratti G., “Rift propagation vs inherited crustal fabrics in the Trans-Mexican Volcanic Belt (Mexico): insights into geothermal investigations from analogue models”
		Francesco Parisio (UFZ/ TU BAF)	Parisio, F., Lehmann, C. and Nagel, T., 2019, December. A constitutive model for the brittle-ductile transition of basalt. In AGU Fall Meeting 2019. AGU.
		Arie Verdel (TNO)	Verdel, A., IJsseldijk, J. van, Ruigrok, E., and Weemstra, C., “Shallow Crustal Reflection Imaging Using Distant, High-Magnitude Earthquakes”
IOP Conf. Series: Earth and Environmental Science	Jan 2020	S. Karytsas (CRES)	Karytsas, S., Mendrinos, D., and Karytsas, C., (2020) Measurement methods of socioeconomic impacts of renewable energy projects
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		Tania Toleda (GFZ)	Toledo T., Jousset P., Gaucher E., Maurer H., Krawczyk C., Calò M., Figueroa A. (2020). Local earthquake tomography at Los Humeros geothermal field (Mexico)
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Cities on Volcanoes 11	Heraklion, Crete, Greece, 23-27 May 2020	Constantine Karytsas, CRES	Karytsas, C., Kalantzis, C., Mendrinos, D., "Monitoring geothermal resources of very high temperature", Poster
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Project publications

60 publications related to the GEMex project are either already published, submitted to a journal or currently under revision:

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2.2.5 Task 2.5 Events

as Annex 1 in Deliverable D2.1 *Strategic communication plan.* It specifies events in 4 categories

- project events
- scientific events
- information events for stakeholders
- workshops for consulting stakeholders

Project meetings have been organised and conducted and are detailed in the report on Task 1.4 *Meetings.*

Scientific events: The GEMex consortium has contributed presentations to several scientific meetings, as specified in the report on Task 2.4 *Promotion of project results*. Additionally, two sessions have been co-organized and co-chaired by GEMex partners:

- session on "Exploration, utilization and monitoring of conventional and unconventional geothermal resources" has been co-chaired by Marco Calo (UNAM), Ivan Granados Chavarria (UNAM), Eugenio Trumpy (CNR)) during the EGU2020 (Vienna, Austria, 3-8 May 2020).
- Session "MR13A - Multiphysics of Geosystems: Coupled Thermo-Hydro-Mechanical-Chemical Processes in Fractured Porous Media I" has been co-organized by Francesco Parisio (UFZ/TUBAF) (https://agu.confex.com/agu/fm19/meetingapp.cgi/Session/86540)

Information event for stakeholders
On 8-9 October 2019, the second information event for stakeholders was organised as a side event of the European Geothermal Workshop (EGW) in Karlsruhe (Germany). At the EGW, 13 contributions treated GEMex topics and one keynote talk was dedicated to the presentation of results from the project.

Webinars
A series of 3 webinars were organised during the project. The first one was on November 28th, 2019 with the title *How to involve citizens in a geothermal project?.* This webinar was focused on the topic ''Social engagement in geothermal projects'' and was composed by a presentation of GEMex conclusions regarding the involvement of citizens in geothermal projects, and 2 presentations of that situation in Europe and Mexico.

The second webinar was carried on December 5th, 2019 with the title *Developing geothermal markets in Europe and Mexico.* This second webinar was focused on ''Market trends'' in Europe, Mexico and the vision from a geothermal project developer.

The third and last webinar was organised on December 12th, 2019 with the title Research & Innovation in Geothermal, presenting the priorities identified by the European and Mexican geothermal industry and research communities.

The three webinars were followed by 85 attendees. They are available in the GEMex website, in the results section.

GEMex Final conference
On 18-19 February 2020 the GEMex Final Conference took place in Potsdam, hosted by GFZ. More than 120 attendances were registered for the two-day conference with 32 technical oral presentations and 40 posters. IGA set-up the online registration as well as the online system for abstract submission and review. IGA prepared the conference proceedings.
One day prior to the conference, on 17 February 2020, the last general assembly of GEMex took place.

No further workshops of the stakeholder board took place in the last reporting period. However, the stakeholder board was invited to the final conference and some of the SB- members participated in the conference.

Finally, during the third reporting period, GEMex WP2 staff participated in the activities proposed by the Innovation and Networks Executive Agency (INEA). GFZ initiated the organisation of a joint booth for geothermal H2020 projects at the EGC 2019, Den Haag, The Netherlands, June 2019, where GEMex was presented together with 5 other H2020 projects. GFZ also initiated the organization of a joint workshop on "Risk assessment in geothermal projects", which took place in Potsdam, Germany, on 28th May 2019. An overview of the GEMex project was given at the INEA meeting held in Bruxelles in November 2019.

2.2.6 Impact

The main aim of WP2 was to facilitate and increase flow of information and collaboration between scientists as well as favour the link with the geothermal industrial community in order to promote the project results and favour the market expansion. Website statistical feedback suggests that interested people took a look of the information and results made available. The printed version of key deliverables as the Brochure and the Action plan will be then distributed in the next main geothermal Congresses (e.g., the postponed World Geothermal Congress 2021) to broadcast the main project results and to pave the way for further future collaboration which will be based on the large work performed in GEMex. Moreover, the broadcast of dissemination material (e.g., E-News) and the organization of dedicated stakeholder events (e.g., side events, final conference, webinars, stakeholder meetings) enlarged the perception of the project to a wider audience in the global geothermal community. In addition, project results in the form of reports, models or datasets were organised and in special repositories (e.g., Zenodo, OADB) able to provide to other interested scientists who want to study the two explored areas in GEMex or industry that start the assessment for new investments a valuable support to begin the activities not starting from scratch but from the robust base of GEMex results.
With all technical deliverables of GEMex being available in open access and the data made available through the OADB, GEMex contributes considerably to the Open Science strategy of the European Commission.

2.2.7 Dissemination activities

Bruhn, D., Jolie, E., Huenges, E., “European research efforts on engineered and superhot geothermal systems within Horizon2020”, GRC Geothermal Resources Council Annual Meeting, Reno, Nevada, USA 14 - 17 October 2018

Kieling, K. and the GEMex consortium “Searching for Superhot and EGS: an overview on geophysical approaches applied in the GEMex joint European - Mexican project”, EAGE Near Surface Conference: 1st Conference on Geophysics for Geothermal-Energy Utilization and Renewable-Energy Storage, 8 - 12 September 2019, The Hague (The Netherlands)

López-Hernández, A., Jolie, E., Gutiérrez-Negrín, L.C., Izquierdo-Montalvo, G., Liotta, D., González-Partida, E., Hersir, G.P., Arango-Galván, C., Romo-Jones, J.M., Ramírez-Montes, M., Improvement of

the conceptual model of Los Humeros: Beyond the GEMex Project, GEMex Final conference, Potsdam, Germany, 18-19 February 2020.

Trumpy, E., Liotta, E., Brogi, A., Manzella, A., Santilano, A., Gola, G., Schill, E., Held, S., Cornejo, N., Arango, C., Benediktsdóttir, A., Hersir, G., Gutiérrez-Negrín, L.C., Wheeler, W., Bastesen, E.,31. Data integration to constrain the geological structures in the Acoculco area, GEMex Final conference, Potsdam, Germany, 18-19 February 2020.

2.2.7.1 Accepted abstracts

Liotta, D., van Wees, J.D., Garduño-Monroy, V. H., Hernández Ochoa, A. F, Deb, P., Aragon, A., Lopéz Hernández, A., Bruhn, D., "The GEMex Project: Investigation of Acoculco (Mexico) as a potential EGS site." WGC 2021, Reykjavik (Iceland), May 2021

Bruhn, D., López-Hernández, A., and the GEMex consortia, "GEMex – Cooperation in Geothermal energy research Europe-Mexico for development of Enhanced Geothermal Systems and Superhot Geothermal Systems", WGC 2021, Reykjavik (Iceland), May 2021

Jolie, E., Liotta, D., Garduño-Monroy, V. H., Gutiérrez-Negrín, L. C., Arango Galván, C., Hersir, G. P., van Wees, J. D.,Aragón Aguilar, A., López Hernández, A., Bruhn, D., Kieling, K. and the GEMex team, "The GEMex project: Developing Los Humeros (Mexico) as a superhot geothermal site", WGC 2021, Reykjavik (Iceland), May 2021

2.2.7.2 Articles directed at the general public

Table 5: Articles directed at the general public.

Title	Type of article	Authors	Target audience	KPI
PIG – PIB na Europejskim Kongresie Geotermalnym i spotkaniu projektu GeMex (Horyzont 2020)	note (in Polish) on the PIG-PIB website (Aktualności – News) about participation of PGI-NRI delegates in EGC 2019 in the Hague and GEMex meeting in Bochum https://www.pgi.gov.pl/o-instytucie-geologicznym/wspolpraca-miedzynarodowa-2/11609-pig-pib-na-europejskim-kongresie-geotermalnym-w-hadze-i-spotkaniu-projektu-gemex-horyzont-2020-w-bochum.html	Kozdrój W., Ziółkowska-Kozdrój M.	Public, scientific community,	142 views (till 4 March 2020)
Super gorąca meksykańska geotermia – spotkanie	note (in Polish) on the PIG-PIB website (Aktualności – News) about participation of PGI-NRI delegates in in	Kozdrój W.,	Public, scientific	144 views (till 4

partnerów i konferencja końcowa projektu GEMex	the GEMex meeting and final Gemex conference in Potsdam https://www.pgi.gov.pl/aktualnosci/display/12138-super-goraca-meksykanska-geotermia-spotkanie-partnerow-i-konferencja-koncowa-projektu-gemex.html		community,	March 2020)
„GEMex: Erkundung und Erschließung unkonventioneller geothermischer Ressourcen in Mexiko" in ESKP (Earth System Knowledge Platform)	Article in German in the thematic special „Volcanim and society" https://themenspezial.eskp.de/vulkanismus-und-gesellschaft/inhalt/geothermie/geothermische-ressourcen-in-mexiko/	Egbert Jolie, David Bruhn	Public, scientific community	
Erschließung „unkonventioneller" geothermischer Systeme in Mexiko	Note on GFZ homepage https://www.gfz-potsdam.de/medien-kommunikation/meldungen/detailansicht/article/erschliessung-unkonventioneller-geothermischer-systeme-in-mexiko/	Philipp Hummel	Public	

2.2.8 Deviations from the Description of Action

- A part of the BRGM's activity (~1.6 PM) is moved to WP2 for 2 main purposes:
    - Preparation and participation to the GEMex Final Conference
    - Preparation of the manuscript for a scientific paper related to WP4 results
- A part of PGI-NRI's activities was shifted to WP2 for the following purposes:
    - presentation of the results from performed isotope and magnetostratigraphic studies at domestic and international conferences
    - participation in meetings of the GEMex project meetings in Bochum and Potsdam.
    - promotion of GEMex results at the joint booth of the cluster of geothermal H2020 projects at EGC2019 in The Hague
- NORCE shifted 1.25 person months from WP5 to WP2 in order to publish results and disseminate results at scientific conferences

2.3 Work Package 3: Regional Resource Models

Lead: UU
Partners: BRGM, CNR, OGS, TUDA, UNIBA, UROMA3, UU
Duration: month 1-44
Status: completed

Objectives:

Work Package 3 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. The key objective of these models was to characterize the geological and geothermal system in close collaboration with the geological and geophysical work respectively performed in WP4 and/or WP5. The understanding at regional scale on how the geological and geothermal systems have evolved and are structured helped the purposes of the other work packages.

Table 6: Status quo of personal resources WP3.

Participant number	4	5	7	8	9	12	14	**Total**
Short name	UNIBA	UU	CNR	TUDA	BRGM	OGS	UROMA3	
PM foreseen in total GEMex	2	20	47	12	22	2	17	122
PM used	11.38	36.1	47.51	0	17.09	2	16.5	130.79

2.3.1 Task 3.1 Integrated regional models and characterisation of the geothermal and volcanic systems

The 3D integrated geomodels activity was coordinated by BRGM.

The volcanological conceptual model activity was coordinated by Uni Roma 3.

2.3.1.1 Activities in the last reporting period

A. 3D integrated geomodels

The last reporting period was dedicated to the integration of the results obtained by the GEMex partners, in the geomodels of Los Humeros and Acoculco. This was mainly the case for geophysical surveys, geochemical interpretations and thermal modelling.

The other activity completed during the last reporting period was the production of the deliverable D3.1 - Report on the integrated geomodels of Los Humeros and Acoculco. This report provides an in-depth description of the work done during the project to construct the Los Humeros and Acoculco geomodels. The geomodels lead to the interpretation of the geothermal systems at both sites that is presented in the report.

B. Volcanological conceptual models of Los Humeros and Acoculco

Detailed petrographic analyses (thin section and SEM analyses) were performed in a joint approach by TUDA, UROMA3 and BGS on 37 reservoir core samples of the Los Humeros geothermal field in order to provide a better sample classification and to determine the intensity of hydrothermal alteration and fluid-rock interactions that occur within the reservoir. The improved understanding of how primary features of the rock mass were changed during fluid circulation is of great importance with respect to analysed rock properties in WP6.1 and for the modeling work in WP7, WP6 and WP3.

2.3.1.2 Main results from the task

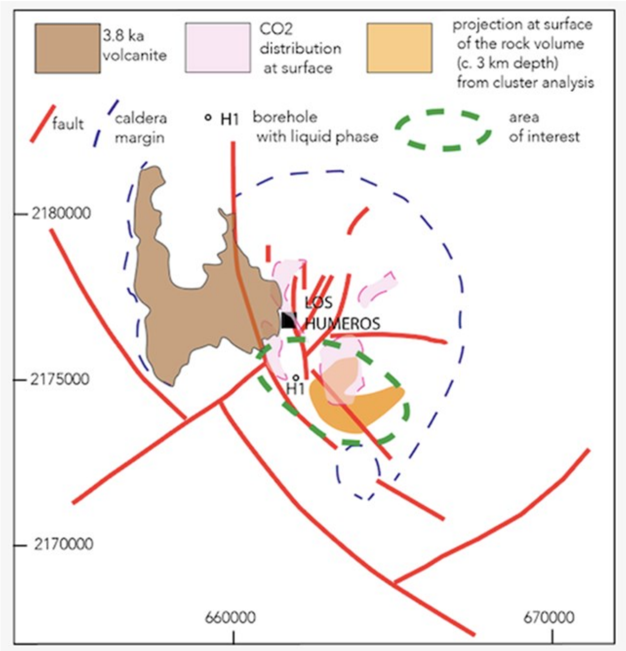
A. 3D integrated geomodels

European and Mexican partners constructed 3D geomodels at regional, local, and integration scales, in a collaborative way on Los Humeros and Acoculco.

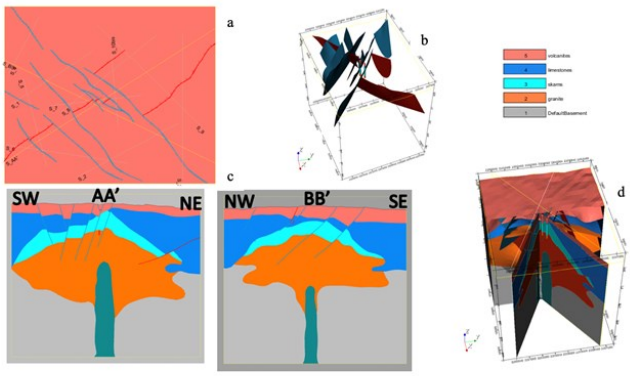
In Los Humeros, the structures were modelled from the geological map, additional field work, volcanos alignment study and results from the study of the exhumed geothermal system of Las Minas. The Los Humeros geological formations were described in four groups at regional and integration scales, and nine units at local scale. The CFE provided records for fifty-six wells to constrain the Los Humeros area at depth. Geophysical data such as resistivity from MT survey, Vp/Vs computation, 3D seismic events, and gravity were used in the integration process. The interpretation based on the integrated 3D geomodel tends to highlight a potential volume of rocks located to the south of the Los Humeros village and where fluids in superhot conditions can be explored at depth between 3.5 and 4.5 km, see Figure 5 (a).

In Acoculco, the data core to build the 3D geomodels was based on the recently published 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 lithological groups 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, see Figure 5 (b). Although the presence of a conventional hydrothermal system cannot be excluded for the Acoculco area, the data collected and organised, the implemented integrated 3D geomodel and the resulting conceptual model is the base for further evaluation in order to assess the feasibility of the stimulation for an EGS development of the area.

The 3D geomodels of Los Humeros and Acoculco were used by the GEMex partners along the course of the project as input for computations and simulations. In addition to the knowledge produced, the outcomes of the geomodelling work include the geomodels themselves that are available on the VRE of GEMex and will be shared in open access, and scientific presentations and papers.



(a)



(b)

Figure 5 - A (a) Los Humeros, interest area inferred from the integrated 3D geomodel. (b) Acoculco, the integrated local 3D geomodel.

The activity of T3.1 regarding the 3D geomodels is fully described in deliverable D3.1 - Report on the integrated geomodels of Los Humeros and Acoculco.

B. Volcanological conceptual models of Los Humeros and Acoculco

The GEMEX project has prompted renewed volcanological studies in the Los Humeros and Acoculco geothermal area. These have resulted in significant improvements of the volcanological conceptual model with very relevant implications for the geothermal model, in some cases drastically changing the previous understandings.

LOS HUMEROS

Magmatic heat sources

Based on the updated stratigraphic, geochronology and geothermobarometry data, including evidence from the resurgence structural patterns of the Los Potreros caldera, the main implications for the geothermal system are:

1. The magmatic plumbing system has undergone significant changes throughout the LHVC 700 kyrs long evolution, so it should not be simplified in a single, chemically stratified magma chamber, feeding a uniform heat flow at the base of the geothermal reservoir, as it has been considered so far.
2. The pre-caldera phase (700-164 ka) correspond to a build up phase of the main magma chamber that was present with its top at an average depth of 5 km at the time of the Xaltipan eruption, and the related heat flow increased over time up to its maximum just before the Xaltipan eruption at 164 ka.
3. The caldera-forming, rhyolite Xaltipan eruption is revised into a much younger age than previously believed, now dated at 164 ka (was 460 ka), implying that we today are much closer in time to the thermal fingerprint of its related magma chamber.
4. The erupted volume rhyolite magma of the Xaltipan ignimbrite is revised at 290 km3 DRE, more than twice larger than the previous estimate at 115 km3.
5. The Caldera phase encompasses a shorter period respect to previous figures due to the revised age of the Xaltipan ignimbrite, lasting between 164 ka and 69 ka, the latter being the age of the Los Potreros caldera forming eruption of the zoned rhyolite-andesite Zaragoza ignimbrite.
6. The temperature of the magma chamber during the Caldera phase cannot be higher than the eruptive temperatures of the related ignimbrites, i.e. 900-1000°C, much lower than temperature used in previous thermal modeling (e.g. 1350°C in Verma et al. 2011).
7. The Post-caldera monogenetic and poly-modal volcanism is fed by a multilayered plumbing system spanning from 30 km depth for basalts to less than 3 km depth for rhyolites and trachytes, indicating that the Caldera-phase magma chamber is largely solidified
8. The present day heat flow is due to the superposition of the residual heat flow provided by the cooling of the solidified Caldera-phase rhyolitic magma chamber with top at average 5 km depth and higher frequency heat flow spikes, related to a more granular assemblage of smaller and shallower magma bodies emplaced at various depths during the Post-caldera phase, with different initial temperatures according to their compositions

The Reservoir-Cap rock system

1. Revision of drill hole stratigraphic logs indicates that the grouping of rock formations in view of the modeling of the geothermal system should not be oversimplified in a “layer-cake” fashion.
2. Within the Pre-caldera Group, the so called vitric tuff separating the andesites should not be considered a continuous layer able to compartmentalize the hydrothermal circulation
3. The permeability of andesites is controlled not only by fracturing but also by micro- and macro-porosity, which may reach up to 15% of the total volume, of which 85% interconnected, resulting in an effective permeability of 1.5 mD; at the same time andesites are virtually impermeable where not fractured and have no porosity.
4. Within the entire sub-surface volcanic stratigraphic sequence, several basaltic to rhyolite bodies previously interpreted as stratigraphically emplaced can be re-interpreted as sill-like to cryptodome intrusions, controlling the local scale deformation, alteration and heat flow.
5. Strong topography of the top of the Caldera group in correspondence of such potentially intrusive bodies can explain the “granular” pattern of resurgence at Los Humeros (see below).

6. Within the Caldera group, the Xaltipan ignimbrite, even if forming a continuous layer, shows variable intensities of welding and alteration, which affect its permeability

Caldera collapses, Resurgence and Related Structures

1. Structural patterns at LH are due to the superposition of three main sources of stress and deformation:
    a. The pre-volcanic regional framework of the Laramide orogen associated with a NE-SW oriented σ_{hmax};
    b. The NE–SW trending regional σ_{hmax} has remained active during syn-volcanic extension, being responsible for the brittle deformation of the crust along steep NE–SW-striking normal faults and extensional fractures developed at tectonic strain rates; this regional stress field must be considered the long-lived “far- stress field”;
    c. The volcano-tectonic framework related to the caldera and the resurgence structures is associated with a nearly vertical σ_{hmax} associated with cycles of magma pressurization-depressurization, in the Xaltipan magma chamber, at strain rates order of magnitude faster than tectonic ones; this magmatic stress field must be considered the “deep local-stress field”, acting with different intensities since the beginning of the LHVC history.
    d. The post-caldera volcano-tectonic framework is also associated with the shallow (< 3 km) intrusions and solidification of small magma bodies of variable shapes in dependence of their rheology, sill (basalts) to cryprodomes (rhyolites); these ephemeral magmatic stress fields must be considered the “shallow local-stress fields”.
2. Observed deformations in the caldera floor, should be considered as polyphased and associated with different pressure sources, variable in intensity (shear and strain rates) and nucleation depths (crustal scale for regional deformation, upper crustal to very shallow scale for magma-related deformation), accounting for the inheritance of pre-existing structures, interplay between far-, deep-local and shallow local stress fields.

ACOCULCO

The Acoculco caldera was built upon a basement formed by Cretaceous limestones, the Zacatlán basaltic plateau and the Miocene pre caldera domes and lavas (~12.7 --~3.9 Ma). The caldera forming eruption occurred ~2.7 Ma ago with an explosive event that dispersed the Acoculco andesitic ignimbrite with a volume of 127 km³. A caldera structure of 20 km ×18 km in diameter formed, followed by the establishment of an intra-calderic lake and sedimentary deposition. Early post caldera activity (2.6-2.2 Ma) was constrained within the caldera ring fault producing 27 km³ of lava flows and domes dominantly of basaltic trachyandesite to basaltic composition. This activity caused bulging of the central part of the caldera. Late post caldera activity (2.0- 1.0 Ma) migrated dominantly to the periphery of the caldera, emplacing 77 km³ of rhyolitic domes, lavas, and the Encimadas ignimbrite (26 km³). Finally, extra caldera activity (0.9-0.06 Ma) vented scoria cones, and lava flows of basaltic trachyandesite to basaltic andesitic composition, and the rhyolitic Tecoloquillo ignimbrite (11 km³ with a total volume of 14 km³. Effusive eruptions dominated the evolution of the complex with ca. 79% of the eruptive products.

In order to elaborate models of the geothermal reservoir, it is very important to know the magmatic history and depth of the system that supply heat to the geothermal field. This is more relevant in caldera complexes where the collapse occurred hundreds of thousands of years ago and there is uncertainty about where and how heat is supplied to the upper crust. The collapse at the ACC occurred 2.7 Ma, a long enough time span to dissipate the heat associated with the magmatic reservoir. However, volcanism has been continuously active until 60 ka, becoming more voluminous through time and compared to other eruptive centers, reaching similar accumulative volumes in much longer periods during the last 2.7 Ma; the total exposed minimum erupted volume over an area of 856 km^2 is ca. 157 km^3 (resulting in an average eruptive rate of 0.058 km^3). These magmas erupted at rates of 22 km^3 during the syn caldera stage, 32.8 km^3 for the Early Post caldera, 70.6 km^3 for the Late Post caldera, and 31 km^3 for the Extra caldera volcanism. Similar accumulative volumes erupted in other volcanoes in less than 0.5 Ma. Hence, the energy input has steadily increased with time. Although we consider the continuous and voluminous magma supply to the surface as an important heat supply, we think that the heat supplied by shallow intrusions and magmas outside the reservoirs is more relevant. We know where, in the plumbing system, the post caldera magmas stagnate, and as shown above we know that heating of the post caldera magmas was pervasive through time. This process ensures a protracted heat supply because the heating magmas are not erupted and yield heat for long periods of time.

The activity of T3.1 regarding the volcanological conceptual models is fully described in deliverable *D3.2 - Report on the volcanological conceptual models of Los Humeros and Acoculco*.

2.3.2 Task 3.2 Integrated geothermal models and resource assessment

2.3.2.1 Activities in the last reporting period

This task finished in 2019 according to planning. The results of the task were reported in March 2019 in deliverable D3.4 - Report on Regional resource assessment and geothermal models. This last reporting period was used for the preparation of a joint publication based on the work and results of this task.

2.3.2.2 Main results from the task

Acoculco

Based on the available temperature data and deep geometries, a time-dependent thermal modelling was performed in order to characterize the thermal structure beneath Acoculco area as well as the deep-seated heat source in terms of emplacement depth, temperature and age of the last magmatic event. In Figure T3.2 the 3D image of the simulated temperature distribution is displayed together with the comparison between the observed and simulated temperatures at borehole locations.

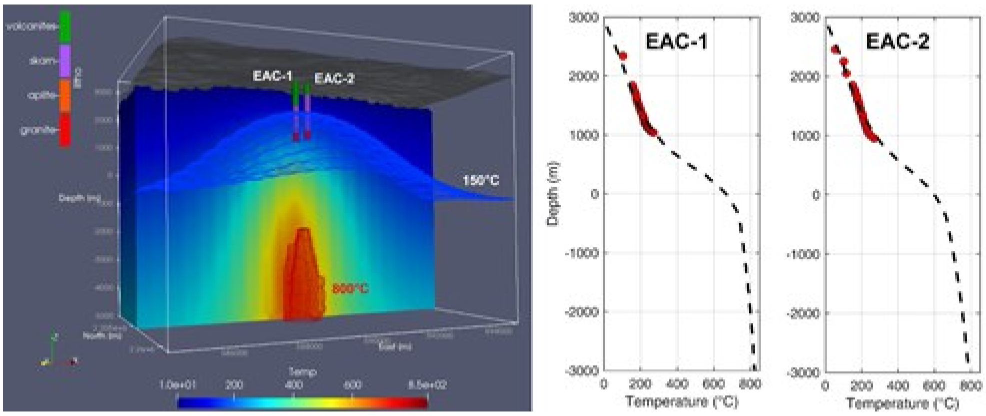


Figure 6: Left: 3D temperature distribution and thermal profiles evaluated at the initial cooling phase (5 ka of cooling) for an emplacement temperature of 900°C and the top of the intrusion at 2300 m b.g.l. Right: equilibrated temperature measurements at EAC-1 and EAC-2 boreholes (red dots) together with the simulated thermal profiles.

2.3.3 Task 3.3 Analogue modelling

The Analogue modelling activity was coordinated by CNR.

2.3.3.1 Activities in the last reporting period

Activity of Task 3.3 'Analogue modelling' during the last reporting period was dedicated to complete the series of analogue models, and to integrate the experimental results produced by the different partners involved in the Task.

In this period, Deliverable D3.5 (Interactions between regional tectonics and volcanoes) and Deliverable D3.6 (Collapse of caldera and volcanic edifices and the associated surface deformation) were completed. These reports provide a detailed description of results of experimental models that were devoted to explore specific volcano-tectonic processes that are pertinent to geothermal exploration of Los Humeros and Acoculco areas

2.3.3.2 Main results from the task

The analogue modelling activity was carried out at the experimental laboratories of partners involved in the Task 3.3 (CNR and Uni Roma Tre). The experimental work addressed different research issues that have been investigated in specific experimental series, which are detailed below by reference to Deliverables 3.5 and 3.6:

- Series D3.5-1: Relationships between a propagating rift and existing crustal faults
- Series D3.5-2: Role of pre-existing discontinuities within the brittle overburden in caldera collapse process
- Series D3.6-1: Symmetric and asymmetric caldera collapse
- Series D3.6-2: Role of pre-caldera volcano-related topography
- Series D3.6-3: Caldera resurgence and interaction with pre-existing structures

- Series D3.6-4: Combined effects of compressional and extensional tectonics structures and magmatic processes on the Los Humeros Volcanic Complex
- Series D3.6-5: Shallow-intra-caldera intrusions

Series D3.5-1 investigated the relationships between continental rifting associated with the Trans-Mexican Volcanic Belt in Mexico and pre-existing crustal discontinuities in the geothermal areas. The experimental results suggest that rifting propagation is expected to reactivate crustal anisotropies that potentially focus the ascent of magmatic fluids, such as at Los Humeros and Acoculco volcanic systems.

Series D3.5-2 explored the role of pre-existing fabrics delimiting magma reservoirs and/or located into the pre-volcanic substratum. The results of scaled analogue models suggest that inherited discontinuities are reactivated during caldera collapse, exerting a strong control on the geometry of experimental calderas that show linear rims in correspondence to the discontinuities. Both Los Humeros and Acoculco calderas are characterized by patterns with similar rectilinear rims. These results may indicate that both model and the natural prototypes share a similar evolutionary model, thereby validating the hypothesis of a regional tectonic influence on the development of the Los Humeros and Acoculco caldera collapse.

Series D3.6-1 investigated the geometry of caldera structures resulting from symmetry or asymmetric collapse, which may be also induced by experimental volcanic edifices (Series D3.6-2) concentric or eccentric with respect to the caldera. Symmetric collapse models confirm the well-known progression from early outward-dipping reverse fault to late inward-dipping peripheral normal faults. Asymmetric collapse yields instead the development of a peculiar, asymmetric fault pattern in which normal faults accommodate the asymmetric sinking of the caldera roof block. This fault geometry may have implications for the uprising of geothermal fluids, and may influence the following caldera resurgence.

Series D3.6-3 explored various boundary conditions of caldera resurgence processes, focusing on the Los Potreros caldera, which is nested into the broader Los Humeros caldera and has been interpreted as resurgent caldera. The Los Potreros caldera hosts most of the geothermal production in the area, which is linked to the complex intra-caldera fault system exhibiting curved fault segments departing at high angle from two main fault segments (Mastaloya and Los Humeros faults). Scaled analogue models performed with relatively shallow intrusion depth (scaled natural depth of ca. 4.5 km) show a remarkably similar pattern, with a main fault crosscutting the whole experimental resurgent block and sub-orthogonal secondary faults. In addition, the main normal fault has a geometry and position in the caldera that are similar to the ca. W-dipping Maxtaloya and Los Humeros faults within the Los Potreros caldera. Such a good correlation between the fault pattern of models and nature suggests a similarity in dynamic processes, and thus we cannot rule out the possibility that the Los Potreros evolution has been mainly modulated by magma resurgence. This model has obvious implications for the geometry of faults at depth that may represent potential targets of geothermal exploration. The modelling has also addressed the role of pre-existing structures in the caldera resurgence process.

Series D3.6-4 investigated and simulated experimentally the whole sequence of geological processes that have been identified in the Los Humeros Volcanic Complex by the structural study presented in Norini et al. (2019, J. Volc. Geotherm. Res.). The modelling results show that inherited compressive and extensional regional tectonic structures play a role in the evolution of the magma feeding system, collapse geometry and post-collapse deformation of the experimental caldera. Main resurgence faults and post-caldera magma-driven hydrofractures reactivated the inherited tectonic weak planes in the pre-volcanic substratum beneath the model caldera. Plan-view geometry of resurgence faults is controlled by the inherited regional structures and volcano-tectonic radial stress field generated by experimental resurgence. The experimental results collectively suggest that secondary permeability in the geothermal reservoir overlying the post-caldera intrusion should mainly be related to the damage zone of resurgence faults delimiting uplifted and tilted sectors of the caldera floor.

Series D3.6-5 investigated the role of shallow-intra-caldera intrusions resulting from the ascent of several, very shallow (<1 km) multiple magma bodies (lava domes and cryptodomes) showing normal faulting at their top. In particular, experimental modelling addressed the relationships between apical graben and the source depth of the magma. The results of the modelling are consistent with the hypothesis that the uplift is driven by small and delocalized magmatic intrusions, as suggested by the field data (Urbani et al. 2020, Solid Earth). This conceptual model has implications for planning future geothermal exploration: siting of future geothermal wells should consider that the presence of shallow heat sources within the caldera may complicate the pattern of isotherms associated with the deeper heat flow.

The comprehensive activity of T3.3 regarding the analogue modelling, which was applied to the study region, is described in deliverable *D3.5 - Report on the analogue modelling of the interactions between regional tectonics and volcanoes* - and deliverable *D3.6 - Report on the analogue modelling of the collapse of caldera and volcanic edifices and the associated surface deformation*. In addition to these reports, the knowledge produced through the experimental work has been, and will be shared in open access articles and scientific presentations.

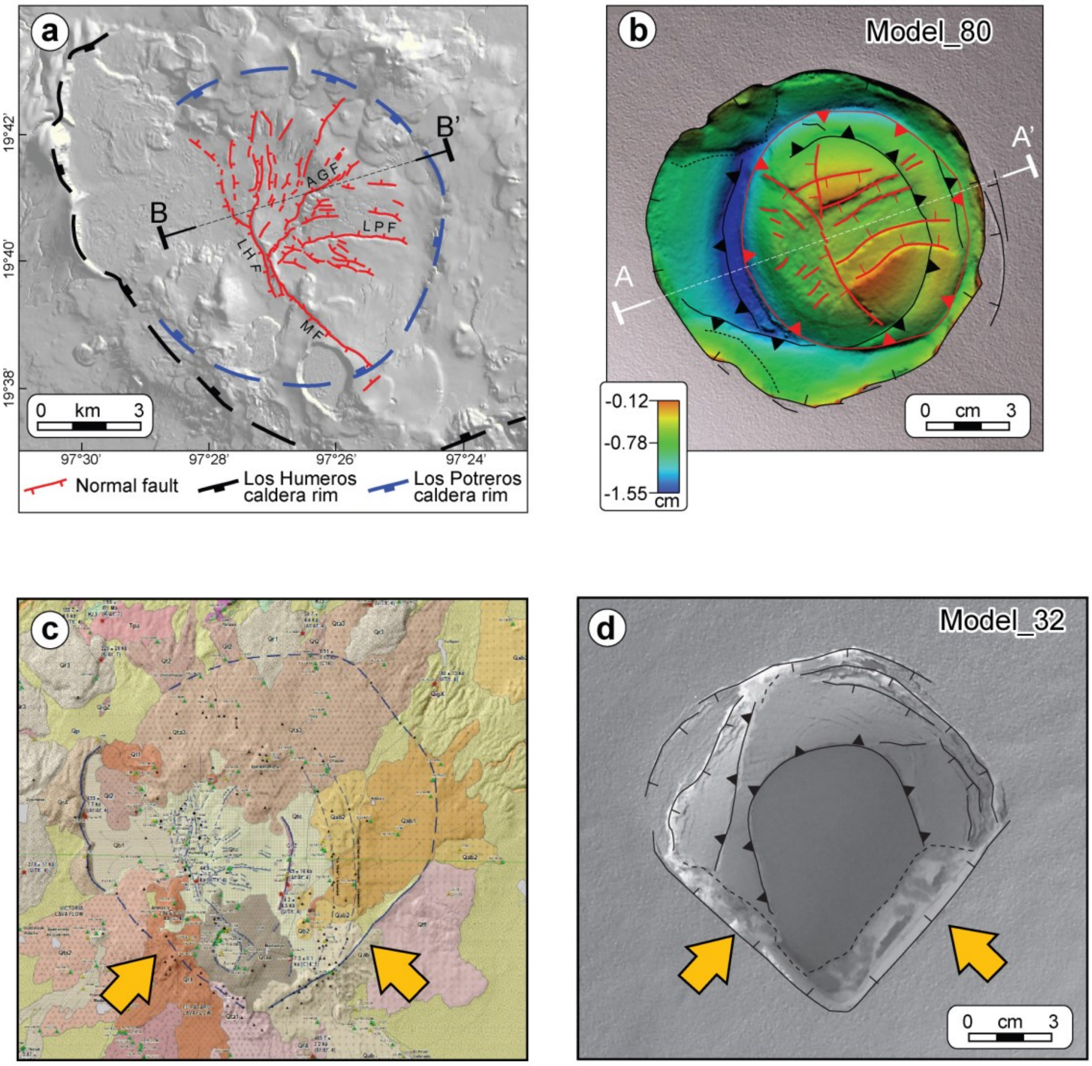


Figure 7: Comparison between experimental modelling results and the natural prototypes. (a) Intra-caldera fault pattern of the Lop Potreros caldera, and comparison with (b) the fault pattern of Model_80 that experienced relatively shallow intrusion of experimental magma. (c) Geometry of Los Humeros caldera rims (after Carrasco-Núñez et al., 2017, Terra Digitalis) and comparison with (d) caldera collapse of the Model_32 with built-in existing discontinuities. Yellow arrows point to equivalent caldera rims in model and nature.

2.3.4 Impact

For the research done in WP3, geological, geophysical and geochemical data were combined and integrated, thus enabling the construction of new regional scale models that provided a detailed 3D characterisation of the subsurface geological structure of Los Humeros and Acoculco. The models, moreover, served to investigate the role and control of various parameters on the geological, thermal and hydrological regional evolution, which resulted in new conceptual models of the geothermal systems in the study areas.

Field data as well as analogue and numerical models all show the importance of pre-existing basement structures, in particular inherited faults and fractures, not only on the evolution of the caldera systems but also on the fluid flow in the subsurface along both natural and hydraulic fractures. It, therefore, is crucial to explore for such basement structures in the early phase of the development of a volcanic geothermal system.

A site-specific result for Los Humeros is the identification of the key role of regional fault and fracture systems in the circulation of geothermal water, which in combination with regional structures led to the identification of a small area as a crucial sector for probable upflow of superhot geothermal resources.

For Acoculco the WP3 results indicated that potential EGS systems will rely on regional fracture systems, and that hydraulic stimulation may improve the permeability of these existing systems.

However, the largest impact on the WP3 results came from the integration of multi-disciplinary data (field observations, modelling data, lab measurements), which turned out to be crucial for both the construction and validation of the new, more detailed conceptual models of the volcanic geothermal systems in Los Humeros and Acoculco. The impact of this is twofold: 1) It has a large site-specific impact for the future development and sustainability of the two unconventional resources investigated; 2) The method developed presents an advancement of the exploration methods which can be applied to geothermal site worldwide and will reduce the exploration risks for future geothermal projects.

2.3.4.1 Publications

Note: Several publications reported in the other WPs of GEMex are related to WP3. They are not duplicated here.

Bär, K.: WP3: Contents of the CFE-Leapfrog Geological model of the Los Humeros Caldera, Mexico. GEMex internal report, 2017, 11 p.

Bär, K.: WP3: Contents of the CFE-Leapfrog Geophysical model of the Los Humeros Caldera, Mexico. GEMex internal report, 2018, 22 p.

Calcagno, P., Trumpy, E., Gutiérrez-Negrín, L. C., Norini, G., Macías, J. L., Carrasco-Núñez, G., Liotta, D., Garduño-Monroy, V. H., Hersir, G. P., Vaessen, L., Evanno, G., and Arango Galván, C.: Updating the 3D Geomodels of Los Humeros and Acoculco Geothermal Systems (Mexico) – H2020 GEMex Project, In Proceedings of World Geothermal Congress 2020 (WGC2020), Reykjavik, Iceland, 27 April – 1 May 2020, 12 p.

Calcagno, P., Evanno, G., Trumpy, E., Gutiérrez-Negrín, L. C., Macías, J. L., Carrasco-Núñez, G., and Liotta, D.: Preliminary 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, 2018.

Carrasco-Núñez, G., Bernal, J. P., Davila, P., Jicha, B., Giordano, G., & Hernández, J. (2018). Reappraisal of Los Humeros volcanic complex by new U/Th zircon and 40Ar/39Ar dating: implications for greater geothermal potential. *Geochemistry, Geophysics, Geosystems*, *19*(1), 132-149.

Evanno, G.: 3-D preliminary geological modelling of the Los Humeros geothermal area (Mexico), M.Sc. Thesis, ENAG/MFE- 088-GB-2017, 123 pp., 2017, Available on VRE: https://data.d4science.net/snwT.

GEMex D3.1 Report on the integrated geomodels of Los Humeros and Acoculco

GEMex D3.3 Report on the hydrogeological model of Los Humeros

Gutiérrez-Negrín, L.C.A., López-Hernández, A., Garduño-Monroy, V.H., Ramírez-Montes, M.A., 2019: Main Outcomes for Mexico at the Half of the GEMex Project. IOP Conf. Series: Earth and Environmental Science 367 (2019) 012012 doi:10.1088/1755-1315/367/1/012012

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

Urbani, S., Giordano, G., Lucci, F., Rossetti, F., Acocella, V., and Carrasco-Núñez, G. (2020) - Estimating the depth and evolution of intrusions at resurgent calderas: Los Humeros (Mexico). Solid Earth, 11, 527–545, 2020. https://doi.org/10.5194/se-11-527-2020

2.3.4.2 publications in preparation

Limberger, J., Bonté, D., Békési, E., Beekman, F., Giordano, G., Kretzschmar, T., van Wees, J.-D. (2020, in prep) Estimating effects of magma chamber emplacement depth, groundwater flux, and local advection on the regional thermal structure of the Los Humeros Volcanic Complex, Mexico.

2.3.4.3 Datasets published (e.g. in zenodo)

BRGM plans to publish the geomodels constructed in T3.1 on an open access platform such as zenodo.

2.3.4.4 Academic theses

Evanno, G., 2017. 3D preliminary geological modelling of the Los Humeros geothermal area (Mexico). Master Thesis, ENAG/MFE-088-GB-2017, 123 pp. Available on VRE: https://goo.gl/XYdBT1

Vaessen, L. (2020a) 3D local modelling of the Los Humeros geothermal site. Master thesis, Utrecht University, in preparation

Vaessen, L. (2020b) New interpretation of the volcano-clastic sediments in the Los Humeros caldera. Guided research thesis, Utrecht University.

2.3.5 Dissemination activities (talks, posters, workshops)

Note: The status of T3.1 was presented twice a year at each GEMex EU and EU-MX General Assembly.

Bonini M., Corti G., Maestrelli D., Montanari D., Moratti G., 2018. Characterising the influence of pre-existing structures on caldera evolution by analogue modelling, (E-news GEMex), http://www.gemex-h2020.eu/index.php?option=com_content&view=article&id=85&Itemid=170&lang=en

Bonini M., Maestrelli D., Corti G., Montanari D., Moratti G., 2020. Collapsed calderas and resurgence vs inherited fabrics: insights from analogue modelling on the evolution of Los Humeros and Acoculco volcanic complexes. GEMex Final Conference, Potsdam, 17-20 February 2020 http://www.gemex-h2020.eu/index.php?option=com_content&view=featured&Itemid=101&lang=en

Bonté, D., Limberger, J., Békési, E., Beekman, F., van Wees, J.-D., 2018. Preliminary estimation of the thermal structure of the Acoculco-Los Humeros area, Mexico. European Geosciences Union General Assembly, EGU2018-16270, Vienna, Austria.

Bontè, D., Limberger, J., Trumpy, E., Gola, G., and van Wees, J.D., 2020. Thermal signature and regional resource assessment in Los Humeros and Acoculco areas. Final conference of the Project GEMex, 18-19 February, 2020, Potsdam, Germany. Oral presentation.

Calcagno, P., Evanno, G., Trumpy, E., Gutiérrez-Negrín, L. C., Macías Vásquez, J. L., Carrasco, G., Liotta, D., and the GEMex T3.1 team, 2018. 3D preliminary geological models of Los Humeros and Acoculco (Mexico) - H2020 GEMex project. European Geosciences Union General Assembly, EGU2018-12811, Vienna, Austria.

Calcagno, P., Trumpy, E., Gutiérrez-Negrín, L.C., Liotta, D., Carrasco-Núñez, G.,, Norini, G., Brogi, A., Garduño-Monroy†, V.H., Benediktsdóttir, A., Gaucher, E., Toledo Zambrano, T.A., Hersir, G.P., Manzella, A., Santilano, A., Gola, G., Macías, J.L., Vaessen, L., Evanno, G., Arango Galván, C., "3D Geomodels of Los Humeros and Acoculco geothermal systems (Mexico) - H2020 GEMex Project: Methodology, products and feedback", GEMex Final conference, 18-19 February, 2020, Potsdam, Germany. Oral presentation.

Giordano, G., Carrasco, G., Lucci, F., Rossetti, F., Urbani, S., Implications of an updated volcanological conceptual model at Los Humeros for geothermal exploration and modelling. GEMex Final conference, 18-19 February, 2020, Potsdam, Germany. Oral presentation.

Gola, G., 2019. Thermal modelling of magmatic geothermal systems: the role of deep-seated heat sources. Extended abstract, 81st EAGE Conference & Exhibition, 3-6 June 2019, London, UK. Oral presentation.

Gola, G., Santilano, A. Trumpy, E., and Manzella, A., 2019. Numerical strategies on modelling deep-seated heat sources in continental, magmatic geothermal systems. Abstract, 27th IUGG General Assembly, 8-18 July 2019, Montréal, Canada. Poster session.

Gola, G., 2019. Thermal modelling of magmatic geothermal systems: the role of deep-seated heat sources. Abstract, 7th European Geothermal Workshop, 9-10 October 2019, Karlsruhe, Germany. Poster session.

Gola, G., 2019. Relationship between reservoir permeability, magmatism and the development of geothermal resources in continental settings. 38° Convegno Gruppo Nazionale Geofisica delle Terra Solida, 12-14 Novembre, Roma, Italy. Oral presentation.

Gutiérrez-Negrín, Luis C.A., 2017. Mexico: Kick-off Meeting of the GEMex Project. IGA News No. 106, January-March 2017, pp. 17-19 (Dissemination note).

Gutiérrez-Negrín, Luis C.A., 2017. Mexico: First Technical Meeting of the GEMex Consortium, and Installation of its BoD. IGA News No. 108, July-September 2017, pp. 12-13 (Dissemination note).

Gutiérrez-Negrín, Luis C.A., 2017. Proyecto GEMex: colaboración científica en geotermia entre México y la UE. Revista Constructor Eléctrico, No. 68, Año 5, agosto de 2017, pp. 14-16. (Dissemination note in Spanish, available at: https://constructorelectrico.com/usos-directos-de-la-geotermia-un-potencial-desaprovechado-en-mexico/)

Gutiérrez-Negrín, Luis C.A., 2017. Second Annual General Assembly of GEMex Project. IGA News No. 109, October-December 2017, pp. 3-5 (Dissemination note).

Gutiérrez-Negrín, LC.A., Kieling, K., 2018. Project GEMex: Meetings of the Mexican & European Consortia. *IGA News* No. 111, April-June 2018, pp. 2-5 (Dissemination note).

Gutiérrez-Negrín, L.C.A., López-Hernández, A., Garduño-Monroy, V.H., Ramírez-Montes, M.A., 2019: Main Outcomes for Mexico at the Half of the GEMex Project. 3rd International Geothermal Conference GEOHEAT2019, Petropavlovsk-Kamchatsky, Russia Federation, 3-4 September 2019.

Limberger, J., Bonté, D., Békési, E., Beekman, F., Kretschmar, van Wees., J.-D., (2019). Studying the effects of magma chamber emplacement depth, groundwater flux, and local advection on the regional thermal structure of the Los Humeros Volcanic Complex, Mexico. European Geosciences Union General Assembly, EGU2019, Vienna, Austria.

Lucci, F., Giordano, G., Carrasco-Núñez, G., Rossetti, F., Urbani, S., The Los Humeros caldera: unravelling the anatomy of the Holocene magmatic plumbing system through a petrological approach, GEMex Final Conference, Potsdam , Germany, 18. - 19.02.2020.

Maestrelli, D., Bonini, M., Corti, G., Montanari, D., Moratti, G., 2018. Exploring the role of inherited structures during caldera collapse: insights from analogue modelling. GEOMOD Conference, Barcellona, Spain, 1-4 October, 2018; http://www.ub.edu/geomod2018/Program_files/Abstracts_book_v1.0_LR.pdf

Maestrelli D., Bonini M., Corti G., Montanari D., Moratti G., 2019. Constraining caldera structures to understand geothermal fluid migration: insights from analogue modelling, and implications for the Los Humeros Volcanic Complex. European Geothermal Workshop EGW, Karlsruhe, Germany, 9-10 October 2019; https://indico.scc.kit.edu/event/343/contributions/

Maestrelli D., Bonini M., Corti G., Montanari D., Moratti G., 2019. Collapsed calderas vs inherited fabrics: insights from analogue modelling. SIMP-SGI-SOGEI, National Conference, Parma, Italy, 17-19 September 2019; http://parma2019.socminpet.it/index.php/abstracts/elenco-abstracts

Maestrelli D., Bonini M., Corti G., Montanari D., Moratti G., 2019. Interplay between rift propagation and inherited crustal fabrics: a case study from the Trans-Mexican Volcanic Belt (Mexico). SIMP-SGI-SOGEI, National Conference, Parma, Italy, 17-19 September 2019; http://parma2019.socminpet.it/index.php/abstracts/elenco-abstracts

Maestrelli D., Bonini M., Corti G., Montanari D., Moratti G., 2020. Rift propagation vs inherited crustal fabrics in the Trans-Mexican Volcanic Belt (Mexico): insights into geothermal investigations from analogue models. EGU2020-666, EGU General Assembly 2020, 3–8 May 2020, Vienna, Austria; https://doi.org/10.5194/egusphere-egu2020-666.

Maestrelli D., Bonini M., Corti G., Montanari D., Moratti G., 2020. Interplay between rift propagation and inherited crustal fabrics: insights into the Los Humeros and Acoculco volcanic complexes. GEMex Final Conference, Potsdam, 17-20 February 2020 http://www.gemex-h2020.eu/index.php?option=com_content&view=featured&Itemid=101&lang=en

Montegrossi, G., Deb, P., Clauser, C., Diez, D., Ramirez Montes, M. A, 2018. Modeling of Los Humeros geothermal field: preliminary results. European Geosciences Union General Assembly, EGU2018-17600, Vienna, Austria.

Sulpizio, R., Massaro, S., Costa, A., Groppelli, G., Vona, A., Giordano, G., Romano, C., Carrasco-Núñez, G., Norini, G., 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), GEMex Final Conference, Potsdam, 17-20 February 2020.

Weydt, L. M., Lucci, F., Carrasco-Núñez, G., Giordano, G., Lacinska, A., Rochelle, C., Bär, K., and Sass, I.:Petrophysical reservoir characterization of the Los Humeros geothermal field (Mexico): comparison of outcrop analogues and reservoir formations. In: GEMex Final Conference, GFZ, Potsdam , Germany, 18. - 19.02.2020.

2.3.5.1 Accepted abstracts

Bonté, D., Gutiérrez-Negrín, L.-C., Calcagno, P., Carrasco Núñez, G., Trumpy, E., Macías Vásquez, J. L., Giordano, G., Lopez, S., Kretzschmar, T., Gola, G., Bonini, M., Liotta, D., Limberger, J., van Wees, J. D., 2020. On the importance of regional characterisation for geothermal energy in volcanic areas: the example of Mexico. WGC2020, Reykjavik, Iceland, ~~April 2020~~ May 2021.

Bonté, D., Limberger, J., Gola, G., Trumpy, E., Lopez, S., Maurel, C., Armandine Les Landes, A., Giordano, G., Kretzschmar, T., Van Wees, J.D., 2020. Thermal and hydrological regional characterisation of Los Humeros and Acoculco (Mexico) using modelling methods – H2020 GEMex Project. WGC2020, Reykjavik, Iceland, ~~April 2020~~ May 2021.

Calcagno, P., Trumpy, E., Gutiérrez-Negrín, L. C., Norini, G., Macías Vásquez, J. L., Carrasco, G., Liotta, D., Garduño-Monroy, V. H., Hersir, G. P., Arango-Galván, C., Vaessen, L., Evanno, G., and the GEMex

T3.1 team, 2020 (accepted). Updating the 3D Geomodels of Los Humeros and Acoculco Geothermal Systems (Mexico) – H2020 GEMex Project. Accepted, WGC2020, Reykjavik, Iceland, Postponed to May 2021

2.3.6 Deviations from the Description of Action

In the reporting period, extra activity (~8PM) was done in WP3 by UU for (1) contributing to the preparation of the Deliverables D3.5 and D3.6; and (2) the preparation of a joint manuscript of the modelling results obtained in Task 3.2 (still ongoing). The extra 8 PM in WP3 is compensated by less UU activities in WP7 and WP8.

TUDA shifted person months from WP3 to WP6 and 7. For WP3, TUDA mainly evaluated pre-existing data provided by CFE and made them accessible to the WP3 team to incorporate this data in the geological models. Since those data was also relevant for WP6, TUDA decided to report the personnel in the context of WP6.

2.4 Work Package 4: Tectonic control on fluid flow

Lead: UNIBA
Partners: BGS-NERC, BRGM, CIPR, CNR, GFZ, IFE, ISOR, PIG, UNIBA, UROMA3
Duration: month 1-30
Status: completed

Objectives:

Work Package 4 developed at an understanding of the relationships among geological structures and physical and chemical properties of high temperature geothermal resources in volcanic systems. The objectives can be summarized as follows:

1. Study of the relationships between brittle geological structures and fluid flow in fossil, analogue, geothermal systems as a key for understanding the deep structures in Los Humeros.
2. Study of the chemical and physical characteristics in the paleo-fluids in order to define their chemical and physical characteristics.
3. Study of the relationships between brittle geological structures and super hot fluid flow in Los Humeros.
4. Study of the relationships between brittle geological structures and fluid flow in Acoculco, for contributing to the understanding of the geological conditions at which EGS can be performed.
5. Physical and chemical characteristics of the geothermal and cold fluids in Acoculco and Los Humeros.

These five objectives include: indications on the stress field, distribution of fractures and geological evolution of the three study areas and geochronological analyses in order to constrain their geological evolution in terms of geothermal issues.

Table 7: Status quo of personal resources WP4

Participant number	1	2	4	7	9	10	13	14	18	21	**Total**
Short name	GFZ	ISOR	UNIBA	CNR	BRGM	IFE	CIPR	UROMA3	UKRI	PIG	
PM foreseen in total GEMex	36	24	69	70	10	12	18	48	8.5	36	331.5
PM used	34.4	11.21	69	70.54	7.94	12.5	17.46	48	7.35	38.87	317.27

Work package 4 was already concluded in the previous technical reporting period. Therefore, only the main results will be summarized in the following subsections.

2.4.1 Task 4.1 Understanding from exhumed systems

2.4.1.1 Activities in the last reporting period

Task 4.1 has been concluded in the previous reporting period.

2.4.1.2 Main results from the task

Studies on the Las Minas exhumed geothermal system indicated that the deep geothermal circulation (i.e. within the carbonate substratum) is controlled by fractures intersection and their damage zones. In particular, permeability was mainly controlled by the NNW-striking fractures, by their intersection with the NE-striking fractures and by the pre-existing foliations (i.e., bedding and granite/limestone boundary), where fluids were channelled when hydraulically connected to the main structural conduits. Hydrothermal fluid properties, studied by fluid inclusions and geochemical analyses, indicated circulation of hyper- to low- saline (meteoric) fluids, and from high (>600°C) to low (about 250°C) temperatures. Hyper-saline and hot to super-hot fluids were present at the deeper structural levels, while fluids with decreasing temperatures and salinity were recognized at shallower structural levels, these latter comparable with the present exploitation carried out in Los Humeros geothermal area. By this, the lesson we learnt is that the research should be addressed to the identification of similar structural relationships in the Los Humeros basement by integration and interpretation of indirect methods, since the outcrop conditions are not favorable. One of the main result is the new structural geological map of Las Minas, here below reported, obtained in cooperation with our Mexican colleagues.

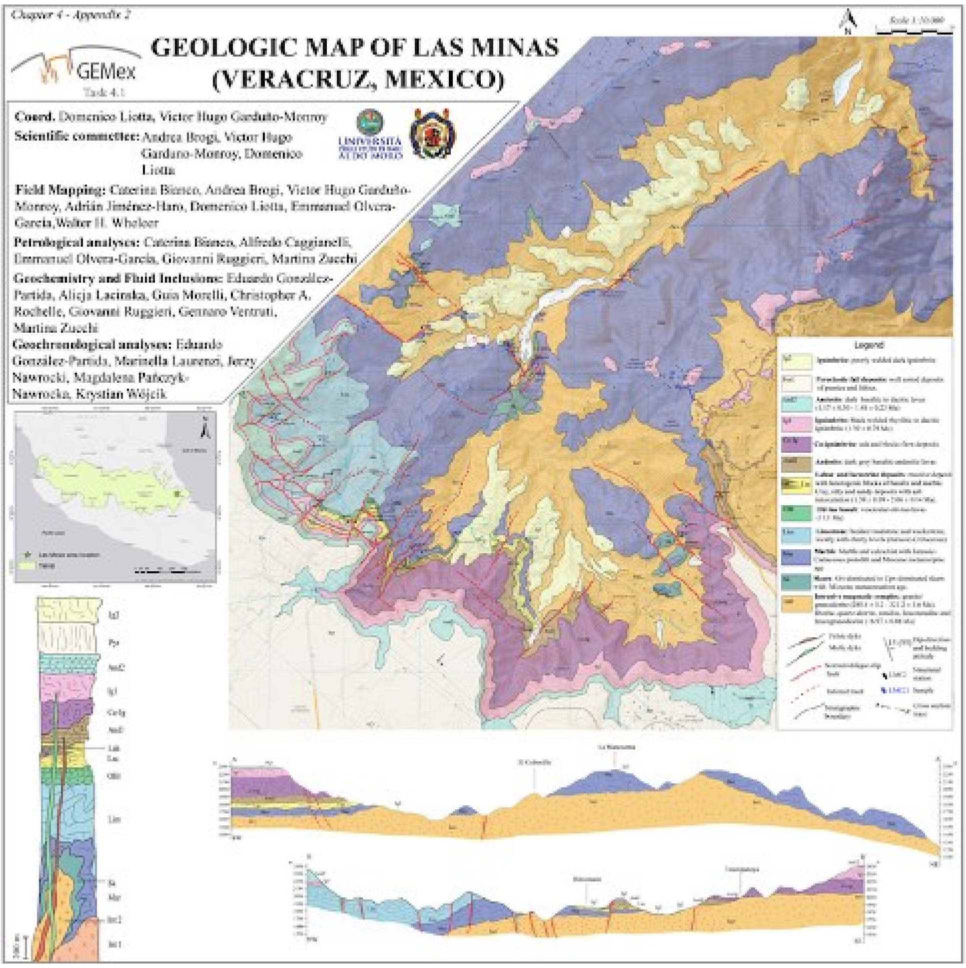


Figure 9: Structural and geological map of the Las Minas area Acoculco (from Deliverable 4.1)

2.4.2 Relationships between brittle structures, and fluid flow in active systems (Los Humeros and Acoculco)

2.4.2.1 Activities in the last reporting period

Task 4.2 has been concluded in the previous reporting period.

2.4.2.2 Main results from the task

Los Humeros

Petrological studies performed in samples from lavas indicate that the recent volcanic evolution is characterized by small and diffuse magma pockets, located at different structural levels. These have been favoring heat transfer and, presumably, trapping of hot to super-hot fluids. Regarding faults and fractures, regional studies carried out in the surroundings of Los Humeros indicate three main groups of fractures: a) regional fractures connected to the extensional tectonics, active since Miocene; b) fractures connected to the Laramide orogenesis in carbonate; c) fractures developed during the caldera collapse. Looking to structures affecting the basement (i.e. where hot to super-hot fluids are located), the main point to be discussed is about the location of the regional fractures since outcrop analyses do not permit to clearly recognize them, as a consequence of the rheological behavior of the Pleistocene-Holocene ignimbrite, hiding brittle deformation and widely covering the area. An indirect way to analyze regional structures is proposed through the study of the morpho-tectonic lineaments and alignment of monogenetic volcanic vents. Both methodologies suggested two main trends of fractures, NNW- and NE-striking, coherent with the previous knowledge. These fractures are delimiting and affecting the Los Humeros caldera rim, reasonably representing pre-existing discontinuities, also activated during the caldera collapse.

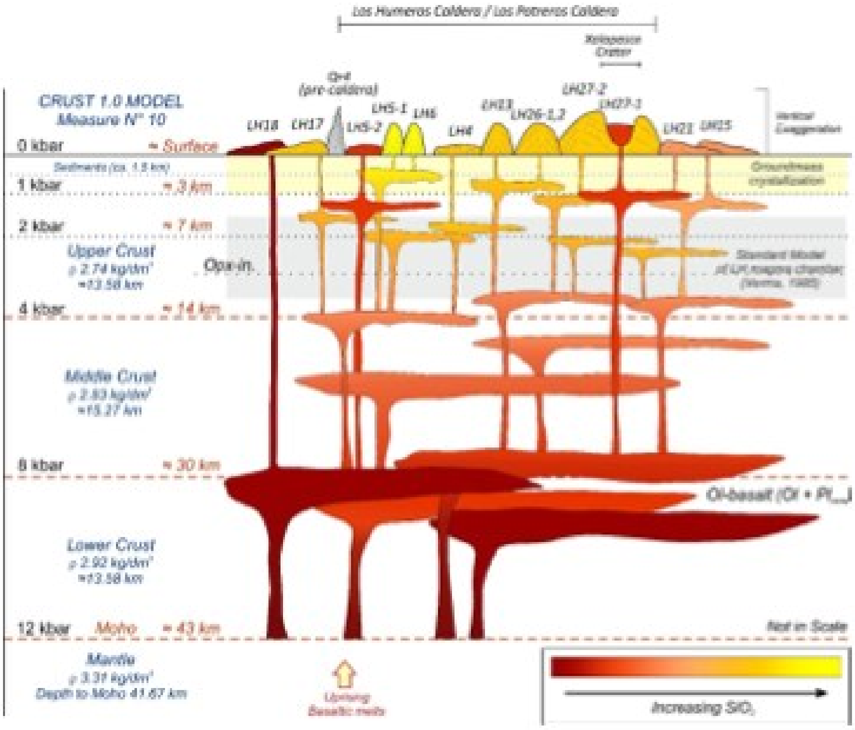


Figure 10 - magmatic conceptual model of Los Humeros (from Deliverable 4.2)

Acoculco

The structural fieldwork was mainly dedicated to collection of kinematic data on recent fault-slip surfaces. The results are summarized as follows:

- under the regional stress field, defined by a NNW-striking stretching direction, two main NNW- and NE-striking fault systems developed. These are accompanied by minor faults, with a slight different orientation, N- and E-striking respectively. The age of deformation is from Miocene to Present, as testified by the age of rocks, sediments and soil, involved in the faults activity.
- The NNW- and NE- striking faults are characterized by a dominant oblique right-lateral and normal movements, respectively. A second kinematic movement, with a dominant vertical displacement, is recognizable in the NNW-striking fault system.These features account for interpreting the NNW-striking faults as transfer faults, acting in the regional extensional

regime which causes the NE-striking faults, too. Coeval processes of crustal uplift reactivated pre-existing structures with a dominant vertical movement.

- Although the regional stress is well defined, in terms of local stress, these results indicated a variability depending on kinematics.
- In the borehole areas, the two previously mentioned fractures trends were also detected, in the frame of a general migration of deformation toward north-northwest. This latter process implies that the EGS chosen area, having sealed fractures, appears to be far from the present permeability.

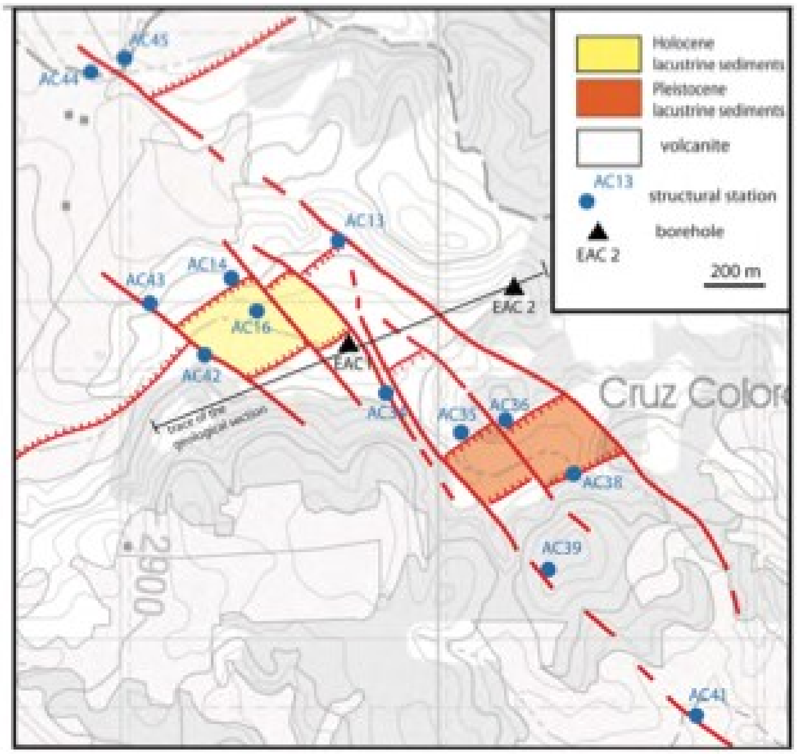


Figure 11 - Structural map of the boreholes area in Acoculco (from Deliverable 4.2)

2.4.3 Geochemical characterization and origin of cold and thermal fluids

2.4.3.1 Activities in the last reporting period

Task 4.3 has been concluded in the previous reporting period.

2.4.3.2 Main results from the task

Water samples from cold and thermal springs, wells taping cold or warm water, maar lakes, reinjection wells and natural gas emissions were collected in both June 2017 and March 2018 (respectively 57 and 87). Stable water isotopes of geothermal fluids are compatible with the occurrence of physical-chemical processes commonly observed in several geothermal fields worldwide, such as oxygen-shift process due to the interaction of meteoric water with reservoir

rocks and fractionation due to boiling and phase separation. Isotopes data are in agreement with the hypothesis of regional meteoric component as source of geothermal fluids. Regional recharge cannot be ruled out for Los Humeros Geothermal Field (LHGF) and it could represent an important percentage of the total amount, in comparison to possible deep magmatic fluids.
Mean values of δ2H and δ18O for cold water collected in the Acoculco geothermal field (excluding the acid waters) are similar to those of Los Humeros. This feature is consistent with the regionalization of a meteoric component.

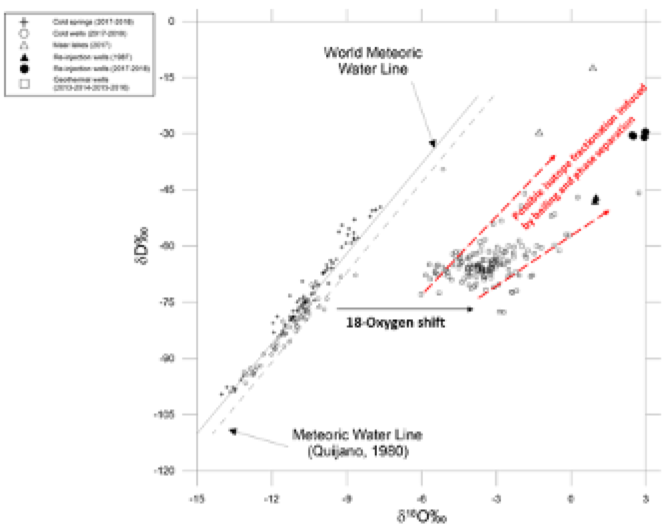


Figure 12 - Deuterium vs 18-Oxygen correlation diagram for water samples (cold and thermal springs and water wells) inside and outside the LHGF, as well as geothermal wells (further details from Lelli et al, under revision)

Several kinds of classical and auxiliary geothermometers are applied and developed for thermal/geothermal fluids of both geothermal systems (see Chapter 3, part 1 of the deliverable 4.3). The Na-Li and Na-Cs auxiliary geothermometers, recently defined, give concordant temperature values (320 ± 30°C) with those estimated using the classical Silica-quartz, Na-K and Ca-K geothermometers, and the isotopic $\delta^{18}O_{H2O\text{-}SO4}$ geothermometer, for the Los Humeros deep dilute geothermal waters, depleted in Ca, Mg and Sr, and enriched in SiO_2, B and Li, after interaction with andesitic rocks in the reservoir. For numerous thermal waters from both geothermal areas, which are mainly constituted of shallow waters rich in Ca, Mg and Sr, interacting with Mesozoic limestone at temperatures estimated from 60 to 100°C, the Na/K and Na/Li ratios similar to those of the Los Humeros geothermal waters and the relatively high B concentrations suggest small inflows of high-temperature deep waters (close to 300°C), despite the low permeability of these areas.

Detailed study of soil degassing was performed inside the LHGF producing zone and also in AGF (see Chapter 2, part 2 of the deliverable 4.3). In LHFG some areas are characterized by good correlation between known faults and the increasing in CO_2 flux rate and elevated radon and thoron concentrations (see Chapter 4, part 1 of the deliverable 4.3). The presence of very high degassing areas (CO_2 efflux > 300 g $m^{-2}d^{-1}$) at the surface can only be explained by convection along permeable faults/ fractures. By carbon isotopic analysis of CO_2 and helium isotopic analysis $^3He/^4He$ determined in gases released by the soil, it is indicated that faults and fractures in the subsurface have a link to the deep geothermal reservoir and favor the upflow of hydrothermal fluids. The results of soil degassing study suggest that the most permeable zone in the Los Humeros geothermal field is located in SW area and extends towards the north and northeast. In Acoculco, gas flux was very low and no significant correlations with alignment of regional faults/fracture were evidenced (see Chapter 2, part 2 of the deliverable 4.3). Just in a few sites, evidences for enhanced gas flow associated to the location of natural gas emissions, drilled boreholes and/or with a few specific tectonic features seems to be present.

Several fluid-rock interaction experiments at different temperatures (T) and pressure (P) have been carried out to constrain the physical-chemical processes occurring in the upper reservoir of the LHGF (see Chapter 5, part 1 of the deliverable 4.3). The obtained results indicate that silicification is the most important alteration process. Analytical methods used suggest that in LHGF high mineralized waters likely reacted with andesitic reservoir. In particular, the presence of wairakite in some experimental products could corroborate the hypothesis that infiltrating waters extensively reacted with crossed rocks before reaching the reservoir.

Geochemical modeling was used in several fluids from Los Humeros geothermal wells, investigating the possible mineral phases and their behavior as a function of temperature. Possible hydrothermal/metamorphic high temperature secondary minerals were identified, together with a group of secondary minerals with scaling potential. Also, some information regarding the origin of chemicals present in the fluids of Los Humeros geothermal field are obtained.

Seven tracer candidates were first tested for thermal stability in closed quarts vials at temperatures from 150 to 250°C (see Chapter 7, part 1 of the deliverable 4.3). Of the seven compounds tested, one tracer candidate (Tracer C) showed satisfactory properties as geothermal tracer and is expected to be suitable at temperatures up to at least 375°C.

2.4.4 Impact

The work done in WP4 highlights the importance of the joined study in exhumed (Las Minas) and active (Los Humeros) geothermal system respectively, as a key for the understanding of the deep structures, and for the interpretation of geophysical data. Furthermore, the integration with the hydrological and geochemical study of fluids permitted to have a preliminary conceptual model of the Los Humeros geothermal system, based on the integration among the results of geochemical, structural, kinematics petrological and mineralogical data permitted us to have a conceptual model of the relationships between geological structures and fluid flow at depth. The outcome led us to define the key-factors for the interpretation of the geophysical data in terms of geothermal resources.

Similarly, in the Acoculco area, where EGS will be promoted, fieldwork data highlighted the major existing fracture system and the stress field active in the area. Both information serves as a basis for the analysis for the potentiality of EGS in the area.

The final key-message is therefore that an accurate conceptual model provides a valuable contribution for a better understanding of geothermal systems, in which geological and structural settings and geochemical processes are interconnected. An integrated study is mandatory (linking geology-tectonics-geochemistry-geophysics) to obtain the required knowledge. For geothermal systems under production, the impact of this kind of approach contributes to use geothermal resources in a more efficient and sustainable way. We did this in GEMex, constructing a methodology of fieldwork, worth to be applied and newly tested.

2.4.5 Publications

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2.4.6 Dissemination activities (talks, posters, workshops)

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Sanjuan, B., Developments of auxiliary chemical geothermometers (Na-Li, Na-Cs) applied to the Los Humeros and Acoculco high-temperature geothermal fields (Mexico), GEMex Final conference, 18-19 February, 2020, Potsdam, Germany. Oral presentation.

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Wheeler W. et al.: “GEMex- Europe-Mexico collaboration for development of Enhanced Geothermal Systems and Superhot Geothermal Systems” GeoEnergi2017 – Geothermal Conference. Bergen (Norway), 22-23 May 2017

Wheeler, W., Bastesen, E., Liotta, D., Brogi, A., Garduño Monroy†, V. H., Jiménez Haro, A., Gómez Álvarez, F., González Partida, E., Fault models of the Acoculco borehole area for 3D architecture and fluid flow appraisal, GEMex Final conference, 18-19 February, 2020, Potsdam, Germany.

2.4.6.1 Accepted abstracts

Bastesen E., et al. : Studying analogue geothermal systems in Mexico: insights on the deep part of Los Humeros geothermal field from Las Minas mining area (eastern Mexico). WGC2020, Reykjavik, Iceland, April 2020, postponed to May 2021.

Jentsch, A., Jolie, E., Pfeiffer, L., Zimmer, M.: “Volcano-tectonic structures and their influence on soil gas emissions in a low permeable geothermal reservoir –A case study from Los Humeros Volcanic Complex, Mexico”, WGC2020, Reykjavik, Iceland, April 2020, postponed to May 2021.

D. Liotta, E. Bastesen, C. Bianco, A. Brogi, A. Caggianelli, V.-H. Garduño-Monroy, E. Gonzalez-Partida, A. Jimenez-Haro, W. Kozdrój, A. Lacinska, B. Lepillier, G. Morelli, J. Nawrocki, E. Olvera-Garcia, M. Pańczyk-Nawrocka, C. Rochelle, G. Ruggieri, A. Torabi, G. Ventruti, H.W. Wheeler, K. Wójcik, M. Ziółkowska-Kozdrój, M. Zucchi (2020). Analogue Geothermal Systems In Mexico: Insights Into The Deep Part Of Los Humeros Geothermal Field From The Las Minas Mining Area (Eastern Mexico). Proceedings of the World Geothermal Congress 2020, Reykjavik, Iceland, April 26 – May 2, 2020, 9pp., postponed to 2021.

Muller, J., Viig, S.O., Stray, H., Laboratory Studies of Organic and Inorganic Geothermal Tracers at Superhot and Supercritical Conditions, EAGE annual meeting, Geothermal Workshop, London, 3 Jun 2020

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Liotta, D., van Wees, J.D., Garduño-Monroy, V. H., Hernández Ochoa, A. F, Deb, P., Aragon, A., Lopéz Hernández, A., Bruhn, D.: “The GEMex Project: Investigation of Acoculco (Mexico) as a Potential EGS Site”. WGC2020, Reykjavik, Iceland, April 2020.

2.4.6.2 Datasets published (e.g. in zenodo)

Lelli M., Cabassi J., Nisi B., Vaselli O., Tassi F. (2020). Geochemical data for fluids collected in Acoculco Geothermal Field. Zenodo open access data base. DOI: 10.5281/zenodo.3727572

Jentsch, A.; Jolie, E.; Jones, D.G.; Taylor-Curran, H.; Zimmer, M.; Peiffer, L.; Lister, B.(2020): CO2 efflux, soil temperature and carbon/helium isotope results from the Los Humeros geothermal field, Mexico. GFZ Data Services. http://doi.org/10.5880/GFZ.4.6.2020.001

2.4.6.3 Academic Thesis

Anna Jentsch: The influence of volcano-tectonic structures on soil gas composition - Examples from two active tectonic areas, University of Potsdam (in cooperation with GFZ Potsdam), *in preparation*

Emmanuel Olvera-Garcia: Fault and fracture network in the Las Minas exhumed geothermal system: insights for the present geothermal system (Mexico). University of Bari, 2020.

2.4.7 Deviations from the Description of Action

No deviations from the Description of Action have to be reported

2.4.8 Patents

Patent WO 2018/093272 A1 has been published by IFE. The patent describes a high-temperature tracer which is suitable for tracer test in superhot geothermal systems.

2.5 Work Package 5: Detection of deep structures

Lead: ISOR
Partners: CIPR, CNR, CRES, GFZ, HBO, ISOR, KIT, OGS, TNO, UU
Duration: month 1-44
Status: completed

Objectives:

The development of seismic and resistivity methods for high temperature geothermal fields have been the subject of the former and ongoing FP-6&7 supported projects I-GET and IMAGE. The objective of this work package 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 EGS field. The existing models from two superhot fields in Iceland (Krafla and Reykjanes) have been 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 have been compared to the Mexican fields.

Summary:

In Work Package 5 - *Detection of deep structures* – several geophysical methods were applied to further our understanding of the geothermal system.

More than 120 MT and TEM resistivity soundings were carried out in Los Humeros and close to 70 in Acoculco. The data were processed, 1D inverted and 3D inverted using two different codes for comparison, resulting in a resistivity model for the two areas.

A micro-seismic network was deployed consisting of 45 stations in Los Humeros and 18 in Acoculco, collecting data for over a year. Seismic activity in Acoculco was minimal but substantial in Los Humeros. The passive seismic data from Los Humeros were used for earthquake analysis, travel time tomography, ambient noise correlation and modelling. Data from four active seismic profiles based on a previous survey in Los Humeros were analysed and interpreted.

Already existing gravity and magnetic data from the two areas were studied and 3D regional models re-sampled. A gravity survey was performed within GEMex on a regular grid, consisting of 341 sites in Los Humeros and 84 sites in Acoculco. For both areas a density model for the subsurface was calculated based on the Bouguer gravity maps. InSAR data from Los Humeros were studied giving information on the deformation of the area.

All these datasets were processed and inverted using the most up-to-date software, many of them applied and tested in previous European Union’s Horizon 2020 funded research and innovation programmes. The different datasets were interpreted jointly in geological terms, considering results from other geoscientific results with special emphasis on their geothermal significance. New methods were tested, and new approaches applied.

All the geophysical results from both areas as well as the outcome from geological mapping and measurements and analysis from boreholes have been uploaded into Paraview, a 3D visualization program. Paraview is a free software and, therefore, easily accessible to scientists in both consortia, the European and Mexican.

The quantitative interpretation of the different geophysical datasets in geological/geothermal terms and the presentation, visualization and qualitative interpretation of all the geoscientific results from Los Humeros and Acoculco in Paraview is the most important contribution from Work Package 5 - *Detection of deep structures* - towards a deeper understanding of the two systems and their conceptual model. The lessons learned through this process have been most valuable for scientists in both consortia and been an addition to the methods applied in geophysical surface exploration studies.

Table 8: Status quo of personal resources WP5.

Participant number	1	2	3	5	7	11	12	13	17	19	**Total**
Short name	GFZ	ISOR	TNO	UU	CNR	CRES	OGS	CIPR	KIT	HBO	
PM foreseen in total GEMex	45	54	20	41	8	22	24	24	45	36	319
PM used	42.1	80.65	18.92	42.56	8.11	26	24,73	16.08	59.57	35.97	354.69

2.5.1 Task 5.1 Resistivity imaging of EGS and SHSG

2.5.1.1 Activities in the last reporting period

All of the subtasks within Task 5.1 have been concluded in the previous reporting period.

2.5.1.2 Main results from the task

From November 2017 to February 2019, some 122 MT and 120 co-located TEM soundings were performed in Los Humeros and 68 MT and 65 co-located TEM soundings in Acoculco through a joint effort by the Mexican and European partners. The MT data for both areas were processed and quality controlled. The dimensionality of the data and geoelectrical structure of the areas were analyzed through phase tensor analysis and strike analysis (tipper-strike and induction arrows). The results were compared with the geological structure.

Resistivity models of the two areas were compiled from the results of 1D joint inversion of the TEM and MT data. Resistivity models were also calculated through 3D inversion of the static shift corrected MT data. The results from Los Humeros and Acoculco were in good agreement with the 1D inversion results, although the structure in the models became clearer. The resistivity structure in Los Humeros is controlled by the faults in the area as well as the outlines of the Los Potreros caldera. Two main zones of interest were identified. In Acoculco the results are very similar to the 1D joint inversion results, which is not surprising given the horizontally layered structure in the survey area. The results were compared with the resistivity models of two superhot geothermal systems in Iceland, Krafla and Reykjanes.

The possibility to apply computational intelligence metaheuristics for the geophysical study of geothermal fields was successfully demonstrated through an innovative approach applied to the geophysical study of the Acoculco geothermal field. Computational Intelligence (CI) methods were exploited for the quantitative data integration of different datasets, by jointly solving the inverse problem of transient EM (TEM), vertical electrical sounding (VES) and magnetotellurics (MT).

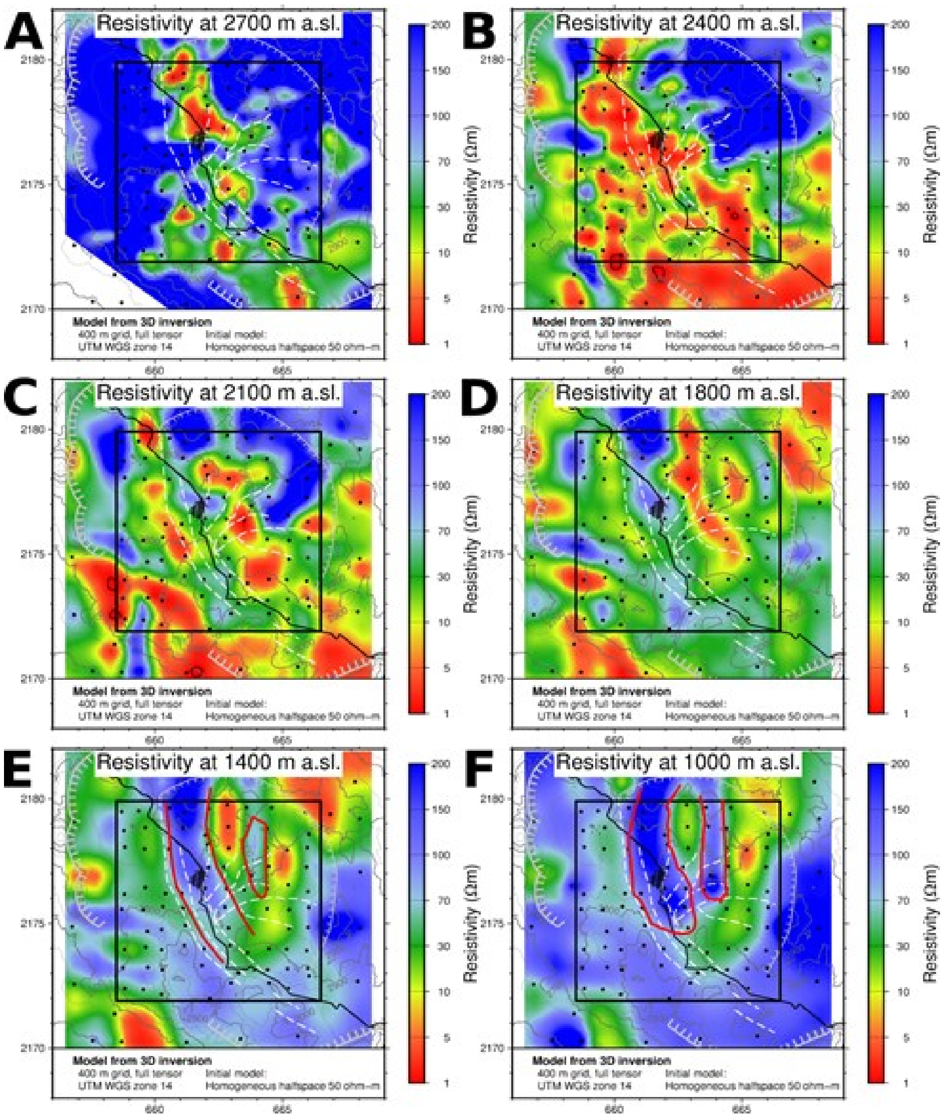

Figure 13 - Horizontal cross-sections through the 3D resistivity model of Los Humeros at different elevations above sea level. Black dots are the MT sites and the black box shows the location of the densely gridded area in the 3D inversion. Thick and thin gray hatched lines are the Los Humeros and Los Potreros Calderas, respectively, white dashed lines are main faults in the area and black lines are roads. Dark gray elevation contour lines every 50 meters. Red lines in E and F outline the anomalous up-doming high resistivity areas.

2.5.2 Task 5.2 Seismic imaging

2.5.2.1 Subtask 5.2.1 Data acquisition:

This subtask finished during the previous technical report period.

2.5.2.2 Subtask 5.2.2 Seismic structure (tomography methods)

LOS HUMEROS

Active seismics methods (OGS)

In the framework of WP5.2.2 'Seismic imaging', OGS reprocessed the legacy active seismic data acquired in the Los Humeros Caldera and provided by the Comisión Federal de Electricidad (CFE), with the support of UNAM. The reflection survey consists of four 2D seismic lines: L2, L3, L4, L5, acquired with Vibroseis source by Compañia Mexicana de Exploraciones S.A. (COMESA), for CFE in 1998. The initial pre-stack depth migration (PSDM) results (deliverable D5.3) are reprocessed by iterative procedure with horizon interpretation and common-image gather (CIG) tomographic inversion, including seismic-velocity analysis with synthetic simulations, and used to determine and update the local Los Humeros seismic-velocity model in depth. Seismic interferometry technique is used to create virtual sources to cover zones with acquisition gaps to provide estimation of wavefields at shorter offsets, absent in the field data (Barison et al., 2019). Tomography analysis of shallow diving waves from the active seismic data (Bohm et al., 21019) is also used to characterize the velocity model in the shallower formations and, therefore, improve the deeper imaging of the Los Humeros superhot-geothermal system (SHGS).

The active-seismic results are also integrated within WP5.4 with geophysical and geological results (D5.10), seismological and gravimetric data (D5.9), and temperature data (D5.11). They are compared with the geological model (WP3), as well as reservoir modelling (WP6), and used for the purposes of the geothermal model simulation with temperature (D5.5).

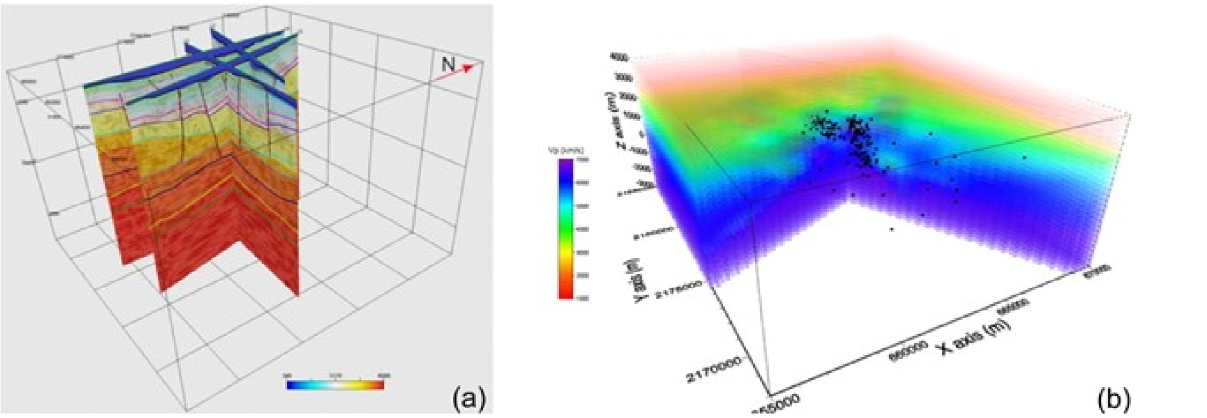

Figure 14 - (a) Pre-stack-depth migration of active-seismic data, (Poletto et., 2020), with a 3D view of the crossing lines observed from the corner between L5 and L3. The superimposed color maps represent the P-velocity model (m/s) obtained by common-image-gather (CIG) horizon-driven interpretative velocity analysis of the active seismic lines. (b) 3D P-wave velocity model obtained by tomographic inversion of passive seismic data. Black points represent the localized earthquakes. Models a) and b) have different sizes.

OGS analyzes also the passive seismic data (WP5.2.2). A 3D velocity model (VP, VS and VP/VS) is created (Böhm et al., 2020) from the travel time inversion of the seismological picked data provided by GFZ. The tomographic inversion is performed using the OGS-CAT3D software (for details see D5.3). The initial velocity model of the inversion derives from the results of the active seismic data by interpolating the velocity models obtained for the four 2D active seismic lines, which were acquired inside the same investigated area (local model).

The data available in the VRE from OGS in the framework of WP5 were prepared for inclusion in the paraview project (Task 5.4)

- Active seismic data:
  1) 2D depth interval velocity models (version 1) of the four active seismic lines, named L2, L3, L4, L5, acquired in Los Humeros Caldera by the Compania Mexicana de Exploraciones S.A. (COMISA) in 1989, for Comision General de Electricidad (CFE) and processed by OGS.
  2) 2D dataset of 9 interpreted horizons (+ topography) along four seismic lines L2, L3, L4 and L5.
  3) 3D interpolation of the seismic horizons identified on the active seismic lines (version 1) in a volume 7x7 km wide in X,Y and from -1.5 to 3.2 km in Z (a.s.l.).

- Passive seismic data:
  1) 3D seismological model (Vp and Vs): 15x17 km wide in X,Y and from -3 to 4 km in Z (a.s.l.); obtained from 2661 P arrivals and 2272 S arrivals associated with 395 earthquakes recorded by 37 stations.

OGS prepared results from the analysis of active and passive seismic datasets for the inclusion in the GEMex Open Access Database and in the zenodo data repository (as reported in section 2.5.6.2 Datasets published below).

Travel time tomography (GFZ)

We performed a local earthquake tomography at Los Humeros geothermal field using retrieved local seismicity from the collected passive seismic data. The obtained seismic catalog was later used to compute a new 1D Vp and Vs models for Los Humeros site. These models were later used as initial values for a joint inversion to obtain the 3D Vp and Vp/Vs structures and associated earthquake catalog. We extended the classical tomography by using a post-processing statistical approach. Several inversions using different model parametrization or gridding were computed and averaged to increase the resolution of the investigated region.

The located seismicity was mainly grouped in three clusters, two of which were located in the vicinity of injection wells. We combined existing well data, new laboratory measurements or core and outcrop samples from Deliverable 6.1, and our calculated Vp model to define approximate geological unit boundaries. We interpreted low Vp/Vs values close to the surface as a gas-filled caprock mainly composed of ignimbrites, and higher Vp/Vs values as possible fluid bearing zones. The Vp/Vs model seems to confirm the hypothesis of resurgence or several local heat source(s), rather a single heat source at depth, with fluid being transported upwards along permeable faults. The found structures indicate remarkable correlations with the inversed resistivity and other data sets from the geological analysis.

During this period finalisation of the travel time tomography was performed. The database was also published.

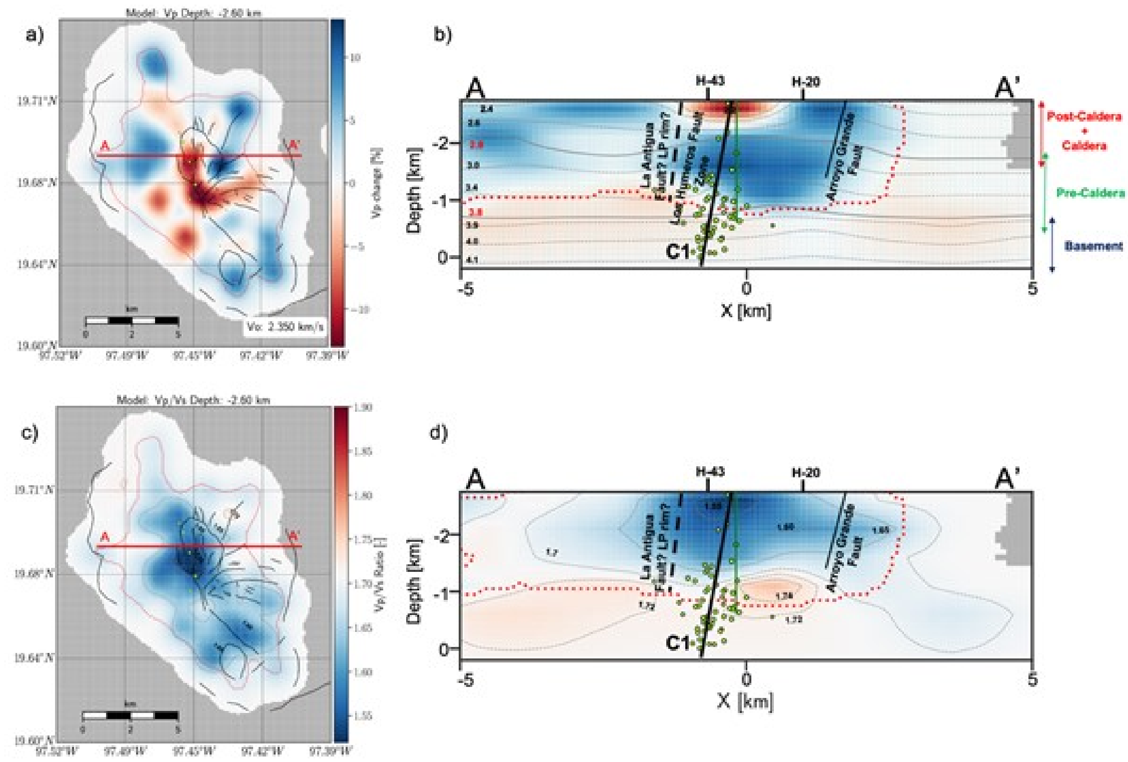

Figure 15- a) Depth slice and b) vertical cross- section of profile A-A' for the resulting Vp model variations. Dashed gray contour lines in the cross-section indicates absolute Vp values. c) Depth slice and d) vertical cross- section of profile A-A' for the Vp/Vs model. Green circles mark the location of earthquakes +/- 200 m away from slice. Dashed and solid black lines indicate some interpreted features. Vertical green lines indicate the position of a neighboring injection well.

Ambient noise seismic reflection interferometry (TNO)

An ambient noise seismic reflection interferometry (ANSI) study was performed by TNO using passive seismic data recorded by two selected seismic stations from the Los Humeros seismic network: DB15 and DS03. These stations were selected based on data-availability and -quality as well as proximity to a location, close to a well (H-27), at which seismic interval velocity information was available from literature. A clear correspondence could be observed between finite-difference (FD) modelled reflectivities using the mentioned interval velocities and single-day autocorrelation stacks produced from these field data, see Figure 16. These results indicate that the locally derived 1D seismic interval velocity profile, which is close to well H-27 in the shallow interval up to ~2 km depth, viz. up to and within the producing geothermal reservoir, can be laterally extended in the directions of stations DB15 (at ~1 km lateral distance) and DS03 (at ~2 km distance), which is relevant for the understanding of the geothermal reservoir that is located in the 1500–2500 metres depth range.

The ANSI auto-correlation technique applied here for zero-offset reflectivity retrieval can be regarded as a promising technique, providing high vertical subsurface image resolution, for obtaining near-vertical velocity contrast information, corresponding with depth information about near-horizontal reflectors. As such, the reflected P-wave information provides structural detail about the field at locations directly underneath the employed seismic stations. These results from the presented passive-seismic method may partially complement and partially confirm subsurface information derived from active-seismic, that can only be acquired at a higher cost, which is more labour-intensive and which has more impact on the environment.

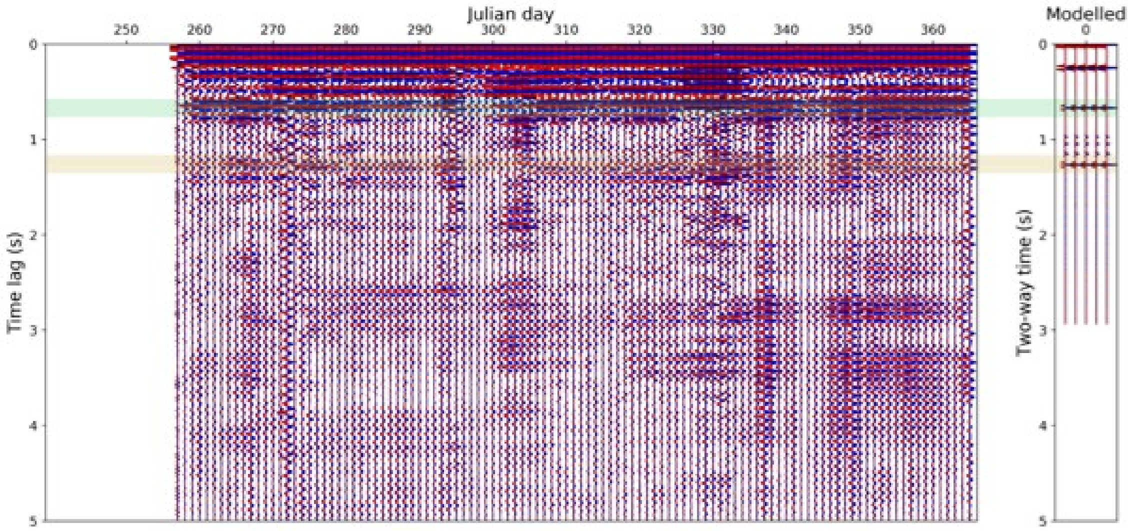

Figure 16 - Panel of 10-40 Hz bandpass-filtered day-stacks of autocorrelated ambient noise (vertical component) recorded at station DB15 throughout year 2017 (from September onwards) in a combined display with FD-modelled 1D reflection response (right). Two key reflectors are highlighted in green and orange.

Beamforming analysis

The depth of the brittle-ductile transition zone below the LHVC has been estimated from ambient seismic noise recordings. 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. Results suggest that brittle structures exist down to 10 km depth below topographic surface despite a positive thermal anomaly, increasing the rock volume available for geothermal exploitation.

An array technique called three-component beamforming has been used to analyse seismic noise measurements. Beamforming provides Rayleigh wave dispersion curves, which are then inverted using a Markov chain Monte Carlo algorithm. From the inversion, a probability density function of the shear-velocity distribution at depth is obtained. This distribution is in good agreement with a shear-velocity profile from local seismicity analysis, which exists, however, only for the upper 4 km. Combining noise-based and earthquake-based models, a shear-velocity profile is constructed down to 15 km depth (Fig. 1), that is, much deeper than any other method applied in the area so far. Matching the profile with well log and outcrop data, different geological sections such as the top of the crystalline basement (*Teziutlan massif*) at ~5 km depth are identified. The decline of shear-wave velocity at ~10 km depth indicates the decline of shear strength and marks the onset of the transition from brittle to ductile structures. The obtained velocity model was also used to locate micro-seismic events using time-reverse modelling.

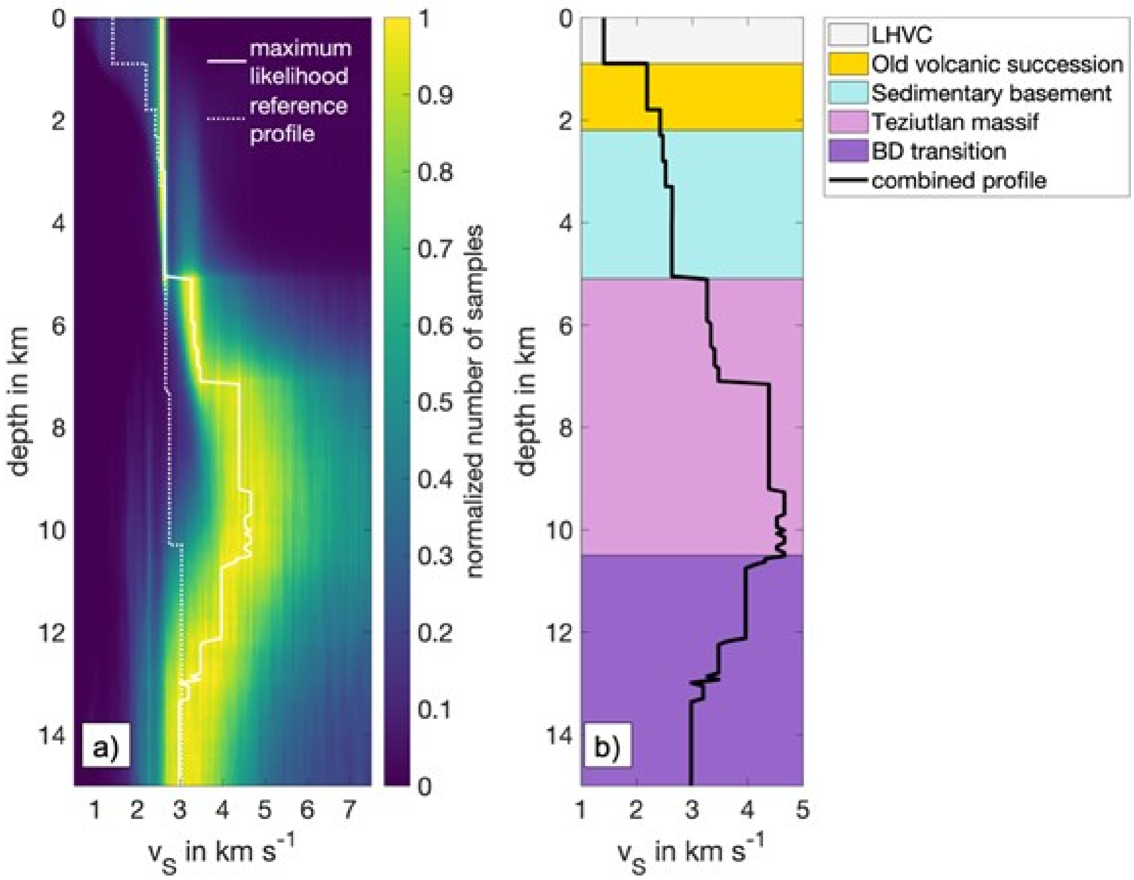

Figure 17 - (a) Probability density function (PDF) of shear-velocity distribution as retrieved from rj-McMC inversion, normalised per depth level. The solid curve indicates maximum likelihood of the PDF, the dotted curve represents the profile retrieved from the analysis of earthquake data and is plotted 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 colours 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.

ACOCULCO

Activities involved mainly our Mexican partners who focused on the seismic characterisation at Acoculco caldera.

In the framework of Work Package 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 us to retrieve stable correlations up to 30 s and we used these results to obtain a velocity structure until 10 km depth.

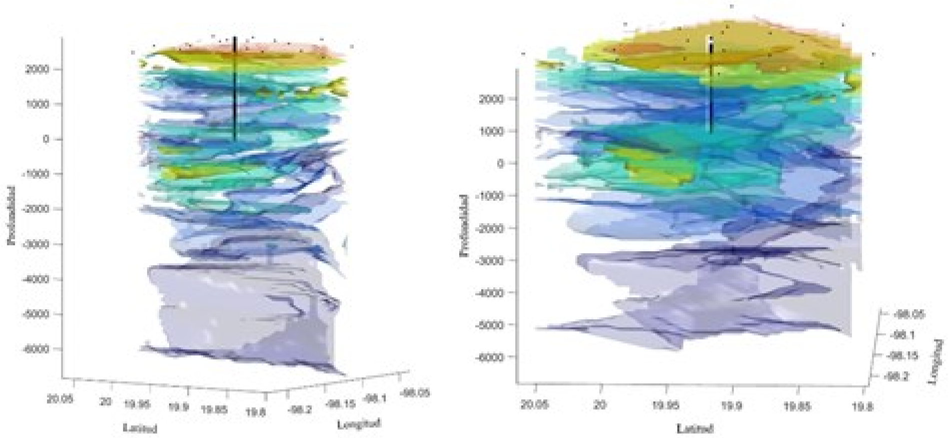

Figure 18 - 3D Acoculco Velocity Model (Vs)

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.

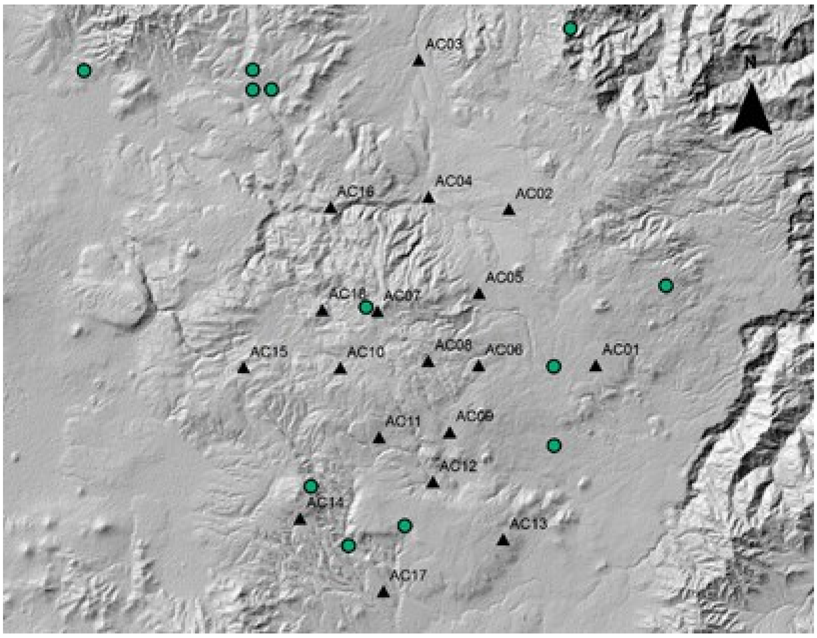

Figure 19 - Local seismicity around the Acoculco Caldera. 11 earthquakes were recorded and localized, preventing any further imaging using earthquake based tomography.

2.5.2.3 Subtask 5.2.3 Time-dependent processes within the structures

As indicated in the last period, the production rate and the seismicity was very stable, therefore the analysis of time-dependent processes was not possible. Results on the analysis on the seismicity evolution over the time recorded are summarized in Deliverable 5.4.

2.5.2.4 Subtask 5.2.4 Modeling

OGS used an innovative approach to simulate the seismic wavefields including temperature in the super-hot geothermal system of Los Humeros and in the potential EGS of Acoculco. Main results are the achievement of a robust approach and testing of the modelling tool to characterize the geothermal sites, and the increased knowledge on integrated use of seismic and geothermal thermodynamic parameters. An overall analysis of the sensitivity of seismic properties to thermal and geothermal parameters has been conducted (Poletto et al., 2018). Effects on seismic properties of supercritical conditions are evaluated. The benchmarking of different simulation methods was verified in comparison with other simulation algorithms, showing the consistency and robustness of the obtained results (deliverable D5.5).

To extend the seismic-thermodynamic analysis to sets of parameters more focused on the specific sites of the GEMex project, the modelling was used to investigate the hydrothermal convective and conductive mechanisms (Farina et al., 2019). The results show that effects due to hydrothermal conditions for the seismic properties can be observed in the proximity to superhot melting zones.

Synthetic seismic simulations were calculated for Los Humeros and Acoculco geothermal systems considering the lithological and temperature models (Farina et al., 2020). Results are shown in Figure 20. The analysis demonstrates that observable effects are visible below 4 km depth when the simulated seismic waves enter in the granite unit where the presence of melted material is considered as a possible scenario.

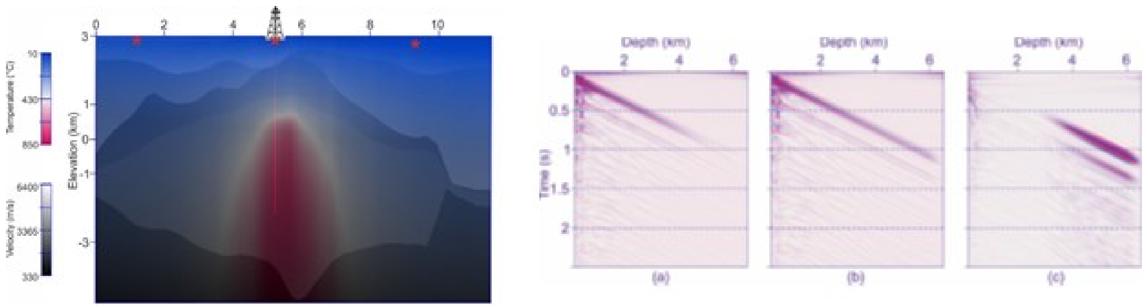

Figure 20 – (Left) 2D model: SW-NE line crossing the two wells drilled in Acoculco with the superimposed thermal model (lithological and thermal models derived from WP3). The position of well EAC-2 is indicated. (Right) the synthetic zero-offset VSP calculated in well EAC-2 a) with melting, b) without melting, c) difference.

The main achievements of the Seismic T5.2 Mexican team have been obtained using several techniques to characterize the structure of the Los Humeros Caldera as well as the seismicity recorded with the stations deployed during the project.

Anisotropic shear wave velocity models obtained using phase and group velocities of the Rayleigh and Love wave retrieved from ambient noise analysis (Figure 21A) allowed to reconstruct the deep part of the caldera. We identified three depths of possible accumulation of the heat sources. The deepest anomalous region is located at 10-15 km of depth, the intermediate one at 5 km and the shallowest one, forming the ongoing reservoir, at 1.5-3 km of depth (Figure 21A).

The seismicity recorded during the project was used to generate Enhanced Seismic Models of Vp and Vp/Vs of the reservoir with a resolution of less than 500 m in the first 4 km of depth. Here we were able to discriminate the finer structure of the field, such as patterns related to faults and layers saturated in fluids (Figure 21B).The shallow structure was also investigated using the H/V analysis allowing to describe the firsts dozens of meters of the caldera beneath each station (Figure 21C).Source parameters of the main events were determined using waveform modeling of the P waves allowing to associate the patterns observed at surface with the deeper structure (Figure 21D).Finally, the spectral analysis of the seismicity allowed to detect and locate low frequency events that helped to better characterize the fluid movements in the geothermal reservoir (Figure 21E).

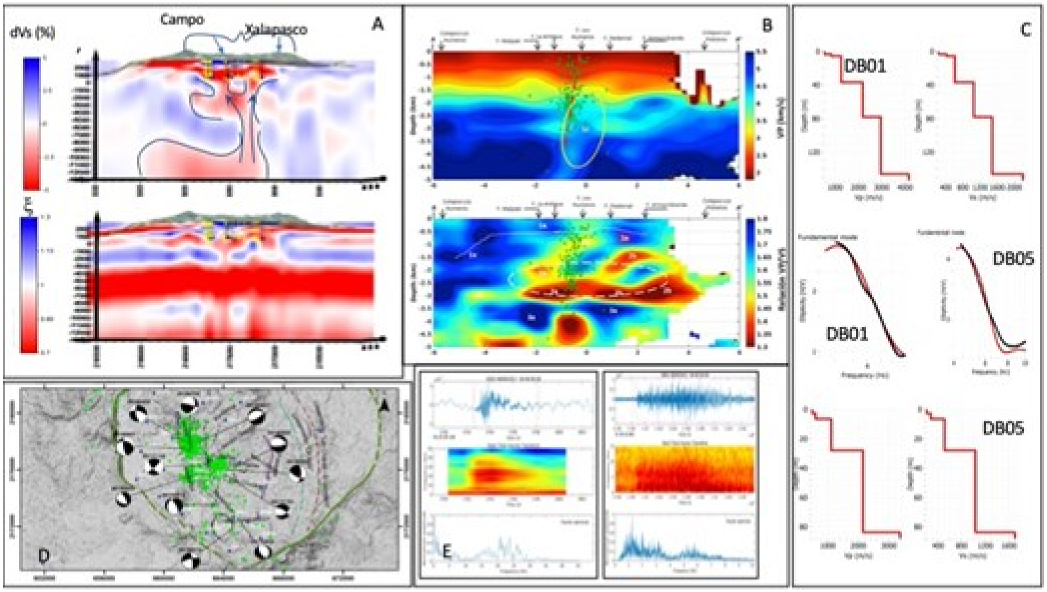

Figure 21 - A) cross section of Vs and Radial anisotropy models obtained using the ambient noise tomography. B) cross sections of Vp and Vp/Vs models obtained using local Earthquake Enhanced Seismic tomography. C) example of 1D velocity models and fitting of fundamental mode using the H/V method. D) focal mechanisms of some major events obtained using the waveform modeling of the P waves. E) example of a high frequency (left) and low frequency (right) events recorded at the Los Humeros.

2.5.3 Task 5.3 Evaluation of other geophysical data

2.5.3.1 Activities in the last reporting period

During the reporting period, Deliverable 5.6, *Gravity modelling,* was completed. A 3D density model of the Los Humeros and Acoculco areas was constructed and included in the Paraview project in Task 5.4. The following data sets were provided for the GEMex Open Access Database within WP2:

- Density cross-section of Los Humeros and Acoculco and file description.
- Density horizontal slices of Los Humeros and Acoculco and files description.
- Upload 3D density datasets of Los Humeros and Acoculco in Zenodo.
- Resampled dataset of the local density models of Los Humeros and Acoculco.

Another activity completed during the last reporting period was the production of the deliverable D5.7 - A report on the results of the analysis of InSAR and GPS satellite data of the Los Humeros and

Acoculco geothermal fields. High-resolution time-series of InSAR and GPS data are used to map surface deformations in the study areas. Analysis and modelling of these observed deformations enable to discriminate between long-term natural (e.g. volcano-tectonic) and short-term man-made (fault reactivation induced by producing from and injecting in the reservoir) causes.

2.5.3.2 Main results from the task

Gravity data were collected within the GEMex project in two field surveys in 2017 and 2018 in cooperation with CICESE in Mexico. In Acoculco, a total of 84 gravity stations were acquired in 05/18 in an about 5 x 3 km rectangular grid oriented NE-SW and NW-SE with a typical station distance of 400 m to each other. In Los Humeros, a total of 344 gravity stations were measured in two different surveys.

From Bouguer anomalies residual anomalies were calculated and analysed in a pseudo-tomography by Butterworth filtering. The residual anomalies of both areas were related to their structural inventory. Indication for caldera structures as well as faults were identified. To obtain unconstrained information on the influence of the caldera and fault structures, the planned forward modelling was replaced by inverse modelling.

Both residual anomalies and inversion results reveal a high fault control on the gravity and thus the density distribution for both research areas. The alignment of the majority of the anomalies follows NE-SW and NW-SE trending fault orientations. This observation provides new insights into the structural setting of the two areas and may contribute to the improvement of the geological models.

At reservoir level, areas of high-density anomalies in Acoculco coincide with areas of relatively low-quality geothermal condition. A significant high-density anomaly is observed down to sea level in the area, where the two geothermal wells were drilled. At Los Humeros, high density anomalies are recorded for the west of the caldera constrained to the east by NW-SE and N-S aligned fault zones. The eastern sector, characterized by the occurrence of E-W and NE-SW oriented fault zones, is dominated by a low gravity signal.

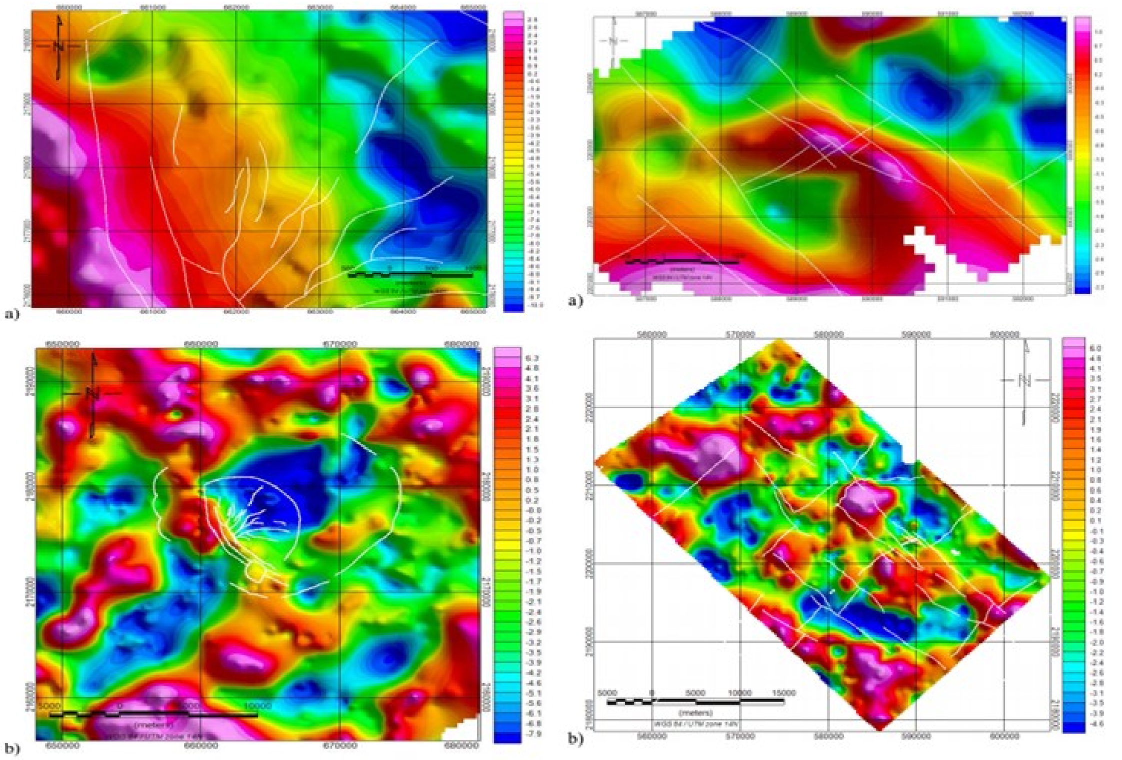

Figure 22 – (Left) Residual gravity anomaly of the Los Humeros area a) geothermal and b) caldera area compared to the fault zones according to Carrasco Nuñez et al., 2017a. (Right) Residual gravity anomaly of the Acoculco area a) geothermal and b) caldera area compared to the fault zones according to Deliverable 4.1.

The main results of the InSAR and GPS task, besides the collection and analysis of inSAR data, include data analysis and modelling of the observed surface deformation in the Los Humeros and Acoculco Fields. In Acoculco a pronounced surface deformation was not expected, as the resource is not yet developed. This has been confirmed by the data which does not evidence a reliable deformation signal. In Los Humeros the data clearly evidences subsidence up to 8 mm/y related to production. The subsidence pattern also indicates that the geothermal field is controlled by sealing faults separating the reservoir into several blocks.

A geodetic and geomechanical analysis was conducted of the seismic source of the Mw=4.2 event, in the Los Humeros Field which occurred in 2016, based on ground deformation inferred from DInSAR. All models locate the activation of the fault at shallow depth: no activation was predicted below ~1200m depth. This implies that the earthquake most likely originated in the top of the reservoir and can be associated by injection. Additionally, all models predict a reverse movement along the trace of the Los Humeros fault.

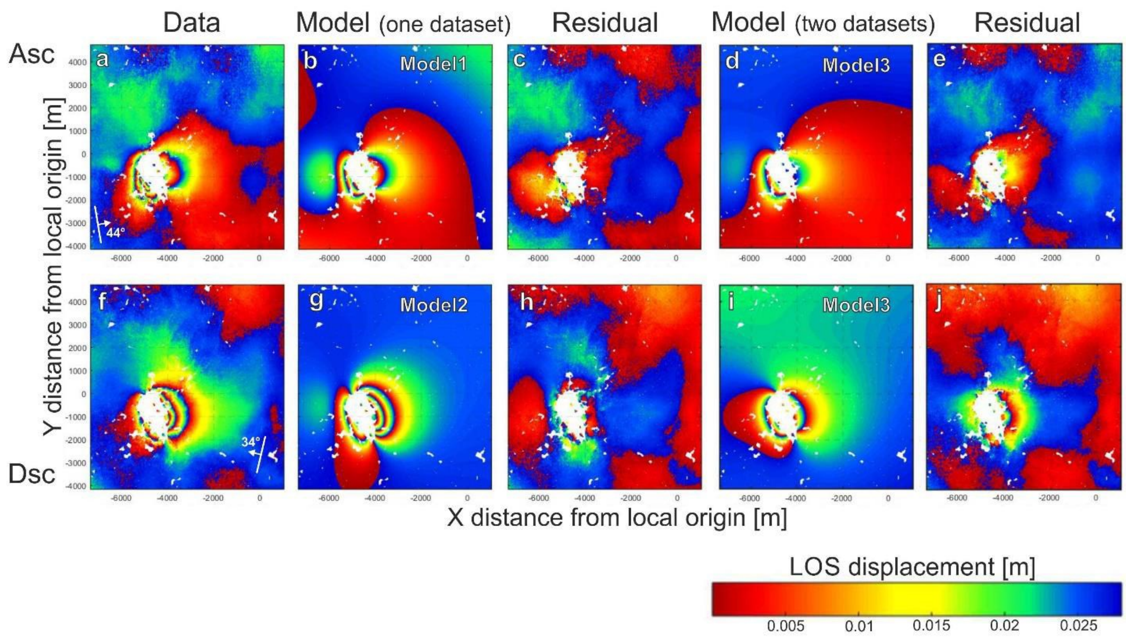

Figure 23 - Observed (a, f), modeled (b, d, g, i), and residual (c, e, h, j) surface displacements of the Los Humeros geothermal field, mapping the coseismic deformation of the 8 February 2016 earthquake. Arrows in a and f indicate the flight direction of the satellite and the look direction with the corresponding incidence angles. Model 1 and Model 2 are obtained by the inversion of the ascending and descending interferograms separately. For Model 3 the two interferograms were used simultaneously. (From Bekesi et al., 2019.)

The InSAR data together with the modeling results suggest two reservoir characteristics. First, they indicate that the pressure within the reservoir is well supported suggesting that recharge is taking place. Second, they imply that the Los Humeros geothermal field is controlled by sealing faults that separate the reservoir into several blocks. However, additional subsurface data, for instance regular pressure measurements from the wells, are needed to improve the modelling results. This would also allow to study fault sealing behaviour that controls reservoir compartmentalization. Still, the results demonstrate that satellite-derived subsidence patterns may help to obtain a better understanding of the pressure conditions within the reservoir and potential local recharge zones. This will facilitate better quality decisions on well planning and operations.

2.5.4 Task 5.4 Integration of methods and inversions constraints

2.5.4.1 Subtask 5.4.1: 3D inversion and modelling of the MT/TEM data from Los Humeros and Acoculco by application of constraints from other datasets.

Deliverable D5.8 within Task 5.4.1: *3D inversion and modelling of the MT/TEM data from Los Humeros and Acoculco by application of constraints* was completed. The deliverable is based on revisiting the 3D inversion of the 122 static shift corrected MT sounding data from Los Humeros and the 68 from Acoculco. The constraints are based on the recent geoscientific findings within the GEMex project from the two areas including geology, gravity and micro-seismic monitoring.

2.5.4.2 Subtask 5.4.2: Improve the seismic modelling by application of constraints from other data e.g. resistivity, gravity) for example by applying cross-gradient methods and structural inversion methods that are being developed in other projects.

Deliverable D5.9 within Task 5.4.2 and Task 5.4.6 was completed, referring to DoW: *Deliverable D.5.9 refers primarily to reporting the results of Tasks 5.4.2 and 5.4.6. In this report we will assess the degree of improvement of seismic modelling with constraints from other data types, as compared to seismic modelling without such constraints. This report will also incorporate assessment of reduction of uncertainty in the estimates.*

2.5.4.3 Subtask 5.4.3: Characterization of geothermal formations by full-waveform seismic modelling including temperature

The activities in the last report period and main results are reported in section 2.5.2.4

2.5.4.4 Subtask 5.4.4 Interpretation of geophysical models

Deliverable D5.10 within Task 5.4.4: *Report on integrated geophysical model of Los Humeros and Acoculco* was completed. D5.10 *refers to task 5.4.7. Includes 3D conceptual models of the Los Humeros and Acoculco geothermal fields based on all available geophysical data presented in 3D visualisation software like Leapfrog or Petrel*, was completed, see description for subtask 5.4.7 below.

2.5.4.5 Subtask 5.4.5 Distribution of rock modulus of elasticity and correlation to temperature:

Correlations to temperature of rock elastic moduli were derived for Los Humeros superhot and Acoculco EGS geothermal systems. The method was evaluated in terms of characterising deep geothermal resources from seismic and gravity survey results. The following datasets were prepared for Los Humeros: (i) 1998 temperature distribution, (ii) 1998 P-wave modulus distribution, (iii) 2018 P-wave modulus distribution and (iv) 2018 S-wave modulus distribution. Deliverable D5.11 within this subtask: *Report on distribution of rock modulus and correlation with temperature*, was completed and submitted.

2.5.4.6 Subtask 5.4.6 Utilize ensemble-based inversion methods facilitating uncertainty quantification

Deliverable D5.9 within Task 5.4.1 was completed, see description for subtask 5.4.2 above.

2.5.4.7 Subtask 5.4.7 Advanced 3D model integration of geoscientific data

Deliverable D5.10 within Task 5.4.4: *Report on integrated geophysical model of Los Humeros and Acoculco* was completed. D5.10 refers to task 5.4.7. *Includes 3D conceptual models of the Los Humeros and Acoculco geothermal fields based on all available geophysical data presented in 3D visualisation software like Leapfrog or Petrel*. It was decided to use the ParaView 3D visualization software as it is a free software and accessible to the rest of both consortia, the European and the Mexican as well as for future work. Geophysical data from Los Humeros and Acoculco were uploaded into the ParaView 3D visualization software for inspection and joint interpretation. These are data recently acquired within the GEMex project but also previous results and well data provided by CFE.

2.5.4.8 Subtask 5.4.8 Implementation and validation of protocol for EGS and SHGS

Deliverable D5.12 within Task 5.4.8 was completed: *Report on implementation and validation protocol for EGS and SHGS.* It concludes WP5 activities, retrieving all the results achieved in Task 5.1, 5.2, 5.3, 5.4 and defines a protocol, i.e. a set of procedures to be followed for data integration in geothermal exploration of EGS and SHSG.

Procedures are described which aim at performing an effective integration from different geophysical methods providing an unambiguous, self-constrained model of a geothermal system. In this framework, crossplotting and clustering procedures are considered as a promising auxiliary tool towards the integration of distinct geophysical datasets. Cluster analyses were applied to the Los Humeros and Acoculco test sites in Mexico and in two geothermal fields in Europe.

2.5.4.9 Main results from the task

Subtask 5.4.1: Several datasets were applied to constrain the resistivity models. One of them is on the depth resolution of MT data. Are the deep seated low-resistivity anomalies "found" in Los Humeros and Acoculco real or are they an artefact when applying an unconstrained 3D inversion of the MT data and how do they relate to other geoscientific results? Secondly, the depth to basement in Los Humeros, based on the recent geological model, was used as a constraint.

Upon removing the deep seated low-resistivity anomalies "found" in the unconstrained inversion and forward calculating the models it is evident that the RMS does not change significantly. Therefore, it is concluded that, although the deep seated low-resistivity anomalies are at the intersection of two main geological fault trends, the resolution of MT data is not sufficient to observe such small bodies. The data only give a slight indication of a conductive body at a depth of around 3 km at the structural intersection.

MT data from Los Humeros were 3D inverted using additional starting models which included the basement according to a recent geological model of Los Humeros. Two inversion schemes were applied, one where the basement was kept fixed (scheme 2) and another one where the resistivity within the basement was allowed to change during the inversion (scheme 1). Indications of the deep seated low-resistivity anomaly is present in the final model in scheme 1 but not in scheme 2. Upon looking at what caused the deep seated low-resistivity anomaly it was evident that either regional noise source is causing soundings within a diameter of 2 km to have the same characteristics, a slightly lower apparent resistivity at longer periods, or the anomaly is simply a real signal.

Subtask 5.4.2 and 5.4.6: An ensemble-based Bayesian approach to combining information from several data types available for Los Humeros. The first approach uses seismic P-wave velocity, gravity, and electric data (TEM and MT), whereas the second approach uses only seismic P-wave velocity and electric data. In the absence of specific cross-property relations determined from Los Humeros, generic relations were applied to go between different geophysical domains, and inversions were done with Bayesian methods to enable uncertainty quantification. In both approaches inversion of MT data was performed last.

The MT inversion results from both approaches yielded different resistivity models, although some general trends were similar. With respect to the resistivity estimate presented in Deliverable D5.2, in our results uncertainty in the upper parts of the resistivity models is reduced while uncertainty in the deeper parts is higher. Comparing our MT inversion results with the ones given in Deliverable D5.2, we saw some similar structures.

Introducing more data types has in general the potential to improve estimation results, but is dependent on well-constrained relations for mapping a property from one geophysical regime into another. Such cross-property relations are specific to local subsurface variations. Cross-property relations have to be calibrated with measurements from the Los Humeros field, but such calibrated relations were not available. Thus the greatest contribution towards improving our estimations would come from having cross-property relations specifically adapted to the site conditions of the basement, reservoir and cap-rocks of Los Humeros.

The legacy active-seismic data provided by CFE and UNAM was processed by OGS in GEMex WP5.2 and reported in D5.3. 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. 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 D5.12.

The analysis showed that the inversion of the passive seismic data is significantly dependent on the choice of the initial velocity model. For the comparison of active and passive seismic data, the authors have calculated synthetic seismograms obtained from tomography of passive data using three different initial velocity models (P-waves): the GeoDepth (from active seismics), the initial model utilized (and provided, courtesy) by GFZ, and a test model (grad-04). These synthetic seismograms have been compared with the real seismograms of the active-seismic, i.e., the real field shots. The synthetic seismograms calculated using the GeoDepth model as initial model gave the best waveform reproduction, inferred to result from higher vertical and lateral velocity resolution, especially in the shallower section.

This interesting result demonstrates that using the active-seismic (with depth imaging results, but also analysis of the full-waveform in the field data) is useful for the definition of an improved initial model and the analysis of passive seismic data: for the location of the earthquakes (passive sources) and for the inversion of the arrival times (tomographic velocity model).

For the joint-comparative use of seismic and gravity data, preliminary tests were performed calculating the elastic waveform results with the substitution of the theoretical (Gardner) density model with the density model obtained from the inversion of the GEMex gravity data. The trends observed in the cross-plot of the density and velocity data indicate large differences between the inverted density models in the shallower, lower-velocity regions with respect to the Gardner and Nafe-Drake calculated ones, which are probably due to the very different resolutions. Future investigation will be required to evaluate the optimal application, and limitations in sensitivity, of the investigated method of seismic-density joint-comparison.

Subtask 5.4.3: see above.

Subtask 5.4.5: Based on evaluation of data collected during past and present reporting periods, provided by CFE and GEMex models generated during WP3 and WP6, the spatial distribution of steady state formation temperatures was estimated for Los Humeros superhot and Acoculco EGS geothermal fields. The legacy active seismic survey was reprocessed and P-wave seismic velocities at well locations were estimated, corresponding to the year the survey was carried out (1998). Using the density and the seismic tomography models provided by the Mexican and European GEMex teams, the 1998 3D P-wave modulus distribution and the 2018 1D and 3D P-wave and S-wave moduli distribution were derived for Los Humeros. Using density and seismic noise models provided by Mexican and European teams, the 1D S-wave modulus distribution was derived for Acoculco. The relationship between rock moduli and steady state rock temperature was evaluated as a method for characterisation of deep geothermal systems.

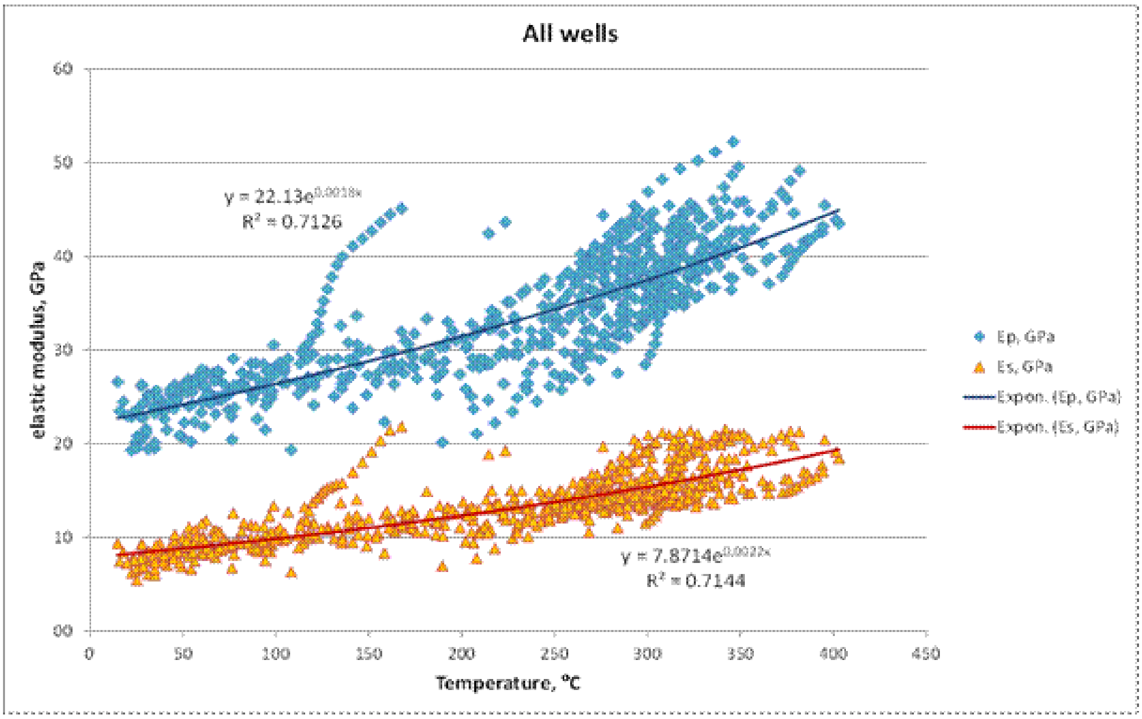

Figure 24 - Correlation with temperature of P-wave and S-wave modulus as derived by 3-D passive seismic and gravity surveys.

Subtask 5.4.4 and 5.4.7: All the geophysical data from Los Humeros show strong correlation with faults and fissures, especially the curved faults east of the Antigua fault. The seismicity shows three main and distinct clusters: one under the main production area, close to injection wells, at the Los Humeros fault, east of the northern part of the Antigua fault; another cluster further south, also east of the Antigua fault, close to another injection well; and the last one to the east between the Las Papas and Las Viboras faults not in the production area.

The resistivity also shows strong correlation with faults and fractures and seismicity. The lower boundary of resistivity lower than 50 Ωm domes up as a ridge at the curved faults around the Los Humeros fault. Another up-doming N-S striking ridge in the lower 50 Ωm iso-surface is seen extending north from the central seismicity cluster. Further to the east, resistivity lower than 50 Ωm extends to great depths, indicating eastern boundary of pronounced geothermal alteration and activity. Gravity and magnetics also draw attention to the faulted area within the Los Potreros caldera.

Geothermal alteration in wells in Los Humeros indicates that the geothermal system(s) in the caldera has gone through several phases. A likely scenario is that the relatively recent resurgence in the eastern part of the Los Potreros caldera has caused faulting, making permeability, and intrusions which are the heat sources for the presently active geothermal system. Numerous monogenetic basaltic/andesitic craters within and at the southern rim of the Los Humeros caldera are nearly absent in the Los Potreros caldera. This could indicate the presence of silicic magma/intrusions forming a sort of a "shadow zone", where basaltic magma cannot cross.

The different anomalies in Los Humeros are structurally controlled. The Antigua fault and the Los Humeros caldera rim play an important role. The north-west part of the Los Potreros caldera shines through with a combination of anomalies from different datasets; a resistivity high, relatively high Vp/Vs ratio, gravity low and a magnetic high. These anomalies are controlled by a north-south trend to the west, which has not been observed in the geology.

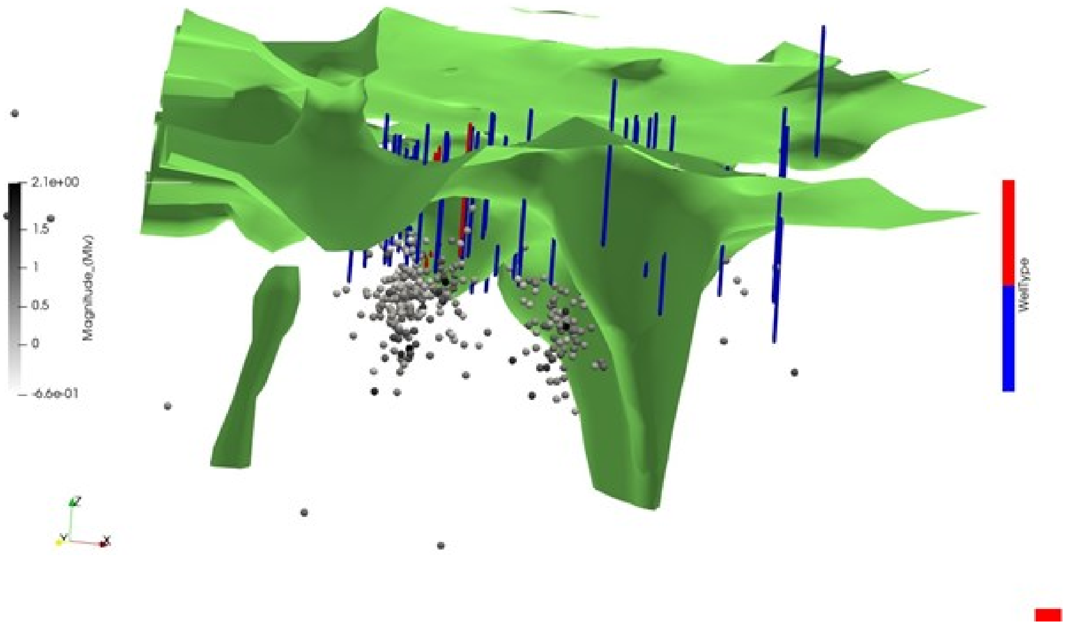

Figure 25 - Los Humeros: The 50 Ωm iso-surfaces in green, earthquakes in grey (magnitude scale left) and wells (blue: production, red: injection).

The integrated visual analysis of the geophysical 3D models for Acoculco performed in ParaView provide hints for a geothermal conceptual model. It is a very complex geothermal system and can be classified as a magmatic play with common features in between volcanic and intrusive.

Classifying Acoculco as EGS (Enhanced Geothermal System) or conventional hydrothermal system is the tricky part of the integrated exploration. No hydrothermal circulation was detected in the two drilled wells. However, some geophysical anomalies shown in this integrated analysis may be interpreted as due to the occurrence of hydrothermal circulation in some sectors of the Acoculco area. It is difficult to establish the reliability of these hypotheses due to the lack of direct well data in the anomalous areas. Moreover, the intensive rock alteration, both at surface and in the underground, testify the effect of a current or fossil hydrothermal circulation; the mineral alteration may strongly affect the geophysical response of the investigated areas, so that it is difficult to establish if the circulation is actual or fossil. It should be noted that the lack of relevant seismic activity suggests, however, the lack of a current hydrothermal circulation.

The density model anomalies point out a relation with the major regional tectonic trends (NE-SW and NW-SE). The integrated geophysical study reveals the occurrence of a main 3D structure elongated with a N100E strike, located in the central part of the area close to the two drilled wells. This structure, characterized by high-density and high-resistivity anomalous values, extends from about 400 m b.g.l. down to at least the sea level. Data from wells indicate low permeability conditions of the volume. The permeability of the shallow levels of the Acoculco system is probably strongly reduced, due to the intense sealing effects of hydrothermal alteration.

A possible mining target can be identified by the coupling of low-density and low-resistivity values at the depth of crystalline rocks. This peculiar condition is verified in the North and Northeastern sectors of the study area. No direct data can support this interpretation but the working hypothesis deserves further investigation.

The deepest low-resistivity and low-density portion of the geothermal system can be explained with the occurrence of still melted recent magmatic intrusions, even if clear images cannot be claimed. These could correspond to the recent cooling magmatic intrusion considered in the thermal numerical simulation to fit wells' thermal data and to simulate the existing thermal field.

Subtask 5.4.8:The application of the clustering method to datasets in various geothermal area has shown that this approach is an effective method to quickly retrieve local relationships between distinct physical parameters. With respect to the visual integration described in D5.10, this approach is much faster: in a few hours it is possible to recognize various branches of clusters that, once mapped back to the space domain, provide easily recognizable volumes of joint parameters.

Velocity is not the only advantage. This approach is analytical, and reduce the bias due to subjectivity. Beside uncertainty, which refers to data quality - how uncertain are the data based on the type of technique employed, including inversion techniques, the joint interpretation of data is often subjective, i.e. shaped by the personal opinions and feelings of operators. With this approach the operator is left with only the decision on the number of clusters in the unsupervised approach, or the definition of classes in the supervised classification approach.

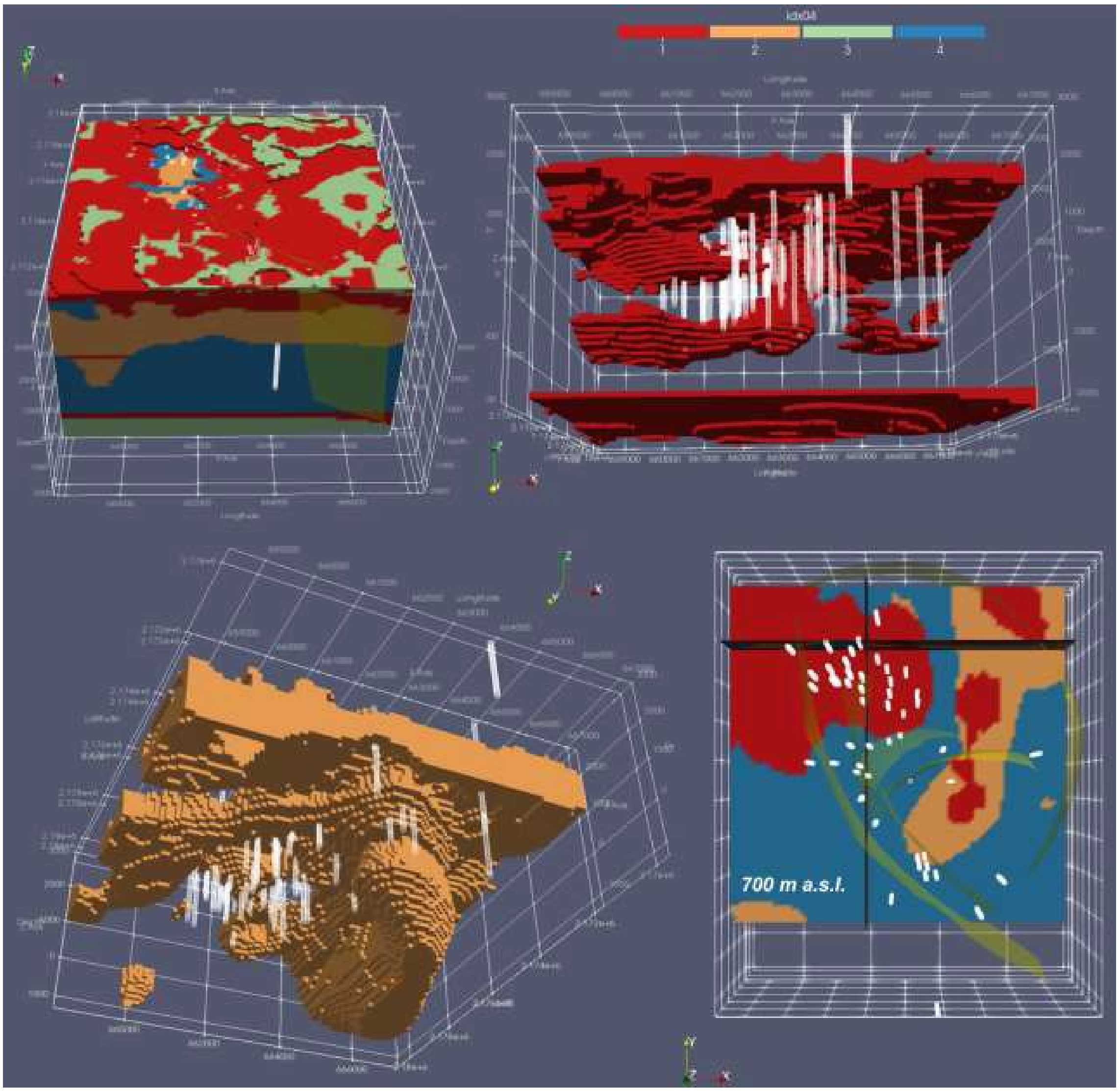

Figure 26 - Los Humeros: 3D visualizations of clusters (4 components) computed using the Local Resistivity and Vp/Vs interpolated dataset (upper left), spatial distribution of the cluster number 1 (upper right) and 2 (lower left), horizontal section (lower right)), horizontal section (lower right) at 700 m a.s.l. together with the main structural features. The wells (white lines) are also reported.

2.5.5 Impact

Site-specific impact

Results from WP5 will have a significant site-specific impact on the development of the two Mexican sites which have been investigated

- The geophysical characterisation of the superhot and the potential EGS site has been improved through better resolution or a larger area covered by the geophysical surveys (GEMex Deliverables 5.2, 5.3, 5.6, 5.8)
- The quantitative interpretation of the different geophysical datasets in geological/geothermal terms (GEMex Deliverable 5.12) and the presentation, visualization and qualitative interpretation of all the geoscientific results from Los Humeros and Acoculco in Paraview (GEMex Deliverable 5.10) is the most important contribution from Work

Package 5 - *Detection of deep structures* - towards a deeper understanding of the two systems and their conceptual model.

→ The results permit to improve the concepts for the exploitation of the unconventional ressources in Acoculco and Los Humeros and, therefore, decrease the exploration risks for both sites and increase the probability to exploit the superhot resource in Los Humeros and to implement the first EGS in Mexico in Acoculco.

Technological impact

WP5 make a step forward in improving exploration methods for geothermal exploration:

- New and innovative data analysis: Ambient noise seismic reflection interferometry and is new and innovative method in seismic data analysis, providing high resolution, comparative to active seismic data analysis, but at much lower costs and environmental impact. (GEMex Deliverable 5.3)
- New and innovative data analysis: beamforming analysis and is new and innovative method in seismic data analysis, providing the possibility to investigate the deeper part of the reservoir, therefore especially suitable for the exploration of deep, superhot systems. (GEMex Deliverable 5.4)

- Advancing of methods: Validation protocol i.e. a set of procedures to be followed for data integration in geothermal exploration of EGS and SHSG: effective integration from different geophysical methods providing an unambiguous, self-constrained model of a geothermal system. In this framework, cross-plotting and clustering procedures are considered as a promising auxiliary tool towards the integration of distinct geophysical datasets (GEMex Deliverable 5.12).

→ The developed methods provide tools to improve the exploration of geothermal reservoirs, thereby lowering the exploration risks for geothermal projects. The application of the advanced methods will lead to a larger number of successful geothermal projects.

Scientific impact

WP5 has a significant scientific impact, improved methods and site-specific exploration results have been published in scientific journals or conference proceedings (21 publications) and presented at scientific conferences (53 contributions).

The WP contributed towards open science in publishing all result in open access. Results from resistivity, gravity, InSAR, active seismic and part of the results from passive seismic data analysis have been included in the GEMex Open Access Database. Passive seismic raw data is already archived at a data repository and will be available to the public after an embargo of 4 years. The open access publishing of the MT dataset is foreseen in the future (pending agreement of the Mexican partners).

2.5.6 Publications

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(168), Near Surface Geoscience Conference & Exhibition, 8-12 September 2019. https://doi.org/10.3997/2214-4609.201902516

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Benediktsdóttir, Á., Arango-Galván, C., Hersir, G.P., Held, S., Romo Jones, J.M., Salas, J.L., Avilés, T., Ruíz-Aguilar, D., Vilhjálmsson, A.M., 2020. The Los Humeros Superhot Geothermal Resource in Mexico: Results from an Extensive Resistivity Survey.

Hersir, G.P., Arango-Galván, C., Benediktsdóttir, Á., Árnason, K., Jousset, P., Calo, M., Schill, E., Perez Flores, M.A., Békési, E., Poletto, F., Manzella, A., Gaucher, E., Toledo Zambrano, T.A., Held, S., Angulo Carrillo, J., Romo Jones, J.M., Cornejo, N., Soto, A.F., and Carrillo, J., 2020. Detection of deep structures in Los Humeros, Mexico: An overview of geophysical results, 3D visualization and a joint interpretation of the different geoscientific disciplines in geothermal terms.

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Toledo Zambrano, T. A., Jousset, P., Maurer, H., Krawczyk, C. M. (2018): Optimized Experimental Network Design for Earthquake Location Problems: applications to geothermal fields' seismic networks, (Geophysical Research Abstracts ; Vol. 20, EGU2018-15056, 2018), EGU 2018, (Vienna, Austria 2018).

Toledo Zambrano, T. A., Passive seismic monitoring at the Los Humeros geothermal field, Mexico: preliminary results, European Geothermal PhD Day, Potsdam, Germany, 25-27 Feb 2019

Toledo, T., Gaucher, E. , Jousset, P., Maurer, H., Krawczyk, C., Calò, M., Figueroa, A., Local earthquake tomography at the Los Humeros geothermal field. GEMex final conference, Potsdam GFZ, Germany, 18-19 February.

Toledo T., Jousset P., Gaucher E., Maurer H., Krawczyk C., Calò M., Figueroa A. (2020). Local earthquake tomography at Los Humeros geothermal field (Mexico). EGU2020, Vienna (Austria), May 2020.

Tveit, S., Mannseth, T., "Identification of geothermal reservoirs from ensemble-based Bayesian inversion of 3D MT data", SEG (Society of Exploration Geophsicists) Annual meeting, Anaheim, CA (USA), Oct. 14-19, 2018

Tveit, S., Mannseth, T., Ensemble-based Bayesian joint utilization of information from multiple data types for Los Humeros, GEMex final conference, Potsdam, Germany, 18-19 February 2020.

Verdel, A., Martins, J., Obermann, A., Toledo, T., Jousset, P.: "Ambient noise seismic reflection interferometry at the Los Humeros geothermal field, Mexico", EGC 2019, De Haag, Netherlands, 11-14 June 2019

Werner, C., Is time reverse imaging suitable for locating microseismic events in geothermal reservoirs? European Geothermal PhD Day, Potsdam, Germany, 25-27 Feb 2019.

Werner, C., Saenger, E.,: "Sensitivity maps for time-reverse imaging", EGU2019-7106, EGU 2019, Vienna (Austria) 7-12 April 2019

2.5.7.1 Accepted abstracts

Békési, E., Fokker, P., Limberger, J., Bonté, D., van Wees, J. D.: “Ground Deformation at the Los Humeros Geothermal Field (Mexico) from 2014 to 2019 Inferred from Sentinel-1 DInSAR Time Series Analysis”, WGC 2020, Reykjavik, Iceland, April 2020, postponed to 2021.

Benediktsdóttir, A., Arango-Galván, C., Hersir, GP., Held, S., Romo-Jones, JM., Salas, JL., Aviles, T., Ruiz-Aguilar, D., Vilhjálmsson, AM, Manzella, A., Santilano, A.: The Los Humeros superhot geothermal resource in Mexico: Resistivity survey (TEM and MT); data acquisition, processing and inversion – geological significance. Abstract submitted to World Geothermal Congress 2020 Reykjavik, Iceland, postponed to 2021.

J. Carrillo, M.A. Pérez-Flores, E. Schill and N. Cornejo: “3D joint inversion of gravity and magnetic data in Los Humeros and Acoculco unconventional geothermal systems”, WGC 2020, Reykjavik, Iceland, April 2020, postponed to 2021.

N. Cornejo, E. Schill, S. Held., M.A. Pérez-Flores, J. Carrillo:”Towards visualization possible fluid pathways using gravity in the Los Humeros and Acoculco geothermal fields.”, WGC 2020, Reykjavik, Iceland, April 2020, postponed to 2021.

Hersir, G.P., Arango-Galván, C., Benediktsdóttir, A., Held, S., Romo-Jones, JM., Salas, JL., Aviles, T., Ruiz-Aguilar, D., Manzella, A., Santilano, A., Vilhjálmsson, AM: The Acoculco High Enthalpy Geothermal Area in Mexico: Resistivity Survey (TEM and MT); Data Acquisition, Processing and Inversion – Geological Significance. Abstract submitted to World Geothermal Congress 2020 Reykjavik, Iceland, postponed to 2021.

Toledo Zambrano, T. A., Jousset, P., Gaucher, E., Calò, M., Figueroa-Soto, A., Krawczyk, C., Maurer, H. (2020): Local Earthquake Tomography at the Los Humeros Geothermal Field in Mexico - Proceedings, World Geothermal Congress (Reykjavik, Iceland 2020), postponed to 2021.

2.5.8 Deviations from the Description of Action

- ISOR reported more person months than anticipated since the implementation of the resistivity surveys and the coordination with the Mexican partner took more time and effort than anticipated.

2.6 Work Package 6: Reservoir characterization and conceptual models

Lead: RWTH
Partners: BGS-NERC, CNR, GFZ, ISOR, RWTH, TNO, TUDA, UFZ, UNITO, UU
Duration: month 1-32
Status: completed

Objectives:

In Work Package 6, the EGS reservoir in Acoculco and the SHGS reservoir in Los Humeros were characterised 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 parameterising discretised structural models used in static and dynamic numerical simulations of fluid flow, heat transport, and phase behaviour 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.

Table 9: Status quo of personal resources WP6

Participant number	1	2	3	5	6	7	8	18	20	23	**Total**
Short name	GFZ	ISOR	TNO	UU	RWTH	CNR	TUDA	UKRI	UNITO	UFZ	
PM foreseen in total GEMex	21	6	5	17	68	3	18	17.5	21	6	182.5
PM used	12.2	7.37	0.50	17.39	60.59	2.99	37.93	5.68	39.67	7	191.3

2.6.1 Task 6.1 Rock, fracture, and reservoir fluid properties

2.6.1.1 Activities in the last reporting period

This Task finished during the previous technical report period.

2.6.1.2 Main results from the task

Within Task 6.1 all relevant key units from the Acoculco and Los Humeros geothermal fields were characterized with respect to petrophysical, thermophysical, magnetic, electric, dynamic and static mechanical rock properties. During six field trips more than 300 rock samples were taken from representative outcrops inside of the Los Humeros and Acoculco calderas, the surrounding areas and from exhumed ‘fossil systems’ in Las Minas and Zacatlán. Additionally, reservoir core material of 16 wells of the Los Humeros geothermal field and a few core pieces from well EAC1 of the Acoculco geothermal field were analyzed. Detailed petrographic and chemical analyses (XRD, XRF, ICP-MS) were performed to provide information about the mineral assemblage, to determine the intensity of hydrothermal alteration and the effect of fluid-rock interactions. An extensive rock property database was created comprising 34 parameters determined on more than 2,160 plugs. Based on the statistical analyses of the rock properties, more than 20 and 14 lithostratigraphic units were defined for the Los Humeros and Acoculco geothermal fields, respectively.

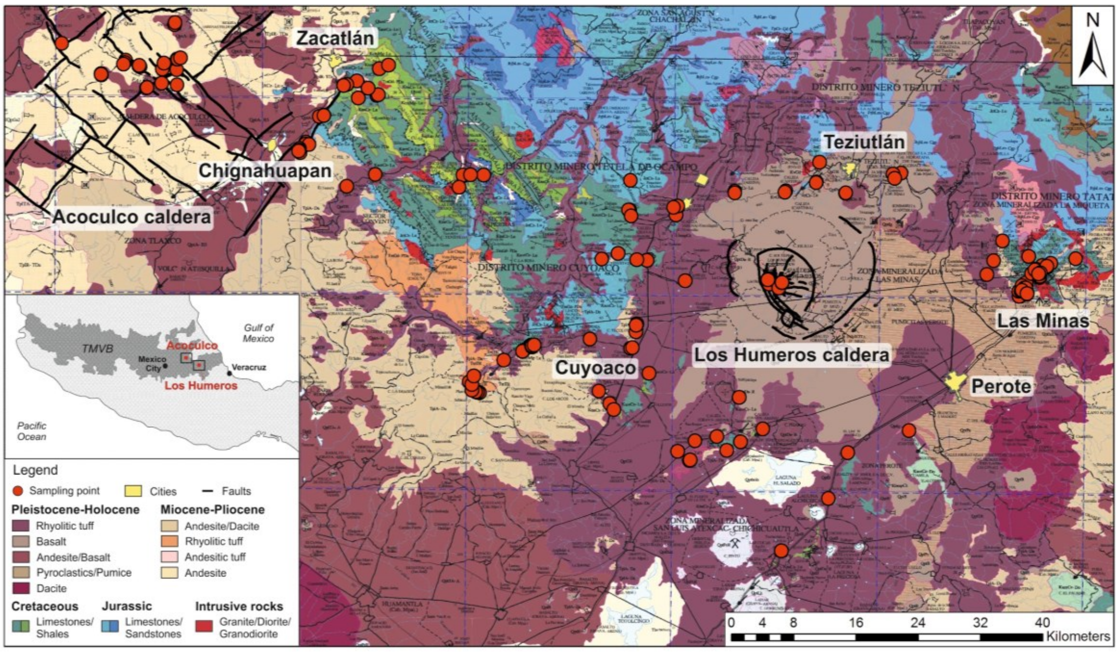

Figure 27 - Overview of the sampling locations in the study area (geological map retrieved from SGM, 2002a and b).

The field work and the results of the petrophysical measurements revealed the complexity of both geothermal systems. Composition, extension and distribution of the volcanic sequences are very variable within the study area. Furthermore, the basement rocks showed a high geological heterogeneity comprising several different rock types including shales, limestones, sandstones, intrusive bodies, marble and skarn. Thus, the results of the petrophysical and thermophysical properties showed a wide parameter range for individual units. Furthermore, hydrothermal alteration observed on the reservoir core samples significantly changed the petrophysical properties, which is shown by a higher matrix porosity, permeability and thermal conductivity compared to the equivalent outcrop samples. Based on the results of the petrographic analyses (D3.2) and the statistical analyses of the rock properties (D6.1), the local model units of the 3D geological model of Los Humeros (WP3.1) were updated as described in 2.3.1.

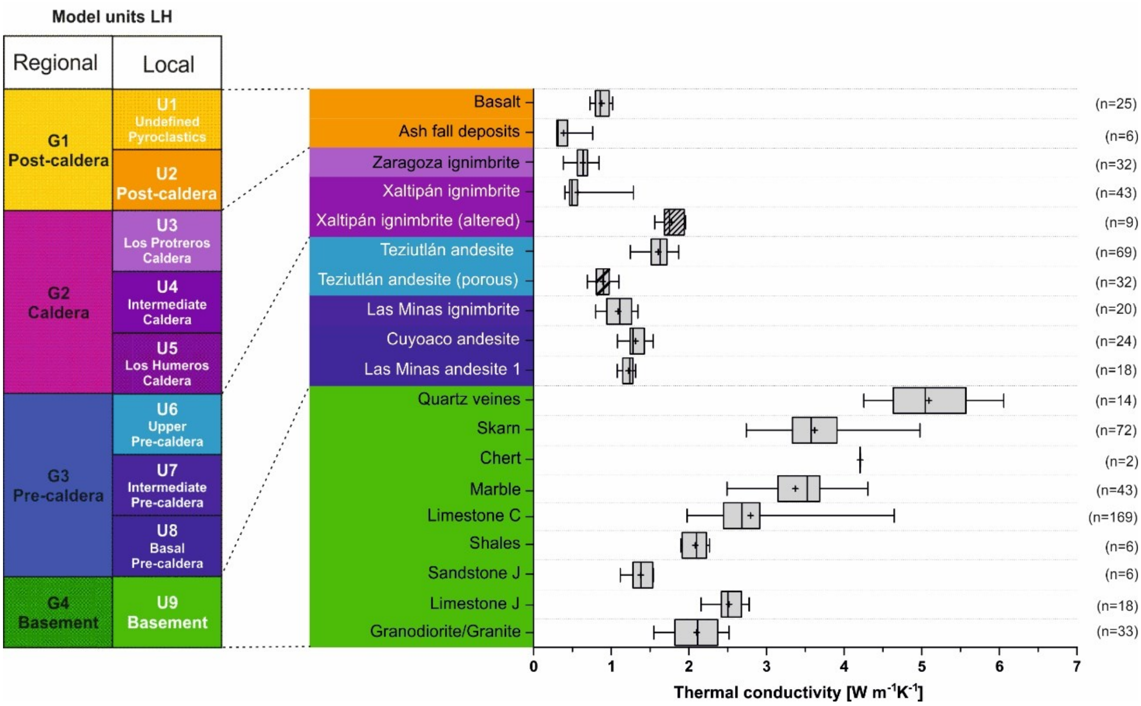

Figure 28 - Thermal conductivity measurements determined on about 640 plugs. The plugs were classified according to their lithostratigraphic units.

The data was used for the parametrization of the numerical models in WP6 and WP7 and for the interpretation of geophysical surveys in WP5. Furthermore, the characterization of the different units improved the understanding of the geothermal system (fluid flow, geochemistry, WP4) and the development of the conceptual geological models presented in WP3.

2.6.2 Task 6.2 Reservoir characterization

2.6.2.1 Activities in the last reporting period

This Task finished during the previous technical report period.

2.6.2.2 Main results from the task

1. Modeling of heat transfer and fluid flow for regional scale model of Los Humeros reported in Deliverable 6.3 https://data.d4science.net/Tz4d

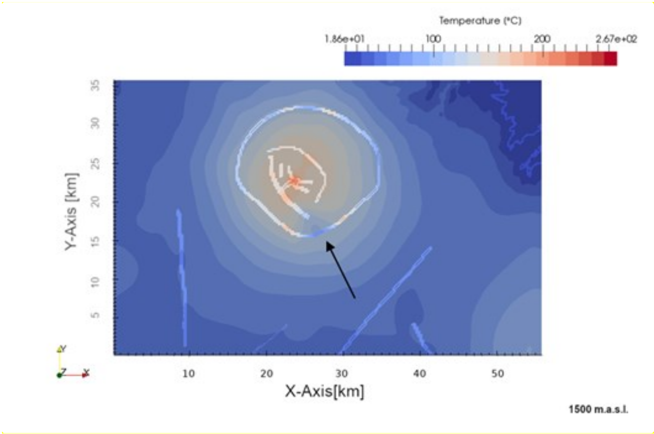

Figure 29 - Temperature at 1500 m.a.s.l. for one of the tested scenarios (check D 6.3 for the other scenarios), where all the faults are open to flow.

2. Thermal modeling of Acoculco geothermal reservoir and evaluation of the potential of Acoculco as an EGS system by simulating different production scenarios. Details are reported in Deliverable D 6.2 https://data.d4science.net/9B2k. The dataset is published via Zenodo repository (check Datasets section for more details). The model serves as a basis for further evaluation of potential stimulation concepts. Study of the different production scenarios can be further advanced by adding operational and production risks.

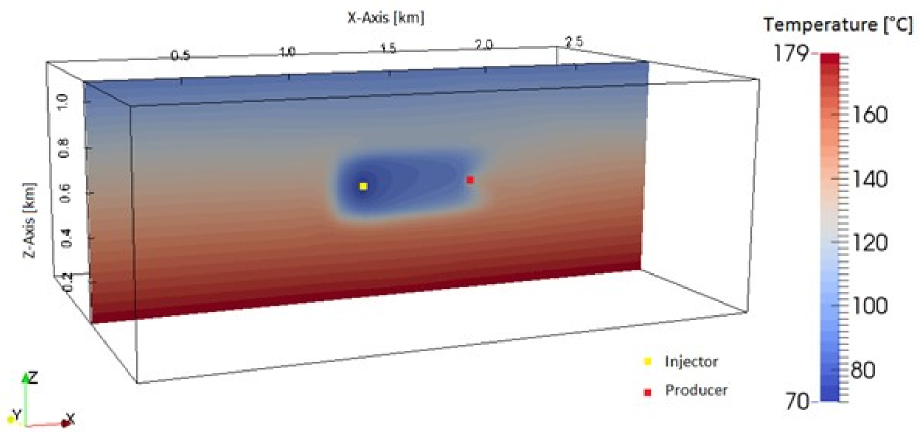

Figure 30 - Temperature distribution within the larger skarn reservoir after 30 years of production in the low permeability scenario of 10–13 m² for a circulation rate of 30 L s–1, the injector and producer stimulation points are indicated by yellow and red respectively.

2.6.3 Task 6.3 Model approaches for EGS

2.6.3.1 Activities in the last reporting period

1. Simulation of laboratory-scale hydraulic fracturing experiments using different numerical codes. Experiments are reported in Deliverable D 6.4 https://data.d4science.net/5Wa9
2. Reporting of the simulation results in Deliverable D 6.5

2.6.3.2 Main results from the task

1. A comparison study of different numerical codes to reproduce laboratory-scale hydraulic fracturing experiments. Please check details in Deliverable 6.5 https://data.d4science.net/Aq18. D6.5 reports on the performance of the numerous EGS stimulation codes. The codes tested are however still under development, but the study might act as a guide for anyone interested to understand the model assumptions and fundamental physics of each numerical code tested along with their performance capabilities to reproduce a well-controlled laboratory-scale hydraulic fracturing experiment
2. Laboratory scale hydraulic fracturing datasets generated from well-controlled experiments in granite and marble for benchmarking numerical codes. The dataset is published via Zenodo repository (check Datasets section for more details) (Reference - 9,10). This complete collection of data, obtained within the framework of European Union's Horizon 2020 project GEMex, is rare in its kind and indispensable for verification of model assumptions and constitutive relationships of numerical codes used for designing field-scale hydraulic fracturing experiments.

2.6.4 Task 6.4 Model approaches for SHGS

2.6.4.1 Activities in the last reporting period

1. Initial-state modeling of Los Humeros in reservoir scale (RWTH, CNR)
2. Finalisation of Deliverable D 6.6

2.6.4.2 Main results from the task

1. Initial-state thermal models of Los Humeros (uploaded in Open Access Database and Zenodo Repository).
2. Deliverable D6.6 describes the approaches used for simulating the natural steady state behaviour of fluid flow and heat transport of Los Humeros geothermal field. Several scenarios investigating the impact of unknown properties are studied. D6.6 is divided into parts. Part 1 documents the contribution of RWTH Aachen University towards initial state modeling of Los Humeros in reservoir scale, which is a continuation of report D 6.3. Part 2 of this report is a contribution of CNR and describes an alternate approach used for initial state modeling of Los Humeros. The dataset is published via Zenodo repository (check Datasets section for more details).

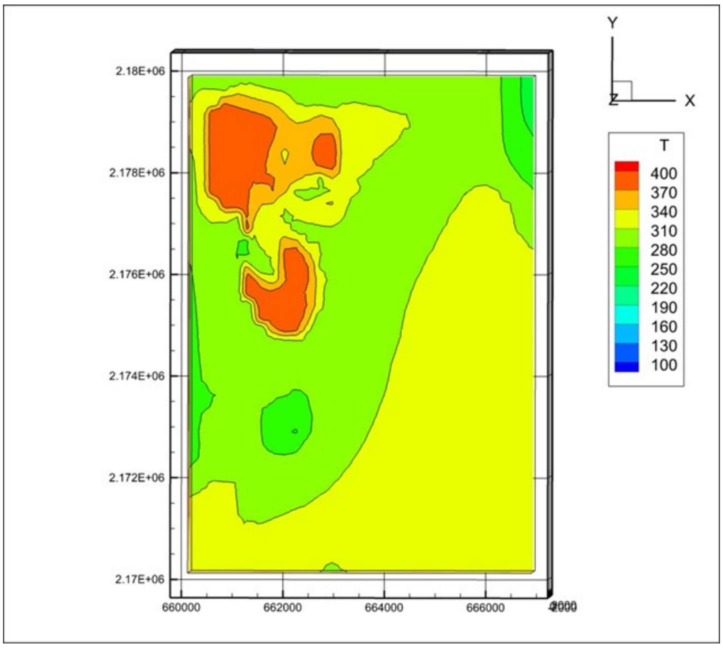

Figure 31 - Figure - Temperature distribution at 500 m asl. The 3 temperature anomaly could be identified. Check D 6.6 reservoir modeling report for details https://data.d4science.net/3Qov

2.6.5 Impact

Work done within WP 6 focuses on reservoir characterization and numerical modeling.

Detailed characterisation of different reservoir units has been performed within Task 6.1 and Task 6.2. Extensive database of petrophysical properties of different rock types has been created and made available through Open Access (check Datasets section for more details). In addition to reservoir modelling purposes for Los Humeros and Acoculco, the data can also be used for exploratory studies in other geothermal sites with similar geological environments but little or no information. It will therefore lead to an improved resource assessment of geothermal sites in a volcanic setting in general, increasing the probability of success for future geothermal projects.

Results from Task 6.3 have a major scientific impact, since the dataset established provides a unique possibility to test the performance of hydraulic fracturing simulation tools. Improved modelling tools, will have an impact of the development of EGS concepts, ultimately leading to more successful EGS projects, not only in Mexico, but worldwide.

Improved modelling tools for fluid flow and heat transport (task 6.4) lead to an improved resource assessment. These tools are transferable to other geothermal system, thus advancing the development of geothermal energy in general.

2.6.6 Publications

Bär, K. and Weydt, L. (Eds.): Comprehensive report on the rock and fluid samples and their physical properties in the Acoculco and Los Humeros regions, Deliverable D6.1, WP6, GEMex H2020 project, European Commission, 1.5, http://www.gemex-h2020.eu, 15-25, 2019. https://data.d4science.net/zVLc

Deb, P., Knapp, D., Marquart, G., Montegrossi, G., (2019a). Report on the calibrated reservoir model for the super-hot reservoir at Los Humeros and its calibration against available field data. GEMex – H2020 project report D6.3 https://data.d4science.net/Tz4d

Deb, P., Knapp, D., Marquart, G., Montegrossi, G., (2019b). Report on the calibrated reservoir model for the super-hot reservoir at Los Humeros and its calibration against available field data. GEMex – H2020 project report D6.6 https://data.d4science.net/xhNC.

Deb, P., Knapp, D., Marquart, G., Montegrossi, G., (2019a). Report on the numerical reservoir model used for the simulation of the Acoculco reservoir in Mexico. GEMex – H2020 project report D6.2 https://data.d4science.net/9B2k

Deb, P., Knapp, D., Marquart, G.,Clauser, C., and Trumpy, E., (2020). Stochastic workflows for the evaluation of Enhanced Geothermal System (EGS) potential in geothermal greenfields with sparse data: the case study of Acoculco, Mexico. Geothermics, Vol. 88, No. 101879 https://doi.org/10.1016/j.geothermics.2020.101879

Deb, P., Düber, S., Guarnieri Calo' Carducci, C. & Clauser, C. (2020). Laboratory-scale hydraulic fracturing dataset for benchmarking of Enhanced Geothermal System simulation tools, Scientific Data – Nature, *Sci Data* **7,** 220 (2020). https://doi.org/10.1038/s41597-020-0564-x

Deb, P., Parisio, F., Hofmann, H., Fokker, P., Dekker, E.,Düber, S. (2019). Report on the robust stimulation model for the EGS-reservoir in the hot magmatic environment at Acoculco and its verification against the laboratory fracking experiment. GEMex – H2020 project report D6.5 https://data.d4science.net/Aq18

Düber, S., Deb, P., Clauser, C. and Feinendegen, M., (2018). Report on the laboratory fracturing experiment, its boundary conditions, and its flow rates and fracture aperture versus time curves. GEMex – H2020 project report D6.4 https://data.d4science.net/5Wa9

Parisio F., Tarokh A., Makhnennko R., Naumov D., Yuan-Miao X., Kolditz O., Nagel T., Experimental characterization and numerical modelling of fracture processes in granite. Journal of the Mechanics and Physics of Solids, 2018, https://doi.org/10.1016/j.ijsolstr.2018.12.019

Parisio F., Naumov D., Kolditz O., Nagel T., Material forces: an insight into configurational energy. Mechanics Research Communication, Volume 93, October 2018, Pages 114-118, DOI: https://doi.org/10.1016/j.mechrescom.2017.09.005

Weydt, L. M., Ramírez-Guzmán, A. A., Pola, A., Lepillier, B., Kummerow, J., Mandrone, G., Comina, C., Deb, P., Norini, G., Gonzalez-Partida, E., Avellán, D. R., Macías, J. L. , Bär, K., and Sass, I.: Petrophysical and mechanical rock property database of the Los Humeros and Acoculco geothermal fields (Mexico), Earth System Science Data, (submitted), https://doi.org/10.5194/essd-2020-139

Weydt, L. M., Bär, K., Colombero, C., Comina, C., Deb, P., Lepillier, B., Mandrone, G., Milsch, H., Rochelle, C. A., Vagnon, F., and Sass, I.: Outcrop analogue study to determine reservoir properties of the Los Humeros and Acoculco geothermal fields, Mexico, Adv. Geosci., 45, 281-287, https://doi.org/10.5194/adgeo-45-281-2018, 2018.

Yoshioka K., Parisio F., Naumov D., Lu R., Kolditz O., Nagel T., Comparative Verification of Discrete and Smeared Numerical Approaches for the Simulation of Hydraulic Fracturing. International Journal of Geomathematics, 2019, https://doi.org/10.1007/s13137-019-0126-6

2.6.6.1 Datasets published

Deb, P., Knapp, D, Marquart, G., and Clauser, C.: Thermal model of the Los Humeros super-hot geothermal system, Mexico. Zenodo. http://doi.org/10.5281/zenodo.3724084, 2019

Deb, P., Knapp, D, Marquart, G., and Clauser, C.: Thermal model of the Acoculco geothermal greenfield, Mexico. Zenodo. http://doi.org/10.5281/zenodo.3833892, 2019

Deb, P., Düber, S., Guarnieri Calo' Carducci, C. & Clauser, C. (2020). Dataset related to the article "Laboratory-scale hydraulic fracturing dataset for benchmarking of Enhanced Geothermal System simulation tools" (Version v1) [Data set]. Zenodo. http://doi.org/10.5281/zenodo.3710746, 2019

Weydt, L. M., Ramírez-Guzmán, A. A., Pola, A., Lepillier, B., Kummerow, J., Mandrone, G., Comina, C., Deb, P., Norini, G., Gonzalez-Partida, E., Avellán, D. R., Macías, J. L. , Bär, K., and Sass, I.: Petrophysical and mechanical rock property database of the Los Humeros and Acoculco geothermal fields (Mexico), TU Biblio, TU Darmstadt, https://tubiblio.ulb.tu-darmstadt.de/, 2020.

2.6.7 Dissemination

Deb, P., Knapp, D., Clauser, C., and Montegrossi, G., Modeling natural steady- state of super-hot geothermal reservoir at Los Humeros, Mexico, European Geothermal Congress, Den Haag, The Netherlands, 11-14 June 2019.

Deb, P., Salimzadeh,S., Düber, S., Clauser, C., Laboratory experiments and numerical simulations of hydraulic fracturing for enhanced geothermal systems, European Geothermal Congress, Den Haag, The Netherlands, 11-14 June 2019.

Deb, P., Vogler, D., Düber, S., Siebert, P., Reiche, S., Clauser, C., Settgast, R.R. and Willbrand K., 2018, Laboratory fracking experiments for verifying numerical simulation codes, Hydro-Thermal-Mechanical Modelling in Tight Formations, 80th EAGE Conference and Exhibition 2018, Jun 2018, Volume 2018, p.1 - 5 https://doi.org/10.3997/2214-4609.201801166

Deb, P., Siebert, P., Düber, S., Vogler, D., Clauser, C., Reiche, S., and Settgast, R.R, Hydraulic-fracturing experiments on a laboratory scale for numerical codes verification, Geophysical Research Abstracts Vol. 20, EGU 2018-16136, EGU General Assembly 2018

Deb, P., Düber, S., Clauser, C., Hydraulic fracturing experiments in laboratory scale to generate benchmark datasets for verification of stimulation design tools. GEMex Final Conference, GFZ, Potsdam , Germany, 18. - 19.02.2020.

Hutka GA, Hofmann H, Farkas MP, Yoon JS, Zimmermann G, Zang A, Benchmarking of hydro-mechanical coupled models against true-triaxial laboratory hydraulic fracturing experiments. 9th European Geothermal PhD Days, Zürich, Switzerland, 14.-16. March, 2018

Kummerow, J., Raab, S., Schüssler, J. (2018). Fluid-rock interactions at near- and supercritical conditions and their effect on physical properties of high-enthalpy hydrothermal systems - Geophysical Research Abstracts Vol. 20, EGU2018-7097, EGU General Assembly 2018.

Kummerow, J., Raab, S., Spangenberg, E., Schleicher, A. M., Schuessler, J., Monitoring reactive flow in geothermal settings: A petro- and fluidphysical approach. Geophysical Research Abstracts Vol. 21, EGU2019-11295-1, 2019 EGU General Assembly 2019.

Lepillier, B., Bakker, R., Bastesen, E., Bruhn, D., Bruna, P.-O., Daniilidis, A., Garcia, O., TTorabi, A., Wheeler, W., "Characterization of a Fracture-Controlled Enhanced Geothermal System (EGS) in the Trans-Mexican-Volcanic-Belt (TMVB) Predictive mechanical model for fracture stimulation in an Enhanced Geothermal System (EGS)", 6th European Geothermal Workshop, Strasbourg, 10-11 October 2018.

Mandrone, G., Comina, C., and Vacha, D.: Faults characterization aimed at geothermal fluid path identification and quantification, In: GEMex Final Conference, GFZ, Potsdam , Germany, 18. - 19.02.2020.

Montegrossi, G. (2020) Reservoir modeling and calibration for the super-hot reservoir at Los Humeros. GEMex Final Conference Proceedings, 18-19 February 2020, Potsdam, Germany.

Montegrossi, G., Deb, P., Clauser, C., Diez, H. and Ramirez, M.A, Modeling of Los Humeros geothermal field: preliminary results, Geophysical Research Abstracts Vol. 20, EGU2018-17600, EGU General Assembly 2018

Nagel, T., Parisio, F., Naumov, D., Lehmann, C., Kolditz, O.. MFront and OpenGeoSys. Connecting two open-source initiatives for simulations in environmental geosciences and energy geotechnics. In MFront User Meeting. 17.–18. Oct. 2019, Paris, France.

Parisio F., Vinciguerra S., Kolditz O. and Nagel T., The lithological control on the brittle-ductile transition in volcanic areas, EGU General Assembly 2018, Vienna, 8th-13th April 2018, EGU2018-2429.

Parisio, F., Vilarrasa, V., Wang, W., Kolditz, O., Nagel., T., Coupled thermo-hydro-mechanical simulations of a supercritical geothermal system. In Decovalex 2019 Symposium. Coupled Processes in Radioactive Waste Disposal and Other Subsurface Engineering Applications. 4–5 Nov, 2019, Brugg, Switzerland.

Parisio, F., Lehmann, C. and Nagel, T., 2019, December. A constitutive model for the brittle-ductile transition of basalt. In AGU Fall Meeting 2019. AGU.

Qin, Y., Schill, E., Weydt, L. M., Bär, K., Sass, I., and Pérez-Florez, M. A.: Concept of Gravimetric Exploration of Enhanced and Super-Hot Geothermal Systems in Acoculco and Los Humeros (Mexico), 5th European Geothermal Workshop, Karlsruhe, Deutschland, 12.-13.10.2017.

Weydt, L. M., Lucci, F., Carrasco-Núñez, G., Giordano, G., Lacinska, A., Rochelle, C., Bär, K., and Sass, I.: Petrophysical reservoir characterization of the Los Humeros geothermal field (Mexico): comparison of outcrop analogues and reservoir formations. In: GEMex Final Conference, GFZ, Potsdam , Germany, 18. - 19.02.2020.

Weydt, L. M., Bär, K., and Sass, I.: Thermo- and petrophysical rock properties of the Los Humeros geothermal field (Mexico): from outcrop analogue analysis to parametrization of a 3D geological-geothermal model, Der Geothermiekongress 2019, München, Deutschland, 19.11 – 22.11.2019.

Weydt, L. M., Bär, K., and Sass, I.: Thermo- and petrophysical rock properties of the Los Humeros geothermal field (Mexico): comparison of outcrop analogues and reservoir formations, 7th European Geothermal Workshop, Karlsruhe, Deutschland, 08.10 – 11.10.2019.

Weydt, L. M., Bär, K., and Sass, I.: New insights on geothermal rock properties of the Los Humeros geothermal field, Mexico, 6th European Geothermal Workshop, Strassburg, Frankreich, 10.10 – 11.10.2018.

Weydt, L. M., Bär, K., and Sass, I.: Outcrop analogue study to determine reservoir properties of the Los Humeros and Acoculco geothermal fields, Mexico, European Geosciences Union General Assembly 2018, Wien, Österreich, 08.-13.04.2018.

Weydt, L. M., Bär, K., and Sass, I.: Outcrop analogue study to determine petrophysical properties of the Los Humeros and Acoculco geothermal fields, Mexico, 5th European Geothermal Workshop, Karlsruhe, Deutschland, 12.-13.10.2017.

Seminar entitled “Enhanced supercritical geothermal systems: toward stimulation design” held at Universidad Politecnica de Catalunya – Instituto de Diagnóstico Ambiental y Estudios del Agua - Consejo Superior de Investigaciones Científicas (UPC-IDAEA-CSIC), March 15th 2018, by Francesco Parisio.

2.6.7.1 Accepted abstracts

Rochelle, C., Lacinska, A., Kilpatrick, A., Rushton, J., Weydt, L. M., Bär, K., and Sass, I.: Evidence for fracture-hosted fluid-rock reactions within geothermal reservoirs of the eastern trans-Mexico volcanic belt, Proceedings, World Geothermal Congress 2020, Reykjavik, Island, 2020, postponed to 2021.

Weydt, L. M., Bär, K., and Sass, I.: Petrophysical reservoir characterization of the Los Humeros and Acoculco geothermal fields, Mexico, Proceedings, World Geothermal Congress 2020, Reykjavik, Island, 2020, postponed to 2021.

2.6.8 Student theses

2.6.8.1 Master Thesis

Xiangyun Shi: Numerical Simulation of Los Humeros super-hot geothermal field, Mexico,Master in Applied Sciences, Faculty of Georesources and Materials Engineering, RWTH Aachen University.

Gergő András Hutka: Benchmark Modelling of True-Triaxial Laboratory Hydraulic Fracturing Experiments, GFZ

E.S.J. Dekker: Modelling the GEMex / Aachen marble and granite fracturing experiments in MFracTM. Utrecht University

2.6.8.2 Bachelor Thesis

1. Title - Thermo- and petrophysical properties in relation to petrological characteristics: an example of the Los Humeros geothermal field, Mexico by Roland Knauthe, Bachelor thesis, Institute of Applied Geosciences, TU Darmstadt.

2.6.9 Deviations from the Description of Action

None

2.7 Work Package 7: Concepts for EGS

Lead: TNO
Partners: CNR, CRES, ENEA, GFZ, OGS, RWTH, SSSA, TNO, TUDA, UFZ, UNITO, UU
Duration: month 7-44
Status: completed

Objectives:

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 optimised stimulation scenarios for Acoculco, based on the collected data and models created in the other WPs of GEMex.

Table 10: Status quo of personal resources WP7

Participant number	1	3	5	6	7	8	11	12	13	15	16	18	20	23	Total
Short name	GFZ	TNO	UU	RWTH	CNR	TUDA	CRES	OGS	CIPR	ENEA	SSSA	UKRI	UNITO	UFZ	
PM foreseen in total GEMex	12	15	6	6	1	3	6	4	0	8	12	0	8	6	87
PM used	9	16	1.5	4.7	1	12.53	7	4	0.13	10.4	12.5	0.8	13.4	7	98.6

2.7.1 Task 7.1 Integrated reservoir model

2.7.1.1 Activities in the last reporting period

- Destructive rock mechanical tests were performed at TU Darmstadt on representative outcrop samples of the Los Humeros and Acoculco geothermal field. More than 650 plugs covering all relevant key units were tested for uniaxial compressive strength, tensile strength, dynamic and static Young's modulus and poisson ratio as well as friction angle and cohesion. The results of the rock mechanical tests for Acoculco are presented in D7.1 and D7.2.
- All results of petrophysical and rock mechanical tests performed within GEMex including data from UNAM, GFZ/TU Delft, TUDA, RWTH Aachen and UNITO (task 6.1 and task 7.1) were compiled in an extensive rock property database. The database includes detailed sample information and sample classification regarding the 3D geological models provided by WP3. A scientific paper was prepared describing the work flow, the applied laboratory methods and sample classification (see 2.6.6.1).

- EGS stimulation concepts from task 7.2 were translated to field development scenarios. The field development scenarios were simulated using dynamic reservoir simulation models to estimate potential production for Acoculco. For each scenario a probability density function of the key performance indicators was estimated using a stochastic approach in which 50 realizations for each scenario were simulated. The main input parameters are the size and permeability of the stimulated area. The quantification of uncertainty on these parameters was based on results from task 7.2 whenever possible and expert judgement otherwise. (TNO, GFZ, HBO)
- The dynamic model needed to simulate the production was constructed based on the local geological model created in task 3.1 and the conceptual geological models developed in task 4.1 as reported in D4.1 and during the GEMex final conference in February 2020. Further parametrization of the model was mainly based on results from WP6 (TNO, CNR, NORCE, RWTH, UKRI, TUD)
- A wellbore model was used to translate the key performance indicators to surface. (TNO)
- based on the results of the field development scenarios, an analysis was done for potential induced seismicity. First the simulated pressure and temperature during production are translated to stresses taking into account the in-situ stress estimated from task 7.2. An in-house developed, fast tool called Macris is used for this purpose. The tool was adjusted to allow simulation of the Acoculco area. Based on the simulated stresses, the induced seismicity is estimated using Dieterich's seismicity rate theory. TNO, UU)

2.7.1.2 Main results from the task

Based on the EGS stimulation scenarios from Task 7.2, four main scenarios of permeability creation were identified: hydraulic fracture (tensile), stimulated fracture network, stimulated fault (zone), combination of stimulated fractures and faults. Each scenario results in a different shape and size of stimulated rock volume and each scenarios was implemented at three different depths. The stimulation scenario was applied to EAC-1 and to a second well, which was added at an appropriate location to form a doublet, assuming that flow connectivity between the wells is achieved.

Only the main uncertainty in the estimation of the production is included in this analysis, namely the size, shape and permeability of the stimulated area. The uncertainty is included via scenario and per scenario via a stochastic approach in which 50 realizations are simulated per scenario. The range in the stimulated rock volume spans three orders of magnitude and the produced heat ranges from less than 2 MW to 40 MW (downhole and averaged over 20 years of production). At this point in time, the information is insufficient to indicate which scenarios are the most likely, and thus the results should be interpreted as indications rather than realistic estimates of the potential production.

The results of the scenarios show that none of the scenarios in which the stimulation affected the area just below the casing at 800 m depth, produced more than 10 MW heat downhole. Also, the wellbore modelling showed that production to surface was difficult for production at this depth. The scenarios with a hydraulic fracture all suffered from premature thermal breakthrough and none of the scenarios produced more than 12 MW. The scenarios at 1500 m and 1800 m depth (see Figure) with stimulated fracture network or fault showed more promise. The stimulated fault suffered from large pressure drop near the wells. The stimulated fracture networks showed the best production characteristics, but it should be noted that the presence of a sufficiently dense and connected fracture network is speculation at this moment in time.

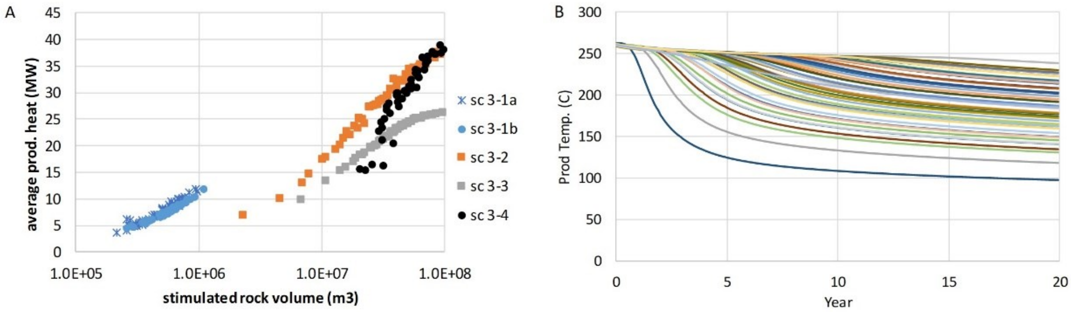

Figure 32 - A: average produced heat for four scenarios at a depth of 1800 m as a function of stimulated rock volume. Every symbol represents one realization. The scenarios are: 3.1a: hydraulic fracture height constrained, 3.1b: hydraulic fracture, not height constrained, 3.2 stimulated fracture network, 3.3 stimulated fault zone, 3.4 combination. B: Production temperature over 20 years for a stimulated fault zone at 1800 m depth. Every line represents a realization.

2.7.2 Task 7.2 Stimulation Design

2.7.2.1 Activities in the last reporting period

- Analysis of the in-situ stress field in Acoculco based on geological data, drilling data, borehole logs, laboratory measurements on collected rock samples and statistical analyses. Based on the predicted in-situ state of stress, the maximum pressure required to enhance the rock permeability was estimated. Publication of the results in *Geothermics* (HBO, GFZ, UMSNH, CNR, UNIBA)

- Development of numerical scheme of hydraulic fracture propagation with phasefield approach (GFZ, UFZ)

- Analytical and numerical analysis of hydraulic fracturing and fracture re-opening. Publication of results in *Geoscience Letters* (UFZ / TU BA Freiberg)

- Analysis of hydraulic stimulation of pre-existing fracture network with OpenGeoSys. Publication of results in *Solid Earth*, (GFZ / TU Delft, UFZ / TU BA Freiberg)

- Hydraulic fracturing simulations using the commercial hydraulic fracturing simulator MFrac: The software was validated within the GEMex WP6 on laboratory hydraulic fracturing experiments (Deliverable D6.5). (GFZ / TU Delft)
- Hydraulic and acid fracturing analysis of EAC-2 with MFrac based on well log data and laboratory data (GFZ / TU-Delft)
- Semi-analytical tool for simulation of induced seismicity during stimulation based on block-spring concept completed. The tool is used for estimating potential for induced seismicity for different stimulation scenarios. (TNO)

- Development of optimised stimulation scenario for the stimulation test in one of the two existing wells in Acoculco. Establishing a EGS development workflow for EAC-1 and EAC-2 (GFZ)
- Numerical simulation of seismic response for the EGS Acoculco scenario with and without melting (Results are included in Deliverable 5.5 and Poster of Farina et al. presented at the Final GEMex conference, Potsdam February 2020).
- Preparation of Deliverable 7.2 (GFZ, HBO, TNO, UFZ, OGS)

2.7.2.2 Main results from the task

Based on the reservoir characterization in SP2 different stimulation scenarios were investigated with different analytical, semi-analytical and numerical tools. Hydraulic fracturing chemical stimulation and shear stimulation treatments were simulated and seismicity due to shear slip on nearby faults was modeled. The calculated range of fracture geometries and properties were then used as input for the integrated reservoir simulations performed in task 7.1 to evaluate the key hydraulic and thermal performance criteria of the different scenarios. This includes production flow rate, production temperature and sustainability.

Overall, the chances to develop a commercially successful EGS with the exploration wells EAC-1 and EAC-2 in Acoculco are considered relatively low. This is due to:

- limited knowledge of the local geology at depth,
- the possibility of no permeable structures that contain significant amounts of fluids near the wells,
- the current wellbore conditions (both wells are not accessible),
- the well completions that make zonal isolation difficult (long open hole sections),
- the stimulation of vertical fractures between two vertical wells due to the expected normal to strike-slip stress regime (that might not hydraulically connect the wells to each other), and
- a possible fault zone in between the two wells (that may be a barrier for fluid flow and fracture development).

Nevertheless, the optimized stimulation scenario for Acoculco wells EAC-1 and EAC-2 involves the following aspects:

- Thermal stimulation and hydraulic shear stimulation of the deep fracture zones in granites and marbles is considered the most suitable stimulation approach.
- A successful EGS with wells EAC-1 and EAC-2 requires to either access permeable structures that contain fluid or hydraulically connect both wells. Fault damage zones and fault intersections may be the only permeable structures in the vicinity of the wells, which intersected an impermeable matrix and sealed natural fractures. These are the primary stimulation targets.
- Stimulation of EAC-1 seems to be more feasible than EAC-2 due to the vicinity to the fault zones and higher fluid losses.
- Isolation of promising target zones is challenging in both wells. Therefore, an open hole stimulation test is advised after ensuring wellbore stability.

- The presented stepwise stimulation approach aims to increase the chance of success at the lowest operational risk. It is tailored to gain knowledge about EGS development in Acoculco even if no commercial EGS can be developed with the exploration wells EAC-1 and EAC-2.
- The knowledge gained by the proposed injection tests in the existing exploration wells can be the basis for a controlled development of an EGS in Acoculco with new wells specifically designed for stimulation.
- The proposed EGS development workflow is displayed in Figure 3Figure ***33***.

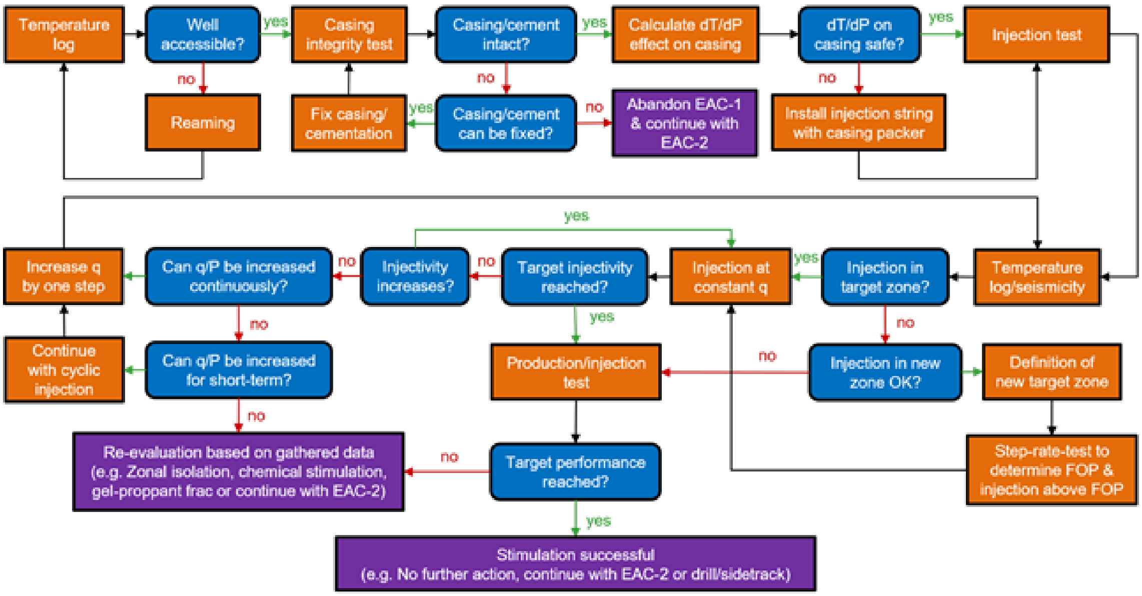

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Figure 33 - Proposed EGS development workflow for Exploration wells EAC-1 or EAC-2 in Acoculco.

2.7.3 Task 7.3 Induced seismicity and environmental hazards

2.7.3.1 Activities in the last reporting period

- Description of the baseline geochemical composition of soil and water in the Acoculco area based on the analysis of samples provided by the Mexican GEMex consortium. Also included is an analysis of the potential risk for contamination of (ENEA).
- Overview of risk for induced seismicity based on baseline monitoring performed by the Mexican GEMex consortium and simulation of potential for induced seismicity during stimulation (reported in D7.2) and production (reported in D7.1) (TNO).
- Investigation of the subsurface in Acoculco in terms of risk for induced seismicity in particular the impact of discontinuities and shallow subsurface characteristics on the translation of seismic events to the surface. A case study in Italy was analysed and the results interpreted in terms of risk in Acoculco (ENEA).
- finalizing paper on the review of traffic light systems for micro-seismic monitoring of induced seismicity. Including also recommendations for micro-seismic monitoring and traffic light system implementation in Acoculco (OGS).
- Completion of the deliverable D7.3 (all).

2.7.3.2 Main results from the task

In this work, environmental concerns relating to a potential EGS development at the site of Acoculco (Mexico) are evaluated and potential mitigation measures discussed. The concerns that are addressed here are related to possible pollution of soil, water and aquifers and induced seismicity. For the latter, different aspects are investigated: potential for induced seismicity, impact of the shallow subsurface on ground motion resulting from induced seismicity, micro-seismic monitoring design and traffic light systems for mitigation.

Geochemical characterization of soil and water has been carried out with the aim to study the potential influence of the geothermal exploitation on these environmental matrices and the potential effects on human health. Concerning the waters, the results have evidenced, for some major and trace elements, concentrations sensibly higher for drinking waters than the guideline values defined by international organizations (WHO, EPA, EU) and Mexican legislation. The water chemistry depends greatly on seasonality (see Figure): dry periods are characterized by enrichment in some elements while in the wet ones the dilution due to rainfall prevails. Some elements, especially arsenic, reach in waters concentrations that might pose serious problems for the animal's health themselves and for that of the consumers since farming is a key activity in the area. The soil geochemistry evidence that minor and trace elements show a large concentration range related to the wide compositional heterogeneity which is typical of the geothermal area's rocks. This applies mainly for S and As, while the Mn variability range can be related to the redox conditions' changes.

Potential for induced seismicity was analysed during stimulation (GEMex D7.2) and production (GEMex D7.1). The results show that the risk for induced seismicity during stimulation appears to be small given the current information on stress and fault orientation. Different scenarios were run with varying stress regimes and fault orientations, but all simulated events were smaller than -0.5. This seems to be in line with the low level of seismicity observed during micro-seismic monitoring (Mexican GEMex PT5.2). During production the injection of large amounts of cold water shows a larger impact.

The impact of the subsurface characteristics on ground motion was studied for two site specific seismic events, one from induced seismicity and one of tectonic origin. It is observed that there are similarities in the measured ground motion characteristics and in the effects on the built environment, that can be related to the presence of lateral discontinuities in the geology. Based on the insights gained from this analysis, the aspects of the Acoculco geology that can amplify the superficial motion are investigated. Because the amplitude and frequency content of the observed micro-seismic data is limited, only tentative conclusions can be reached, which show that locally generated earthquakes can travel through discontinuous media rich in faults with relevant lateral discontinuities that can modify the seismic field in the sense of producing refractions/reflections capable to shift the frequency content of seismic motion to higher frequencies and then to higher peak values. In some of the station sites, the possibility of stratigraphic amplification of seismic motion is apparent.

Finally an extensive literature review is presented on micro-seismic monitoring and traffic light systems for EGS development. Based on the literature review, a set of recommendations for micro-seismic monitoring network design is presented, which includes technical details and suggestions for supplementary monitoring options such as monitoring in a deep borehole and geodetic measurements. Experience with and recommendations for EGS management procedures conclude the report, with special attention to risk-based traffic light systems and public outreach.

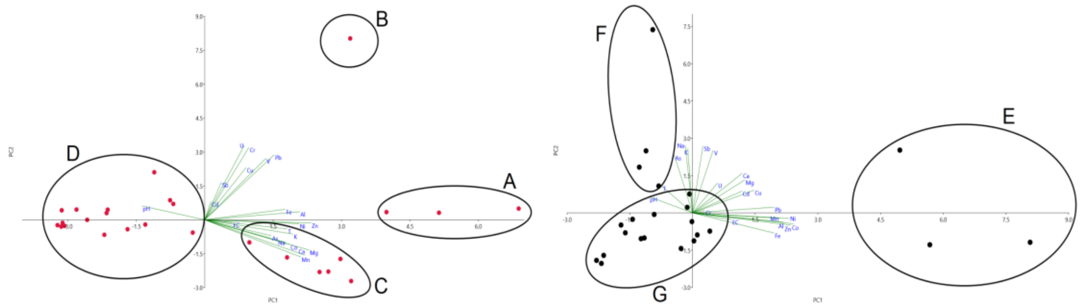

Figure 34 - Results of the Principal Component Analysis (PCA) of the water sampled from Acoculco in the wet (left) and dry (right) season.

2.7.4 Task 7.4 Public engagement

2.7.4.1 Activities in the last reporting period

Based on the results of the analysis of questionnaires and unstructured interviews carried out with citizens, companies, public authorities and local communities both in Mexico, Europe and a selection of developing countries, 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. Different levels of public engagement were identified namely: Information level, Communication level, Collaboration level and Participation level. These four levels were structured according to an increasing public engagement, from the lowest level – i.e. the Information level – to the highest level – i.e. the Participation level. The conceptual model simultaneously provides an integrated framework of three different perspectives from the actors involved (company, society and public authorities), and serves as a guideline to interact with them, according to the level of engagement desirable and achievable. In addition, qualitative scenarios for a public engagement strategy were built, adapted to particular technical development options – i.e. deployment of power generation, and deployment power generation and direct uses. Last, a qualitative assessment was carried out to define sustainability scenarios and explore systemic influences between communities and companies that might affect sustainability and the regional environment in the long term. Such scenarios were built by using a behavioural model proposed in the last chapter of the report and the conceptual model already mentioned. The input-output (I-O) approach was also outlined to guide future analysis and assessment of the impact of renewable energy developments at the regional level. All results of the task 7.4 were finalized in Deliverable 7.4

2.7.4.2 Main results from the task

- *Literature review* addressed the main themes relating to the current debate on public engagement, considering private and public actors' perspectives, geothermal energy specificities, and practices and measurement methods to assess social impacts and develop engagement.
- *Multi-source and quali-quantitative investigation on different stakeholders* to discover their interpretations and perspectives on geothermal energy development issues and build a multidisciplinary approach.
- *Questionnaire survey and unstructured interviews, considering the private actors' perspective*. The questionnaire survey with consumers from Brazil, Russia, India, China, South Africa and Mexico provides evidence about energy companies' reputation, considering consumers' perception of corporate social responsibility activities and service quality. Moreover, the questionnaire survey provides insights on consumers' loyalty identifying the type of activities considered by consumers as ''good corporate social responsibility activities''. Differently, unstructured interviews were carried out with two companies that develop geothermal projects (i.e. Comision Federal de Electricidad - CFE and Enel) to focus on the organisational dynamics they implement to engage with local communities. Such interviews highlight differences between these two companies, CFE lagging behind Enel in terms of the level of maturity in the engagement strategy implemented. However, results show a quite strong alignment of interviewees' opinions regarding the engagement strategy implemented in each company.
- *Questionnaire survey and unstructured interviews, considering the social context of local communities and public authorities through the Social Impact Assessment (SIA) approach*. Unstructured interviews were carried out with Mexican local authorities and local communities (Acoculco area), while a questionnaire survey was performed with only local communities. The unstructured interviews with local authorities and local communities provide additional information about the local- and municipal-level context, considering communities' perceived strength, weaknesses, opportunities, threats (SWOT) and aspects such as cultural and governance/institutional dynamics, communities' knowledge about geothermal energy, economy and local employment, and externalities for the communities - which can be positive and negative such as better infrastructures or water contamination. The questionnaire survey with local communities provides information on socio-economic and environmental perceived issues and the impacts of energy production, and trust towards stakeholders such as institutions regarding information about energy issues.
- *Conceptual model* (figure below) that simultaneously provides a shared and multi-perspective vision to public engagement, considering the most important stakeholders involved in public engagement - i.e. communities with SIA professionals, companies and local authorities. The interplay of the different perspectives results in the definition of different degrees of public engagement, which are the Information level, Communication level, Collaboration level and Participation level. This simultaneous representation of multiple perspectives is important since it is able to align actor-specific processes and approximate real-life situations in which strategies and activities are evaluated.

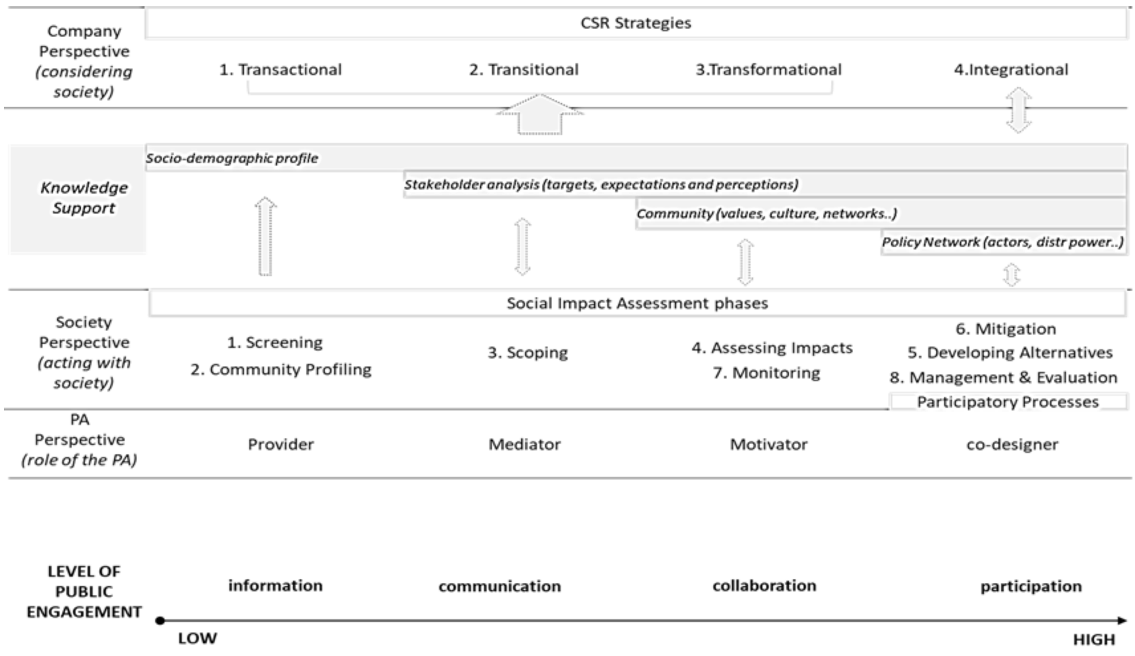

Figure 35 - The conceptual model for guiding the strategy for the consultation process for public engagement (PE) (source: Deliverable 7.4).

- *Qualitative scenarios for a public engagement strategy to approximate real-life situations* provide the examples of public engagement processes by developing two scenarios – i.e. deployment of power generation, and deployment power generation and direct uses. Such scenarios give evidence concerning how the engagement strategy could change among the different levels of engagement, including efforts such as engaging workshops, open forums and partnerships with local communities.
- *Qualitative assessment to define sustainability scenarios for exploring systemic influences in the engagement between companies and communities*. By including – whenever possible – information on employment, market diffusion, environmental sustainability of the technology, the sustainability scenarios provide insights on cases where: (a) there is a mutual proportional response among the company and the community; (b) there is a large effort to promote from the company and a less than proportional response from the community; (c) there is a relative smaller effort to promote engagement from the company and a more than proportional response in the the community. Last, information on variables and indicators/quantitative models and approaches were described, such as the input-output (I-O) approach, giving insights on how to guide future analyses.

2.7.5 Impact

Within WP7, methods and workflows were demonstrated for development of an EGS at Acoculco. Bringing together the characterization of the Acoculco area gained in the other WPs, different scenarios for EGS stimulation were analysed, covering a wide range of aspects such as the technical feasibility of the stimulation, operational risks, sustainability of the created resources, environmental hazards and public acceptance.

EGS stimulation and production

The characterization work from the other WPs of GEMex was successfully merged to ensure that the work in this WP was based on the latest insights gained in GEMex. The characterization from the other WPs was complemented by a detailed analysis of the well logs and drilling reports provided by CFE. This resulted in much improved characterization of the magnitude and uncertainty of in situ stress, which is essential for simulation of the EGS stimulation and estimates of induced seismicity. Based on numerical modelling and evaluation of different stimulation methods (thermal, chemical, shear and tensile fracturing), a detailed workflow was elaborated with attention to operational risks, such as well stability, and monitoring to maximize the chances of achieving a successful EGS stimulation. The sustainability of the different stimulation scenarios in terms of production temperature and flow rate was estimated which highlighted limitations and possibilities of different EGS development options.

Despite the considerable advancement in the characterization made within the GEMEx project, the uncertainty analysis that was carried out shows that the EGS development as Acoculco still faces large uncertainties. Therefore, the proposed workflow advocates a stepwise development approach that allows to further reduce these uncertainties.

→ Stimulation concepts and productivity analysis will have a site specific impact on the potential EGS site in Acoculco. Recommendations for stimulation test in one of the existing wells permit to gather the data necessary for the subsequent design of an EGS concept with new wells specifically designed to establish the first EGS system in Mexico. Since Mexico has an enourmous EGS potential, this would have a huge impact on the future development of the geothermal market in Mexico.

Environmental hazards

The potential hazards to the environment were highlighted, in particular the risk for induced seismicity. A comprehensive analysis of the potential for induced seismicity during stimulation and production, extended with an analysis of possible risks posed in the shallow subsurface of Acoculco provides a solid base for estimating the risk of induced seismicity in the Acoculco area. Detailed recommendations for traffic light systems for induced seismicity based on an exhaustive literature study complete the work.

→ The analysis of environmental hazards, provides the tools to avoid or mitigate environmental risks during the implementation of the EGS concepts, thus increasing the success probability of the EGS development.

Public Engagement

By using the developed conceptual model, a shared and multi-perspective vision of the social aspects to be addressed and the public engagement strategies to be implemented can be designed and implemented, allowing the adoption of an overarching approach to geothermal energy projects. This would create not only direct benefits for the actors involved, but it could generate positive spillovers that (perhaps) were not considered in the first place. As an example, communities barely affected by the project may still be interested in engaging with the energy company responsible for the geothermal development and creating synergies and business partnerships with both the company and other local communities. Within the context of the GEMex project, the methodological approach developed in Task 7.4 can be used by all actors involved. Companies involved in the development of geothermal energy projects, such as CFE, can benefit from better understanding of consumer-related dynamics and organisational structure dynamics related to engagement strategies, targeting the desired level of engagement and defining scenarios on the possible consequences. Local communities, together with professionals, can provide the knowledge support required, through an assessment of socio-economic needs and environmental threats. Local authorities can better understand their role in project developments by supporting different phases of the engagement process.

→ The concept for public engagement will increase the social acceptance of the EGS development. It is applicable not only to the specific case in Acoculco, but also to geothermal developments worldwide. Therefore, it is an important tool to overcome non-technical barriers of geothermal projects.

→ Since the approaches and concepts developed in WP7 contribute to the development of an EGS in Acoculco, this could also have a social impact on the local communities, generating jobs and improving the local infrastructure.

2.7.6 Publications

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Lepillier, B., Daniilidis, A., Gholizadeh Doonechaly, N., Bruna, P.-O., Kummerow, J., Bruhn, D., "A fracture flow permeability and stress dependency simulation applied to multi-reservoirs, multi-production scenarios analysis", Geothermal Energy, 7, 2019, DOI: 10.1186/s40517-019-0141-8

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Lepiller, B, Daniilidis, A., Parisio, F., Yoshioka, K., Bruna, P.-O., Bruhn, D., A fully integrated EGS evaluation workflow, Proceedings, 45th Geothermal Reservoir Engineering Workshop, Stanford, February 2020.

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2.7.7 Dissemination and communication activities

Angelone M., Spaziani F., Verrubbi V. (2020). Geochemical assessment of the Acoculco geothermal area's waters and their potential impact on population. Gemex Conference, Superhot Geothermal Systems and the development of EGS Potsdam, GFZ. 18-19 February 2020.

Angelone M., Spaziani F., Verrubbi V. (2020) Geochemical characteristic of the Acoculco geothermal soils. Gemex Conference, Superhot Geothermal Systems and the development of EGS. Potsdam, GFZ. 18-19 February 2020.

Bongiovanni G., Angelone M., Verrubbi V. (2020). Some aspects of seismic risks in Acoculco. Gemex Conference, Superhot Geothermal Systems and the development of EGS Potsdam, GFZ. 18-19 February 2020.

Candela, T., E. Peters and J.D. van Wees. (2020), An integrated modelling approach for predictions of induced seismicity at the EGS Acoculco geothermal site. GEMex final conference, Potsdam GFZ, Germany, 18-19 February.

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Lepillier, B., Daniilidis, A., Torabi, A., Bruhn, D., Bastesen, E., Parisio, F., Hofmann, H., Kummerow, J., Yoshioka, K., Doonechaly Gholizadeh, N., García, O., Bruna, P.-O., Bakker, R., Wheeler, W., and the GEMex consortium, A predictive mechanical model for hydraulic fracture stimulation in Acoculco geothermal reservoir system., GEMex final conference, Potsdam GFZ, Germany, 18-19 February 2020.

Manzella A., (2019) "Social aspects in geothermal energy development: a European perspective". GEMex Webinar presented on 28 November 2019.

Parisio, F., Vilarrasa, V., Wang, W., Kolditz, O., Nagel, T., Modelling fault reactivation and induced seismicity in supercritical geothermal systems, GEMex final conference, Potsdam GFZ, Germany, 18-19 February 2020.

Peters, E. B. Lepillier, H. Hofmann, (2020) Simulation of Enhanced Geothermal Production (EGS) scenarios at Acoculco Geothermal site. GEMex final conference, Potsdam GFZ, Germany, 18-19 February.

Sciullo, A., (2019), "Measuring the social impact of renewables infrastructure: the potential of integrating counterfactual approach and Social Impact Assessment methodology", presented during the "XIV European Sociological Association Conference", Manchester, UK, 20-23 August

Sciullo, A., (2019), "Evaluating the impact of energy renewable infrastructure on local communities: a case study on geothermal energy in Mexico", presented at XL Aisre Conference, L'Aquila, Italy, 16-18 September

Measurement methods of socioeconomic impacts of renewable energy projects, uploaded at the Horizon 2020 results platform.

2.7.7.1 Accepted Abstracts

Annunziata, E., Contini, M., Diaz, F., Karytsas, S., Manzella, A., Padovan, D., Sciullo, A., (2018), "Public engagement strategy: a conceptual model for enhancing the development of geothermal energy" presented during the conference "Breaking the Rules! Energy Transitions as Social Innovations, International conference hosted by the Leibniz Research Alliance on Energy Transitions", Berlin (Germany), June 14-15.

Hofmann, H., E. Peters, A.F. Hernández Ochoa, F. Parisio, B. Lepillier, 2020. Hydraulic stimulation scenarios for a potential Enhanced Geothermal System (EGS) in Acoculco, Mexico. Proceedings of the World Geothermal Congress 2020, Reykjavik, Iceland, April 26 – May 2, 2020 (postponed to 2021).

Lepillier, B., Bruhn, D., Predictive Mechanical Model for Fracture Stimulation in an EGS Context. Proceedings of the World Geothermal Congress 2020, Reykjavik, Iceland, April 26 – May 2, 2020 (postponed to 2021).

Parisio, F., Yoshioka, K., Lepillier, B., Kummerow, J., Kolditz, O.,. Hydro-fracturing Scenarios for a High-Temperature Geothermal System. Proceedings World Geothermal Congress 2020 Reykjavik, Iceland (postponed to 2021).

2.7.8 Deviations from the Description of Action

In the reporting period only minor deviations from the Description of Action were made:

- Deliverable D7.1 and D7.3 are 4 weeks delayed because of the COVID-19 crisis. Part of the work on these deliverables is based on the results of task 7.2 and had to be done during the last months of the project.
- The work done by UFZ is reported entirely in D7.2 and not in D7.1, because the work is related to the stimulation rather than production modelling.
- UKRI added a minor contribution to task 7.1, since results from WP4 and WP6 had to be transferred to WP7 in order to help WP7-partners to progress towards a better understanding of hot-EGS

2.8 Work Package 8: Concepts for Superhot Geothermal Systems

Lead: GFZ
Partners: CRES, ENEA, GFZ, HBO, IFE, ISOR, OGS, RWTH, TNO, UFZ, UU
Duration: month 1-44
Status: completed

Objectives:

In WP8 we aim to develop and verify 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 SP1 and SP2 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 material suitable for installation in super-hot conditions
- To prepare a best-practice guide for drilling and completion in super-hot setting
- To to give recommendations for a thermal loop design
- To provide propose a monitoring systems in order to avoid or mitigate potential threads for the environment

Table 11: Status quo of personal resources WP8

Participant number	1	2	3	5	6	10	11	12	15	18	19	23	Total
Short name	GFZ	ISOR	TNO	UU	RWTH	IFE	CRES	OGS	ENEA	UKRI	HBO	UFZ	
PM foreseen in total GEMex	15	20	6	6	6	2	6	3	8	0	10	6	88
PM used	18.1	8.57	5.46	2.3	17.64	0.5	9	3,4	5.17	6.65	10	8	94.8

2.8.1 Task 8.1 Prediction of reservoir properties

2.8.1.1 Activities in the last reporting period

GFZ:

- Continued long-term flow-through experiments (up to 3 month per experiment) to determine electrical and hydraulic properties of limestone and andesite at conditions simulating superhot hydrothermal reservoirs (p_{fluid} = 25 MPa, T_{max} = 520 °C). In particular, the impact of reactive fluid-rock interactions on spectral induced polarisation measurements was investigated. → Abstract submitted for WGC2020 (Kummerow et al. 2020)
- Electrical measurements were performed on high-enthalpy mixed salt solution of various salinity.
- XRD and XRF data for 26 volcanic samples from Los Humeros were analysed
- Measurements were conducted on electrical properties and gas permeabilities

- Thin-sections of the samples from high pressure/ high temperature experiments were prepared and analysed on the electron-microprobe to correlate variations in physical properties with fluid-rock interactions, manifested in the rock's microstructure. Samples of the percolated fluids were analysed by ICP-OES/ ICP-Ms
- Analysis of the productivity and injection data from Los Humeros with the aim to analyze the productivity behavior of new wells and verify the forecasting model of productivity for new wells as well as identify possible signs of depletion of the reservoir

TNO:

- Finalized peer-reviewed paper on semi-analytic poro-elastoplastic modelling
- Further development of coupled numerical modelling (FLAC-TOUGH)
- Formulated integration idea for modelling and well trajectory design (MS37)
- Contributed to D8.1 with summary of coupling paper.

RWTH

- Updating the numerical modeling of Los Humeros with new structural model and information obtained from results of other WPs.
- Contribution towards D8.1 with summary on thermal modelling
- Workshops for combining WP 8 results, e.g. during project meeting, Bochum (Germany), June 2019.

OGS

- Continuation of analysis on geothermal systems by seismic simulation including temperature and fluid (synergy with WP5).

UKRI

- Using data obtained in T4.1 and T6.1 and taking that forward towards a better understanding of the SHGS.
- Adding additional new data (such as further analysis of samples) to the above where appropriate to help formulate/confirm system understanding.
- Write up work in publications to ensure dissemination of scientific results.

2.8.1.2 Main results from the task

- The state of stress in Los Humeros caldera is very complex and, although few measurements exist, well-log observations indicate a stress regime that may fluctuate in space between strike-slip and reverse faulting regime.
- Numerical simulations of conductive and convective heat transport have shown the non-uniform distribution of heat flow within the Los Humeros area and the role of faults in the geological heat transport processes.
- A model for the depth of the brittle-ductile transition was developed based on the theory of temperature-dependent plasticity. Within the given assumptions, the model estimates that an overlap between the possibly-fractured brittle crust and supercritical resources could be found between 3 to 5 km depth at the Los Humeros field.
- Complex models of temperature-dependent seismic wave velocity models have been developed by including plasticity and creep of the solid along with the full equations of state of the fluid. The methods are particularly useful to interpret seismic surveys and provide information about fluids states and the possible presence of partially melted materials.

Indirectly, the model can provide information about drilling performance as a function of temperature.

- A coupled thermo-hydro-mechanical solution for wellbore stability has been developed based on Mohr-Coulomb plasticity theory. The model has advanced capabilities in estimating the wellbore integrity throughout the whole series of operations, from drilling through injection, testing, and production.

2.8.2 Task 8.2 Materials for installation in super-hot systems

2.8.2.1 Activities in the last reporting period

ISOR:

- Working on the tested casing materials from a super-hot well in Los Humeros (XRD analysis, weight loss measurements,
- Supervision of Mexican team during the analysis of the tested materials in slow strain tensile testing
- Preparation and completion of Deliverable 8.2 and Deliverable 8.5

2.8.2.2 Main results from the task

Corrosion of selected candidate materials used for downhole casings have been tested in the superhot well H-64 of the Los Humeros geothermal field. This well has a pressure around 40 bar and a temperature of around 250°C at well-head conditions, and temperature of 290°C at 2300 m depth. The pH at the well-head is measured as 3.5. For corrosion testing, a hexagonal bar was constructed with a total of 35 test specimens from seven different alloys, both samples for weight loss measurements and slow strain tensile tests. The hexagonal bar was lowered down to 1290m depth (T ~260°C and superheated steam of 6°C) and kept in the steam downhole for 14 days.

Figure 36 - Hexagonal bar with attached material samples as it is lowered into the well in Los Humeros for the material test.

Weight loss measurements indicate that the corrosion rate is very high for commercial used casing materials from medium carbon steels, much higher than corrosion rates observed in test in superheated steam in Iceland. The more noble materials tested were all under the commonly used corrosion limit of 0.1 mm per year, though evidence was found of more complex corrosion as shown by reduction in ductility in slow strain tensile test.

This testing of corrosion behavior of materials includes not only weight loss measurements but also slow strain tensile testing. Verification of the results will help to guide power producers in Los Humeros towards better materials for mainly production casings. It will also help to increase both lifetime and productivity of the geothermal wells.

Detailed results from the material test are found in Deliverables 8.2 and 8.5.

2.8.3 Task 8.3 Drilling and completion

2.8.3.1 Activities in the last reporting period

HBO:

- Research work on the in-situ stress field estimations and implications for enhanced geothermal system (EGS) development for the Acoculco geothermal field. Paper entitled "Integrated stress field estimation and implications for enhanced geothermal system development in Acoculco, Mexico" in review in the Geothermics journal.
- Research work on the in-situ stress field estimations from borehole observations for the Los Humeros geothermal field. Paper entitled "Determination of the In-Situ Stress State of the Los Humeros Volcanic Complex (Mexico) Based on Borehole Observations" submitted to the Rock Mechanics and Rock Engineering journal.
- Paper entitled "Alkali-activated Aluminosilicates Sealing System for Deep High-Temperature Well Applications" under review in the Geothermics journal.
- Contributions to deliverables from WP7 i.e., Task 7.1 and Task 7.2, and WP8 i.e., Task 8.1.
- Finalized the final deliverable for the Task 8.3.

OGS

- Analysis aimed at preparing recommendations for use of drilling monitoring and borehole measurements while drilling by seismic methods, Contribution is included in Deliverable 8.4

2.8.3.2 Main results from the task

- A comprehensive review of super-hot drilling campaigns carried out worldwide with their failure modes, recommendations, and already implemented improvements in regard to drilling and well completion technology.
- An investigation on the local in-situ stress tensor of the Los Humeros geothermal field based on borehole observations.
- A model for prediction of the cement sheath failure in super-hot wells, based on an example of the H-64 well, drilled in the central parts of the Los Humeros caldera,
- Results of the experimental laboratory studies on non-Portland sealants for the well completions of the future super-hot geothermal wells.

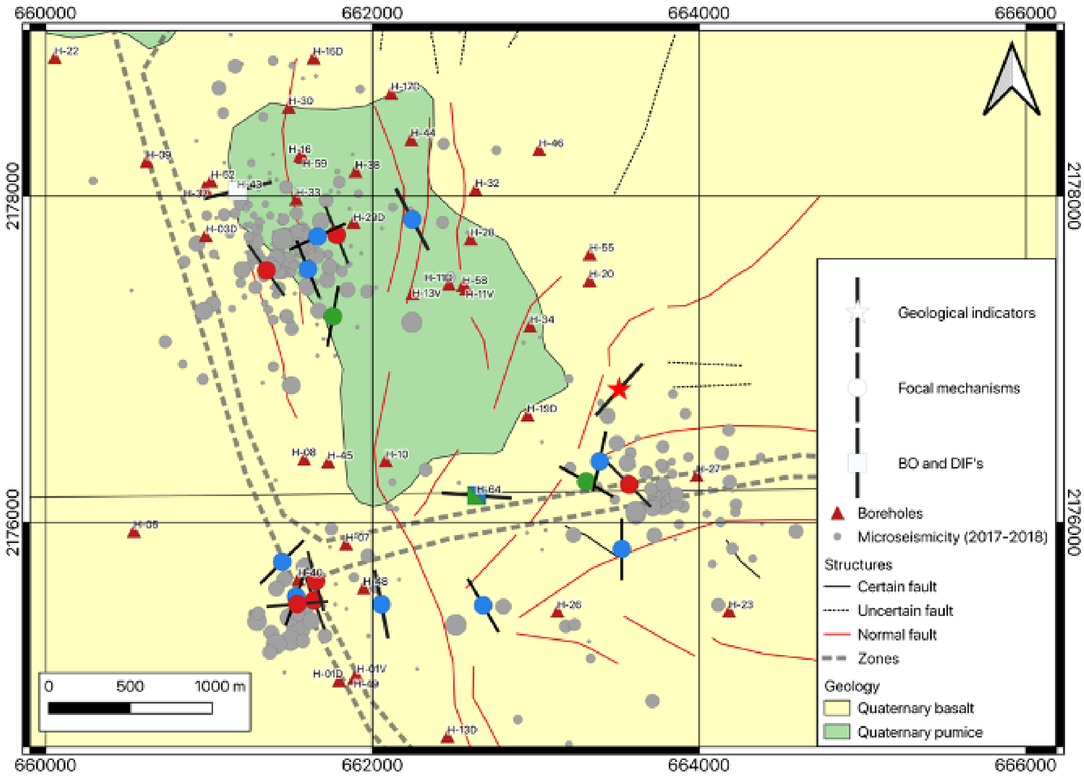

Figure 37 - The map of LHGF with stress indicators from the H-64 well and studies by Heidbach et al. (2016), Lermo et al. (2016), Lorenzo-Pulido (2008), and Toledo et al. (2019); blue marker color indicates reverse faulting, green – strike-slip, red – normal faulting, and white – unknown; SHmax azimuth represented with a thick black line; microseismicity data recorded between 2017 and 2018 by Toledo et al. (2019) with dot size proportional to the earthquake magnitude.

2.8.4 Task 8.4 Thermal loop design and performance monitoring

2.8.4.1 Activities in the last reporting period

- CRES: Geological, geophysical, geochemical, production and reservoir testing and monitoring methods that have been or are currently being applied in characterising and monitoring the Los Humeros geothermal reservoir have been analysed, discussing their application to the deep superhot part of the system, when it is drilled and exploited.
- OGS: Newly introduced and currently under development geophysical methods were evaluated for the future characterisation and monitoring of the deeper part of the Los Humeros system, which can be coupled with, but not limited to the drilling of the first deeper well.
- ENEA: Innovative procedures were developed and tested, as a new method towards monitoring soil pollution during the exploitation of the deeper superhot part of Los Humeros geothermal resource.
- IFE: A new tracer stable at superhot temperatures, was proposed for reservoir testing of the deep part of Los Humeros, and related procedures were drafted. Surface loop configurations, and tests of new materials and steam purification methods associated with the exploitation of superhot geothermal fluids were discussed.

All partners of the task contributed to the completion of Deliverable 8.4

2.8.4.2 Main results from the task

In order to characterise and monitor the evolution of the physical and chemical properties of the deep superhot reservoir of the Los Humeros geothermal system the following methods are proposed to be applied before and during drilling the first deep well, as well as during future exploitation:

- Continuing state of the art geological, geophysical, geochemical, production monitoring and reservoir testing practices, that have been or are currently being applied in Los Humeros
- Introduce vertical seismic profiling (VSP), seismic while drilling (SWD) and optical fibre DAS seismic monitoring methods
- Carry out tracer tests using new high temperature resistant tracers
- Monitor the mobility of potential harmful elements (PHE) in the soil using sequential extraction procedures (SEP)
- Test new innovative materials and steam scrubbing methods for corrosion and scaling inhibition and steam purification, during production of superhot geothermal fluids

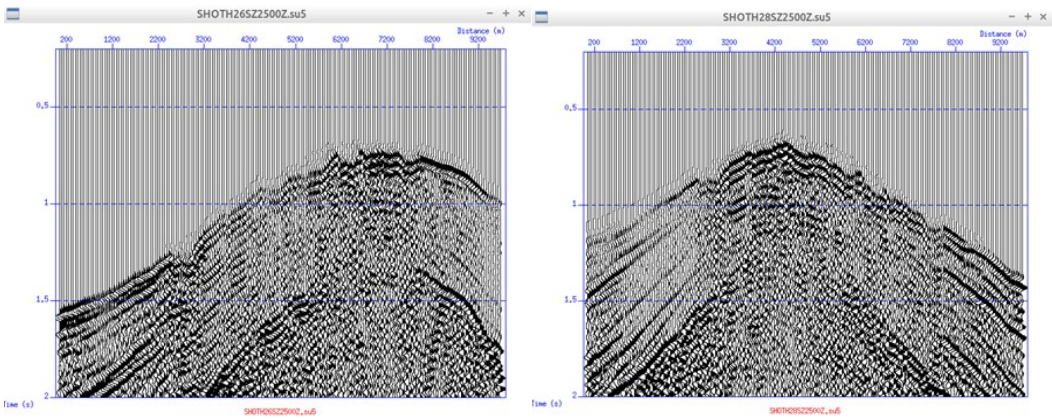

Figure 38 - Comparison of seismic while drilling (SWD) synthetic shots calculated with the source at 2500 m depth in wells H26 (left side panel) and well H28 (right side panel). The horizontal dimension is the distance at surface. Due to the complexity of the caldera area in the subsurface but also at the shallow surface, the shape of the shots is different, depending on and conveying information on local recording conditions.

2.8.5 Impact

All results from WP8 contribute to a better understanding of superhot geothermal resources and provide tools that will have an impact on success rates of superhot geothermal projects. Consequently, this work package mainly has the technological impact:

Improved resource assessment

Physics-based models have been developed based on GEMex-data to forecast the complex interaction between deep wells and the surrounding rocks in a superhot environment. Despite the vast uncertainties that are typical of such ambitious goals, the models can pin-point future development strategies and scenarios and can guide laboratory and in-situ investigations in a two-way feeding loop that is aimed at reducing uncertainty. Ultimately, those models provide tools to improve the resource assessment for superhot geothermal sites.

Preventing failures during drilling and completion

The comprehensive review of super-hot drilling campaigns carried out worldwide with their failure modes, recommendations, and already implemented improvements in regard to drilling and well completion technology provides valuable knowledge to operators, which can prevent future failures during drilling and completion. The suggested non-Portland sealants for the well completions are potential candidates for more sustainable cementing of superhot wells. These results will lead to a higher success rate and sustainability of superhot geothermal wells.

Sustainable exploitation of superhot resources

The results from the test of materials for installation at a superhot geothermal site will guide the operators to a selection of suitable materials for the specific case in Los Humeros, but will also be transferable to other superhot sites with similarly challenging geothermal fluids. Improved material selection will lead to a longer lifetime of geothermal installations and, therefore, to a more sustainable exploitation of superhot resources.

Improved understanding and managing of environmental issues

The developed SEP methods for monitoring potential harmful elements mobility in the soil, as affected by the exploitation of the deep part of the resource, provides practical indications for understanding and managing important environmental issues related to the exploitation of deep geothermal energy.

2.8.6 Publications

Börner, J. H., Herdegen, V., Kummerow, J., Raab, S. Spangenberg, E. (2019): Spektrale Induzierte Polarisation reaktiver Systeme unter Reservoirbedingungen. - Mitteilungen / Deutsche Geophysikalische Gesellschaft: Sonderband, 1/2019, 13-25

Fokker, P.A., Singh, A., Wassing, B.B.T., “A semianalytic time-resolved poro-elasto-plastic model for wellbore stability and stimulation”, *International Journal for Numerical and Analytical Methods in Geomechanics*, Jan 2020, pp. 1-21, DOI: 10.1002/nag.3048

Kruszewski, M., Hofmann, H., Gomex Alvarez, F., Bianco, C., Jimenez Haro, A., Garduño, V.H., Liotta, D., Trumpy, E., Brogi, A., Wheeler, W., Bastesen, E., Parisio, F., “Integrated stress field estimation and implications for enhanced geothermal system development in Acoculco, Mexico.” Submitted to *Geothermics*

Kruszewski, M. and Wittig, V., “Review of failure modes in supercritical geothermal drilling projects”, *Geothermal Energy* (2018) 6:28, DOI: 0.1186/s40517-018-0113-4

Kruszewski M., Ramirez M., Wittig V., Sanchez M., Bracke R., "Drilling and Well Completion Challenges in the Los Humeros Geothermal Field, Mexico", *GRC Transactions*, Vol. 42, 2018, Proceedings of a meeting held 14 – 17 October 2018, Reno, Nevada, USA

Kruszewski, M., Montegrossi, G., Ramírez Montes, M., Wittig, V., Gomez Garcia, A., Sánchez Luviano, M., Bracke, R., “A wellbore cement sheath damage prediction model with the integration of acoustic wellbore measurements”, *Geothermics* 80:195-207, 2019, DOI: 10.1016/j.geothermics.2019.03.007

Kruszewski et al. (2020), Determination of the In-Situ Stress State of the Los Humeros Volcanic Complex (Mexico) Based on Borehole Observations, Rock Mechanics and Rock Engineering (Springer), submitted.

Kruszewski et al. (2020), Alkali-activated Aluminosilicates Sealing System for Deep High-Temperature Well Applications, Geothermics (Elsevier), submitted.

Kruszewski et al. (2020), A wellbore cement sheath damage prediction model with the integration of acoustic wellbore measurements, ERDÖL ERDGAS KOHLE, Oil Gas European Magazine, I/20.

Kummerow, J., Raab, S., Schuessler, J.A., Meyer, R. (2020): Non-reactive and reactive experiments to determine the electrical conductivities of aqueous geothermal solutions up to supercritical conditions. - Journal of Volcanology and Geothermal Research, 391, 106388. https://doi.org/10.1016/j.jvolgeores.2018.05.014

Parisio F., Naumov D., Kolditz O., Nagel T., Material forces: an insight into configurational energy. *Mechanics Research Communication*, Volume 93, October 2018, Pages 114-118, DOI: https://doi.org/10.1016/j.mechrescom.2017.09.005

Parisio, F., Vinciguerra S., Kolditz O., Nagel T., (2019), The brittle ductile transition in active volcanoes, *Scientific Reports*, https://rdcu.be/bgVA3, DOI: 10.1038/s41598-018-36505

Parisio, F., Vilarrasa, V., Wang, W., Kolditz, O., Nagel, T., The risks of long-term re-injection in supercritical geothermal systems, *Nature Communications*, Vol. 10, No. 4391 (2019), https://doi.org/10.1038/s41467-019-12146-0

Reinsch, T., Dobson, P., Asanuma, H., Huenges, E., Poletto, F., Sanjuan, B., (2017): Utilizing supercritical geothermal systems: a review of past ventures and ongoing research activities. - *Geothermal Energy*, 5, 16., DOI: 10.1186/s40517-017-0075-y

2.8.7 Dissemination activities (talks, posters, workshops)

Glißner M., Lefebvre M., Hahn S., Kruszewski M., Wittig V., Bracke R., Alternative Cement for Deep High Temperature Wells based on Alkali-Activated Alumino-Silicates, German Geothermal Congress, 27 – 29 November 2018, Essen, Germany.

González García, H., Huenges, E., Francke, H., Parisio, F., Estimation of depression well cones in Los Humeros, GEMex final conference, Potsdam GFZ, Germany, 18-19 February 2020.

Gonzalez-Garcia H., Francke H. And Huenges E., Estimation of the radius of influence of the wells in Los Humeros, Mexico, European Geothermal PhD Day, Denizli, Turkey, 24-26 February 2020.

Gonzalez-Garcia H., Estimation of energy reserve at Los Humeros geothermal power plant, European Geothermal PhD Day, Potsdam, Germany, 25-27 Feb 2019.

Kruszewski et al., Improving Wellbore Sealing Integrity in Deep High-Temperature Well Applications, GEMex Final Conference, Potsdam, Germany, 18-19 February 2020.

Kruszewski et al., A Wellbore Cement Sheath Damage Prediction Model with the Integration of Acoustic Wellbore Measurements, Celle Drilling 2019, Celle, Germany, September 2019.

Kruszewski et al., Crustal Stress Determination and Wellbore Stability Analysis: Los Humeros Geothermal Field Case Study, Proceedings of European Geothermal Congress 2019, Den Haag, The Netherlands, 11-14 June 2019.

Kruszewski M., Developments and Challenges of Deep (High-Temperature) Geothermal Drilling, International Geothermal Association's Board of Directors meeting, Budapest, Hungary, 12th of May 2019.

Kruszewski et al., Wellbore Stability and Scientific Basis for Geomechanical Modeling on the Example of the Los Humeros Geothermal Field, Mexico, Geophysical Research Abstracts Vol. 21, EGU General Assembly 2019, Vienna, Austria, 2019.

Kruszewski et al., Crustal Stresses Prediction and Scientific Basis for Geomechanical Modeling: Los Humeros Geothermal Field Case Study, 8th Minisymposium on Poroelasticity, Bochum, Germany, February 2019.

Kruszewski M., An Influence of Mechanical Properties of Cement and Rock Formations on Wellbore Cement Stresses in a Geothermal Well, German Geothermal Congress, 27 – 29 November 2018, Essen, Germany.

Kruszewski M. and Wittig V., Influence of Elastic Properties of Cement and Rock Formation on Cement Sheath Stresses in Geothermal Reservoirs, Society of Petroleum Engineers Student Technical Conference, Freiberg, Germany, 8 – 9 November 2018.

Kruszewski M. and Wittig V., The Influence of Mechanical Material Properties of Cement and Rock Formations on Stresses in the Wellbore Cement Under Defined Reservoir Conditions of a Geothermal Well, VI Polish Geothermal Congress, Zakopane, Poland, 23 – 25 October 2018.

Kruszewski et al., Drilling and well completion challenges in the Los Humeros Geothermal Field, Mexico, GRC Geothermal Resources Council Annual Meeting, Reno, Nevada, USA 14 - 17 October 2018.

Kruszewski M., Cementing Challenges in High Temperature Geothermal Wells, 11. Sitzung DGMK-Arbeitskreis Bohrspülung, Bochum, September 2018.

Kruszewski et. al., Supercritical Drilling – Casing Design Review, Methodology and Case Studies, 5th European Geothermal Workshop - Characterization of Deep Geothermal Systems, Karlsruhe, Germany, October 2017.

Kruszewski M., Methods of Assessing Casing Setting Depths for High-Temperature Geothermal Wells in New Areas, Society of Petroleum Engineers Student Technical Conference, Clausthal-Zellerfeld, Germany, November 2017.

Kruszewski M., Drilling and Well Completion Technologies for Super (Hot) Geothermal Systems, European Technology & Innovation Platform on Deep Geothermal, Deep Drilling WG, Pisa, Italy, March 2017.

Kummerow, J., Raab, S., Spangenberg, E., The impact of reactive flow on electrical and hydraulic rock properties in supercritical geothermal settings, GEMex Final Conference, Potsdam, Germany, 18-19 February 2020.

Lacinska, A. M., Rochelle, C., Kilpatrick, A., Rushton, J., Weydt, L. M., Bär, K., Sass, I., Evidence for fracture-hosted fluid-rock reactions within geothermal reservoirs of the eastern Trans-Mexican Volcanic Belt, GEMex final conference, Potsdam GFZ, Germany, 18-19 February 2020.

Mendrinos, D., Kalantzis, C., Karytsas, C., “Monitoring methods for Los Humeros superhot geothermal system: state-of-the-art”, Poster, GEMex final conference, Potsdam GFZ, Germany, 18-19 February 2020.

Mendrinos, D., Karytsas, C., “Thermal loop design aspects in Ultra Hot Geothermal Systems”, Poster, GEMex final conference, Potsdam GFZ, Germany, 18-19 February 2020.

Montegrossi, G., Reservoir modelling and calibration for the superhot reservoir at Los Humeros, GEMex final conference, Potsdam GFZ, Germany, 18-19 February 2020

Thorbjornsson, I. O., González, L. E., Ramírez, M., Morales, L., Diez, H., Jonsson, S.S., Kaldal, G. S., Gudmundsson, L., Material testing downhole at well H-64 at the Los Humeros geothermal field in Mexico, GEMex final conference, Potsdam GFZ, Germany, 18-19 February 2020

2.8.7.1 Accepted Abstracts

Gonzalez Garcia H, Francke H., Huenges E., Parisio F., Energy reserve estimation of Los Humeros geothermal system., WGC 2020, Reykjavik, Iceland, postponed to 2021.

Karytsas, C., Kalantzis, C., Mendrinos, D., (2020) “Monitoring geothermal resources of very high temperature”, Cities on volcanoes 11, Heraklion, Crete, Greece, 25-30 September.

Kummerow, J., Raab, S., Spangenberg, E., Schleicher, A. M.,, Schuessler, J.,. Reactive flow in supercritical geothermal settings and its impact on electrical fluid and rock properties. Proceedings World Geothermal Congress 2020 Reykjavik, Iceland, postponed to 2021.

2.8.8 Deviations from the Description of action

- UKRI had to add some person months to WP8 in order to use in Task 8.1 data obtained in T4.1 and T6.1 and taking that forward towards a better understanding of the SHGS.

2.9 Work Package 9: Ethics

Lead: GFZ
Duration: month 1-44
Status: completed

Objectives:

This work package sets out the 'ethics requirements' that the project must comply with. There is only one deliverable which must provide details on the material which will be imported to/exported from EU and provide the adequate authorizations.

Use of personnel ressources:

No person months are associated with this work package. The coordinator takes care of the compliance with the ethic requirements.

Activities:

Import and export to/from Mexico included mainly two things:

- Equipment or scientific measurements: all equipment which is imported to Mexico and was / will also be exported. Hence, the project partners acquired a permission for temporary import of scientific equipment which was checked by the Mexican customs.
- Export of samples of rocks, fluids and gas: all samples were of scientific value only and had no significant content of fossils or minerals. Consequently they neither represent a commercial value, nor are they of historical value to the Mexican people. Again, the export of samples was always checked and authorized by the Mexican customs.

3. Impact

The Impact as detailed in section 2.1 of the DoA is still relevant. In addition to the DoA, we can report the following impact of the project after the second reporting period subdivided into a “scientific”, and “technological” impact:

3.1 Scientific

GEMex contributed to the advance of scientific knowledge, to the networking and interaction between different European and Mexican institutions but also between different disciplines. The project put a large effort into the dissemination of results in scientific journals and in scientific conferences. The transfer of knowledge to young researchers is evident from the number of academic theses prepared during the course of the project.

- Peer reviewed publications: 48 published, 12 submitted/in press and several more are in preparation. (see section 2.2.4 “Promotion of project results”)
- Presentations at conferences: 244 (see ***Table 4***)
- Master theses: 9
    - Bech, M. (2018): Petrophysical and hydraulical properties of andesitic geothermal reservoir rocks of Acoculco and Los Humeros, Mexico, unpublished Master thesis, XII and 73 p., 70 Fig., 38 Tab., 2 Attachments, 1 CD-Rom including further digital Appendix, Institut für Angewandte Geowissenschaften, TU Darmstadt.
    - E.S.J. Dekker: Modelling the GEMex / Aachen marble and granite fracturing experiments in MFracTM. Utrecht University
    - Evanno, G., 2017. 3D preliminary geological modelling of the Los Humeros geothermal area (Mexico). Master Thesis, ENAG/MFE-088-GB-2017, 123 pp. Available on VRE: https://goo.gl/XYdBT1
    - Gergő András Hutka: Benchmark Modelling of True-Triaxial Laboratory Hydraulic Fracturing Experiments, GFZ
    - Kramer, T. (2018): Petrophysical and Hydraulical Properties of Cretaceous and Jurassic Limestones of the Acoculco and Los Humeros Geothermal Reservoirs, Mexico, unpublished Master thesis, IX and 73 p., 50 Fig., 6 Tab., 1 Attachment, 1 CD-Rom including further digital Appendix, Institut für Angewandte Geowissenschaften, TU Darmstadt.
    - Patricia Pinkowski (2019): Geohydrochemical processes characterization of the superhot geothermal system Los Humeros, Mexico, GFZ / TU Berlin
    - Perizonius, J. (2018): Petrophysical and hydraulical properties of volcanic reservoir rocks of Acoculco and Los Humeros, Mexico, unpublished Master thesis, XIII and 75 p., 37 Fig., 27 Tab., 1 CD-Rom including further digital Appendix, Institut für Angewandte Geowissenschaften, TU Darmstadt.
    - Sejan, K. (2018) Forward and inverse modelling of gravity anomaly for geothermal applications: Case study of Los Humeros. Master thesis, Utrecht University.
    - Xiangyun Shi: Numerical Simulation of Los Humeros super-hot geothermal field, Mexico, Master in Applied Sciences, Faculty of Georesources and Materials Engineering, RWTH Aachen University
    - Vassen, L., (2020): 3D local modelling of the Los Humeros geothermal site. Master

thesis, Utrecht University, *in preparation*

- Bachelor Thesis: 1
    - Knauthe, R. (2019): Thermo-and petrophysical properties in relation to petrological characteristics: an example of the Los Humeros geothermal field, Mexico, Bachelor thesis, Institut für Angewandte Geowissenschaften, TU Darmstadt.
- PhD Thesis: 9
    - Békési, E., Geophysical characterization of geothermal fields: Inversion of temperature data and ground motions, Utrecht University, *in preparation*
    - Cornejo, N., Towards Visualization of the Reservoir Settings in the Los Humeros and Acoculco Geothermal Fields Using Gravity, Technical University Darmstadt, *in preparation*
    - Deb, P., Unconventional geothermal reservoirs in volcanic rocks, RWTH Aachen, *in preparation*
    - Finger, C., Potential of time-reverse imaging to locate and characterise microseismicity. Submitted to Ruhr University Bochum.
    - González García, H., Key factors that define the sustainability in a geothermal system: Los Humeros as a case of study, Technical University of Berlin, *in preparation*
    - Jentsch, A.: The influence of volcano-tectonic structures on soil gas composition - Examples from two active tectonic areas, University of Potsdam (in cooperation with GFZ Potsdam), *in preparation*
    - Olvera-Garcia, E.: Fault and fracture network in the Las Minas exhumed geothermal system: insights for the present geothermal system (Mexico). University of Bari, 2020.
    - Lepillier, B.: Characterisation of a fracture-controlled Enhanced Geothermal System (EGS) in the Trans-Mexican-Volcanic-Belt (TMVB). Dept. of Geoscience & Engineering, TU Delft (in collaboration with GFZ); *submitted*
    - Toledo, T., Seismology applied for exploration, imaging, and monitoring of geothermal systems, Technical Universtity Berlin, *in preparation.*
    - *Weydt, L.,* "Reservoir characterization of super-hot unconventional geothermal systems, Mexico", Technical University Darmstadt, *in preparation*

- Transfer of knowledge: Through collaboration within GEMex, we strengthen the transfer of knowledge between the 31 involved Mexican and European partners
    - with strong links to other H2020 projects (GeoWell, DESTRESS, SURE, DEEPEGS, DESCRAMBLE and IMAGE) as well as the recent Mexican project CEMIE-Geo, we additionally ensure a transfer of knowlegde gained in other H2020 projects to the European and Mexican research community
        - as an example, GFZ organised a joint booth for the deep geothermal H2020 projects during the GeoTHERM in Offenburg 2018 and prepared and contributed to another at the EGC 2019 (The Hague)
        - a joint workshop on “Risk assessment for geothermal projects” was prepared and took place 28 May 2019 in Potsdam, Germany, with participation of various H2020 projects, public authorities, executive authorities and

geothermal operators

- The GEMex final conference was successfully conducted. Among the 125 participants were many scientists, but also guest from industry, SME (geothermal consulting) and public authorities. Hence the conference successfully transferred the scientific results to the stakeholders of the projects.

- Open Science: GEMex has closely followed an Open Science policy
    - All technical GEMex deliverables are available in Open Access through the project website or the CORDIS tool of the EC
    - All GEMex journal publications are available in Open Access
    - GEMex partners have submitted at least seven datasets to open access repositories
    - The GEMex Open Access Database includes 102 layers, out of which 89 are based on GEMex datasets or results.

3.2 Technological Impact

GEMex essentially contributes to the R&I Activities 3 and 5 of the Implementation Plan of the SET-Plan temporary working group on Deep Geothermal[1] and to a minor extend to Activities 2 and 6

Contributions to SET-Plan Implementation Plan's Activity 3 "Enhancement of conventional reservoirs and deployment of unconventional reservoirs"

- Modelling approaches to investigate the feasibility and sustainability of hydraulic fracturing and hydraulic shearing in a volcanic, hot-EGS setting (GEMex Deliverable 7.2)
    ➔ Increase the probability of successful stimulations of geothermal sites and increase the number of economically viable EGS sites
- Modelling approaches to forecast the complex interaction between deep wells and the surrounding rocks in a superhot environment (GEMex Deliverable 8.1)
    ➔ Increase the number of successfully drilled superhot wells and, therefore, decrease overall costs of geothermal projects.

→ Overall, the achieved results will contribute to the development of hot-EGS and SHGS resources that carry enormous potential to expand the known geothermal resource base and to multiply the energy output, thus contributing to the renewable energy transition.

Contributions to SET-Plan Implementation Plan's Activity 5 "Exploration techniques (including resource prediction and exploratory drilling)"

- Patent on a tracer for superhot resources (GEMex Deliverable 4.3)
- Advancing of methods: Integrated geological modelling: this approach allows a better understanding of the geothermal systems by integrating complementary knowledge in an interactive process. The process of iterating between geological modelling and

[1] https://setis.ec.europa.eu/system/files/setplan_geoth_ip.pdf, SET-Plan Temporary Working GroupDeep Geothermal; Implementation Plan; January 2018

implementation of external constraints (structural geology, analogue models, geophysical results) provides more robust and reliable models that are in agreement with many of the obtained results from different disciplines (GEMex Deliverable 3.1)

- Advancing of methods: Validation protocol, i.e., a set of procedures to be followed for data integration in geothermal exploration of EGS and SHSG: effective integration from different geophysical methods providing an unambiguous, self-constrained model of a geothermal system. In this framework, cross-plotting and clustering procedures are considered as a promising auxiliary tool towards the integration of distinct geophysical datasets (GEMex Deliverable 5.12)

  → The developed methods will decrease the exploration risks for geothermal projects and, therefore, lead to a higher number of economically viable geothermal wells.

Contributions to SET-Plan Implementation Plan's Activity 2 "Materials, methods and equipment to improve operational availability (high temperatures, corrosion, scaling)"

- List of material properties and selection guide for sustainable superhot geothermal installations (GEMex Deliverable 8.5)

  → will increase the lifetime of geothermal installations and therefore reduce overall costs of superhot geothermal energy generation

Contributions to SET-Plan Implementation Plan's Activity 6 "Advanced drilling/well completion techniques"

- comprehensive review of super-hot drilling campaigns carried out worldwide with their failure modes, recommendations, and already implemented improvements in regard to drilling and well completion technology (GEMex Deliverable 8.3)

  → will reduce number of failed drilling attempts and therefore reduce technical risks

- laboratory test of non-Portland sealants for well completion (GEMex Deliverable 8.3)

  → will increase the lifetime of geothermal wells and therefore reduce overall costs of superhot geothermal energy generation

3.3 Economic and Social impact

- The developed conceptual model for public engagement (GEMex Deliverable 7.4), a shared and multi-perspective vision of the social aspects to be addressed and the public engagement strategies to be implemented can be designed and implemented, allowing the adoption of an overarching approach to geothermal energy projects. An application of the conceptual model will lead to a greater social acceptance of specific geothermal projects, but will also have a positive impact on the acceptance of geothermal energy generation in general

- GEMex has put a lot of effort into a wide dissemination of project results, to all key target groups identified – industry, public authorities and research (see GEMex Deliverable 2.1) - and via a multitude of channels (public GEMex final conference, website, Open Access Database, side-events, publications, conference contributions, geothermal fairs, social media). Therefore, we expect that industry and public authorities will pick-up the project's results and thus enable further economic and social impact of the project

3.4 Site-specific impact

Beyond the technological progress, which will impact developments in Europe as well as in Mexico, the uncertainty in the potential of the two very promising Mexican resources will be drastically reduced by:

- An in-depth characterisation of the potential EGS site Acoculco through geology (GEMex Deliverable 3.1, 3.2, 3.5, 3.6, 4.1), geophysics (GEMex Deliverables 5.2, 5.6, 5.8, 5.10, 5.12), reservoir characterisation (GEMex Deliverable 6.1, 6.2)
- A site-specific evaluation of stimulation and production scenarios and a concept for a stimulation test in one of the two existing wells in Acoculco (GEMex Deliverables 7.1, 7.2)
- An in-depth characterisation of the superhot resource by geology (GEMex deliverables 3.1, 3.2, 3.5, 3.6, 4.1), geochemistry (GEMex Deliverable 4.3), geophysics (GEMex Deliverable 5.2, 5.3, 5.4, 5.6, 5.7, 5.8, 5.10, 5.11, 5.12) and reservoir characterisation (GEMex Deliverables 6.1, 6.3 and 6.6)
- An improved conceptual model of the superhot site at Los Humeros, which builds on the characterisation mentioned before, combined with the understanding obtained from the study of the exhumed analogue geothermal system at Las Minas (GEMex Deliverable 4.2), in order to indicate the most interesting area within Los Humeros for the drilling of a superhot well (GEMex Deliverable 3.1).
- A concept for public engagement that will allow to achieve good social acceptance at both geothermal sites in Mexico (GEMex Deliverable 7.4)

Once the concepts for the development of both sites will be applied, this will boost the geothermal development in Mexico, which is particularly important in view of the country's growing energy demand and decline in oil production. A sizeable development of Mexico's vast geothermal resources, including the so far not exploited unconventional sites, will reduce the dependence on gas imports and increase the use of non-fossil fuels (so far 4% of the national energy consumption), thus reducing the country's carbon footprint.

Since the approaches and concepts developed in WP7 contribute to the development of an EGS in Acoculco, this could also have a social impact on the local communities, generating jobs and improving the local infrastructure.

4. Deviations from Annex 1 (if applicable)

4.1 Use of resources

There have been some changes to the expenditure of resources, person months and budget, which are explained in the table below. More details can be found in the financial statements of each partner.

There are several partners who exceed the foreseen budget, some by a substantial sum. The partners are aware that there is no guarantee that the costs exceeding the originally foreseen budget in the GA can be reimbursed. However, seen that some partners also did not fully spend their budget, the Consortium decided to include all the costs which occurred in the implementation of the project. Budget may be shifted from the partners who underspend to partners who overspend.

Table 12: Changes in the use of resources (compared to the Grant Agreement). More details can be found in the financial statements of each partner.

Partner	Not planned resources	Explanations/ Change
GFZ		GFZ used less person month in WP6. The budget was used instead for Other goods and services, mainly travel, since the coordination with the Mexican partners necessitated a lot more travel than previously anticipated. Also, during the preparation of the GA, costs for project meeting were not properly incorporated in the estimated budget – part of the budget had to be used to finance the project meetings, stakeholder meetings and side-events. GFZ shifted 50000 € of personnel costs to ISOR since ISOR took over a major part of the scientific management and part of the data integration for WP4,5,8.
	Adjustment of RP1 and RP2	GFZ adjusted -22154 € in RP 1 and +17163€ in RP2 in ODC. This results mainly from the fact that depreciation costs for one instrument were falsely included in RP1 while they should have been reported in RP2 (and RP3). Consequently, the adjustment reflects the shift of depreciation costs.
ÍSOR		ÍSOR decided not to purchase the Gas chromatograph specific for analyzing geothermal gases, this was solved differently and did not have an impact on the project. ÍSOR spent much more PM in the project management than anticipated mainly because of the heavy cooperation with CFE and the Mexican consortium. In WP5, task 5.1 ÍSOR also spent considerably more PM than anticipated, since working together with the Mexican consortium was more time consuming than expected, including two times working in the field in Mexico.

UNIBA	3215 €	Domenico Liotta and Andrea Brogi should have participated at the 36th International Geological Congress in New Delhi - India from 29/02/2020 to 08/03/2020. The congress was postponed to November 2020. Reimbursement of the costs has been requested, but the organiser of the congress has refused to reimburse the conference fee. UNIBA has adjusted costs for RP1 and RP2 since double claimed costs have been discovered.
UU	More person month in WP3	UU: In the reporting period, extra activity was done in WP3 by UU for (1) contributing to the preparation of the Deliverables D3.5 and D3.6; and (2) the preparation of a joint manuscript of the modelling results obtained in Task 3.2 (still ongoing). The extra work in WP3 is compensated by less UU activities in WP7 and WP8.
	Adjustment of 5969€ in RP1	The adjustment of personnel costs in RP1 results from the appointment of one person to the project in February and March 2018 which was forgotten to be declared in the previous reporting.
RWTH	Subcontract	RWTH has paid the subcontract, which was added during the amendment of the project, in two payments – one in reporting period 2 and one in reporting period 3. Therefore, part of costs of the subcontract have been reported in RP2 and part in RP3. Those two payments however belong to the same subcontract, which is the one approved during the amendment.
	Adjustment	In RP2 personnel costs had to be adjusted since the annual special payment was estimated at the time of the reporting but turned out to be lower than the estimate. Hence the partial claim of the annual special payment for the first quarter of 2019 had to be corrected.
CNR	+30200 € Travel costs	extra costs for the travel related to the managerial dissemination activity (participation to meetings and side events) and to a number of extra travels required for WP4 (mainly for the geological and geochemical fields) which were not planned at the time of the proposal
	-15900 € Other goods and services	Goods and services were less expensive than expected
	-12200 € Equipment	Some of the equipment was not purchased, since alternative ways to fulfill the tasks have been found. This had no influence on the project and all tasks have been fulfilled as promised.
	Adjustments RP2	For WP2: in RP2 we forgot to report the hours worked by one person from CNR-ISTI

<table>
<tr><td></td><td></td><td>For WP3 and WP4: when we finalized the financial report we revised the costs and decided not to account for two travel expenses, but we forgot to adjust the timesheets. Therefore, the hours subtracted are related to the person months of these travels.</td></tr>
<tr><td>BRGM</td><td>Shift of person months</td><td>BRGM: A part of the BRGM's activity (~1.6 PM) is moved to WP2 for 2 main purposes:
Preparation and participation to the GEMex Final Conference
Preparation of the manuscript for a scientific paper related to WP4 results</td></tr>
<tr><td>TUDA</td><td></td><td>More work effort in person months was needed to carry out the allocated tasks, especially the lab measurements in WP6 and WP7.
Additionally, sample shipping from Europe to MExico was way more expensive than anticipated and longer field trips to Mexico were needed to acquire the required amount of samples for the project implementation.</td></tr>
<tr><td>IFE</td><td>-39000 € ODC

+59000 € personnel costs</td><td>IFE has spent less budget on travel and consumables, due to the impact of the Corona pandemic and less than estimated laboratory costs.
IFE has spent more on personnel costs, since laboratory work was more complicated and time consuming than anticipated.
In sum, IFE overspend the budget by roughly 26000€ (~8% of their budget)</td></tr>
<tr><td>CRES</td><td>22,635.98 €</td><td><table>
<tr><th></th><th>budget</th><th>expenses</th><th>difference</th></tr>
<tr><td>Salaries</td><td>136'000.00</td><td>142'152.77</td><td>6'152.77</td></tr>
<tr><td>Travel</td><td>12'000.00</td><td>26'955.83</td><td>14'955.83</td></tr>
<tr><td>Other</td><td>10'000.00</td><td>7'000.18</td><td>-2'999.82</td></tr>
<tr><td>Indirect</td><td>39'500.00</td><td>44'027.20</td><td>4'527.20</td></tr>
<tr><td>Total</td><td>197'500.00</td><td>220'135.98</td><td>22'635.98</td></tr>
</table>
<u>Justification</u>
More work effort in person months was needed to carry out the allocated tasks.
Additional, not initially planned trips to Mexico and Europe were necessary for the project implementation, as follows:
participation in two project meetings in Mexico (kick-off and for WP7),
participation in EGC2019 in Netherlands, and
participation in additional meetings for the implementation of WP5.4, WP7.4 and WP8.4.</td></tr>
</table>

NORCE	Adjustment RP2 Shift of person months	At Uni Research Institute individual pricing was used. When UniResearch merged to the new research institute NORCE the pricing policy was changed and they are now charging calculated unit cost. The former cost statement for period 2 did not reflect this change in pricing. This is now adjusted. NORCE shifted 1.25 person months from WP5 to WP2 in order to publish results and disseminate results at scientific conferences
UNIROMA3	Adjustment RP2 1568,53 €	The small difference of €1568 is due to a previous error in the calculation of the hourly cost of personnel. Additionally, person months were shifted from WP3 to WP4, since the work done was stronger related to WP4 than to WP3 (even though in this case the activities performed are relevant for both work packages).
ENEA	-9200 € ODC +9200 € personnel costs	ENEA spent less for "direct costs" (about -9000€) due to changes in the activities. The foreseen seismograph was not purchased (because, in agreement with the partners, it was decided that seismic measures, necessary for the activities of WP 7.3, would be acquired by other participants in the project and, subsequently, shared with Enea). The need to elaborate more data than previously foreseen, created the necessity to increase the number man/months, so we compensated the difference in terms of personnel (+9000€). The total financing remains unchanged.
UKRI	Shift of person months	A part of UKRI's activity from WP4 and WP6 is moved to WP7 and WP8 ○ added a minor contribution to task 7.1, since results from WP4 and WP6 had to be transferred to WP7 in order to help WP7-partners to progress towards a better understanding of hot-EGS ○ added some person months to WP8 in order to use data obtained in T4.1 and T6.1 in Task 8.1 and take that forward towards a better understanding of the SHGS.
HBO	Subcontract 27.761,35 €	The introduction of the subcontract was necessary, since the institute of HBO which was conducting the work in WP5 was merged into a new organisation (Fraunhofer IEG) and the specialized personnel necessary for the completion of the task was no longer available in HBO. The PO of GEMex was informed about this change via email (27 April 2020). Costs for the subcontract are compensated by less personnel costs of HBO.

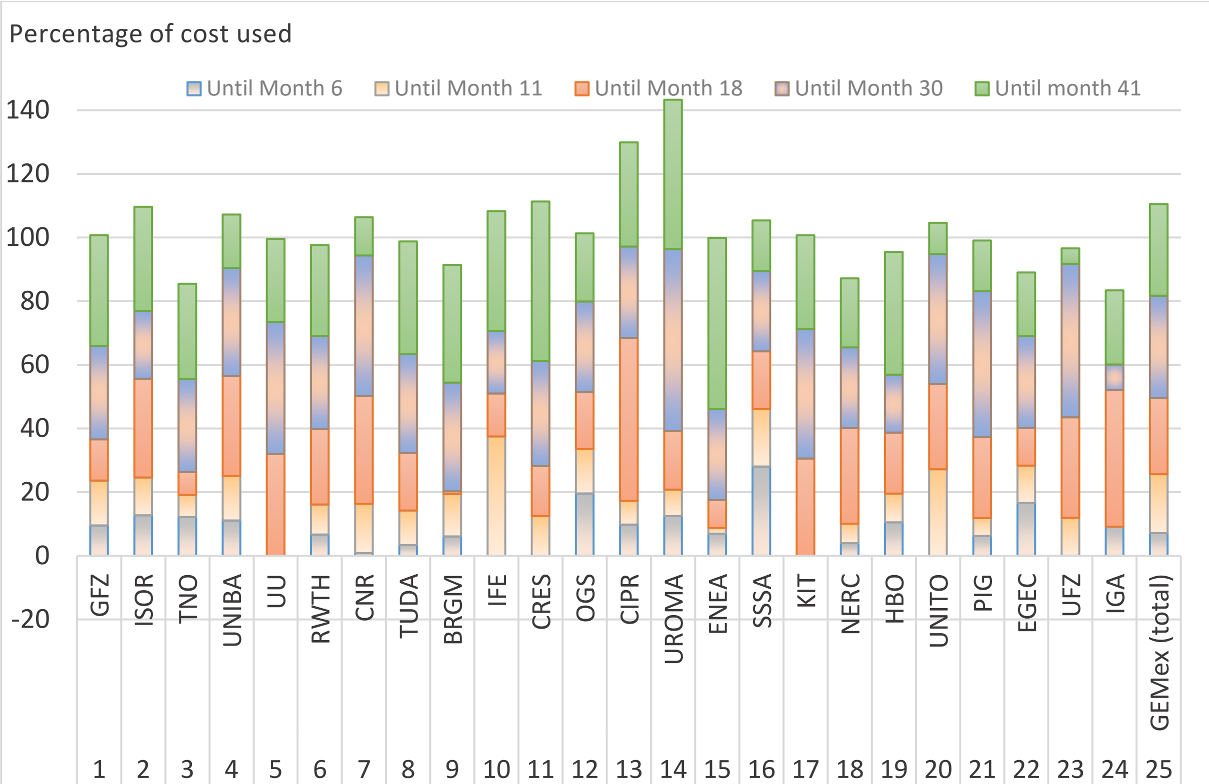

Figure 39: Percentage of budget used.

5. Recommendation from previous reporting periods

5.1 Gender equality

Recoomendation from RP2: *According to Art. 33 of the GA, beneficiaries must aim — to the extent possible — for a gender balance at all levels of personnel assigned to the action, including at the supervisory and managerial levels (Article 33 of the GA). The consortium is asked to continue its efforts in putting in place specific measures to support this requirement. Beneficiaries should keep appropriate documentation about the steps taken and measures put in place (Article 18 of the GA). If a beneficiary cannot achieve the balanced participation of women and men in its team despite active recruitment efforts, the reasons should be explained (see Articles 20.3 and 20.4).*

GEMex partners have tried to enhance gender equality during the project. The table below lists the number of male and female staff employed during the project. It shows that for some partners, the distribution is balanced, but still there is a substantial number of partners who employed more male than femal staff in the project. The main reason for this is that the organisations performed most of their task with persons who have been employed at their institute already prior to the project, such that an increase of the number of women was rarely possible. When looking at the newly employed staff (for this project) during the lifetime of GEMex, the numbers of women and men are much more balanced.

Most of the partners have a solid policy concerning gender equality / equal opportunities. The table below list also the measures in place to support gender equality at the GEMex partner organisations.

Table 13: Number of female and male staff working in GEMex per partner and equal opportunities measures to support the support gender equality.

Partner	M / F	Newly employed	Measure to support gender equality
1 - GFZ	8 / 6	4 / 4	GFZ has established a plan for Gender equality which was reviewed in 2018. Women are chosen over men if they have equal qualfications. GFZ is promoting family friendly working conditions with flexible working hours, seminars and meetings at family-firendly times and offers the possibility to apply for child-care on the campus.
2 - ISOR	5 / 4	0 / 0	ISOR has a Equal Opportunities Policy in place which aspires to even the number of women and men in different professions within the company. Same wages should be paid for equally valuable and comparable positions regardless of employee's gender.
3 - TNO	8 / 4	0 / 0	Policy and specific programs to promote 'women in science and leadership positions'.
4 - UNIBA	4/1	1/1	The activity of the Equal Opportunities Board of the University of Bari, which began almost twenty years ago, is dedicated to the whole university community. It is characterized by five main guidelines: 1. clearing up situations of inconvenience and discrimination in a working context; 2. balance between working and leisure time; 3. selection of innovative socio-educational services; 4. activities aimed at deepening the gender culture and at improving the quality of life; 5. activities of training/information/involvement for those working within the University.
5 - UU	5/1	0/1	
6 - RWTH	7 / 4	4 / 3	In accordance with the guidelines of the RWTH, women with the same qualifications are given preference. In the application procedure, women are specifically asked to apply. The institute offers flexible working hours and home office to support the compatibility of family and career. Fixed-term employment contracts are extended by the time of maternity and parental leave, and continued financing is also possible after the end of the

			project.
7 - CNR	21 / 11	3/2	The National Research Council (CNR) established in 2011 the Unique Guarantee Committee (CUG) which exercises a role of study, proposal, consultancy, and participation to the decisions, being the reference, for all the issues related to equality and equal opportunities. CUG promotes the substantial equality in the workplace between women and men, and intends to guarantee equal dignity in the workplace to all the represented categories, pointing out any form of discrimination, direct or indirect, representing an obstacle to its fulfillment.
8 - TUDA	12 / 4	4 / 1	In accordance with the TUDA guidelines, women with the same qualifications are given preference. In the application procedure, women are specifically asked to apply. The institute offers flexible working hours and home office to support the compatibility of family and career. Fixed-term employment contracts are extended by the time of maternity and parental leave, and continued financing is also possible after the end of the project.
9 - BRGM	6 / 4	0 / 0	Please refer to BRGM's gender equality annual report (contact: contact-BRGM@brgm.fr)
10 - IFE	2 / 1	0 / 0	
11 - CRES	4 / 2	1 / 0	
12 - OGS	2 / 4	0 / 1	OGS has included equal opportunities and gender issues in its Action Plan on human resources strategy which foresees to guarantee the respect of equal opportunities and support females researchers in their professional career.
13 - NORCE	7 / 1	2 / 0	Uni Research's guidelines for equal opportunity and gender equality were followed, including international advertising and interviewing (also the guidelines of the University of Bergen, for the Ph.D. student)
14 - UNIROMA	3 / 0		The Single Committee for the Guarantee of Equal Opportunities and the Promotion of Workers' Welfare and Non-Discrimination promotes equal opportunities for the whole university community, proposing measures and actions

			aimed at preventing and contrasting any form of discrimination, also according to the University Ethical Code (CUG). The CUG promotes, in particular, effective gender equality, identifying possible direct and indirect discrimination in professional training, access to employment, working conditions, career progression and salary, proposing the necessary initiatives to remove them. It also proposes to the central government bodies positive action plans aimed at preventing and contrasting discrimination, promoting effective gender equality, and shared verification criteria.
15 - ENEA	7 / 5	1 / 0	According to the law n. 183 of 2010, public administrations as ENEA, must set up within themselves the Single Guarantee Committee (CUG) for equal opportunities, the enhancement of the well-being of those who work and against discrimination (CUG), which has unified the competences previously attributed to the Equal Opportunities Committees and to the Joint Committee on the phenomenon of mobbing (art.57, paragraph 01, of Legislative Decree 165/2001. The pourpose is the fair representation and gender dignity and the objectives of the intervention as area are as follow: • Enhance the skills within the organization in all sectors. • Promote the adoption of good practices in the management of human resources, in order to contrast gender stereotypes. • Spread cultural models based on the promotion of equal opportunities.
16 - SSSA	5 / 1	1 / 0	The Institute of Management follows the policy established by Sant'Anna School of Advanced Studies in terms of gender equality, which is promoted and put in place through the work of the Central Committee for Guaranteeing Equal opportunities, Workers' Welfare and Non-discriminations.
17 - KIT	1 / 2	0 / 1	The KIT maintains and promotes equal opportunities for women and men in all areas of research, studying and teaching, innovation and administration and conceives equal opportunities as a consistent guiding principle in all fields of activity. Since 2010, the KIT has been certified as a "University Suitable for Families Audit". Currently the KIT is certified for the third time until September 2020. Since July, 17th 2014 the KIT is member of the Baden-Württemberg initiative on "Women in STEM-professions". The initiative pursues the goal to get more girls and women interested in

			STEM-professions (science, technology, engineering and mathematics).
18 - UKRI	6 / 4	1 / 0	BGS has ‘Athena Swan’ bronze award status. Athena swan is a UK-wide system that helps organisations measures gender equality in the workplace and sets out ways to improve representation over time. https://www.ecu.ac.uk/equality-charters/athena-swan/
19 - HBO	3 / 2	1 / 1	HBO has a commission for equal opportunities, a team of equal opportunities officers and an established set of measures to enhance equale opportunities for different gender and in different phases of life. Since 2008, the HBO has been certified as a "University Suitable for Families Audit"
20 - UNITO	6 / 3		
21 - PGI-NRI	2/3	0 / 0	
22 - EGEC	2/1	1/1	
23 - UFZ	3/0	1/0	UFZ has established a plan for gender equality which is regularly evaluated and revised. There is a working group for equal opportunities which work on improved of processes and working conditions.
24 - IGA	1 / 2	0 / 1	The IGA Board, while targeting the election of an equal share of men and women, has seen a fundamental shift by a strong representation of highly talented women in the IGA. After an election for the new board of directors we are pleased to announce that more than 60 % of the newly elected board members are female. We are very proud to see these results and hope to utilise this dynamic for the wider goal of the IGA and give geothermal energy a more diverse and stronger voice to help promote what we as an industry have to offer in the global energy and heat transition.

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