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The successful experience of IGCP636 project “Unifying international research forces to unlock and strengthen geothermal exploitation of the Americas and Europe”

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Geothermal fluids are extracted through deep wells drilled in a geological reservoir, which can be represented by highly heterogeneous volcanic complex, sedimentary basins or deep basement rocks. The main objective of this project was to propose suitable methodologies and techniques for the characterization and modeling of fractured geothermal reservoirs, to ensure their sustainable exploitation and, therefore, ensure acceptance of this kind of energy by local communities. This goal was achieved with experiences from the volcanic complex of the Nevado del Ruiz (Colombia), the St. Lawrence Lowlands sedimentary basin (Québec, Canada), the Carboniferous limestone reservoir in the area of Mons (Belgium), the Soultz-Sous-Forêts power plant and the Ploemeur fractured rock hydrogeological experimental site (France), and various areas of interest for geothermal exploration in Chile. The work conducted provided new insights into the construction of conceptual and numerical models for geothermal reservoirs and allowed the creation of a solid research network between Europe and Americas, fostering participation in geosciences of young researchers, students, and women.

Introduction

The project Unifying international research forces to unlock and strengthen geothermal exploitation of the Americas and Europe started in 2016, following an earlier collaboration between Colombia and Canada undertaken 2 years before. The IGCP636 project was proposed as a wider collaboration between Colombia, Canada, Chile, Belgium, and France. The project was conducted as a 3 year young-researchers project. The leader institution was the Universidad de Medellín (UdeM), in collaboration with the Institut national de la recherche scientifique

(INRS), Universidad de Chile (UCHile) with its Andean Geothermal Center of Excellence (CEGA), Université de Mons (UMons), Université de Rennes1 (URennes), and Bureau de Recherches Géologiques et Minières (BRGM). Other countries have reached the IGCP636 team since then, such as Madagascar and Iceland, while others, including Italy, Sweden, and Argentina are ready to participate in the next proposal to keep the group active.

The project focused on geothermal fluids that can be extracted through deep wells drilled in a geological reservoir, which can be hosted in volcanic complexes, sedimentary basins or deep basement rocks. If the reservoir is not enough permeable for a profitable extraction of geothermal fluids, it can be enhanced through different engineered techniques in order to improve its exploitation. The main objective of this project was to propose suitable methodologies and techniques for the characterization and modeling of fractured geothermal reservoirs, to ensure their sustainable exploitation and, therefore, ensure acceptance of this kind of energy by local communities. From a technical and scientific point of view, this work provided new insights into the construction of conceptual and numerical models for geothermal reservoirs, using available information from different sites. Moreover, in relation with social aspects, an online survey about the public perception and level of knowledge about geothermal energy in the five leading countries of the project (Colombia, Chile, Canada, France, and Belgium) was conducted.

Annual Meetings

Three annual meetings were organized, starting from Colombia in 2016, then Chile in 2017, and finally France in 2018. The most important outcome was the creation of a multidisciplinary research team that was able to develop new collaborations, to receive new funding, and to foster student mobility.

Colombia 2016

More than 250 people, mainly undergraduate students, attended the first annual meeting organized at UdeM. The meeting allowed to build bridges with the Colombian Geothermal Association (AGEOCOL; www.ageocol.org). Since then, AGEOCOL and the IGCP636 team, particularly the Colombian researchers, have been working together to promote geothermal resources characterization and knowledge in the country, through courses, conferences, and networking. A Memorandum of Understanding (MoU) has been signed between AGEOCOL and UdeM in November 2018. During the 2016 IGCP636 Annual meeting, a poster session with around 60 undergraduate students from the UdeM Environmental Engineering program was organized, where they presented their research work about geothermal energy conducted during one semester. The students had the opportunity to be challenged by the international researchers of the IGCP636 team assessing their poster quality. Likewise, more than 80 students developed a research project during the first semester of 2017 about geothermal power plants in different countries of the world. The best papers have been accepted for publication in a special issue of the *Fragua* student journal, which is published by UdeM. A successful field trip to the volcanological and seismological observatory in Manizales (Caldas, Colombia) and to the *Los Nevados* natural national park was organized after the workshop in Medellín. In the observatory, the IGCP636 team attended a talk about the volcanic complex *Los Nevados*, focusing on geological, volcanological, and monitoring aspects (Fig. 1).

Then, in the field, several stops were made to observe outcrops of geothermal interest, mainly the andesite cap rock and the Cajamarca metamorphic complex, which is supposed to host a fractured reservoir; hot springs and outcrops with hydrothermal alteration were also observed and rock samples collected (Fig. 2). Then, the *Los Nevados* natural national park was visited (Fig. 3).

Chile 2017

The second annual meeting was held in Santiago de Chile, at Universidad de Chile (Fig. 4), hosted by CEGA. Africa joined the research group at this meeting, with a PhD candidate and a researcher that participated to the meeting by giving a talk and presenting a poster, respectively, about the assessment of geothermal resources in Madagascar. The IGCP636 team visited CEGA laboratories, where sophisticated instruments will allow to implement and operate a set of world-



Figure 1. IGCP636 2016 field trip: visit to the volcanological and seismological Observatory in Manizales.

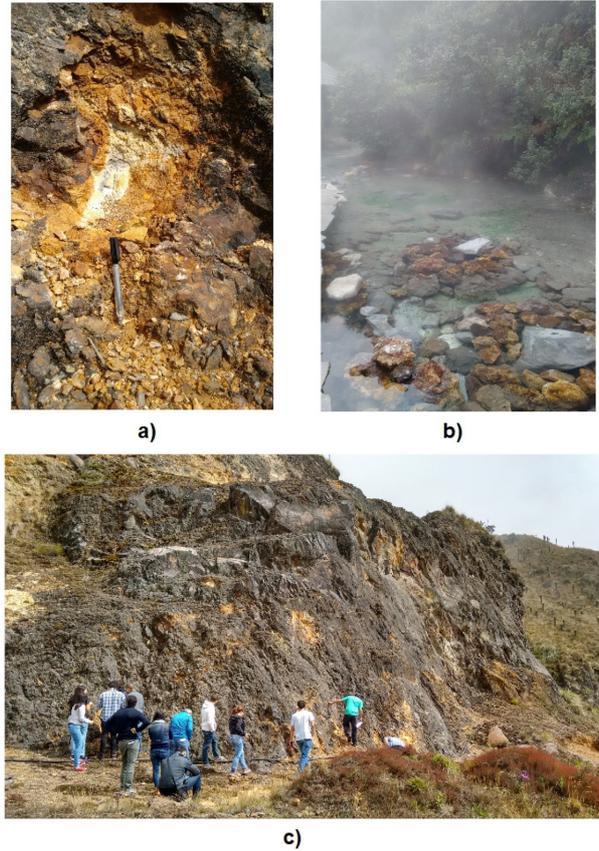


Figure 2. IGCP636 2016 field trip: hydrothermal alteration at outcrops in the Los Nevados natural national park (a) and (c) Termales del Ruiz hot spring.



Figure 3. IGCP636 2016 field trip: (a) main researchers and students at Los Nevados natural national park, b) Valle de Las Tumbas (4300 m a.s.l.), one of the stops where lava and pyroclasts can be observed.



Figure 4. IGCP636 annual meeting 2017: Universidad de Chile, Santiago.

class laboratories. The instruments are used by researchers and students from CEGA, collaborating institutions in Chile, and are also available to the international geothermal community (<http://www.cega.ing.uchile.cl/en/laboratorios/>). A 2-day field trip was organized to *San Jos del Maipo* and *San Felipe-Los Andes* in the *Valle de Aconcagua* geothermal areas by students and professors from CEGA (Fig. 5). In the first day, sampling of thermal waters was conducted and exhaustive explanations of structural geology were given by students working on those study areas. Groundwater circulating through a fractured rock massif and fault zones could be clearly observed in the second day.

France 2018

The third IGCP636 annual meeting was organized in France, with a secondary objective to attend the 6th European Geothermal Workshop (EGW) in Strasbourg (Fig. 6). Four researchers of the IGCP636 team also had a meeting at the UNESCO HQ in Paris with several UNESCO National Delegations (Canada, Madagascar, Colombia and Iceland), as well as with Özlem Adiyaman Lopes, the responsible for the IGCP projects (Fig. 7). Delegates provided useful comments and suggestions for future research goals and their dissemination throughout the society. The whole IGCP636 research team then met at BRGM office in Orléans to share and discuss the results obtained during the last year, to plan future activities, and to visit the BRGM experimental



Figure 6. IGCP636 annual meeting 2018: Strasbourg, 6th European Geothermal Workshop.



Figure 7. IGCP636 annual meeting 2018: Paris, UNESCO HQ, with Özlem Adiyaman.

geothermal platform, where different configurations of ground heat exchangers are being studied to improve the understanding of heat transfer mechanisms and to optimize the efficiency of geothermal heat pump systems. The current focus is the underground thermal energy storage needed to integrate intermittent renewables, such as wind and solar, on energy networks.

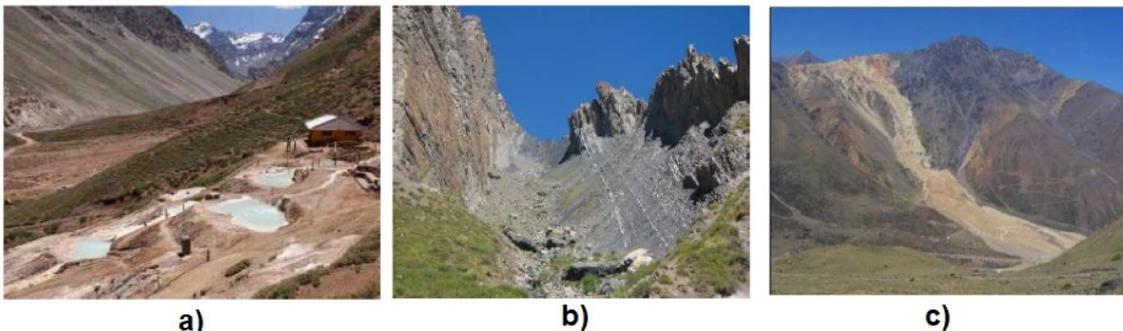


Figure 5. IGCP636 annual meeting 2017: field trip to El Cajon del Maipo, Chile (from field guide provided by CEGA): a) Baños Morales hot springs, b) Los Valdés sequence: limestones, shales and sandstones with marine origin, conglomerates, breccia and andesitic lavas, c) Las Amarillas debris flow, with yellow color because of hydrothermal alteration.

Main Results

The most important aspects that must be highlighted at the end of this 3-year project are the participation of students at all levels (undergraduate, master, and PhD candidates), analysis of social perception of geothermal energy, and several scientific achievements.

Student Participation

IGCP636 formally concluded at the end of 2018. In terms of its extensive network of scientists and enrollment of undergraduate and graduate students, IGCP636 has been a successful experience. Several exchanges were accomplished with additional scholarships and mobility grants for researchers between the following countries:

- Colombia and Canada, through the Emerging Leaders in the Americas Program and with a research project funded by the *Fonds de recherche du Québec Nature et Technologies*.

- Chile and France, through CONICYT funding to PhD students, where CONICYT is the Chilean *Comisión Nacional de Investigación Científica y Tecnológica*.

- Colombia and France, in both directions, thanks to the French program ECOS-Nord, where “ECOS means *Evaluation-orientation de la COopération Scientifique*, whose goal is to promote scientific and academic cooperation with Hispanic America.

- Colombia and Iceland, thanks to a MSc Candidate from the Iceland School of Energy that spent a semester in Colombia in 2017.

Canada and France, through an internationally associated laboratory (LIA).

- Canada and Iceland, with MSc and PhD students from Canada that attended the Iceland Summer School of Energy, a 3-week intensive course about sustainable technologies, held at the Iceland School of Energy, and MSc students from Reykjavik University doing research in Canada funded by the *Institut nordique du Québec*.

- Belgium and Canada, with a MSc student performing his thesis about geothermal operations in an old mine thanks to a collaboration between UMons and INRS. A scientific stay of five months was achieved in Quebec in 2019.

In Colombia, studies focused mainly on the characterization of the *Nevado del Ruiz* geothermal reservoir area. A preliminary assessment was presented by Velez et al. (2018a), while Moreno Rendon et al. (2018) analyzed the influence of faults on fluid flow and heat transfer mechanisms related to hot springs. Social perception analysis in the area of a potential construction of a geothermal pilot power plant was also conducted (Ramirez Restrepo et al., 2017).

Several MSc and PhD students in Canada, as well as postdoctoral fellows, have been involved in research activities linked to the characterization of geothermal resources in the St. Lawrence Lowlands sedimentary basin, in the North of Quebec through the Northern geothermal potential research chair, in Madagascar, and in Djibouti. Other research topics focused on the estimation of the subsurface thermal properties through thermal response tests (Vélez et al., 2017, 2018b) conducted to design geothermal heat pump systems.

PhD students from URennes in France have been involved in research activities to better understand heat transfer in fractured media, using spatially distributed temperature sensing with fiber optics in boreholes.

Other works focused on clogging processes in shallow geothermal heat pump systems and on the development of heat storage in fractured media through thermal tracer test data acquired at the Ploemur site, which is part of the H+ network of hydrogeological observatories. A student from INRS Québec and cosupervised by a UdeM professor spent six months in BRGM in order to perform some tests at the geothermal platform. Moreover, a researcher from BRGM, with extensive experience on deep geothermal resources of sedimentary basins in the Rhine graben, spent a year in Canada, transferring her expertise to student starting working in this field, and participating to the evaluation of their research activities.

In Chile, students from PhD to undergraduate level have been involved in geothermal and hydrogeology research in fractured geological media at the CEGA and they presented their results and ongoing work during the IGCP636 2017 Annual Meeting. Main areas of interests are Baños Morales and Baños Colina hot springs (Anselmo et al., 2017), the Aysen region (Negri et al., 2018), Pica thermal spring area (Placencia-Marin et al., 2017), the Aconcagua Basin (Taucare et al., 2017), and the El Tatio Geysir Field (Slagter et al., 2017).

In Belgium, the deep Carboniferous limestone reservoir in the area of Mons is the object of study for heat exploitation (Licour, 2014). Three geothermal wells are operated in the area and used to heat administrative and public buildings. A new geothermal doublet will be drilled to provide heat to the main city hospital. Students are studying the limestone reservoir for improving characterization and developing numerical models to be used as decision support tools (Gonze et al., 2018). Studies about the possibilities to use old coal mines to store and produce heat/cold were also initiated and an active collaboration with INRS was established on this topic, through a master thesis work in 2018-2019.

Society

This project aimed at analyzing the public perception with respect to geothermal resource exploitation in the participating countries (Colombia, Chile, Canada, France, and Belgium). A public opinion survey was conducted, enclosing six main sections focusing on specific topics: 1) energy issues, 2) energy production, 3) awareness of deep geothermal energy, 4) acceptability of deep geothermal energy, 5) use of stimulation in deep geothermal energy project, and 6) concerns about the use of deep geothermal energy. This exercise is a clear example showing how to increase awareness about renewable energy sources and sustainable exploitation of resources, which is to the benefit of the whole society.

Preliminary analysis was shared in the Second IGCP636 annual meeting in Chile and were published in the GRC online library (Ramirez Restrepo et al., 2017). A detailed analysis was presented at the EGW2018 in Strasbourg in 2018, where differences among countries were highlighted and discussed (Lopez-Sanchez et al., 2018). The main conclusions were that Chile is the country with the highest acceptability level of geothermal energy production, while social acceptance is lower in European countries (France and Belgium) when compared to the remaining American countries (Canada and Colombia). Moreover, the population of American countries is favorable to energy exports while the population of European countries prefers to produce energy for local needs. This public opinion survey was a positive experience showing

that It is essential to go beyond technical science and evaluate the perception of communities involved in any kind of natural resources development. Scientists can therefore help building bridges between communities, promoters and decision makers, helping to increase the level of knowledge required to take sound decisions.

Scientific Achievements

Publications that could not have been published without this project are Comeau et al. (2017), Giordano et al. (2018), Malmberg et al. (2018), Miranda et al. (2018), Ramirez Restrepo et al. (2017), Rajao-belson et al. (2017), Velez et al. (2017; 2018a; 2018b), Moreno Rendon et al. (2018), Lopez-Sanchez et al. (2018). Further research outcomes emerging from IGCP collaborations are expected for 2019.

Achievements also concerned the LOG (*Laboratoire Ouvert de Geothermie*), which is a new state-of-the-art infrastructure installed with major funding from the Canadian Foundation for Innovation, starting operations at INRS in 2018. Thermal and hydraulic properties of geological materials necessary to simulate geothermal systems can be measured in this laboratory. A guarded heat flow meter, a thermal conductivity scanner, a needle probe, a combined gas permeameter and porosimeter and portable gas permeameter are freely available. The LOG operates in an open fashion, like an open-source software, providing a free space to make analysis in exchange of sharing their results in a common database. The goal is to improve understanding of heat transfer in complex geological systems to increase geothermal system efficiency.

Congratulations must be given to students that brilliantly participated to IGCP636 activities: Estefania Ramirez Restrepo from UdeM won the 2018 Geothermal Resources Council (GRC) undergraduate student award scholarship to attend the GRC Annual Meeting in Reno (Nevada). Mafalda Miranda during her PhD at INRS won the *Mon projet nordique* award to present her thesis in 5 minutes at the Arctic Circle Assembly in Iceland. Finally, PhD candidate Matias Taucare from Universidad de Chile - CEGA won the 2nd place poster award at the 6th European Geothermal Workshop in Strasbourg. Several undergraduate students, MSc and PhD candidates have concluded their research work and graduated during the development of IGCP636 project, including 6 students in environmental engineering at UdeM and 4 MSc degrees in earth sciences enrolled at INRS.

Conclusion

A bright future can be envisioned for IGCP636 team with their strong interest to continue working together about geothermal resource characterization and modeling, as well as analysis of social and environmental aspects related to geothermal resource exploitation. The constructive assessments received over the past 3 years, in addition to the fruitful meeting held in Paris with UNESCO delegates and representatives, are the motivations to prepare a new geothermal energy research proposal in 2019. Sharing expertise and knowledge between young and experienced scientists, training of undergraduate and graduate students, and increasing women's participation in scientific studies, have helped achieve scientific developments in the geothermal sector with positive impacts on society. Participation of students in

such an international project brings benefit to both science and society. Undergraduate research training in a multi-disciplinary and -cultural context is expected to generate either responsible workers or graduate students that may become future project leaders.

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