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Geothermal - The Energy of the Future

Contents

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Foreword

EurGeol. Vítor Correia, EFG President

"Happy families are all alike; every unhappy family is unhappy in its own way."
Leo Tolstoy

The radioactive decay that feeds the flow of heat from Earth's interior to the surface is, from the perspective of the longevity of mankind, an infinite source of energy, making our planet, alongside with the Sun, a very effective energy source in the long run. This is in line with the World Energy Assessment published by the United Nations in 2000, where it was underlined that geothermal energy has twice the potential of all other renewables combined. However, and despite the fact that geothermal energy is reliable, weather-independent and available 24 hours a day, 365 days a year, the Earth is not perceived by a large majority of the population as a source of energy[1].

The questions that pop into mind are: why are geothermal and other renewables lagging behind fossil and nuclear energy? And why is it so difficult to change that? I'll try to use the *Anna Karenina*[2] principle to advance an answer, encompassing historical, economic and political reasons.

Before the 17th century the use of fossil fuels was rare: wood, wind and hydropower were the main sources of energy. This changed with the industrial revolution. The heating value of coal was greater than that of wood, making it a cheaper source of energy. And coal was abundant in the UK. Coal, together with the steam engine –first developed to pump water out of coal mines – became the drivers of the industrial revolution. Another technological leap forward happened in the 19th century, thanks to the internal combustion engine. This engine led to a revolution in transport, and oil became of paramount importance to feed war tanks, warships and airplanes, as well as military trucks. Oil was abundant and easy to exploit in the US and in 1925 the US was producing 75% of the world's oil production. The existence and abundance of oil to feed combustion engines lie at the foundation of US leadership in the world.

WWII brought us nuclear energy, first for bombs, and later for transportation and production of electricity. Nuclear plants started to appear and submarines with nuclear engines became common (they have much more autonomy, and don't need to come to the surface periodically for air.). Technologically advanced countries invested in this technology to produce electricity, especially those who were keen on reducing dependency on oil and coal imports.

The rise of renewables happened as a consequence of a 70% increase in oil prices by OPEC countries in 1973, alongside with an export embargo to countries that were backing up Israel in the Yom Kippur War. This triggered a surge of investment in alternative energy and drastic improvements in energy efficiency. The receptors of these investments were hydropower (which combines production of electricity with the important benefit of water storage) and biofuels. But the impact of hydropower and biofuels on the production of energy was modest, and below the growing demand for energy. And limitations on storage of the energy produced and/or intermittency of production, alongside with technological constraints and higher costs, kept other renewable sources behind fossil fuels.

1 There are locations where geothermal plays a core role in the energy supply system (the best examples come from Iceland, but there are also inspiring examples from developing countries, from El Salvador or Kenya to Indonesia), but technological difficulties and investment costs have been deterring the use of geothermal energy.
2 The famous opening lines of Leo Tolstoy's *Anna Karenina* have coined a principle of statistics used to describe significance tests: there are any number of ways in which a dataset may violate the null hypothesis and only one in which all the assumptions are satisfied. In management, this means a successful endeavour is one where every possible deficiency has been avoided.

On the other hand, nuclear and oil & gas were mature industries with a superior cost position[3]. And fossil fuels can be easily transported and stocked. This is the reason why the military and politicians call oil & gas secure and reliable sources of energy. The main predicament of using fossil fuels is CO_2 emissions (and its impact on air quality and global warming). Nuclear power doesn't have CO_2 emission problems, but poses safety and security concerns[4], the most relevant drawbacks of nuclear. But the production of electricity in nuclear reactors is cheap, in spite of high investment costs.

Considering limitations to transportation, storage and higher production costs, no single renewable energy source is strong enough to win over and replace conventional energy sources. However, we are on the dawn of technological leaps that can change this, and boost the use of renewables, including geothermal.

Incremental innovation is already increasing the efficiency of solar panels and wind generators, lowering their operational costs. The same is happening with heat pumps and electric batteries, having increasing capacity and lower costs. But the game change factor will happen with the surge of new, more effective types of batteries and the transformation of the electric energy distribution model.

The consumers wish for self-sufficiency from energy providers, combined with the surge in more effective energy storage systems and lower costs of domestic (renewables) systems, will most likely trigger a boom in the production of electricity by domestic consumers, making them the main suppliers of energy to the electric distribution grid. This will empower consumers, and the probable rise of environmental constraints will make electricity production facilities using conventional energy sources a rarity.

In this probable future, the big producers of electricity will use renewable sources and will compete for a superior cost position. This will probably be obtained by the combination of different sets of services/benefits, as happens in hydropower, which combines energy production and water storage. In this framework, geothermal power will probably have an advantage. Ongoing research is investigating the possibility of using deep geothermal sources to provide metals, alongside with heat for electricity production, hence contributing to solving societal needs for raw materials and energy in a single stroke. This issue of the EGJ provides a glimpse over geothermal energy and its applications, and this is one of the possible prospects described.

The future is uncertain, but we can trust that (happy) combinations among renewables will contribute to bringing society a step closer to having cheap, clean and endless energy.

3 It's this superior cost position that allowed the OPEC countries the on-going price war against US oil shale, in an effort to shut down natural gas production. And the fact that coal still is the most cost-effective energy source (and it is also abundant) led China and India to invest in coal power stations to support their fast development.

4 Remember the Iran embargo was related to the construction of a nuclear reactor, and think of the impact of the Three Mile Island, Chernobyl and recently Fukushima accidents on the industry.

Combining energy production and mineral extraction – The CHPM2030 project

Éva Hartai[1]*, Balázs Bodó and the CHPM2030 Team**

The H2020 project "CHPM2030 – Combined Heat, Power and Metal extraction from ultra-deep ore bodies" aims to develop a novel technology which combines geothermal resource development, metals extraction and electro-metallurgy in a single interlinked process. In order to improve the economics of geothermal energy production, the project will investigate possible technologies of manipulating metal-bearing geological formations with geothermal potential at a depth of 3-4 km and even deeper. In this way, the co-production of energy and metals will be possible and may be optimised according to market demands in the future. The project will provide a proof of the technological concept on a laboratory scale. It will be implemented through the cooperation of 12 partners from 10 European countries.

Le Projet H2020 "CHPM2030 - Combinant Chaleur, Energie et Minerais métalliques, à partir de l'extraction de gisements très profonds" a pour objectif le développement d'une nouvelle technologie associant le développement des ressources géothermiques, l'extraction de substances métalliques et l'électrométallurgie au sein d'un seul processus commun. Pour améliorer la rentabilité de la production d'énergie géothermique, le projet va étudier les technologies potentielles d'action sur le marché à partir de l'interférence entre formations géologiques riches en substances métalliques et leur potentiel géothermique à des profondeurs de 3 km à 4 km, voire au-delà. De cette manière, la coproduction d'énergie et de métaux sera possible et pourrait être optimisée en fonction des demandes du marché, dans le futur. Le projet témoignera du concept technologique à l'échelle du laboratoire. Il sera mis en œuvre grâce à la coopération de 12 partenaires provenant de 10 pays européens.

El proyecto H2020 "CHPM2030 - Extracción combinada de calor, energía y metal de mineralizaciones ultra profundas" tiene como objetivo desarrollar una nueva tecnología que combine la extracción de recursos geotérmicos, metales y electro-metalurgia en un solo proceso interconectado. El proyecto investigará las tecnologías que permiten de manipular formaciones geológicas ricas en metales con potencial geotérmico a una profundidad de 3-4 km e incluso más profundas, con el fin de mejorar la economía de la producción de energía geotérmica. De esta manera, la coproducción de energía y metales será posible y podría ser optimizada de acuerdo con las demandas del mercado en el futuro. El proyecto producirá una prueba del concepto tecnológico a escala de laboratorio. El proyecto se llevará a cabo mediante la cooperación de 12 socios de 10 países europeos.

Introduction

In the coming decades, the European energy market will face major challenges to become less dependent on imported fossil fuels and to reduce the environmental impact of its energy supply. A major option, geothermal energy is already being used worldwide, including in many parts of Europe, because it is clean, renewable and constant. The European Commission actively promotes research and development on Enhanced Geothermal Systems (EGS). The main problems related to these systems are improving the efficacy of the underground heat exchanger, increasing the economic lifetime of EGS plants and lowering capital and operative costs.

Europe has another major challenge: securing the supply of critical raw materials, in particular metals, for industry and society. The dependency on metal is growing every year, despite significant efforts in the development of recycling and substitution.

The CHPM2030 project (Combined Heat, Power and Metal extraction from ultra-deep ore bodies with an aim of implementation by 2030) aims to develop a novel technological solution that can help satisfy the European needs for energy and strategic metals in a single interlinked process. In the CHPM technology vision the metal-bearing geological formation (deep orebody) will be manipulated so that the co-production of energy and metals will be possible (***Figure 1***). The project started in January 2016 and lasts for 42 months, but aims to initiate a new type of geothermal exploitation that will endure for much longer, and to have an operational plant by 2030.

Background

Although metals are available in the Earth's crust, current exploration and mining technologies limit accessibility. Metal concentrations (ore deposits) can form at any depths, from the Earth' surface to the deepest zones of the lithosphere. However, there are physical barriers hampering our access to mineral deposits at several kilometers' depth. The deepest operating mine in Europe (Pyhäsalmi in Finland) goes down to about 1400 metres

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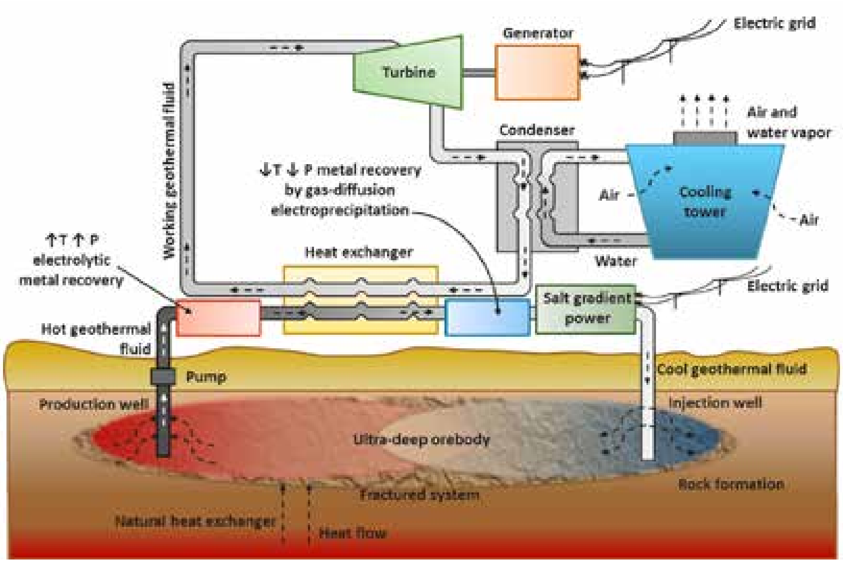

Figure 1: Schematic overview of the envisioned CHPM Facility. © CHPM2030 Team

(Weihed, 2013). Everything that lies below 3000 metres is considered "ultra-deep" for conventional mining and out of scope for minerals prospecting in Europe. Whilst we have detailed knowledge of the surface geology in many regions, the amount and quality of information dramatically reduces with depth. However, from recent 3D and 4D geological modelling we know that metallic mineralisation in most mineral belts in Europe exists also at depths beyond those previously targeted by commercial exploration.

As for the energy aspects, with the current state of technology, the worldwide technical potential for geothermal electricity generation is six times higher than the currently installed capacity (Fridleifsson *et al.*, 2008). It is clear that the development of geothermal power production is not in line with its theoretical and technical potential. Although it could be a base load energy source, financing geothermal projects has been difficult, and the development of Enhanced Geothermal Systems (EGS) in Europe has fallen short of initial expectations. This is due to the combination of high risk and high capital costs required for investment. Metal extraction from the geothermal fluid can provide added value to the system, which has the potential to increase the financial feasibility of geothermal development.

The presence of metals in geothermal fluids is well unknown. Some geothermal systems are sites of precious metal transport and deposition. For example, wells drilled to 3 km depth in geothermal systems of the North Island, New Zealand were sampled and it was found that deep reservoir waters have Au concentrations that range from 0.1 to 20 ppb and Ag concentrations that range from 2 to 2000 ppb (Simmons *et al.*, 2015, 2016).

Extraction of minerals from geothermal brines is also an applied technology in a few geothermal fields (***Table 1***).

Methodology and work structure

The CHPM2030 project is composed of eight work packages. The linkage between the work packages and the work organisation are shown in ***Figure 2***.

The project work started with the formulation of the conceptual framework. The objective of this work phase was to synthesise our knowledge on ultra-deep (> 4 km) metallic mineralisations that could be converted into an "ore body EGS". Four reports were prepared within this work package (***http://www.chpm2030.eu/outreach***).

The first report provides a review of metallogenic provinces in Europe. The ore-forming processes, the structure and the metal content of the ore deposits are discussed. Special focus is put on the mineral potential at depth and in temperature zones that are currently the target of EGS (Hartai *et al.*, 2016).

The second report is an overview of four major ore districts in Europe, namely in SW England, southern Portugal, NW Romania and central and northern Sweden (these are the potential test sites by 2030). It is completed with a survey of existing boreholes in the European countries where temperatures at depth in access of 100 °C are observed. The report includes descriptions of the geological settings and on-going geophysical efforts to probe more deeply, and with increasing resolution, in order to detect mineralised zones at depth, as well as attempting to estimate their geothermal potential (Schwarz *et al.*, 2016).

The third report summarises the results of laboratory investigations on ore samples that represent the study sites of the

Table 1: Technological methods for extraction of chemical compounds from hydrothermal heat carriers (based on Potapov et al.*, 2008; Richter, 2016).*

Field	*Extracted chemical compounds*	*Extraction methods*	*Phase of the work*
Kaweraw, Wairakei, Brodlands, New Zealand	SiO_2	*Addition of CaO, ultrafiltration*	*Pilot plant*
	As	*Treatment by ferric sulphate for flocculation, sorption of arsenic with preliminary pre-oxidation of natrium hypochlorite*	*Pilot plant*
Cerro Prieto, Mexico	SiO_2	*Addition of coagulant CaO*	*Pilot plant*
	KCl – NaCl	*Evaporation, crystallisation, flotation*	*Pilot plant*
	SiO_2	*Flocculants of Magnifloc, Calgon, Separan, Purifloc series*	*Industrial production*
Salton Sea, USA	*Zn*	*Ion exchange, liquid extraction, electrolysis*	*Industrial production*
Salton Sea, USA	*Li*	*In testing phase*	*Proposed by Tesla*

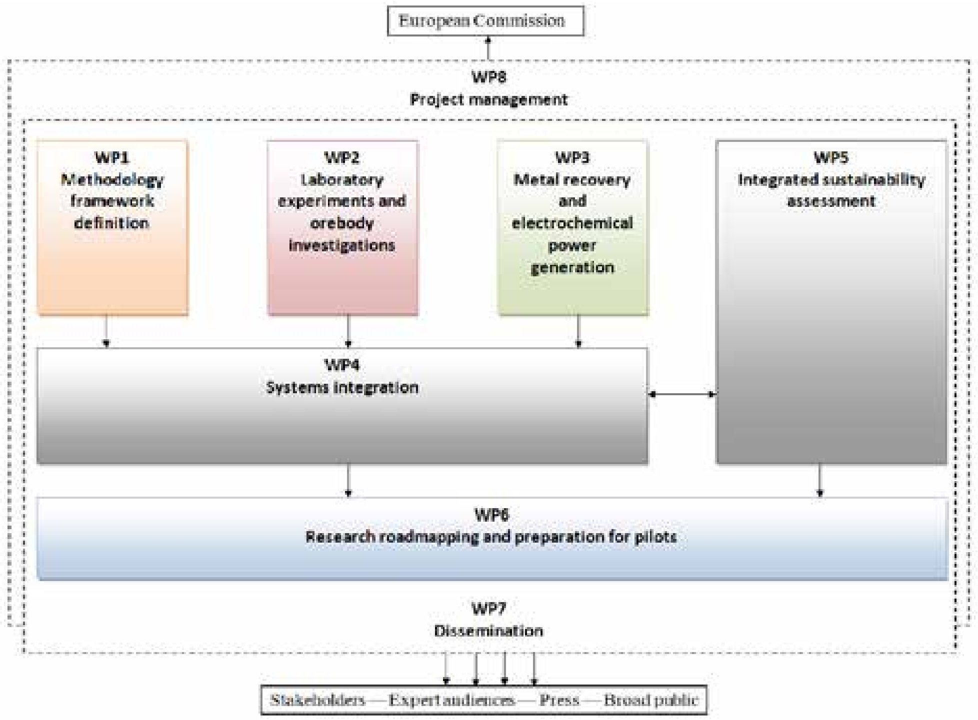

Figure 2: Work organisation in the CHPM2030 project. © CHPM2030 Team

CHPM2030 project, completed with samples from other ore types. The results are evaluated with a relevancy to the CHPM technology (Németh *et al.*, 2016).

The fourth report provides a methodological framework to be used as a guide for the laboratory measurements in work package 2, and also for data collection for modelling heat transport. The currently existing reservoir enhancement technologies are also reviewed (Szanyi *et al*., 2016).

In the second year of the project, the focus will be on laboratory measurements in order to test the following hypotheses:

(1) The composition and structure of orebodies have certain advantages that could be used when developing an enhanced geothermal system;

(2) Metals can be leached from the orebodies in high-enough concentrations over a prolonged period of time;

(3) The continuous leaching of metals will increase the system's performance over time in a controlled way and without using high-pressure reservoir stimulation, minimising potential detrimental impacts of both heat and metal extraction.

Laboratory examinations will be carried out to determine heat conductivity, fracture enhancement possibilities and stress field determination. Metal content mobilisation will be tested by relatively mild leaching methods (i.e. not using very strong acids), and also with the use of functionalised carbon nanoparticles. The specific aim of this task is to obtain shaped carbon particles with unique structural and chemical properties for the selective and reversible adsorption/complexation of the targeted metals.

Work package 3 will focus on the recovery of metals and electrochemical power generation. It involves the recovery of the metal content by high-temperature, high-pressure geothermal fluid electrolysis (electroprecipitation and electroreduction) and also by gas-diffusion electroprecipitation and electrocrystallisation. Amongst the targeted metals are Cu, Fe, Ag, Zn, Fe, Au, Ni, Pt, In and Mo. Furthermore, also examined will be the potential for salinity gradient power generation from pre-treated geothermal fluids. The output will be the technical feasibility of additional power generation from geothermal fluids.

Based on the outcomes of the above-mentioned work phases, work package 4 will integrate downstream and upstream processes into a single system and develop optimisation strategies for energy and metals production. This task will combine the Consortium's past experience with the design of medium and high-enthalpy geothermal systems and the outcomes of WP2 and WP3 to create a novel technology line that will produce energy and saleable metals in a single process. This knowledge will be utilised to adapt the design of a contemporary power plant to the expected temperature and extreme salinity conditions that will occur under the CHPM2030 scheme.

In parallel with the laboratory research, environmental and socio-economical assessments will be carried out, paying due attention to ethical considerations. The expected social, economic and environmental impacts for each component of the proposed CHPM technology will be considered. This work will be followed by an overall systems-level performance assessment. It will include a preliminary life cycle assessment and investigations concerning the environmental footprint of the envisioned technology scenarios. Comparison will then be made with existing systems (both for power generation and mineral extraction) to gain a thorough understanding of the relation of CHPM2030 to existing solutions from environmental and economic performance point of view. Performance indicators will consider the fact that CHPM envisions the integration of two – so far independent – processes for improved economics: the production of energy and the production of metals.

CHPM2030 is a research project at a low technology readiness level (TRL), based on a novel idea that needs further nurturing and support beyond the immediate duration of the project. However, work package 6 will move towards these goals by generating new knowledge about specific areas of geothermal and mineral deposit potential, and will set the scene for subsequent pilot implementation. Converging technology areas will be assessed and a research roadmap will be developed that will help bring forward the realisation of the envisioned CHPM scheme. Two roadmaps will be provided: roadmap 2030 will provide a timeline and direct support towards the implementation of the first CHPM pilots at the four potential test sites: SW England, southern Portugal, NW Romania and three mining regions in central and northern Sweden. Roadmap 2050 aims at supporting breakthrough research for further development of the CHPM technology.

The dissemination work package seeks dialogue and engagement as well as dissemination of thematic work package outputs towards the stakeholder communities, research organisations, companies, investors, funding organisations, relevant technology platforms, and the general public. The management will ensure smooth and on-time execution of the project, based on the description of work and in accordance with the European Union's regulations.

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Towards geological-economic modelling to improve evaluating policy instruments for geothermal energy - Case study for Belgium (Campine Basin)

Estelle Petitclerc, Kris Welkenhuysen, Steven Van Passel, Kris Piessens, Dries Maes and Tine Compernolle*

Deep geothermal energy appears to be currently on the edge of a take-off in Belgium. However, the actual emergence of this technology is subject to developments in legislation and incentives from regional governments. Different risk/return expectations across stages of the investment continuum exist and the financial structures that are employed at each stage may require different types of public support. In this context, the ALPI project aims at developing a geological-economic model to calculate the impact of different policy instruments on development of the Belgian geothermal energy sector. Due to the lack of underground information describing the Campine Basin, economic methods are used to deal with these large geological uncertainties.

L'énergie d'origine géothermique profonde apparait actuellement, en Belgique, comme en passe de décoller. Cependant l'émergence actuelle de cette énergie est liée aux développements d'ordre législatif et incitatif de la part des gouvernements régionaux. Les attentes différentes en termes de risques/bénéfices tout au long des étapes d'un investissement en continu sont présentes et les structures financières, utilisées à chaque étape, pourraient exiger différentes sortes de support public. Dans ce contexte, le projet ALPI a pour objectif de développer un modèle géologique et économique pour le calcul de l'impact des différents outils politiques sur le développement du secteur énergétique de la géothermie en Belgique.

La energía geotérmica profunda parece estar cerca de despegar en Bélgica. Sin embargo, la emersión real de esta tecnología depende de la evolución de la legislación y de incentivos de los gobiernos regionales. Diferentes expectativas de riesgo / retorno existen a través de las distintas etapas de inversión, siendo necesario diferente tipo de apoyo público en cada una de dichas etapas. y las estructuras financieras que se emplean en cada etapa puedan necesitar diferentes tipos de apoyo público. En este contexto, el proyecto ALPI tiene como objetivo desarrollar un modelo geológico-económico para calcular el impacto de los diferentes instrumentos de la política para el desarrollo del sector geotérmico belga. Debido a la falta de información existente en la Cuenca de Campine, los métodos económicos se utilizan para hacer frente a estas grandes incertidumbres geológicas.

Belgium is one of the most densely populated countries in the world (363 inhabitants/km² in 2015) with a population density similar to that of Japan, India and the neighbouring Netherlands. The ambitious European 20-20-20 goals play an important role in incentivising the upward trend of Renewable Energy Sources (RES) and geothermal energy in Belgium. These targets require 13% of total energy consumption in Belgium to be produced from RES in 2020. In 2011 RES comprised 5.1 % of total energy consumption.

The past five to ten years have seen a substantial effort in geothermal research and development in Belgium (USD 14.42 million) between 2010 and 2015). Despite being in an intra-continental setting, it was demonstrated by several national, regional and cross-European projects that favourable geological conditions for geothermal energy may exist over large regions of Belgium, yet these conditions are mostly based on sparse exploratory data and indirect determination.

A great deal of uncertainty remains due to the lack of deep exploration boreholes, leading to high geological risk. This geological uncertainty was highlighted in the 1980s with the failure of the Meer geothermal well in the Campine Basin, due to Namurian strata thickening significantly above the targeted Dinantian limestones, a fact previously unknown. This led to a bottleneck for geothermal projects during several decades. However, recent projects (Balmatt wells) will improve geological understanding.

In anticipation of the opening-up of the deep geothermal market in Belgium, Hasselt University, the University of Antwerp and the Geological Survey of Belgium are investigating the regional potential for geothermal heat and electricity production.

Petitclerc *et al.* (2016) developed a methodology to refine the probability of success for a geothermal investment. This methodology also forms the first step in integrating geological modelling in techno-economic simulations. This paper focuses on how to fully account for geological uncertainties in the overall economic evaluation, which allows the level of geological knowledge to be directly linked to the economic viability of potential future projects.

Geological setting

The Belgian subsurface presents a large geological diversity resulting from tectonic events and the evolution of different sedimentary basins over a period of 550 million years. The sedimentary basins in the northeast (Campine Basin) and south

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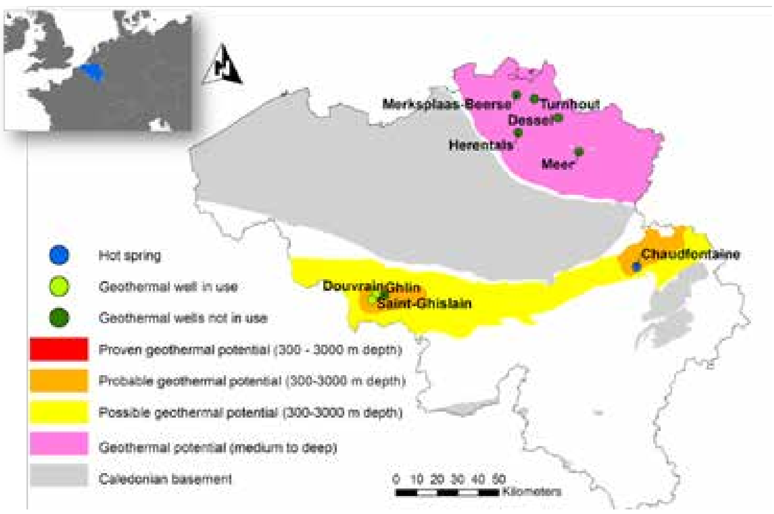

Figure 1: Mapped medium-deep geothermal potential and geothermal wells in Belgium. Inset shows location of Belgium in Europe (Loveless et al. *2015):*

(Namur-Dinant Basin) of Belgium (Dreesen *et al.*, 1985) provide the largest potential for deep geothermal energy. The recognised geothermal resources and hydrothermal processes observed in Belgium are localised in the thick sequences (up to 500 m) of Devonian-Carboniferous platform carbonates. However, the basins differ in structure and characteristics. This case study focuses on the Campine Basin, which is an intermediate basin between the Brabant Massif and the Roer Valley Graben (itself an extension of the active Lower Rhine Graben) primarily within the Netherlands. Much of the knowledge of the subsurface of Flanders comes from seismic surveys undertaken since the 1950s.

In the 1970s and '80s, five geothermal wells (Meer, Merksplas, Dessel, Turnhout and Herentals) were drilled in Flanders in the low temperature chalk and Dinantian reservoirs, but none of these wells remains in operation today (***Figure 1***). Deep geothermal targets have been mapped for some exploration (Vandenberghe, 1990) and exploitation projects. The most recent project in Flanders, (the Geoheat-App project in 2014) better defined the geothermal potential of four reservoir intervals across the border with the Netherlands.

Methodology

Use of decision tree

The probability of success of a deep geothermal project is typically rather low, especially when the level of knowledge of the reservoir is still at a regional level. This may lead to a situation where there is a general consensus that a reservoir is well suited for geothermal development, but its actual development is hampered by the high geological, technical and financial risks of individual projects.

Zooming in on this hurdle requires a methodology which deals with virtual project simulations to evaluate what types of projects could work and which kind of policy instruments could be implemented. A decision tree was set up (***Figure 2***) to reflect the pre-investment point of view of a private investor. This investor analyses one single case study to be executed in a defined region, and has to optimise the outcome in terms of return on invested capital. Policy instruments are considered as external factors that change the investment conditions.

During the elaboration of such a project, the project team goes through several decision stages, each based on the information gained from the previous stage, with an evolution of the risk that the project fails (is abandoned). The liberty that the investor has to redirect or abandon the project at each step is incorporated as detailed in Petitclerc *et al.* (2016).

Outcomes of a geothermal decision tree

The decision tree model (***Figure 2***) reflects the generic development of a deep geothermal project, applied to the Campine Basin in Belgium, and is similar to that of the deep geothermal project that is currently under development (the Balmatt project).

Depending on the water temperature and the flow rate, several options are available in the pre-project simulation: Failed; Low-Temperature (LT) heat plant; High-Temperature (HT) heat plant; and a Binary power plant with or without Enhanced Geothermal System (EGS). Due to the medium temperature gradient (25 °C to 30 °C/km) in Belgium, only the binary power plant is relevant for electricity production.

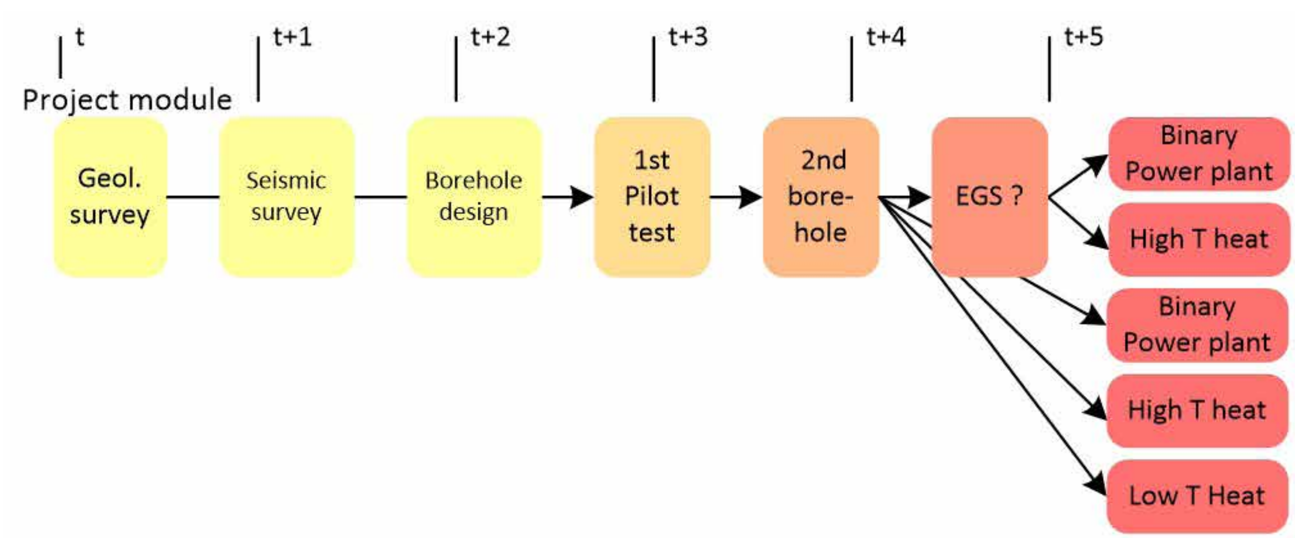

Figure 2: Decision model for the generic Campine Basin deep geothermal project (based on the Balmatt site).

A significant upfront investment is related to the drilling, posing an important risk for a geothermal project. In reaction to this, risk insurance funds have been set up in different European countries (France, Germany, Iceland, the Netherlands and Switzerland).

Regardless of such measures, the question remains how geological risks should be approached when assessing potential projects. Correctly doing this is vital, because the outcome of a project is determined largely by geological parameters.

Towards fully addressing geological uncertainty

Techno-economic simulations will almost as a rule involve the input of experts. This allows to realistically develop tools such as decision trees that summarise when investment decisions are taken. Similarly, expert input is typically used for dealing with geological data gaps. Working with expert input requires specific methodology and awareness of likely pitfalls. When it comes to integrating geological uncertainty in techno-economic simulations, also the way the actors (historically) interact and approach a problem becomes important.

Consider the following geothermal example, which ends in either an incorrect or a very vague result. After setting up a model focused on the engineering aspects of a doublet system, the modeller decides to ask the geological expert to provide a best estimate on the temperature of the reservoir water and the expected flow rate. These are logical questions in his view, because these are his direct input parameters for calculating the profitability of the project.

The geologist will provide information, but at the same time complain that flow rates have been insufficiently measured, and that in general the available information is not complete enough to make reliable estimates.

What happens then largely depends on who is most convincing or stubborn: geological uncertainty is either not mentioned, or the end result of the whole study is considered as indicative only.

So how to improve this very typical situation? First it is important to understand what goes wrong: the modeller asks the wrong questions, and the geologist sees only uncertainty.

Geologists are very aware that their descriptions are based on very little information. This is especially true for deep geological settings, such as those for geothermal projects aiming at binary heat and power production.

What they do not realise is that economic methods are able to deal with exactly that: very large uncertainties. This is especially true for decision tree-based analyses, such as the real option approach that is used here. A best estimate does not have to be a value ± 20%; ± 2000% will also still work.

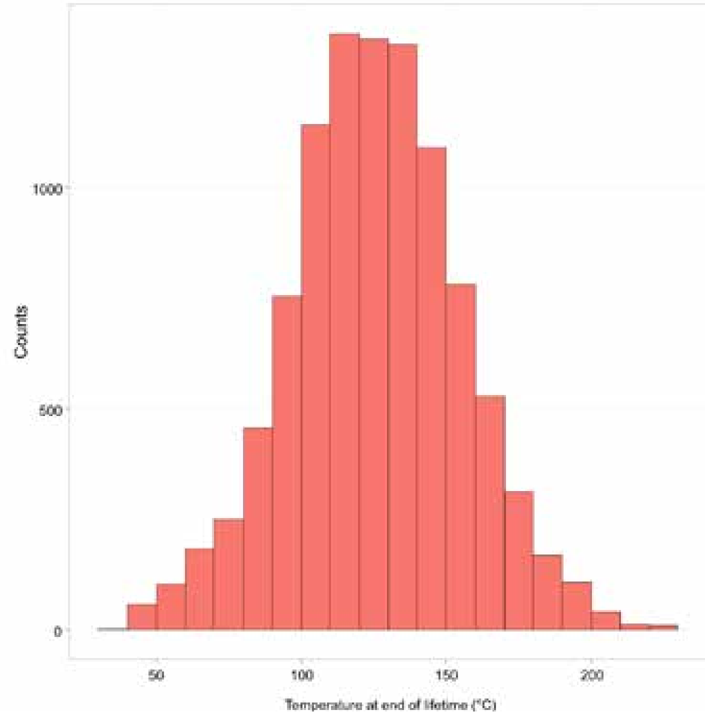

Figure 3: The uncertainty range of the temperature at reservoir depth includes the uncertainties on the temperature gradient, depth to the top of the reservoir and its thickness.

The modeller on the other hand sees only his data gaps, but should realise that questions should be properly formulated. Using expert data is very common and has scientifically been proven to be reliable, provided that certain rules are respected (e.g. Henrion & Fishoff, 1986; Bier, 2004; Lin & Bier, 2008; put into geological context by Welkenhuysen *et al.*, 2013).

Especially when it comes to geological information, an expert needs to be able to translate his view or idea regarding a specific part of the subsurface as directly as possible into input for the model. For geothermal energy, a correct approach is outlined in the following section.

But in general, the important lessons for making such an exercise work are: (1) 'modeller to geologist'– formulate questions for input with respect for how a geological expert understands the subsurface and its uncertainties, and (2) 'geologist to modeller' – specifically include uncertainty ranges, even when orders of magnitude are large, as they are the most essential part of the input.

Approach applied to the Campine case study

This case study targets the geothermal reservoir of the Campine Basin: the Carboniferous Limestone Group. The reservoir concept is described by probabilistic distributions for 10 parameters that form the input of the geological model: the chance of geotechnical failure of the reservoir, depth, total thickness, productive thickness, the geothermal gradient, transmissivity, flow rate, effective porosity, distance between doublets and distance between wells.

Five independent experts from three institutes were consulted. All have an academic background in geology and are well acquainted with the deep geology of Belgium. Data were collected in spring 2016.

The probabilistic input of the different experts is combined by averaging with equal weights, assuming that each expert's opinion is equally valuable. The analytical model for geothermal heat recovery from doublet systems developed by Gringarten (1978) was used as the basis, and modified to allow for partially penetrating wells (Chang & Chen, 2003).

This model is used to stochastically calculate 100,000 realisations of the extractable heat and the optimal configuration of a single doublet system and a field of doublets. For each realisation the input parameters are sampled from the input parameter distributions. The reservoir's

Table 1: Distribution of outcomes over the different end-uses of geothermal energy.

Scenario	*Reference case*	*Subsidy case*
1) Failed	*80.3%*	*80.4%*
2) LT Heat plant	*0.0%*	*0.0%*
3) HT Heat plant	*19.7%*	*16.3%*
4) EGS & PP	*0.02%*	*3.0%*
5) Power plant	*0.01%*	*0.4%*

temperature (***Figure 3***), and optimal flow rate and depth are calculated by the model. It was decided to use an analytical model instead of a numerical model, in order to reduce calculation time for generating stochastic input parameters while still ensuring sufficient accuracy. The choice to calculate 100,000 realisations is made to test model performance (a secondary study objective). In practice this number could be an order of magnitude lower for this specific study.

Both models adopt a similar stochastic approach. The level of complexity of the decision tree is such that the geological model can be run independently from the techno-economic model. This means that all results of the geological model can be calculated prior to running the techno-economic model. This is not necessarily possible for more complex situations; such cases would requires integrating the two models.

Case-study simulation and probability distributions

The first part of the research derived estimated probability distributions of the main subsurface parameters. Petitclerc *et al.* (2016) describe how the decision tree for a geothermal project development has been executed based on these distributions. These calculations are repeated for 50,000 runs to approximate the final distribution of outcomes.

Two cases were tested:

- A reference case of a regular geothermal project without any public investment or subsidies to stimulate renewable energy production.
- A subsidy case where additional subsidies are granted only for renewable electricity production, for an amount of 250 EUR/MWh.

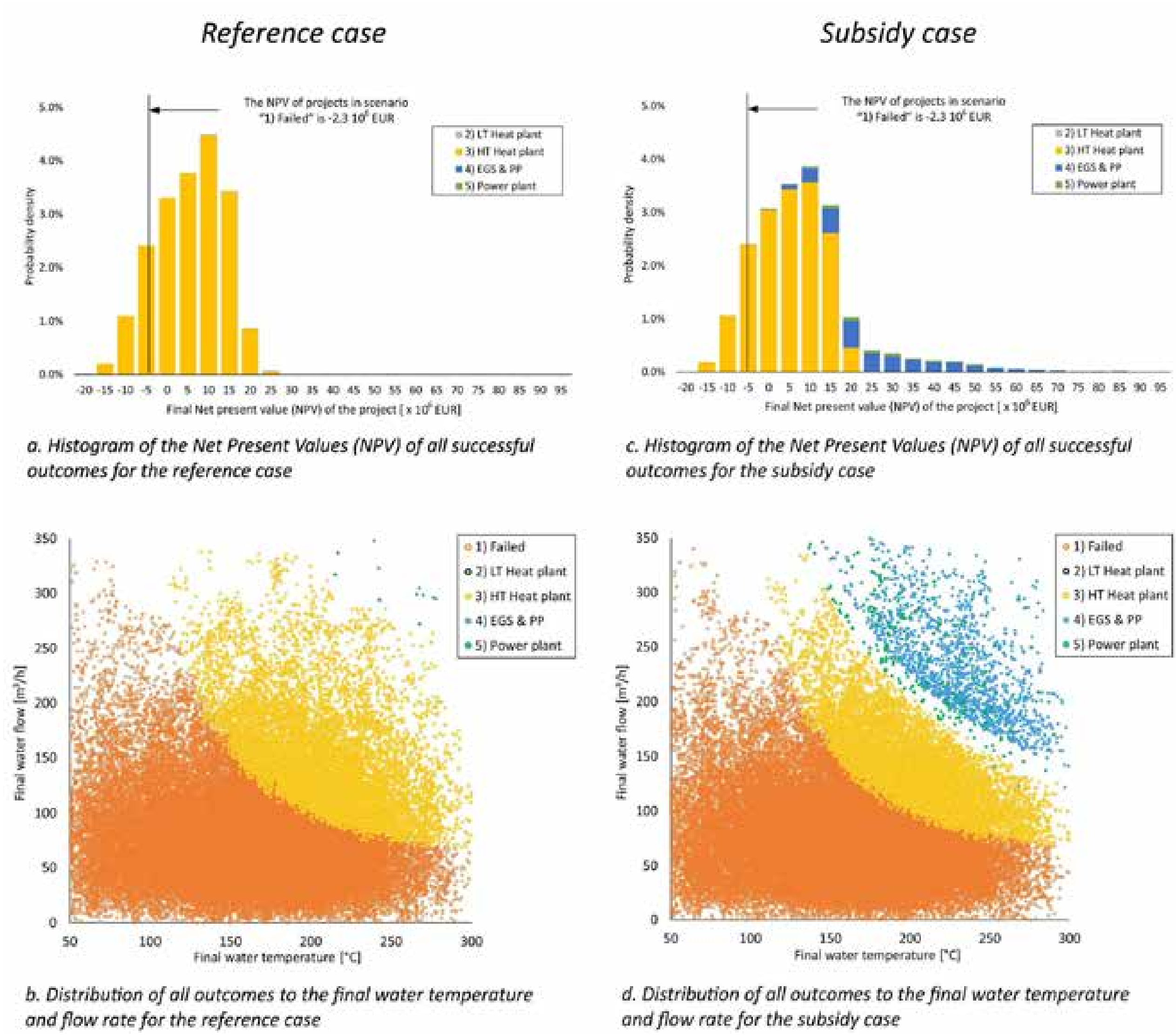

Figure 4: Reference and subsidy case outcomes. a and c: histogram of the Net Present Values; b and d: distributions of all outcomes according to the final temperature and flow rate.

The geological, economic and technical assumptions were kept identical. The subsidy scenario is a test case for the effect of electricity stimulating policies. The level of subsidy is similar to the subsidies granted for photovoltaic panels during the emergence of this technology.

The results in ***Table 1*** illustrate the distribution of outcomes for a project with a location similar to the Balmatt site before any new survey for the reference and subsidy case. These show already that over 80% of the projects do not survive the preliminary survey phase or the execution. The large majority of the remaining 20% of the projects are focused on delivering HT heat. When an added stimulus is created for the production of electricity, there is a moderate shift from HT heat to the power plants. However, the overall success rate of projects remains exactly the same. So the subsidy does not seem to change the overall success rate of the project. This finding intuitively seems difficult to explain, but, as is shown in the discussion, boils down to a simple rule: subsidies need to take into account geological reality.

Discussion

Reference case: no subsidy

In the reference case, most of the successful projects (19.7%) are HT heat plants. ***Figure 4a*** shows that even projects that are realised may still be faced with operating conditions that are insufficient to earn back exploration and investment costs. Failed projects in general end with a negative NPV of €-2.3 million, equal to the exploration costs.

The distribution of successful and failed projects in ***Figure 4b*** shows that successful projects require a good combination of geological conditions (temperature and flow rate). Power plants are only installed under highly optimal combinations.

Subsidy case: 250 EUR/MWh

When subsidies are granted for renewable electricity production, the amount of failed projects remains unchanged, and the distribution of NPV remains largely the same (***Figure 4c***). The main difference is the appearance of combined heat-power plants, skewing the histogram to the right. Electricity generation is attempted in cases with optimal combinations of underground parameters. These projects were already chosen for HT heat plants in the reference case, so the electricity subsidy allows the transformation of existing HT plants into heat-power plants.

Figure 4d shows more clearly how a subsidy on electricity production fails to pull this technology into the market, and instead only favours already profitable projects. This demonstrates that a subsidy needs to be tailored to the geological conditions. The subsidy fails because it is too improbable that geological conditions will, even with subsidies, allows power to be economically co-produced.

The study presented here clearly demonstrates that the choice of subsidy mechanism is crucial. Copying the method from another renewable energy source, in this case photovoltaic electricity production, where the subsidy has proven to work, is not a proper starting point. More appropriate policy instruments that take into account the geological conditions and uncertainties exist in neighbouring countries, such as geological or drilling risk insurance and recoverable advance for the feasibility phase. These two instruments, coupled with a feed-in tariff for electricity production, are currently recommended to stimulate the power geothermal sector development. This combination of measures adapted to the Belgian context will be evaluated in the near future.

Consistency check of geothermal parameters and reliability of the reservoir model

The experts were consulted in such way that a validation of the accuracy of the expert data and the analytical model was possible. Two parameters, flow rate and well distance, were estimated directly by experts and alternatively calculated from other parameters (***Figure 5***). Based on the assumptions for setting up the questionnaires, these are the calculated parameters that should be most reliable. Both can be compared in light of the recently obtained

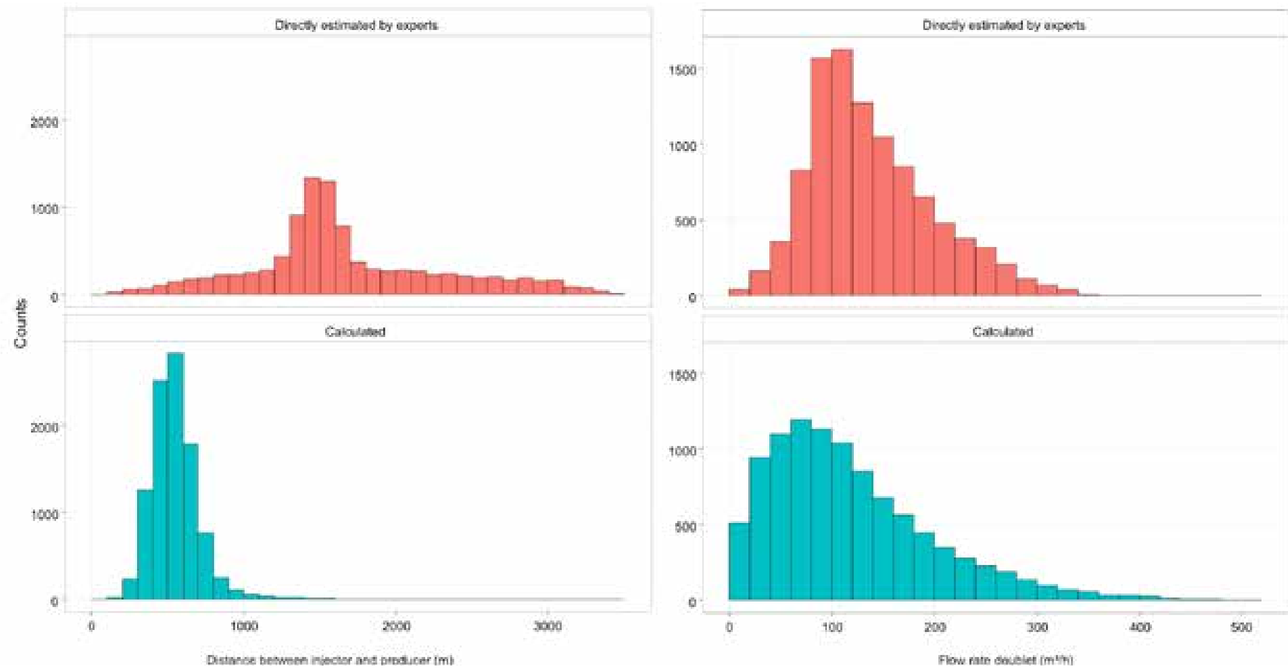

Figure 5: The upper histograms present the expert estimates on the distance between the doublet wells and the flow rate that can be achieved. The lower histograms present the results for the same parameters, but this time calculated indirectly from expert input. The significant difference for well distance is probably due to the definition of project life time, which was differently perceived by the experts than it is defined in the model.

pumping tests on the Balmatt wells.

A first observation is that for both flow rate and distance, the ranges of calculated results are about two times larger than those from the experts. The distribution of the calculated flow rate is more skewed than that of the experts. This is evident from the lower mode and the longer tail towards higher values. The single well pumping tests seem to indicate values towards the higher end of these distributions. Since these experiments indicate upper limits for flow rates, this seems to confirm that the calculated estimates are realistic.

A larger difference is observed for the well distances. The calculated distance is much smaller, to the point where it approaches unrealistic values. The mode is around 600 m, while the experts estimate it to be around 1500 m.

The difference is probably an unintentional side effect, and an example of the great care with which parameters need to be handled in these exercises. In the analytical calculation, the lifetime (35 years) is an average. The experts, however, intuitively perceived it as a safe minimum.

Preliminary sensitivity analysis has shown that lifetime (non- stochastic input parameter) needs to be multiplied by a factor of 8 in order to close the gap. This looks very high, but not impossible with the uncertainty ranges estimated here.

Uncertainty and the value of flexibility

In spite of what geological experts often assume, geological uncertainties can be very large without inhibiting conclusions regarding the potential outcome of projects. However, correctly addressing them does require an in-depth understanding of geological uncertainty, how it is being perceived, and how it is optimally translated for techno-economic modelling.

This does not imply that obtaining geological information is not useful; the contrary is actually true. Embedded in the decision tree is the assumption that additional data becomes available and uncertainty largely resolves as the different project stages are executed. Without such assumption, the simulation would show that geothermal projects would not be realised.

There is a fundamental difference between geological uncertainty – the focus of this paper – and market uncertainty. Under price uncertainty, investment is not a 'now or never' decision. The firm has an option to invest and there is value in waiting. If the firm invests, it kills the option to invest and it loses the flexibility to wait. In the economy, this represents a cost. In contrast, under geological uncertainty, investment creates flexibility: the investment in exploration reveals information and creates an exploitation option. This count as a revenue. Hence, market uncertainty postpones investment, geological uncertainty stimulates investment.

For a project dominated by geological uncertainty, it is highly relevant that all parties involved correctly understand such 'geology-specific' aspects in order to come to a correct understanding. The value of learning and the trade-off between market and geological uncertainty are only a few of the challenges in geological economics.

Acknowledgements

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Development of the first deep geothermal doublet in the Campine Basin of Belgium

Stijn Bos and Ben Laenen*

In the fall of 2015 the first deep geothermal well was drilled in the municipality of Mol, Belgium. The primary objective was to explore the geothermal reservoir characteristics and the exact depth of the Carboniferous Limestone Group. Based on the test results of exploration well MOL-GT-01, a second well was drilled in spring 2016 creating a geothermal doublet of one vertical well (3,610 m along hole) and one deviated well (4,341 m along hole). Both wells give new stratigraphic and structural insights into the geological history of the Campine Basin. Furthermore, the presence of a geothermal reservoir at depths below 2,500 m has been demonstrated for the first time in Belgium, unlocking opportunities for new developments elsewhere.

A l'automne 2015, le premier puits géothermique profond a été réalisé sur la commune de Mol, en Belgique. Le but initial était de déterminer les caractéristiques du réservoir géothermique et la profondeur exacte de la série de calcaires du Carbonifère. Basé sur les résultats du puits exploration MOL-GT-01, un deuxième puits a été foré au printemps 2016, pour créer un doublet géothermique: un puits vertical (3610 m forés) et un puits dévié (4341m forés). Les deux puits ont fourni un éclairage nouveau du point de vue stratigraphique et structurel dans l'histoire géologique du Bassin de la Campine Belge. De plus, la presence d'un reservoir géothermique aux profondeurs supérieures à 2,500 m a été reconnu pour la première fois en Belgique, ouvrant des opportunités pour de nouveaux développements, ailleurs.

En el otoño del 2015 se perforó el primer pozo geotérmico profundo en el municipio de Mol, Bélgica. El objetivo principal fue explorar las características del yacimiento geotérmico y la profundidad exacta del Grupo Carbonífero Calcáreo. Se perforó un segundo pozo en la primavera del 2016, que fue basado en los resultados del pozo de exploración MOL-GT-01, creando un doblete geotérmico de un pozo vertical (3.610 m a lo largo del agujero) y un pozo desviado (4.341 m a lo largo del agujero). Ambos pozos proporcionan nuevas perspectivas estratigráficas y estructurales de la historia geológica de la Cuenca de Campine. Además la presencia de un embalse geotérmico a profundidades inferiores a 2.500 m ha sido demostrada por primera vez en Bélgica, abriendo así oportunidades para nuevos desarrollos en otros lugares.

Deep geothermal in Belgium

In Belgium four stratigraphic units exist that have been identified as potential geothermal reservoirs. These are, from youngest to oldest, the Chalk Group of Late Cretaceous age, the Buntsandstein Formation of Triassic age, the Neeroeteren Formation of Late Carboniferous age and the Carboniferous Limestone Group of Early Carboniferous age. Berckmans and Vandenberghe (1998) estimated the extractable thermal energy content of the four stratigraphic units at 11 EJ (***Table 1***). This estimate was based on a techno-economic maximal depth of 2,500 m.

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Today, geothermal wells targeting reservoirs at depths of 3,500 to 4,500 m are no longer exceptional (EGEC, 2014). In the context of the INTERREG-project GEOHEAT-APP, the extractable heat content of the four stratigraphic units has been recalculated (GEOHEAT-APP, 2014). The lower boundary was defined by a techno-economic evaluation that takes into account the expected thermal output of a geothermal doublet, the investment costs and the operational costs to extract the heat. This approach puts the techno-economic maximal depth for wells targeting the Carboniferous Limestone Group in the Campine region at 4,000 m. As for the estimate made by Berckmans and Vandenberghe, a minimal temperature of 25 °C and a recovery factor of 33% were used. Due to its deepest stratigraphic position and wide occurrence, the Carboniferous Limestone Group has the highest geothermal potential, with an estimated extractable heat content of 13 x 10^{18}J (***Table 1***). The higher estimates for the Carboniferous units is mainly due to the fact that the potential at depths below 2,500 m is also included.The geothermal potential of the Lower Carboniferous lime- and dolostones in Belgium was first described by Grosjean in 1954 based on the results of a coal exploration well in Turnhout. This well (17E225 in ***Figure 1***) showed an increased geothermal gradient (up to 50 °C/km) in the Upper Carboniferous shales overlying the limestones, and airlift tests revealed reservoir properties in the top of the limestones with permeabilities up to 1.5 Darcy at depths below 2,000 m. Wells in the vicinity of Loenhout (07E178 in ***Figure 1***) revealed even higher permeabilities (up to

Table 1: Recoverable thermal energy in selected geothermal reservoirs in Campine region assuming a return temperature of 25 °C and a recovery factor of 33%.

Geothermal aquifer	Recoverable heat (GJ)		Area (km²)
	Berckmans & Vandenberghe (1998)	GEOHEAT App (2014)	
Cretaceous chalks	1.77×10^9	0.46×10^9	2,185
Triassic sandstones	5.08×10^9	1.18×10^9	695
Neeroeteren sandstone	0.12×10^9	4.42×10^9	654
Lower Carboniferous limestone	4.45×10^9	13.02×10^9	3,120
Total	11.42×10^9	19.07×10^9	-

3.5 Darcy), however at shallower depths.

This led in the early eighties to exploration projects in Meer (07E225IIb in ***Figure 1***) and Merksplas (17W265 in ***Figure 1***). These were abandoned for various reasons before a doublet was installed (Vandenberghe, 1984; Vandenberghe *et al.*, 1988, 2000). Since then no new exploration initiatives have been taken. Up to this point the limestones were drilled to a maximum depth of 2,700 m. Measured formation water temperatures in a loss zone between 2,185 and 2,225 m were up to 103 °C (Grosjean, 1954).

Geological setting

Whereas the Lower Carboniferous geothermal reservoir is also present in the southern part of Belgium, all other potential geothermal reservoirs are only present in the northeastern part of the country, geologically known as the Campine Basin. The Campine Basin is part of the extensive Carboniferous basin of north-western Europe and its northern border is formed by the Krefeld high and IJmuiden ridge. Eastward the basin extends into Dutch Limburg, where the NE-SW striking Variscan Anticlinaal fault/Oranje fault system (***Figure 1***) forms the boundary with the German Carboniferous Wurm Basin. To the west and south, the basin is bounded by the subcropping early Palaeozoic rocks of the Caledonian London-Brabant Massif.

Predominantly clastic Devonian sediments unconformably overlie the Caledonian basement. The Devonian strata are covered by Early Carboniferous dolostones and limestones. In a large part of the basin, these carbonates are karstified and fractured. The transition from the Lower to the Upper Carboniferous is marked by a shift from a carbonate to a siliciclastic setting that is characteristic of the Late Carboniferous paralic coal basin of north-western Europe.

The area is transected by a predominant set of (N)NW - (S)SE striking normal faults, which locally display a shear component (***Figure 1***). Most of these faults already existed during the Early Carboniferous. Most faults were reactivated during the Jurassic, and some, e.g., the Feldbiss Fault and the Heerlerheide Fault, are still active today. A tectonic inversion of these reactivated faults during the Late Cretaceous and Early Cenozoic was followed by the subsidence of the Roer Valley Graben in the late Oligocene (Langenaeker, 2000). Locally, the (N)NW - (S)SE striking faults intersect with subordinate N-S to NE-SW striking thrust faults that are relicts of the compressional regime related to the Variscan uplift of the basin. The resulting pattern is one of a series of elongated, NW-SE striking fault blocks that are generally tilted towards the north/northeast. The tilting was caused by the uplift of the London-Brabant Massif during the Cimmerian orogenic phases (Langenaeker, 2000). This causes the Carboniferous subcrop to deepen quickly towards the north and northeast, and resulted in the preservation of the most complete Silesian sequence in northeast Limburg.

Results of the first deep wells

In 2010, the Flemish Institute for Technological Research (VITO) initiated a new two-dimensional seismic campaign covering the area between the cities of Turnhout, Herentals and Mol (see ***Figure 1***). Although the seismic data could be tied to well 30W371, which reaches the top of the Lower Carboniferous Limestone Group at a depth of 1,481 m below surface in Poederlee (***Figure 1***), uncertainties about the top reservoir interpretation were significant in the order of several hundreds of metres. This uncertainty resulted mainly from the correlation of the top-limestone seismic reflector over the faults downthrowing the limestones to the east between Poederlee and Mol-Donk. The seismic data pointed towards the presence of the Carboniferous Limestone Group at depths between 2,800 and 3,800 m at Mol-Donk.

A prospect was defined that could make use of potential reservoir improvement near a fault that affected the lower part of the Chalk Group and the older strata. A drilling location to drill a vertical exploration well towards the fault zone and the possibly fractured limestones and dolostones could be found on the Balmatt brownfield site that VITO acquired in Mol-Donk. Proving the potential of geothermal energy at this location and converting the brownfield into a greenfield with a geothermal power and heating plant would meet the sustainability goals of VITO.

On 14 September 2015 exploration well MOL-GT-01 was spudded. The start of the drilling activities was attended by over 300

Figure 1: Palaeozoic subcrop map of the Campine Basin (compiled after Langenaeker, 2000; Patijn & Kimpe, 1961). The map shows the location of the Balmatt site at Mol-Donk, offset wells used to define the Balmatt geothermal project and the geometry of the 2D seismic campaign of 2010.

people, including several local and regional politicians, symbolic of strong public awareness. This well was financed by VITO and Flanders Innovation & Entrepreneurship (Agentschap Innoveren & Ondernemen). Additionally, NIRAS/ONDRAF co-funded the first section up to the base of the Cenozoic for their research in the field of nuclear waste storage.

The well architecture was designed with an anticipated top of the Lower Carboniferous Limestone Group at 2,800 m vertical depth. It was foreseen to drill the reservoir with an 8½" (216 mm) drill bit and to complete the reservoir section with an 7" (178 mm) partially slotted liner. However, the reservoir was encountered some 370 m deeper than anticipated. This led to drilling technical issues which resulted in loss of the lower 400 m of the 12¼" (311 mm) section. In order to be able to continue drilling, the upper part of the section was stabilised by running a 95/8" (244 mm) liner. Subsequently, a side-track, MOL-GT-01-S1, was drilled from the 95/8" (244 mm) liner

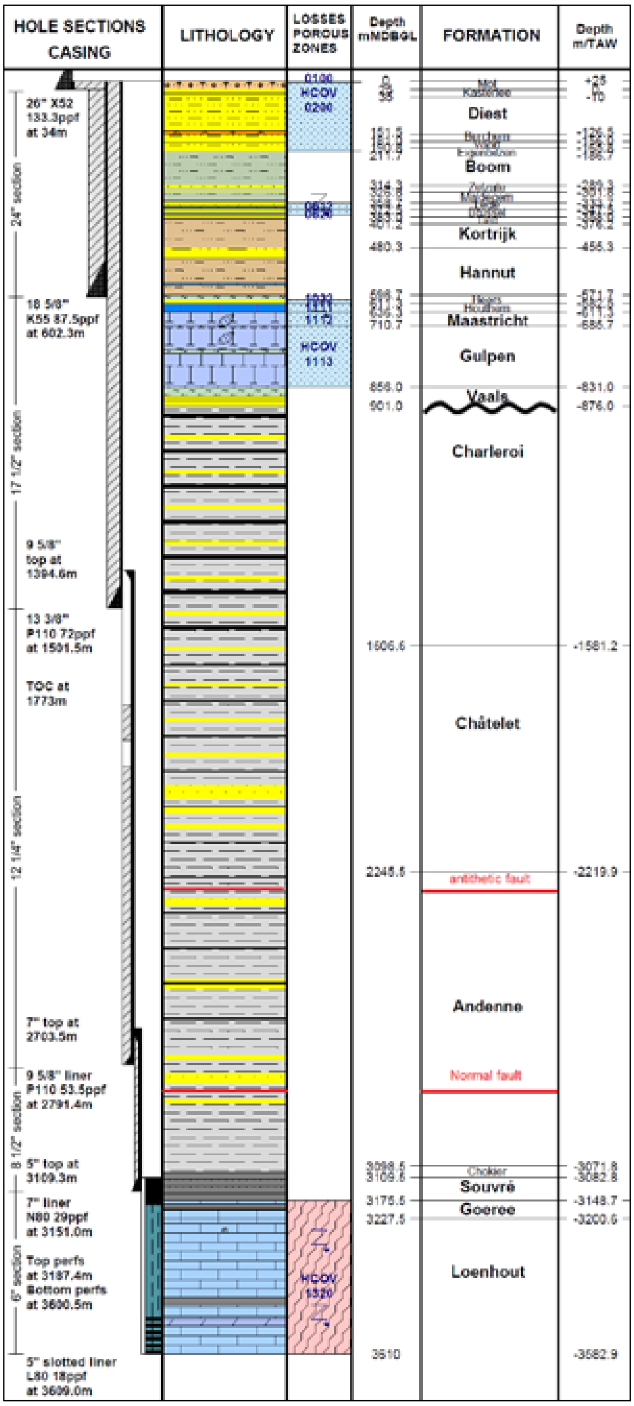

Figure 2: Geosummary of Well MOL-GT-01(-S1) with indication of well architecture on the left. Hole sections 24" (610 mm), 17½" (445 mm) and 12¼" (311 mm) and their casings are part of the original hole; the lowest two sections are part of the side-track. All aquifers are indicated with their respective HCOV-code (Hydrologische Codering Vlaanderen). Lithologies are based on cutting descriptions. TAW (Tweede Algemene Waterpassing) = regional reference level for Belgium.

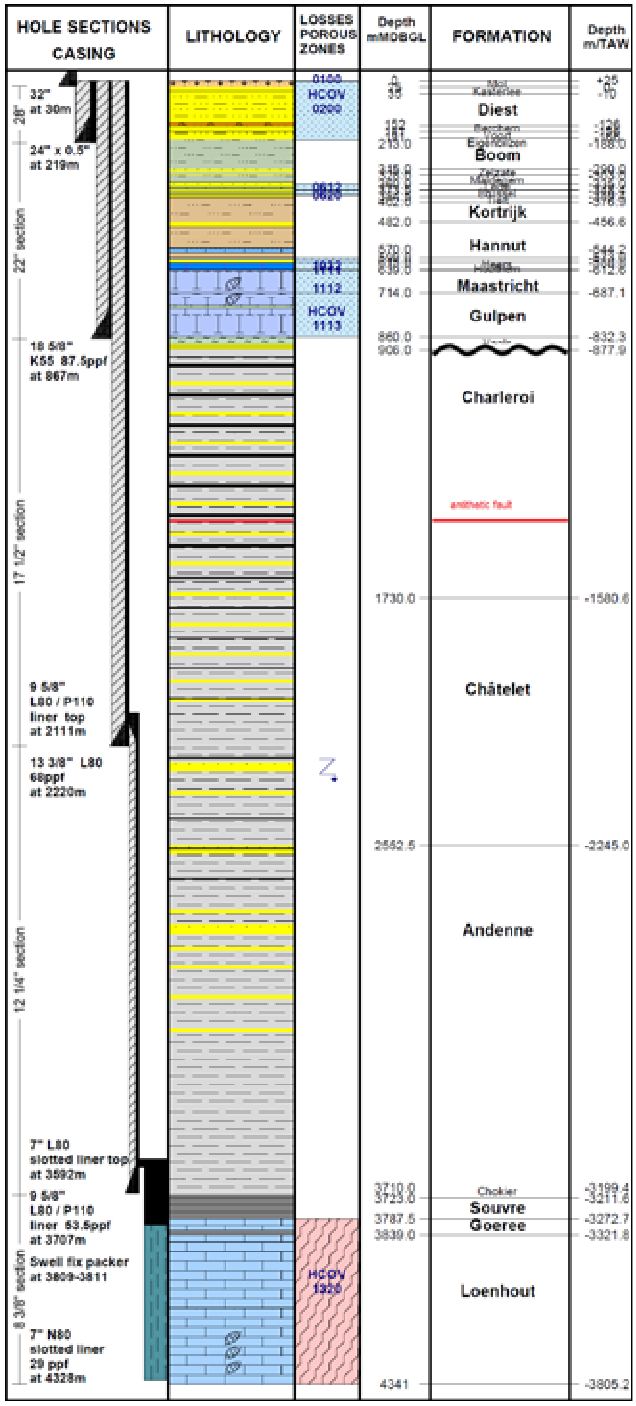

Figure 3: Geosummary of Well MOL-GT-02 with indication of well architecture on the left.

Table 2: Concentration of major and minor cations and anions measured in 2 downhole samples taken at 3,280 and 3,400 m in well MOL-GT-01-S1.

Parameter	Unit	MOL-GT01-3400m	MOL-GT01-3280m
Na^{+}	mg/l	49,800	49,600
K^{+}	mg/l	2,770	2,870
Ca^{2+}	mg/l	9,160	9,130
Mg^{2+}	mg/l	557	560
Sr^{2+}	mg/l	396	400
Ba^{2+}	mg/l	16.8	16.5
Fe^{2+}	mg/l	809	806
Mn^{2+}	mg/l	13.6	13.6
NH^{4+}	mg/l	267	264
Cl^{-}	mg/l	98,100	100,200
HCO_3^{-}	mg/l	1,117	1,129
SO_4^{2-}	mg/l	323	380
Br	mg/l	153	134
F^{-}	mg/l	< 0.88	< 0.88
pH		5.47	5.44
EC	mV	184.8	182.7

with an intermediate 8½" (216 mm) section that reached the top of the Carboniferous Limestone Group at a depth of 3,175 m. The limestones were drilled with a 6" (152 mm) bit down to 3,610 m and completed with a 5" (127 mm) slotted liner. Final well architecture of the well is given in ***Figure 2***.

Well MOL-GT-01-S1 was completed by 19 January 2016 and subsequently tested for its production capacity. While drilling the 6" (152 mm) section total mud losses were encountered, therefore indicating the presence of transmissivity at least in the immediate vicinity of the well. The production test confirmed the productivity with a calculated productivity index PI of 4 - 5m³/h/bar and production temperatures up to 128 °C.

The formation water is a Na(Ca)Cl brine with up to 165 g/l total dissolved solids. Sodium and chlorine sign for 90% of the dissolved ions. Besides, the water contains minor amounts of Ca^{2+}, Mg^{2+}, K^{+}, and $SO4^{2-}$. Downhole water samples reveal a pH of 5.4 for the formation fluid. The fluid is slightly reducing (redox potential SHE; 141–152 mV at 20 °C) and contains 800 mg/l dissolved iron (***Table 2***).

The gas content is about 2.5 Nm³ of gas per m³ of formation water. The main component is CO_2 (75–80% by volume). Besides, minor amounts of methane (8–11%), nitrogen (2–4%) and hydrogen (~11%) are present.

Based on the test results, VITO decided to drill a second well in the same location in order to be able to test a full geothermal doublet. Well MOL-GT-02 was spudded on 2 March 2016 and was drilled with an increasing angle up to an inclination of 40° in order to reach a distance from MOL-GT-01-S1 of at least 1,500 m at the top of the Carboniferous Limestone Group. MOL-GT-02 was deviated towards the NE, parallel to the seismic line MH10-04 and targeting a zone at the top of the reservoir in a more pristine area, not influenced by faults. The target for the second well was chosen in order to minimise the risk of fault activation when injecting large amounts of water and to investigate the reservoir characteristics of the limestones at larger distance from faults. The well was drilled without major drilling technical issues and along the planned well design (***Figure 3***). Again, the top of the Lower Carboniferous Limestones was found some 200 m deeper (at 3,300 m true vertical depth(TVD)) than predicted. The throw along the previously mentioned normal fault proved to be larger than anticipated.

MOL-GT-02 reached its final depth on 23 July 2016 at a depth of 4,341 m along hole. This corresponds to 3,830 m TVD. The well drilled through 530 m (true vertical) of limestones and dolostones and was completed with a 7" (178 mm) slotted liner (***Figure 3***). The well was tested for its injection capacity in September 2016, resulting in an injectivity index II of 1.5- 2 m³/h/bar. These values indicate rather poor reservoir conditions, which could be explained by the absence of a fault in the vicinity of this well.

Structural insights

The final structural interpretation is shown on the cross section in ***Figure 4***. The targeted normal fault was identified based on drilling parameters and fault mineralisations in the cuttings in both MOL-GT-01 as well as in MOL-GT-01-S1, resulting in an apparent dip of the fault plane towards the northeast. Both in MOL-GT-01 and in MOL-GT-02, a westerly dipping (antithetic) fault could be identified based on detailed correlations of the Upper Carboniferous sequences between both wells. All wells intersect the faults above the Lower Carboniferous reservoir level, however in MOL-GT-01-S1 the distance from the fault intersection to the top of the reservoir is only 300 m. From a calculated fault dip of 60°, the lateral distance to the fault at the top of the reservoir is some 175 m. Additionally, image logging (FMI, Schlumberger) performed over the reservoir in MOL-GT-01-S1 shows that several persistent fractures are present with a general NNW-SSE orientation, parallel to the assumed fault orientation. Accordingly, the presence of the fault near MOL-GT-01-S1 most probably

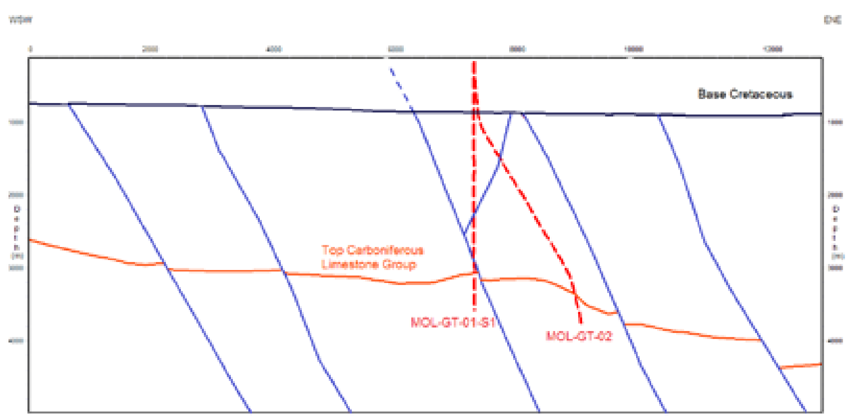

Figure 4: WSW-ENE depth section along strike of Well MOL-GT-02 with indication of the base Cretaceous (black) and top Carboniferous Limestone Group (orange) as well as the fault locations (blue) tied to both wells. Total length of the cross section is 13,000 m.

has improved the reservoir characteristics in this well; this conclusion is supported by the test results in MOL-GT-02, for which the distance to the nearest fault is roughly 1 km.

Future potential in the Campine Basin

The regional, cross-border potential of the Carboniferous Limestone Group was indicated in the GEOHEAT-APP report in 2014. However, for areas where the Lower Carboniferous strata are present at depths below 2,500 m, the risk of encountering poor or no reservoir conditions was still significant at the time of publication of the report. With the results of the first deep drillings at Mol-Donk, this risk has now been strongly reduced. The high potential zone suggested by the GEOHEAT-APP project can now be further explored and, if succesful, valorised.

The exploration drillings at the Balmatt site yield critical input for the business case of deep geothermal energy projects in the area. The results of the pumping tests indicate that the reservoir performance is sufficient to warrant further investment in a geothermal production unit at the Balmatt site, which is expected to provide heat for at least 20 years. Moreover, the production temperature is high enough to allow electricity production using binary technology. In order to explore the economics of low-temperature power generation in the Campine area, a prototype of a new, flexible binary unit will be installed at the Balmatt geothermal site.

The expertise and knowledge that have been gathered enable the drilling of additional wells to provide sustainable heat to neighbouring businesses and residential sites in an area covering the north-east of the Antwerp province and the northern half of the Limburg province. Depending on the effectiveness of further technological developments and the degree of implementation, between 10% and 25% of the Flemish energy (mainly heat) needs could be covered by local production (Laenen *et al.*, 2015).

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The successful geothermal risk mitigation system in France from 1980 to 2015

*Christian Boissavy**

The late 1970s saw the use of geothermal resources located 2,000 metres under the Ile de France region. These low temperature geothermal resources were regulated from 1978 by a decree allowing their use, as in France the ground below the surface belongs to the State. To encourage this expansion, a Short Term Fund was set up prior to 1981 to cover the geological risks linked to the performance of deep drilling. In 1982, a Long Term Fund took place managed by the SAF Environment subsidiary of the Caisse des Dépôts et Consignations, to cover the operating life of the geothermal installations for 15 years. These are the measures that made possible the installation of 500 MW of thermal power for a cumulative saving in 3 MTOE of fossil fuels over a 35-year period. This article is a synthesis of the study to summarize the 35 years of geothermal risk mitigation system in force from 1980 until now, executed for ADEME (The French Environmental and Energy Management Agency) in 2016.

La fin des années 1970 a vu l'essor de l'utilisation des ressources géothermiques localisées à 2000 m de profondeur, dans la région Ile de France. Depuis 1978, ces ressources géothermiques de basse température ont fait l'objet d'un décret autorisant leur utilisation puisqu'en France, le sous-sol appartient à l'Etat. Pour encourager ce développement, un Fond à court terme a été mis en place avant l'année 1981 pour couvrir les risques géologiques liés aux travaux de forage profond. En 1982, un Fond à long terme l'a remplacé, géré par la Société SAF Environnement, société auxiliaire de financement, filiale de la Caisse des Dépôts et des Consignations, pour couvrir les opérations d'installation géothermique pendant 15 ans. Ce sont ces dispositions qui ont rendu possible l'installation de centrales de puissance thermique de 500 MW avec une économie cumulée de 3 MTOE de carburant fossile, sur une période de 35 ans. Cet article représente la synthèse de l'étude résumant le volet de 35 années d'opérations destinées à la réduction du risque géothermique, volet toujours en opération aujourd'hui et réalisé pour le compte de l'ADEME (Agence française de l'Environnement et de la Maitrise de l'Energie), en 2016.

El uso de recursos geotérmicos situados a 2.000 metros bajo de la región Ile de France empezó a finales de los años 1970. Estos recursos geotérmicos a baja temperatura fueron regulados a partir de 1978 por un decreto que permite su uso, ya que en Francia el suelo por debajo de la superficie pertenece al Estado. Antes de 1981, un Fondo de Corto Plazo cubriendo los riesgos geológicos relacionados con la perforación profunda se creó para fomentar esta expansión. En 1982, un Fondo de Largo Plazo fue gestionado por la filial SAF Medio Ambiente de la Caisse des Dépôts et Consignations, para cubrir el periodo de explotación de las instalaciones geotérmicas durante 15 años. Estas medidas permitieron la instalación de 500 MW de energía térmica para un ahorro acumulado en 3 MTOE de combustibles fósiles durante un período de 35 años. Este artículo es una síntesis del estudio que resume 35 años del sistema de mitigación del riesgo geotérmico vigente desde 1980 hasta ahora, ejecutado por ADEME (La Agencia Francesa para el Medio Ambiente y la Gestión de la Energía) en 2016.

The Short Term Fund

In 1981, the need to set up a system to cover geological hazards soon came to light, when the decision was made to expand geothermal energy usage in France. It became clear that potential operators were faced with the lack of insurance products against geological risks. Initially, a system that offered both an incitement and a guarantee was set up directly under the authority of the Ministry of Industry. Projects were assessed by DRIRE (the Regional Research and Industry Departments). The mechanism put into place comprised a subsidy worth 30% of the cost of the first well, completed by a loan of 70% of this cost. The extra geological costs born of a random and unpredictable event during the works could also be covered.

In 1982, when the French Agency for Energy Management was founded, the level of subsidy was lowered to 20% of the cost of drilling. A new guarantee system needed to be implemented to replace the one-off coverage mechanism, using a statistical mechanism based on shared risks.

This Fund was fully operational until 1986. Finally, after 1986 – the year of the reverse oil crisis – no new operation that was able to qualify for the guarantee procedure was set in motion. The next drilling project only re-started in 2007, some twenty years later, as shown in ***Figure 1***.

Given the technical difficulties encountered with the operations that used the Dogger aquifer in the Paris Region, the Fund was also used for other purposes, especially to finance high-priority research programs. These actions amounted to €3.4 million over the six years from 1986 to 1992. This very significant support allowed

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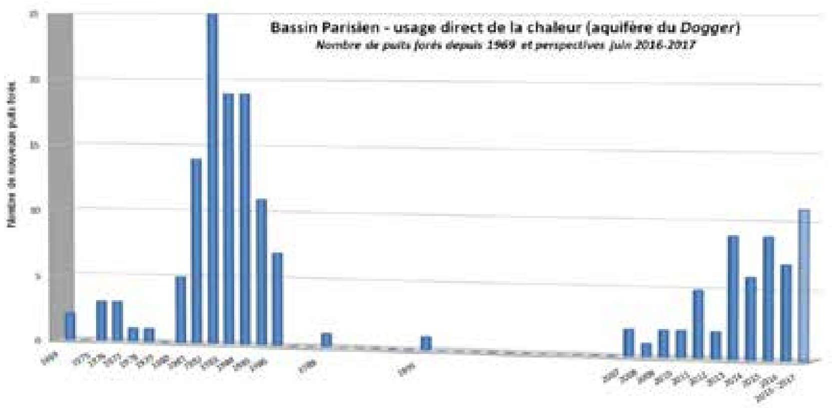

Figure 1: Number of geothermal wells drilled in Ile de France from 1969 to 2017.

undertakings in both in-depth studies into the corrosion-deposit problems encountered and in how to repair damaged wells. This help was spent addressing cross-functional research able to benefit the entire sector, in the following areas: sludge-free rehabilitation, corrosion, scaling inhibitors, audits, bacteria killers, inflatable packers, calibration loggings, tests into new kinds of downhole well treatments, studies into interference between wells in the Dogger aquifer, drawdown measurements for drillings, etc. Direct support was also addressed to implement specific measures, abandoning non-viable operations, dedicated to specific studies or for on-site experimentation.

In 1996, the ADEME "owners" of the Short Term Fund finally decided to definitively suspend its operations. It was effectively wound down in April 1999 and the leftover balance of about €1.5 million was transferred to ADEME's budget.

Short Term Fund principles and results

The principle of the Short Term Fund was based on compensating project owners if the results of the first drilling did not allow the planned operation to operate under economically satisfactory conditions. The concept of success or failure is determined from the flow rate/temperature combination shown in ***Figure 2***. This graph, which shows the temperature as a function of flow rate, illustrates success areas along with total and partial failure areas. The borderlines between the areas are determined by curves showing stable profitability using the internal rate of return as the relevant indicator. Profitability is calculated over a 20-year period, using current economic assumptions. The difference between the success and failure curves is calculated in such a way that the compensation paid makes it possible to restore the profitability ratio of the success curve.

The Short Term Fund was independent from the Long Term Fund, but any project owner who took out Short Term cover was required to join the Long Term Fund. The initial fund amount of €2.6 million allowed guaranteeing some 24 operations on the basis of a failure rate of 25%. The cost of the project owner's contribution was set at 1.5% of the maximum guaranteed amount. In case of failure, compensation was set at 20% (the subsidy amount) of the guaranteed amount at the very least and 90% at the most (after deducting the subsidy). The concept of a geological incident was characterised by the fact that it must be random, unpredictable and not result from any failure to comply with state of the art practices.

Figure 2: Success/failure curves to manage the Short Term Fund projects.

Figure 3: Contrast between the results from the operations in the Paris Basin (78%) and those undertaken in the other sedimentary basins (62%).

Table 1: Balance of the Short Term Fund (1980-1999).

Amount paid by the government	*2,630,000*
Fees paid by the operators	*3,350,000*
Financial products generated by cash in bank	*2,700,000*
Total resources of the fund, in €	*8,680,000*
Research and technological programmes	*3,450,000*
Sums repaid to the operators	*3,000,000*
Personnel and management of the fund	*830,000*
Total expenses of the fund, in €	*7,280,000*
Final balance of the fund, in €	*+1,400,000*

Figure 3 shows the contrast between the results from the operations in the Paris Basin (78%) and those undertaken in the other sedimentary basins (62%).

The Short Term Fund was able to cover 15 claims during the period 1982–1990, amounting to a total compensation amount of about €3 million. There were 12 operations which failed totally, at Bourg en Bresse, Valence, Avignon, Reims, Epernay, Clermont Ferrand, Provins, Condé sur Escaut, Ile de Ré, Plaisir and Meudon, and 3 partial failures took place at Jonzac, Fontainebleau and Fresnes.

The financial results as closed on 30 April 1999 (a new fund based on the same structure restarted only in 2007 for new projects) show that over the entire life of the Short Term Fund, this represented an amount of about €3.5 million to finance 56 different projects. ***Table 1*** indicates the balance of the Fund.

The Long Term Fund and its results

As geothermal projects are mainly loan financed, lenders wished to see guarantees set up to cover any geological incidents that could arise during operations. This is the reason why a mechanism able to cover these kinds of risks was set up. This mechanism was covered by an agreement between the Ministry of Industry and SAF-Environment in April 1981 setting out the terms of its formation and its operation. This mechanism was based on the existence of a balancing mutual fund called the Long Term Fund, backed up by an additional insurance policy taken out with a pool of insurers.

The Fund was initially provided with €1 million by the state. To this amount were later added a number of instalments of top-up funding from the state, payments by beneficiaries (3% of the cost of the installations guaranteed) and financial income from investing available cash. Initially the guarantee duration ran for fifteen years, but changes were made from 1999. This is because most of the geothermal projects that were undertaken between 1980 and 1987, for the most part on behalf of local authorities, were financed with loans taken out at high interest rates, given the high rates of inflation that were prevalent at the time, and before inflation started to fall significantly, hence the progressive rise in real interest rates on these loans.

In parallel, operating income, which was indexed to the cost of fossil fuels, started to fall sharply after 1987 in the wake of crashing oil prices. Faced with these economic and financial difficulties, starting in 1990 geothermal installation project owners, with the support of the authorities, initiated a policy of renegotiating their initial debts. This resulted especially in a substantial lengthening of the term for paying down the debt. On average, this period went from 15 to 25 or even 30 years for some operations.

The guarantees covered the wells, the materials and the equipment used in the geothermal loop, as long as the claim was made before the normal end of life of the equipment, the flow rate and temperature of the geothermal fluid. The other causes for a claim, e.g. a lack of maintenance, electrical failures, manufacturing or assembly faults, poor operating optimisation, sabotage and fire were excluded. Decisions on whether to approve new operations or whether or not to pay out on claims were left solely to the Technical Committee.

The guaranties covered three kinds of claims:

- Where the incident is not repairable (i.e. if the loss of power is definitive) then there were two possible cases:

1. The loss of installation heating power does not fall below the 50% threshold, but it does however significantly lower the level of operating income (triggering a partial claim). In this case, the compensation level is calculated on the basis of a factor that takes into account both the age of the installation and the loss of installation power in relation to the reference value taken out when the contract was signed. This compensation is paid out annually.
2. An irreversible loss of geothermal resource power such that it no longer allows the installations to be operated (a total loss claim). In this case compensation to the project owner is paid in one lump sum and it equals a fraction of the Fund intervention limit calculated proportionally to installation write-off aspects.

- Where the incident is repairable (or where the installation power loss is temporary and can be recovered): in this case, the guarantee takes on the cost of repairing the damage, so long as it results from a geological or geothermal cause, as well as paying out compensation for interrupting operation.

Table 2: Balance of the Long Term Fund (19 May 2016).

Amount paid by the government	*8,500,000*
Fees paid by the operators	*9,790,000*
Fees paid for the guarantee extension of 10 years	*3,000,000*
Financial products generated by cash in bank	*3,320,000*
Total resources of the fund, in €	*24,610,000*
Sums repaid to the operators	*19,500,000*
Personnel and management of the fund	*4,600,000*
Total expenses of the fund, in €	*24,100,000*
Final balance of the fund, in €	*+510,000*

For every claim that gave rise to compensation, the Fund's coverage was limited to €520,000 before deducting a deductible of €68,000. Between €520,000 and €3.4 million, 15-year cover provided by a first group of insurers came to bear. Over €3.4 million and up to the value of the guaranteed total, a second group of insurers provided risk cover for a five-year period. The guarantee provided by each group of insurers was covered by an insurance policy taken out by SAF as the business manager and by the Project Owner.

Nevertheless, this lengthening period of financial write downs for geothermal installations raised the issue of the matching extension in the guaranties. This is how a ten-year extension was decided on, after the initial 15-year cover period.

Starting in 2000, new fund governance was initiated with the formation of a Technical Committee presided by ADEME, where DRIRE and Project Owners especially were represented. The insurers for their part withdrew from the mechanism, with the system becoming wholly reliant on the fund.

An additional €3.8 million was given to the Fund by ADEME in three successive instalments paid in 1999, 2000 and 2001, with the project owners paying fees worth a total amount equivalent to the fresh cash put up by ADEME. The operations in the other part of the territory (mainly Aquitaine) did not subscribe to this ten-year extension, so they exited the guarantee mechanism.

Many operations were also shut down after a few years in service. This was due to technical reasons linked to corrosion-deposit phenomena that had not been anticipated at the outset, but also for economic reasons, as the business plans drawn up had been upset by the oil crises. Cities preferred to abandon geothermal use during a period when the performance of dual well drillings was negative due to the physical and chemical nature of the geothermal water, as well as the poor durability of the submerged pumping equipment transposed directly from the oil industry and not sized or designed for continuous operation at very high flow rates.

The Long Term Fund was closed down at the end of 2015. The Fund balance as of 19 May 2016 is detailed in ***Table 2*** for a total operating duration of 35 years. It is worth remarking the quasi-parity between public funding and payments made by the beneficiaries as well as the major contribution provided by the financial income generated.

During this 35-year period, 72 projects were processed by SAF-Environment, but this does not necessarily mean that a contract was signed: 123 issues were declared at 42 different operations. There have only been three cases where litigation could not be avoided, in the operations at Bondy, La Celle Saint Cloud and Porte de Saint Cloud (CCPCU). All of these cases were won by SAF-Environment.

SAF-Environment: the Fund manager

SAF-Environment was founded specifically by the authorities in 1980 with the assignment of setting up and then managing the guarantee system. An administrative, accounting and financial management agreement was put in place in October 1982 between AFME and SAF, when the guarantee fund was transferred from the Ministry of Industry to AFME. This agreement is renewable every three years. SAF is a Caisse des Dépôts et Consignations subsidiary that also has a number of public and private sector financial establishments among its shareholders, all directly involved in expanding the use of geothermal energy (see ***Figure 4***).

SAF-Environment is assisted by a Technical Committee comprising:

- the management committee represented by the Chairman of SAF-Environment and its Managing Director,
- an ADEME representative – acting on

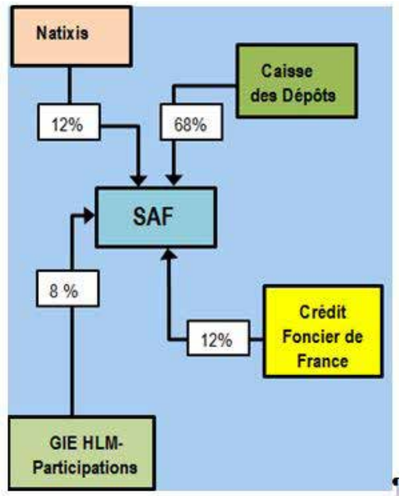

Figure 4: Organization of SAF-Environment.

behalf of the State –with veto power over the decisions reached by the Technical Committee,

- a representative of BRGM (French geological survey),
- a representative of the insurers acting in excess of the Fund ceiling,
- one or more qualified parties co-opted by the Technical Committee.

Technical Committee sessions may also be attended by technical experts drafted in by the Committee or by representatives of the beneficiary project owners designated by their organisations, within the framework of the Committee's extraordinary sessions. Decisions to approve new operations or to pay out compensation for claims are exclusively up to this Committee, an independent body instituted by the Fund's statutes.

Final results of the two funds

As an estimate, the cumulative production of the operations covered by the Fund was 34,360,000 MWh, which represents approximately 3 million geothermal TOE and over 6 million tons of CO2 emissions avoided during the period. The SAF Environment Short and Long Term Funds allowed 102 wells to be drilled over a 34-year period.

For the Short Term Fund, there were few failures and they tended to be located outside the Paris Basin, where the knowledge of the deep level ground was the least accurate. Of the 116 geothermal wells bored in France during the period, 102 benefitted in one way or another from the support of one or both of these Funds. This represents 81% of the geothermal wells drilled in France, as some geothermal wells had already been drilled before the Fund was set up.

For the Short Term Fund, €200 million investment spending was guaranteed during the drilling phase, with only €5 million financed by the authorities.

For the Long Term Fund, 42 operations saw their operating period insured against damage linked to the geology and the hydrogeology of the fields used. These were mainly geothermal operations in the Dogger aquifer. During the life of the Fund, some project owners even prolonged the coverage period for their operations by taking out cover for an additional ten years, extending the length of their guarantee to 25 years.

Over the Long Term Fund, investment worth €260 million was guaranteed, including not only the cost of the drilling works but also of the geothermal loops for 63 operations nationwide. The payments made by the State came to €8 million, meaning that for every €1 put up by the State, €33 of investments were covered for a period of 25 years.

Lastly, regarding the new dual wells bored in these last few years at the same locations as former dual wells that had been closed and abandoned, without exception, the public and private sector project owners took out new Short and Long Term Fund coverage contracts, although the geological risk could be considered as low or even nil after the dozens of wells that had been drilled in the same Dogger deep level aquifer. The owners did so either on their own initiative or at the behest of the financiers called on to finance the new investments.

It is therefore obvious that expanding the use of geothermal energy by deep level drilling can only be significant if the initial geological risk faced by the project owner for most of the capital expenditure is insured.

By extension, at the European level, we observe that all of the private sector insurance packages attempted in Europe (Germany) and around the world have failed. These mechanisms generally allowed the geological risks for one or two operations to be covered before winding down due to the cost of the premiums, which sometimes represented as much as 25–30% of the cost of the drilling. Another factor was insurers withdrawing after achieving a success to failure ratio that was too low to produce any profitable business. Such mechanisms have been established in a developing market, not yet mature, where not enough projects were developed to ensure mutualisation of the risk.

Successful experiments regarding this kind of fund for operations intended to produce heat do exist in Europe. The government of the Netherlands set up a mechanism very similar to the SAF Environment Funds, one that has allowed 30 geothermal wells to be drilled in that country in the past ten years.

With the notable exception of a few European market participants operating in well-developed geothermal regions, project developers have very little capability to manage the financial risk owing to the poor knowledge of the deep subsurface, lack of technological progress and high cost. In effect the probability of success/failure weighted net present values of project cash flows tend to be overly negative, thus effectively shutting out private capital from investing in geothermal energy.

However, with technology development (increasing the probability of success of finding and developing geothermal reserves) coupled with experience and thus reductions in cost, project developers will eventually be able to accept and –where appropriate – transfer project risks (technical, economical, commercial, organisational and political) so that private funding will become available. Until then, a Geothermal Public Risk Insurance Fund (GRIF) is seen as an appealing public support measure for supporting geothermal development.

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Potential of geothermal systems in Picardy

*Estelle Dourlat**

Geothermal systems are not only about electrical plants or urban heating networks, but also concerned with geothermal energy assisted with a heat pump. In the former region of Picardy (North of France), 97% of the territory is suitable for very low temperature geothermal power. The French Agency for the Environment and Energy Management and the Picardy Region decided in 2016 to finance a facilitator to encourage geothermal use. To carry out this aim, it is important to consider the geothermal context in Picardy, its regulation and the potential, but also the local tools available, such as an inventory of geothermal installations or training sessions for architects. The objective is to help increase the number of geothermal projects in Picardy.

La géothermie ne concerne pas seulement les centrales électriques et les réseaux de chaleur urbains, mais également la géothermie assistée par pompe à chaleur. Dans l'ancienne région Picardie (dans le nord de la France), 97% du territoire est favorable à la géothermie très basse température. L'ADEME (Agence de l'Environnement et de la Maîtrise de l'Energie) et la Région Picardie ont décidé de financer une mission d'animation en géothermie il y a un an. L'animateur connaît le contexte géothermique en Picardie, avec la réglementation et le potentiel, mais également les outils locaux comme le recensement des installations de géothermie ou la formation pour les architectes. La mission consiste ensuite à aider à l'augmentation du nombre de projets de géothermie en Picardie.

Los sistemas geotérmicos no sólo se refieren a plantas eléctricas o redes de calefacción urbana, sino también a la energía geotérmica asistida por una bomba de calor. En la antigua región de Picardía (Norte de Francia), el 97% del territorio es apropriado para la energía geotérmica a muy baja temperatura. La Agencia Francesa para el Medio Ambiente y la Gestión de la Energía y la Región Picardía decidieron, en 2016, financiar un sistemapara fomentar el uso de la energía geotérmica. Para llevar a cabo este objetivo, es importante considerar el contexto geotérmico en Picardía, su regulación y el potencial, así como las herramientas locales disponibles, tal como un inventario de instalaciones geotérmicas o sesiones de formación para arquitectos. El objetivo es ayudar a aumentar el número de proyectos geotérmicos en Picardía.

When we hear about geothermal systems, we usually picture electrical plants or urban heating networks. But high near-surface underground temperatures are not available everywhere. In the North of France, the former region of Picardy (now included in the new region called Hauts-de-France, gathering together the former Picardy and former Nord-Pas-de-Calais Regions) is a perfect example. Indeed, 97% of the territory is suitable for very low temperature geothermal power. This article describes the geothermal context in Picardy, the tools available, key actions already taken and the promotion of shallow geothermal use.

Geothermal context in Picardy

Environmental objectives and geothermal potential

Following the Grenelle Environment Forum in 2007 and the law "Grenelle II" in 2010, Picardy was given some ambitious objectives: to multiply by 21 times its actual geothermal heat production by 2020 (SRCAE, 2012). In Picardy, there is no possibility to create geothermal electrical plants and there are only a few cities suitable for a geothermal urban heat network, mainly in the south of the region (Analy, 2013). Indeed, only for 23 cities do all three major factors occur: high thermal consumption (linked to the population density), high enough temperatures, and sufficient flow rate of the Dogger (a geological formation whose aquifer can reach 70 °C and 160 m^3/h in southern Picardy).

As 23 cities creating an urban heat network by 2020 is not likely, the French Agency for the Environment and Energy Management (ADEME) and the former Picardy region turned their attention to very low temperature projects to enhance geothermal heat production. For that, they lead different programmes described further in this article and also propose different possibilities of funding for the projects.

Very low geothermal energy (Maton *et al.*, 2012, volume 2) is assisted with a heat pump, as the extracted temperatures are often below 25 °C. It can work with geothermal probes (also called a closed loop) or with a water table (open loop) and finally gives about 45 °C to a building's heat. It can cover heating or cooling needs of collectives (pools, schools, etc.) and private (office) buildings. According to the Geothermal Atlas of the French Bureau of Geological and Mining Research (BRGM), there is a real potential for this kind of geothermal project, with 97% of the territory suitable for very low temperature geothermal power (Maton *et al.*, 2012, volume 1).

French Mining Code reform

The French Mining Code was reformed in 2015 (Decree n°2015-15) concerning very low geothermal heat projects called Geothermal installations of Minimal Importance (GMI). If the geothermal installations meet some criteria, the project formalities are simplified.

For geothermal probes and water table, the criteria are:

- boreholes less than 200 m deep,
- power taken from underground amounting to less than 200 kW.

Extra criteria for water table systems are:

- water temperature below 25 °C,
- flow rate less than 80 m^3/h,
- water is returned to the same aquifer it was taken from.

Of course, there may be some additional local specific constraints such as protection

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zones of drinking water wells.

The last element to take into account is the administrative constraint map, drawn up by the BRGM with methodology described in Herbaux *et al.* (2013) and located on the website Geothermie-perspectives (ADEME BRGM, 2015). This map shows three different possibilities for both geothermal loops (closed or open): a green, orange or red square. If the square is green, there are no administrative constraints and the project is only subject to registration. If the square is orange, declaration is required, but a hydrogeological expert must approve it. For a red square, an authorisation request is necessary.

Tools available and keys actions already done

Inventory

In the frame of geothermal development in Picardy, ADEME Picardy, in partnership with the Regional Council, commissioned the Geother engineering consulting firm to carry out an inventory of geothermal installations in the former region. The goal was to know precisely the number of geothermal installations in Picardy, with their technical characteristics. It also aimed to update the geothermal figures of the Energy, Air and Climate Regional Scheme (SRCAE, 2012) of Picardy and change the environmental objectives concerning geothermal systems. The inventory consisted of a quantitative part for private individual installations and both a quantitative and qualitative part for public/private installations.

Based on the inventory results (Geother, 2016), the main conclusions are:

- The geothermal sector is less developed in Aisne, an area in the east part of Picardy, than in Oise, in the south-west, and Somme, in the north-west.
- There are 11 times more water table geothermal installations than geothermal-probe installations. This could be explained by the relatively recent appearance of probe technology (the first probe installation in Picardy took place in 2008).
- 77% of the installations belong to private individuals and 23% are run by public and private project managers.
- The number of public projects is roughly equal to the number of private projects.
- Private individuals aside, cold production reaches 54 TOE (0.6 GWh)[1].
- The whole geothermal heat production in Picardy is estimated at 1238 TOE (14.4 GWh), with 77% of it coming from public/private installations.

Architect training

Another action was the creation of a professional training course for architects about possible geothermal uses in construction and renovation. This training was proposed by Afapi (a local training organism for architects) and conducted by Ecome, an engineering consulting firm.

This training allows architects to become familiar with the administrative and regulatory aspects of geothermal projects, as well as the different actors of the sector. They are also taught some technical notions, and an economic scale to projects is given, along with possible sources of funding.

Two training sessions took place in 2016, in January in Soissons (Aisne) and in April in Amiens (Somme). Other regions of France have asked for the same training (Grand-Est in June 2017, for instance).

Audit of geothermal installations in progress in Hauts-de-France

ADEME Hauts-de-France (the new region including former Picardy and former Nord-Pas-de-Calais) commissioned the Ecome engineering office to audit 19 geothermal installations of the region (10 in Picardy and 9 in Nord-Pas-de-Calais). Beyond the 19 different analyses and advice for improvement, the aim of this study is to make a crossing analysis of installations and find the main defects that can occur in very low temperature geothermal installations. There is also a project to make 6 example sheets to expand the data catalogue of geothermal installations in Picardy.

Geothermal promotion in Picardy

Facilitator functions

In 2016 the former Picardy region and ADEME financed the position of facilitator for geothermal promotion thanks to FREME – the Regional Fund for Environment and Energy Management – and Fonds Chaleur funds.

The facilitator is in charge of promoting geothermal installations in former Picardy and is based in UniLaSalle, a post-graduate engineering school in geosciences in Beauvais. The objective is to increase the number of geothermal projects in Picardy. As the potential for geothermal heating networks is not so easy to exploit, the strategy is to create a number of little projects with very low temperature geothermal installations. The role of the facilitator is to boost and structure the sector, linked to the development of renewable energies in the region, by:

- improving and promoting communication about very low geothermal systems and associated technologies,
- improving communication among the different actors,
- offering free technical advice for project managers (not including private individuals) with pre-feasibility studies.

In one year, the facilitator was requested to carry out 18 potential or pre-feasibility studies; 2 of these led to more complete feasibility studies and 8 are still on-going due to a lack of information on the project or their recent start.

Maps from the inventory

Based on the inventory of geothermal installations in Picardy, maps were created (***Figure 1***) (Dourlat, 2017), showing different things:

Geothermal installations exploited on 31 December 2015 in Picardy (public/private institutions).

Most of the geothermal projects running were carried out in Somme and Oise and there is an overwhelming majority of open loop geothermal projects. As mentioned above, this could be explained by the relatively recent appearance of probe technology. Concerning the geological context, the chalk water table, which is known to be favourable to geothermal energy, covers Somme, three quarters of Oise and the northern Aisne territories. Thus, projects were created where geothermal energy could be easily accessed. Even though Picardy is in the North of France, there is an increasing need for cooling alone or in parallel with heating. The total geothermal heat production then reaches 982 TOE/year (11.4 GWh) and the total cold production reaches 54 TOE/year (0.6 GWh). There is a difference of 3 GWh between the heat production announced from the inventory (14.4 GWh) and that calculated for this map because the inventory takes into account the installations that are not running (which could run again if restored).

1 1 TOE= 1 Ton Oil Equivalent = 11,630 kilowatt per hour (KWh) = 11.6 gigawatt per hour (GWh)

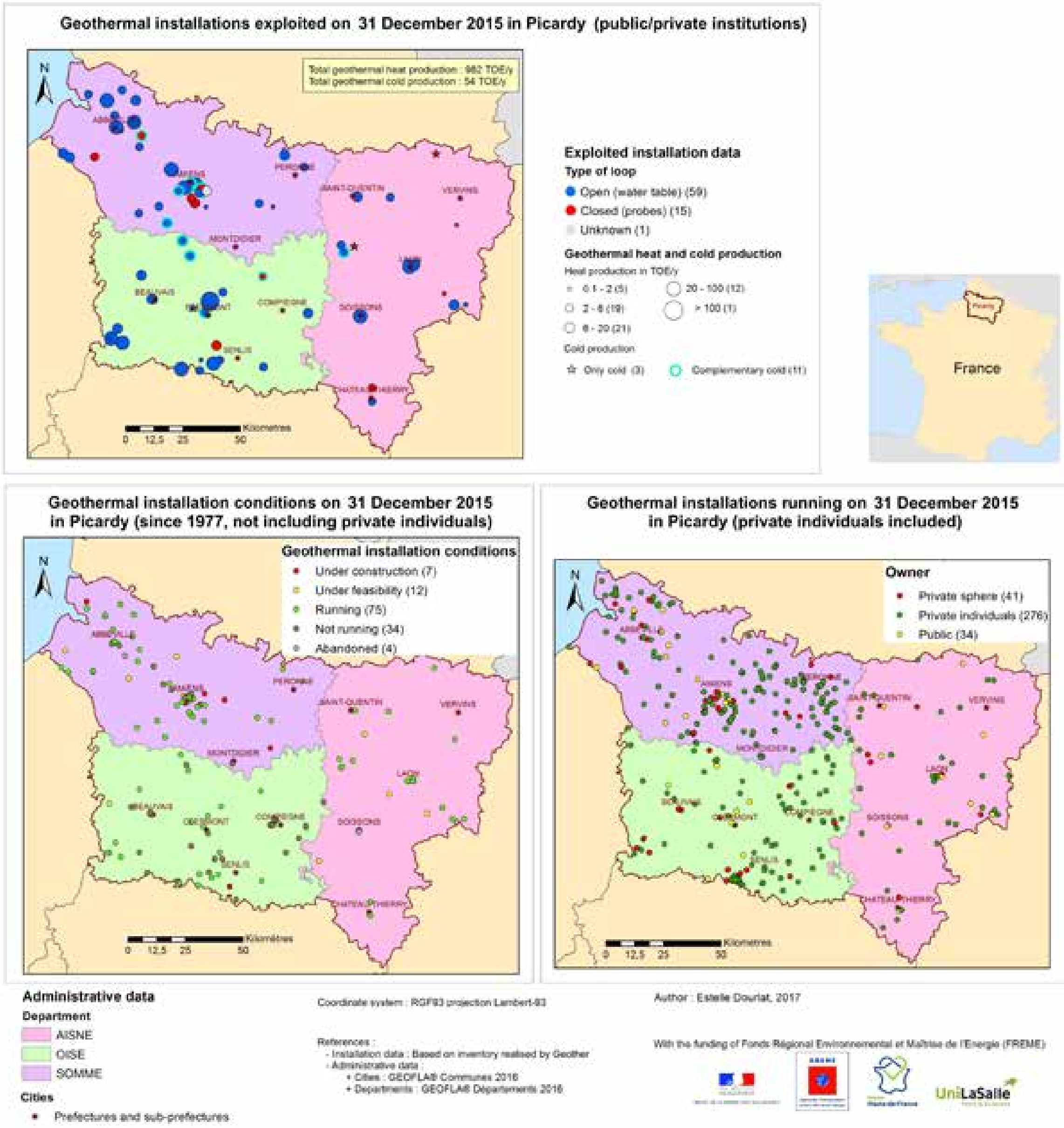

Figure 1: Three maps showing different characteristics of geothermal installations in Picardy, France.

Geothermal installation conditions on 31 December 2015 in Picardy (since 1977, not including private individuals).

This map shows that most of the geothermal installations are running or in the feasibility study stage, a reflection of the ongoing development of the technology since 1977. Still, 75 running installations 40 years after the first geothermal project in Picardy shows that the sector needs help in its development. Another point is that most of the abandoned or not running installations are located in the southern Picardy, in the department of Oise. Many of the geothermal installations in this department were constructed before the 1990s and suffered from the aftermath of the second oil price shock and from the lack of knowledge of the importance of maintenance.

Geothermal installations running on 31 December 2015 in Picardy (private individuals included).

The majority of geothermal installations belong to private individuals. The number of installations owned by public structures and the private sphere (companies) is almost the same. But these installations added together do not reach even half of the number of private individual installations. That means that both public and private sector are wary about geothermal energy, and a great deal of work is needed to increase these figures.

An update is planned once a year, since new geothermal projects should be declared online.

Construction site coverage

One project of the facilitator assignment is to create a database of photographs and videos about geothermal installations in Picardy.

For that, the first video – subtitled in English – was produced (Dourlat, 2016) at the probe field construction site of Sir John Monash Centre in Villers-Bretonneux (Somme). This geothermal project mainly aims to cool the centre and to do this, 41 probes of 185 m deep were carried out.

Entitled "Geothermal in the Service of History", the video introduces drilling images, with the explanations provided by Geoforage. The project is also put in context by a Project Manager (Australian Government, Department of Veteran Affairs) and

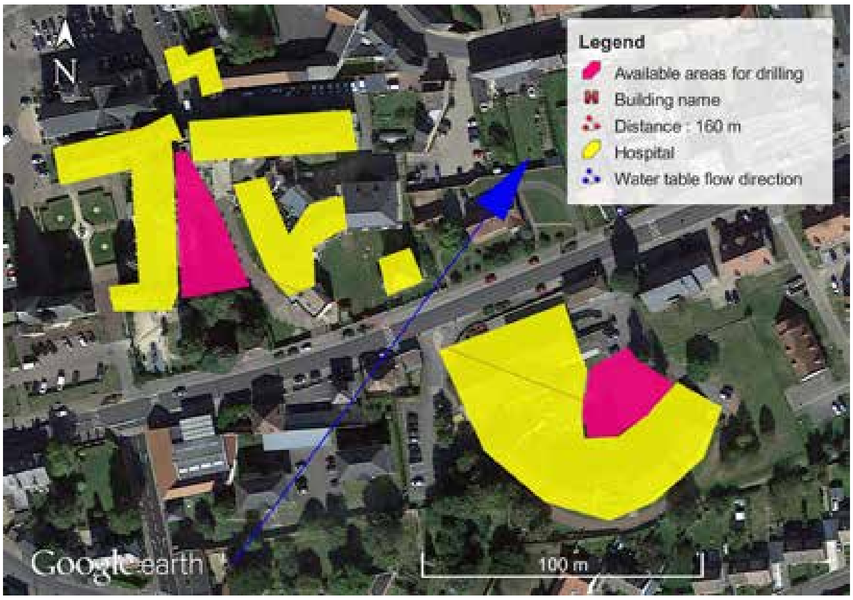

Figure 2: Land and building constraints for the geothermal project of Crèvecoeur-le-Grand Hospital.

an architect (from COX). They present why the Australian Government decided to use geothermal energy and some motivations (governmental constraints, producing both heat and cooling, renewable energy, long lasting, invisible).

This video (Dourlat, 2016) brings a practical view of a geothermal project to people who wish to learn more, but cannot visit a work site. In fact, once the work is finished, only the machine room will be visible. So geothermal energy will simply be invisible to unaware visitors.

This first coverage from Picardy allows those who are curious to discover more about probe-type shallow geothermal energy. It also shows with images that geothermal projects are a reality in the northern part of France.

Example of a pre-feasibility study

Crèvecoeur-le-Grand Hospital wished to switch from oil-fired boilers to a renewable source of energy. As it is partly classified as an historic site, they decided to study geothermal energy, since it is much less visible than wind turbines or solar panels. They asked for a pre-feasibility study from the facilitator to gather arguments to decide the relevance of geothermal installations for their project. They wished if possible to stay in the frame of Geothermal installations of Minor Importance (GMI) to avoid administrative procedures.

The first step of this study was to explain the different types of geothermal installations that could possibly exist for the project. The necessary steps to follow in a project were also detailed (feasibility, drilling, heat pump, maintenance), as well as the possible subsidies for such a project.

The second step was to present the study context (size of the field, siting of the buildings, expected heat consumption).

Then comes the underground potential. According to the map (ADEME BRGM, 2015), there is no administrative constraint for closed or open geothermal loops for GMI. The database of boreholes shows that chalk is from 9 to 125 meters deep. As the thermal conductivity of chalk may be from 0.92 to 3.8 W/(m.K) and as the use of probes is possible as of 1.5 W/(m.K), there is a potential for geothermal probe implantation.

For water table geothermal energy, the Geothermal Atlas puts the water table's depth at 38 m underground. The flow rate is supposed to be from 10 to 50 m^3/h, for a temperature between 10 and 15 °C. The crossing of the data from the hydrogeological map, the boreholes around the project site and the measures taken from a piezometer located 500 m southwest of the project site, shows that the water table chalk is indeed found between 32 and 41 m deep. Unfortunately, there is no flow rate registered in the sector. That means that there is a potential for water table geothermal energy, provided the flow rate values are high enough.

Then, there is a reminder about heat consumption: the geothermal heat should be dimensioned so that 50% of the needed power can cover about 75% of the consumption. The 25% of consumption needs left should be covered by a non-renewable complementary energy source. Indeed, this residual need for heat is experienced only a few weeks a year (about 3 weeks), when the weather is the coolest. Dimensioning for 100% of the needed power is less efficient (economically and energetically) than using a complement.

For an approximate heat consumption of 2 GWh, and with different underground hypothesis, a pre-dimensioning gives between 9,750 and 15,200 linear meters of probes. For the water table geothermal energy, with a flow rate of 10 m^3/h and a borehole doublet, only 8% of the needs would be covered by the geothermal energy. With a flow rate of 50 m^3/h, about 50% of the needs would be covered by the geothermal heat.

The different scenarios are compared to the site map (***Figure 2***). It seems very difficult to place more than 50 probes in the available space. The best choice seems to be water-table geothermal energy. If granted, the AQUAPAC warranty is advised in this case, as the flow rate is not precisely known.

Thanks to this pre-feasibility study, the hospital obtained enough information to decide to go further with a feasibility study and is currently choosing the office to commission for the study.

Conclusion

The purpose of this article was to show that geothermal potential can exist where it is not possible to create geothermal power plants or urban heating networks. Picardy led some key actions to promote shallow geothermal systems and encourage new projects in its territory. There will be a real challenge with the merger of the former regions of Picardy and Nord-Pas-de-Calais, now a single region called Hauts-de-France. Indeed, some actions such as the inventory of geothermal facilities, architect training or establishing a facilitator of geothermal energy do not yet exist in the northern part of the new region, so this gap needs to be filled in order to homogenise the actions on the scale of the new region and to better promote the use of shallow geothermal resources and geothermal heating networks.

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Geothermal energy developments in the district heating of Szeged

Máté Osvald [a], János Szanyi [b], Tamás Medgyes [b], Balázs Kóbor [a], Attila Csanádi [b]*

The District Heating Company of Szeged supplies heat and domestic hot water to 27,000 households and 500 public buildings in Szeged. In 2015, the company decided to introduce geothermal sources into 4 of its 23 heating circuits and started the preparation activities of the development. Preliminary investigations revealed that injection into the sandstone reservoir and the hydraulic connection with already existing wells pose the greatest hydrogeological risks, while placement and operation of wells in a densely-populated area are the most significant above-the-ground obstacles. In the present study, the first project planned for the "Odessza" housing estate is summarised, and an analysis of integrating geothermal into district heating is offered.

La Compagnie de chauffage urbain de Szeged fournit chauffage et eau chaude à 27 000 ménages et à 500 édifices publics de Szeged. En 2015, la compagnie décida d'introduire de l'énergie géothermique dans 4 de ses 23 circuits de chauffage et se lança dans les activités de préparation propres à un futur développement. Des recherches préalables révélèrent qu'une injection dans le réservoir de grès ainsi que les relations hydrauliques avec les puits déjà existants sont à l'origine des risques les plus élevés tandis que l'emplacement des puits et leur utilisation dans un secteur de dense population constituent, en surface, les obstacles les plus significatifs. Pour l'étude actuelle, le premier projet élaboré pour le lotissement Odessza est résumé et une analyse de l'intégration d'énergie géothermique dans le chauffage urbain, est proposée.

La empresa de calefacción urbana de Szeged suministra calor y agua caliente sanitaria a 27.000 hogares y 500 edificios públicos en Szeged. En 2015, la empresa decidió introducir fuentes geotérmicas en 4 de sus 23 circuitos de calefacción y empezó la preparación del desarrollo. Las investigaciones preliminares revelaron que la inyección en el embalse de arenisca y la conexión hidráulica con los pozos ya existentes planteanriesgos hidrogeológicos, asi mismo la colocación y la operación de pozos en una zona densamente poblada son los obstáculos más importantes en la superficie. En el presente estudio se resume el primer proyecto previsto para la urbanización "Odessza" y se propone un análisis de la integración de la geotermia en la calefacción urbana.

Szeged is a municipality with 170,000 inhabitants located in the Southern Great Plain of Hungary. The municipal district heating system has 23 heating centres and supplies heat and domestic hot water to 27,000 households and 500 public users with a total energy output of 224 MW (***Figure 1***). 100% of this energy is produced by fossil-fueled furnaces. However, as the city is located on a sedimentary basin with great geothermal potential, and there is a growing need for sustainable energy utilisation systems with low emissions, introduction of geothermal energy into the system has been proposed. In our study, we give an overview of the supply and demand sides and suggest possible solutions for system integration.

Geological background

The Pannonian Basin is a sedimentary basin located in East-Central Europe, the basement of which consists of variously sided basins and horst-like blocks. Apart from the main mass of the basement, which is made up of metamorphic Paleozoic rocks, the Mesozoic carbonate formations, which can be good aquifers, are found in some areas (Horváth *et al.*, 2015).

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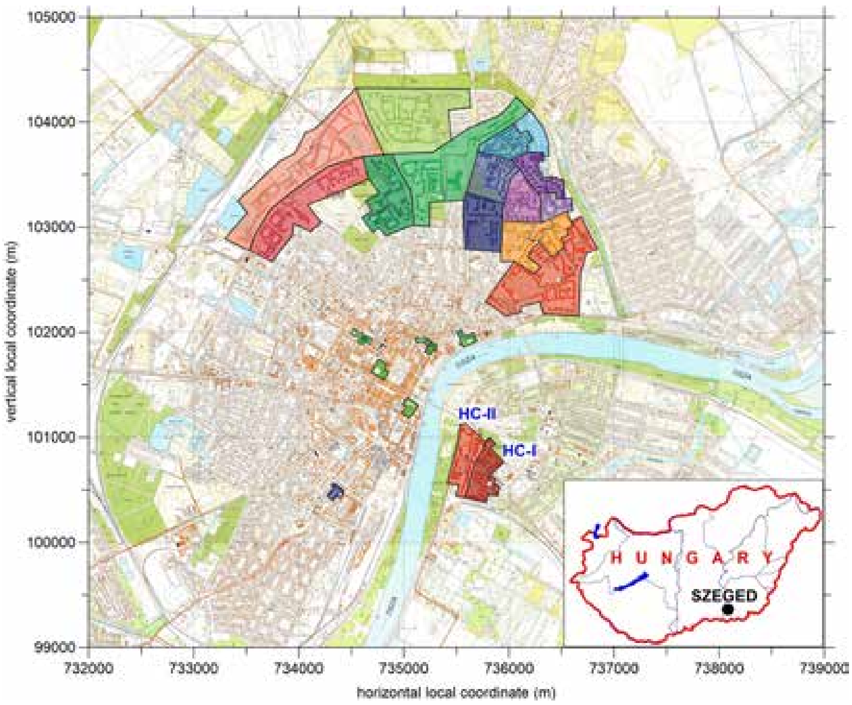

Figure 1: Heating circuits of the district heating system in Szeged, Hungary.

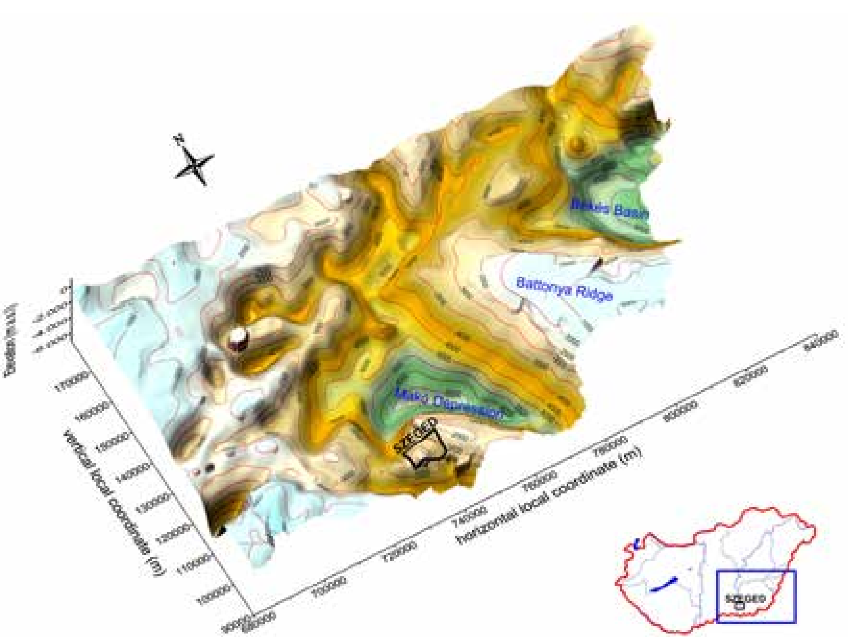

Figure 2: Structural geology of the region.

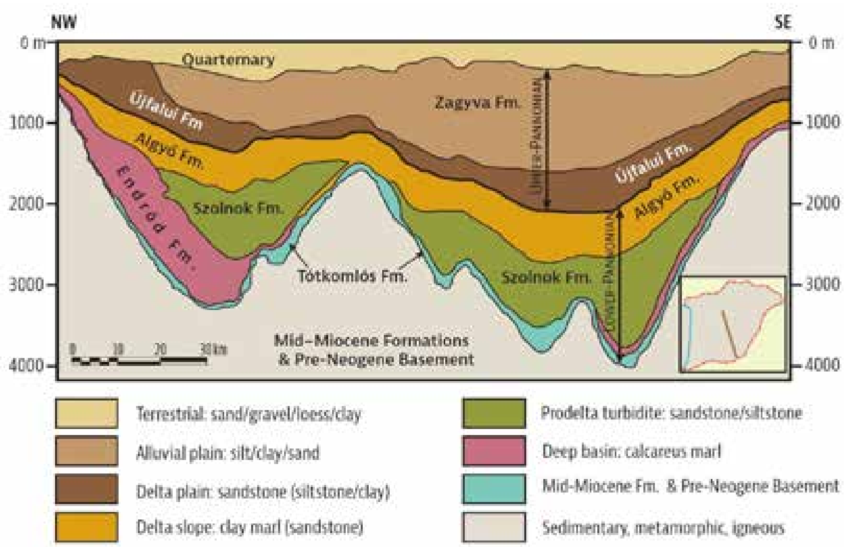

Figure 3: Sedimentological and stratigraphical geological cross-section of the Great Plain, Hungary (based on Juhász, 1991; Tóth and Almási, 2001; Szanyi et al., 2015)

The Makó Depression and Békés Basin, divided by the Battonya Ridge, are the two main depressions of the Southern Great Plain (***Figure 2***). A thick layer of porous sediments covers this subsiding basement, which was deposited in the Pannonian period (Juhász, 1991).

At the beginning of the Lower Pannonian period the Endrőd Marl Formation was formed, consisting of calcareous marl and clay marl. The latter is covered by the fine sand turbidite set of the Szolnok Formation, reaching a thickness of several hundreds of metres at some points. Above the turbidites, in the shallower basin areas, the hemipelagic marls are covered by the thick clayey-silty layers of the Algyő Formation with a prodelta facies (***Figure 3***) (Haas *et al.*, 2012). The main feature of the set is the extremely high overpressure below and everywhere within the set. The sand content of the Algyő Formation is higher in areas with a shallower basement, thus the upper part of the formation can be regarded as water-bearing at some points. Generally, the Lower Pannonian formations are characterised by poor water-bearing features.

The Lower Pannonian layers are covered by the Újfalu Formation and the Zagyva Formation. The Újfalu Formation has delta front and delta plain facies, and it is the most important Upper Pannonian sediment from a hydrogeological point of view. The sediment layers of the Zagyva Formation have deltaic background and alluvial plain facies. The dominant sediments are bed-filling and bay-mouth bar sediments that have good water-bearing features and limited horizontal dimensions, but they are hydrodynamically connected to multiple linear erosions and overlapping (Juhász, 1991). The bottom of the Upper Pannonian sequences is 2,500 m from the ground surface at the SW part of the study area and 2,000 m at the NE wing. The thickness of Upper Pannonian sediments in the Southern Great Plain reaches 1,800 m in the Makó-Hódmezővásárhely Depression, and exceeds 2,000 m in the Békés Basin.

In the Carpathian basin, there are two main flow regimes: an upper, gravity driven flow system (Upper-Pannonian sequences) and a deeper, overpressure driven system (Lower-Pannonian) concerning essentially the finer deep sea sediments and underlying formations (Tóth and Almási, 2001; Mádl-Szőnyi and Tóth, 2009). The main cause of the high overpressure (up to 40 MPa over the hydrostatic pressure) is the tectonic compression of the formations, although gas formation during the maturation process of the sediments is a contributing factor (Tóth and Almási, 2001). In the region of Szeged, according to pressure-depth profiles, the dynamic pressure gradient exceeds the hydrostatic pressure in the Quaternary formations by 0.13 MPa (which is approximately 13 m hydrostatic head), and in the Upper Pannonian set by 0.44 MPa (approximately 44 m hydrostatic head), while in the Lower Pannonian sequence super-hydrostatic pressure has built up, as the dynamic pressure gradient exceeds the hydrostatic pressure by more than 60 MPa.

The effective porosity of Upper Pannonian sandstone reaches 22–25%. The permeability of the Upper Pannonian reservoir, which consists of highly permeable sand layers, reaches 2000 mD (1.97×10^{-12} m^2); this corresponds to a hydraulic conductivity of 5–10 m/day. Depending on the cementation degree of the sandstone grains (usually by quartz overgrowth, calcite or kaolin), the sandstone can be consolidated or unconsolidated. The cementing status of the sandstone plays a key role in porosity and stability, especially during production and injection. The sandstone induration increases with depth, as the cementitious material precipitates into the pores from the fluid extracted during compaction. The sand bodies are divided by thinner fine-grained sediments (Korim, 1991; Bálint and Szanyi, 2015; Szanyi *et al.*, 2015). The presence of the permeable reservoir and the outstanding geothermal conditions make the Pannonian basin suitable for geothermal energy utilisation (Szanyi *et al.*, 2009).

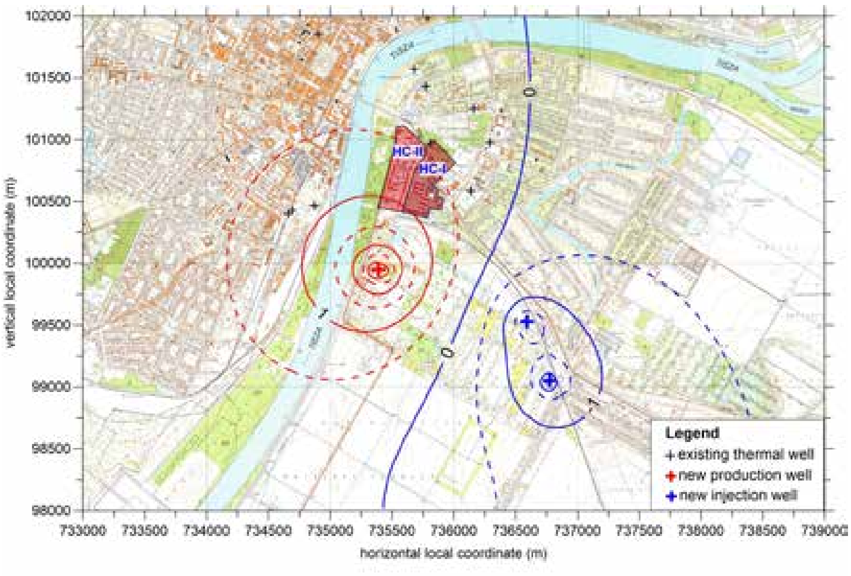

Figure 4: The hydraulic effect of the new wells on the hydraulic head.

The geothermal system

Due to the position of district heating circuits and the number of already existing geothermal and hydrocarbon production wells in the city of Szeged, there is space for no more than 6–8 new geothermal heating systems (***Figure 4***). The first of these, to be set up on the left bank of the Tisza River in the "Odessza" housing project, is designed to operate with one production and two reinjection wells, and will provide more than 60 TJ energy. This article discusses the feasibility of such a system.

According to the plans, a 2,000 m deep production well will be completed and screened between 1,800 m and 1,900 m. The structure of the well is telescopic, the diameter of casings ranges from 13 3/8" (340 mm) to 5 1/2" (140 mm), and the operational lifetime is planned to be a minimum of 50 years. A submersible pump provides maximum 80 m^3/h flow rate to the 90 °C thermal water from the production well. The flow pressure is at 2 bar in the whole cascade system, which is air-tight and pressurised until the buffer tank of the injection well. This implies that there is no degassing at the production well. There are 2 reinjection wells designed, both with 2,000 m depths and a 40 m^3/h flow rate. The perforation is between 1,800 m and 1,900 m. The structure of the wells is telescopic, the diameter of casings starts at 13 3/8" (340 mm) and ends at 7" (178 mm). There is a 50 m^3 buffer tank before the injection wells. The filter system has a pore size of 50 µm and is fully automated with pressure meters to indicate clogging and to control the automatic washing.

The heat is utilised through a main titanium heat exchanger with 3.5 MW performance. The primary circuit fluid is 90°C in temperature and has a flow rate of 70 m^3/h and the secondary circuit fluid has an 88/50°C heat step and a flow rate of 80 m^3/h. This central heat exchanger provides heat to two heat centres, and it is there that the geothermal system is integrated with the already existing district heating system. The current "Odessza" system is 100% natural-gas-based and utilises three heat circuits, each has 90/65 C, 80/60 C and 60/40 C heat steps with the following performance:

- Odessza heat circuit 1 (HC-I): 4950 kW + 250 kW domestic hot water
- Odessza heat circuit 2 (HC-II): 4480 kW + 250 kW domestic hot water

There are 12 main consumer blocks within these 2 circuits, and the total heat consumption of three of these is to be fully supplied by geothermal energy at all times. In case the ambient temperature is warmer than -2°C the use of fossil-fuelled furnaces is not needed in HC-I at all. If the ambient temperature is warmer than +2°C but cooler than +7°C, which is approximately 80% of the total heating days, the need of 9 consumer blocks is fully satisfied by geothermal energy from the 2 heating circuits. All of the heat demand can be fully covered by geothermal energy if the ambient temperature is warmer than +7°C. By design, 70% of total heat demand will be satisfied by geothermal in an average winter (***Table 1***).

Approximately one fifth (18%) of the 1144 residences in HC-I recently had fenestration renovation and 46% had external insulation installed. These ratios are slightly better in the case of HC-II, where 65% of the 1163 residences had window renovation and 59% had external insulation. Large scale energetic modernisation would significantly lower the energy need for heating in both circuits and would make a higher utilisation rate of geothermal energy possible with a lower heat step of 60/40°C. This would remarkably increase the ratio of geothermal energy use (up to 90%). The total estimated savings in natural gas is detailed in ***Table 2***.

The natural gas saving also contributes to lower environmental impact through lower greenhouse gas emissions in the system. The emission of carbon dioxide is decreased by 2,957 t, sulphur dioxide by 343 kg and nitrogen oxide by 2,992 kg annually. The greenhouse gas emission prognosis is less than 90,000 t CO_2 equivalent for 30 years' lifetime.

The interaction between the new wells and with the already existing wells was modelled and is shown in ***Figure 4***. The model resulted in a minimal (almost zero metre) change in the hydraulic head due to the effect of simultaneous injection. This means that, with responsible operation and with proper reinjection, the pressure of the reservoir can be maintained and the geothermal resource can be harnessed in a sustainable way.

Table 1: Natural gas and thermal energy use.

	Natural gas use (GJ)	Thermal ratio (%)	Natural gas saving (GJ)	Utilized thermal energy (GJ)
HC-I	37,629	97.4	36,651	32,986
HC-II	44,348	47.2	20,932	18,839
Total	**81,977**	**70.2**	**57,583**	**51,825**

Table 2: Natural gas usage balance.

	Natural gas consumption (m3)	Consumption (GJ)
Before development	2,411,088	81,977
Natural gas saving	1,693,618	57,583
After development	717,470	24,394

Approximately 52 TJ of geothermal energy will be utilised by the project with these settings. The total capital cost of the project is approximately EUR 420,000 net, which includes well construction, pipeline installation and other related works. With governmental and European Union funding the return rate is calculated to be less than 10 years. The maintenance cost is calculated at net 2.18 EUR/GJ (at 51,825 GJ/year).

Conclusions

The heating system discussed in this study can supply more than 50 TJ of geothermal heat in a sustainable way. The project is designed to satisfy 70% of the total heat demand in the area by geothermal energy; however, with further insulation and other energy saving refurbishments on the end-user side this rate could reach 90%. Later on, consumers with lower temperature demand can be attached to the system, increasing pay-off. As is shown by the calculations, a remarkable decrease in greenhouse gas emissions will be achieved, which makes the project eco-friendly. The sustainability of the geothermal system's operation is ensured by the reinjection of the heat depleted thermal fluid in order to maintain the pressure of the reservoir.

Acknowledgement

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Assessment of deep geothermal energy potential in Northern and Central Portugal

M.M. Miranda, N.V. Rodrigues, J. Willis-Richards and A.J.S.C. Pereira*

Northern and Central Portugal are being intensively studied to identify geological environments with high potential for Enhanced Geothermal Systems/Hot Dry Rock (EGS/HDR). The Beira granite is the selected target for geothermal feasibility studies. This granitic mass shows a heat production of 5 µW.m⁻³. Surface heat flow is estimated to be 100–120 mW.m⁻². The depth for a possible geothermal reservoir suitable for electricity generation is predicted to be 6 km. Simulations carried out to assess the potential for the development of an EGS reservoir on the Beira granite show that, although these reservoirs in Portugal are not as easily created by stimulation as they might be in other regions, reservoirs of potential commercial interest were generated in the majority of model realisations.

Le Nord et le Centre du Portugal sont intensément étudiés pour identifier les environnements géologiques à fort potentiel pour les systèmes de géothermie profonde (EGS/HDR). Le granite de Beira est la cible sélectionnée pour les études de faisabilité géothermique. Cette masse granitique présente une production de chaleur de 5 µW.m⁻³. Le flux de chaleur de surface est estimé à 100–120 mW.m⁻². La profondeur d'un éventuel réservoir géothermique adapté à la production d'électricité est estimée à 6 km. Des simulations effectuées pour évaluer le potentiel de développement d'un réservoir EGS au granite de Beira montrent que, bien que ces réservoirs au Portugal ne soient pas aussi facilement créés par stimulation que dans d'autres régions, des réservoirs d'intérêt commercial ont été générés dans la majorité des réalisations du modèle.

El Norte y el Centro de Portugal están siendo intensamente estudiados para identificar ambientes geológicos con alto potencial para sistemas geotérmicos profundos (EGS/HDR). El granito de Beira es el objeto seleccionado para los estudios de viabilidad geotérmica. Esta masa granítica muestra una producción de calor de 5 µW.m⁻³. El flujo de calor de superficie se estima en 100–120 mW.m⁻². La profundidad de un posible reservatorio geotérmico adecuado para la generación de electricidad se prevé que sea a 6 km. Las simulaciones realizadas para evaluar el potencial de desarrollo de un reservatorio EGS en el granito de Beira muestran que, a pesar de estos reservatorios en Portugal no son tan fácilmente creados por la estimulación como podrían ser en otras regiones, se generaron reservatorios de interés comercial en la mayoría de las realizaciones del modelo.

1. Introduction and background geology

Northern and Central Portugal are characterised by wide outcrops of Hercynian granitic rocks Middle to Upper Carboniferous in age emplaced into a metasedimentary sequence, the Schist-Greywacke Complex, of Pre-Cambrian to Lower Palaeozoic age. The granitic rock masses were emplaced during and after the last thickening and subsequent post-collisional extensional events of the Hercynian orogeny (D3 ductile compressive deformation and D4 brittle extensional phases) that occurred from the Mid-Carboniferous to Permian. Their emplacement was associated with a high temperature event that occurred mainly during and after the ductile deformation phase D3 (Namurian–Westphalian in age).

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These regions of mainland Portugal may have significant potential for enhanced geothermal system style geothermal energy. This is supported by the occurrence of several thermal springs with temperatures ranging up to 76 ºC (IGM, 1998) in the outcropping Hercynian granites. The available heat flow density maps (e.g., Correia and Ramalho, 2005) suggest that these regions have surface heat flow values in the range 65–80 mW.m⁻², with an average of 78 mW.m⁻². However, there are no reliable deep temperature measurements from the granitic plutons themselves to support this conclusion.

In the present work we discuss the geological evidence that suggests higher heat flow values are likely and that pinpoints, within the several granitic units, which one has the highest geothermal potential for Enhanced Geothermal Systems/Hot Dry Rock (EGS/HDR) exploitation. Studies of the heat-producing elements (HPEs) and their host minerals, rock thermal properties and estimates of radiogenic heat production (RHP) were carried out, leading to estimates of temperature-at-depth and simulations of an EGS reservoir within the target area.

2. Heat-producing elements, radiogenic heat production and rock thermal properties

A total of 314 samples were collected from the different granitic units outcropping in northern and central regions (***Figure 1***). The methods used to assess the HPEs concentrations and the results obtained are described in detail in the work of Lamas *et al.* (2017). Briefly, it was observed that there is a substantial increase of U and Th concentrations from the oldest granitic units to the younger ones, as can be seen in ***Figure 2***. The A-group (A1 and A2) shows a U average concentration of 4.5 mg.kg⁻¹ and a Th average concentration of 9.1 mg.kg⁻¹ (Lamas *et al.*, 2017). For the C-group the U average concentration is 5.5 mg.kg⁻¹ for C1, 8.2 mg.kg⁻¹ for C2, and 7.5 mg.kg⁻¹ for C3 (Lamas *et al.*, 2017). Regarding Th average concentrations in the C-group, C1 shows a value of 22.9 mg.kg⁻¹, C2 21.3 mg.kg⁻¹, and

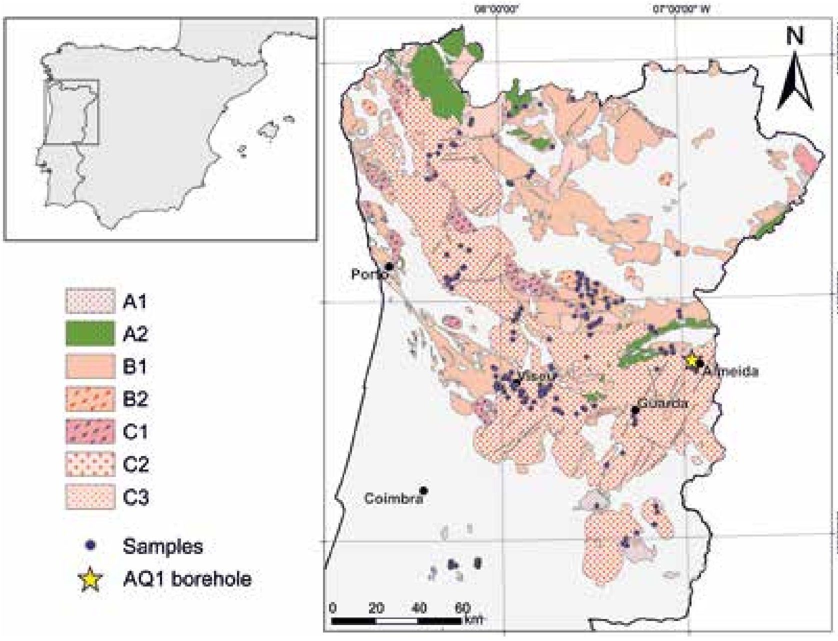

Figure 1: Geographical and geological framework with location of the samples analysed and the different granitic units studied. A to C indicate each granitic unit, with A being the oldest granites emplaced in the northern and central regions, and C the younger ones; "Samples" refer to the surface samples, and "AQ1 borehole" to the subsurface samples. For more explanation see Lamas et al. *(2017).*

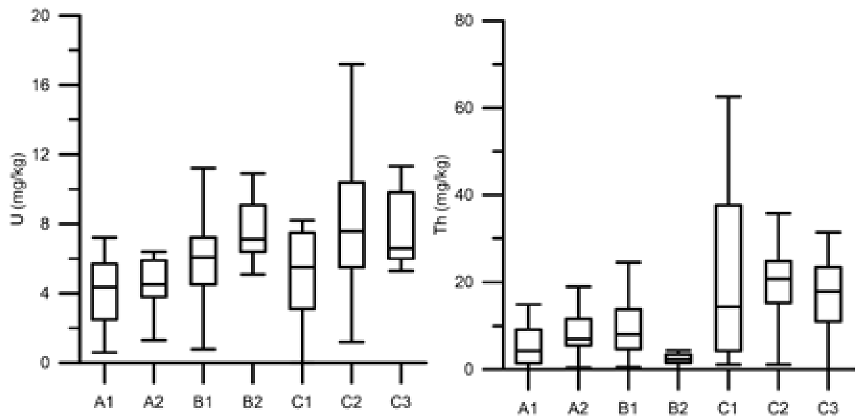

Figure 2: Tukey boxplots showing the U and Th distribution amongst the different granitic units studied. Adapted from Lamas et al. *(2017).*

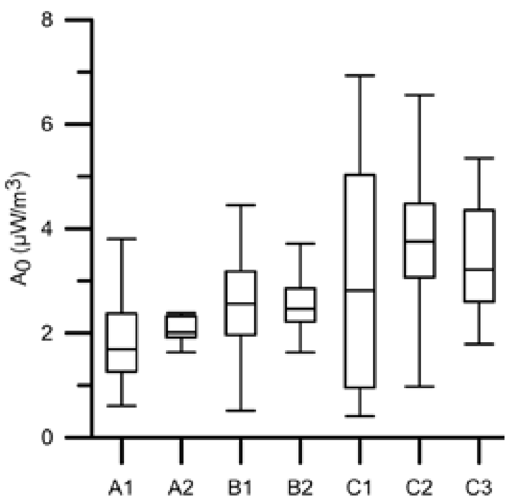

Figure 3: Tukey boxplots showing the surface radiogenic heat production distribution amongst the different studied granitic units. Adapted from Miranda et al. *(2015).*

C3 shows an average Th concentration of 18.7 mg.kg^{-1} (Lamas *et al.*, 2017).

As U and Th concentrations tend to increase from the older granitic units to the younger ones, the same tendency is observed for radiogenic heat production, as discussed in Miranda *et al.* (2015b) and shown in ***Figure 3***. The A-group presents a surface heat production of 2 µW.m^{-3} while C-group 4 µW.m^{-3} (Miranda *et al.*, 2015).

Based on the highest U and Th concentrations, and consequently the highest radiogenic heat production, and due to their estimated thickness (5 km mean and 10 km maximum; Machadinho, 2014) the C2-lithology was chosen as the target lithology for more detailed studies. Lamas *et al.* (2015a) pointed out that within the C2-unit, the granitic rock mass that occupies the central region of Portugal (between Viseu, Guarda and Almeida***; Figure 1***), known as the Beira granite, is the most radiothermal granite.

The existence of a deep well near Almeida (see ***Figure 1***) with core recovery allowed us to study the distribution of the heat-producing elements with depth (see Lamas *et al.*, 2017, for further details). Due to hot spring fluid flow from fractures, this well is not suitable for estimation of heat flow. The U concentration at Almeida increases from surface to subsurface by about 30 %. At the surface its average concentration is 9.9 mg.kg^{-1} (Lamas *et al.*, 2015), whilst in the subsurface it increases to 14.3 mg.kg^{-1} (Lamas *et al.*, 2017). Consequently, the heat production of the Beira granite increases with depth. The surface value is 4.5 µW.m^{-3} while at depth it increases to 5.2 µW.m^{-3} (Miranda *et al.*, 2015).

From our study of the subsurface samples it was shown that the radioelements, and consequently the heat production, have a remarkably uniform distribution along 1,000 meters depth (***Figure 4***; Lamas *et al.*, 2017), a trend noted in other deep boreholes of the Hercynian chain (e.g., Sams and Thomas-Betts, 1988 and references therein).

Our study of the subsurface samples highlights that even when surface samples are apparently freshest, the mobility of U due to weathering had taken place, and thus surface samples are not representative of the whole rock mass for geothermal studies.

Beyond the heat-producing elements and heat production distribution, we also studied the thermal properties of samples from the Beira granite. The method used and the results obtained are described in Miranda (2014). The average thermal conductivity obtained is 3.1W.m^{-1}.K^{-1}, for thermal diffusivity the obtained value is 1.6 x10^{-6} m^{2}.s^{-1}, and thermal capacity 1.9

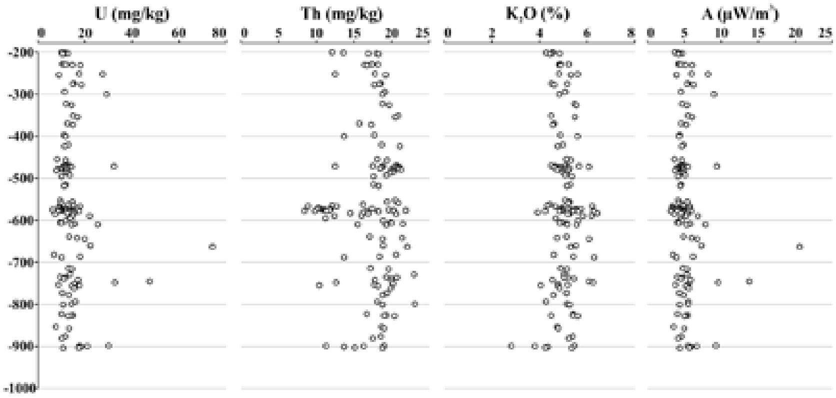

Figure 4: Heat-producing elements (U, Th and K2O) and radiogenic heat production (A) distribution at depth.

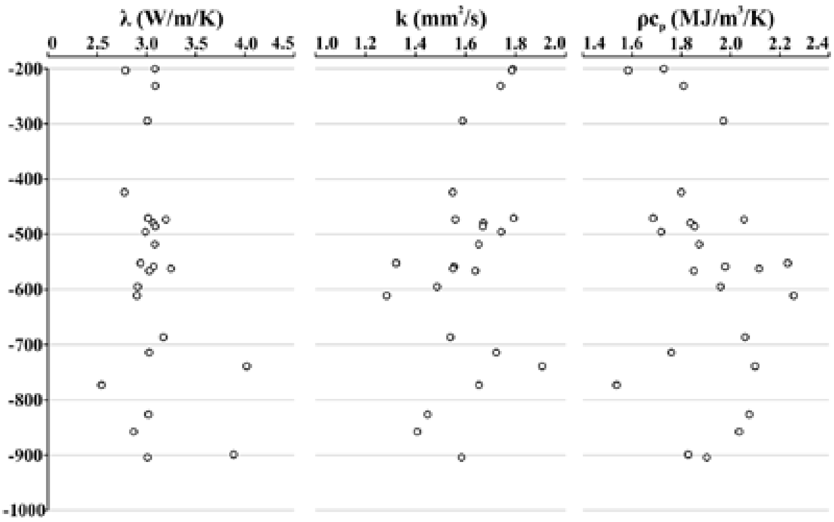

Figure 5: Distribution of thermal properties with depth, Almeida borehole. λ – thermal conductivity; k – thermal diffusivity, ρc_p – thermal capacity.

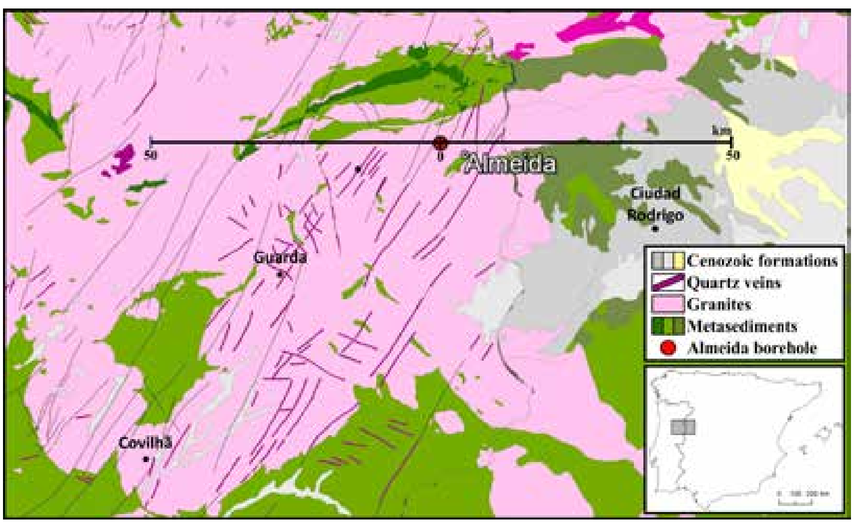

Figure 6: Detail of the geological map seen in Figure 1 with the location of the linear segment studied for heat flow and temperature estimations. From Pereira et al. *(2016).*

x106 J.m^{-3}.K^{-1} (equivalent to 720 J.Kg^{-1}.K^{-1}). Their distribution with depth is shown in ***Figure 5***.

3. Heat flow and temperature modelling

Heat flow and geothermal gradient estimations were carried out for the Beira granite using an approach described in Pereira *et al.* (2016). A 100 km linear traverse was selected within the granite of interest, in such a way that AQ1 borehole at Almeida (see ***Figure 1*** and ***Figure 6***) was the central point of the model.

A conceptual crustal model for the area of interest was built based on available geophysical and geological data (see Pereira *et al.*, 2016 for a detailed discussion), and was assumed to be as depicted in ***Figure 7***. The heat production was assumed to follow a stepwise distribution in which each crustal layer is composed by a uniform value. In this way, the values of 5.2, 10.9, 1.4, and 0.8 µW.m^{-3} were considered for the granite, upper crust II, mid-crust, and lower crust, respectively. The value of heat production assumed for the low-velocity layer upper crust II is based on a purely mathematical hypothesis and it was calculated by the vp-A relationship, in which A increases with decreasing v_p (e.g., Rybach and Bunterbath, 1984).

A similar assumption of each crustal layer being composed by uniform values was followed for thermal conductivity, in which the granitic layer was considered to have a value of 3.1W.m^{-1}.K^{-1}, the upper crust II and mid-crust the value of 2.5 W.m^{-1}.K^{-1}, and the lower crust was given the value of 2.1 W.m^{-1}.K^{-1}. For the schist layer thermal conductivity of 3.0 W.m^{-1}.K^{-1} and heat production of 1.6 µW.m^{-3} were considered (Pereira *et al.*, 2016).

The simulations of present-day in-depth temperatures and heat flux distributions were carried out using MATLAB, based on the numerical solution of the 2D steady-state heat conduction equation over the rectangular domain shown in ***Figure 7***. A uniform Moho heat flux (q") of 25 mW.m^{-2}, characteristic in Palaeozoic folded units (Cermak, 1993), was assumed to be entering the domain through the lower horizontal boundary and the top boundary is considered to be at a constant and uniform surface temperature of 16 ºC. The vertical boundaries are both assumed to be adiabatic (i.e., no horizontal heat flow) (see Pereira *et al.*, 2016 for more details).

Different model geometries and several thicknesses for a schistose metasedimentary cover were assessed, enabling us to study the effect of each layer thickness and the effect of a thermal blanket on heat flow and temperature. For the granitic part of the model the surface heat flow was estimated to vary from 114 to 130 mW.m^{-2}, and the geothermal gradient from 32.5 to 37.3 °C.km^{-1} (Pereira *et al.*, 2016). The average surface heat flow obtained is 123 mW.m^{-2}, which is higher than previously published synoptic data (e.g., Correia and Ramalho, 2005). For the geothermal gradient the average value is 35.3 °C.km^{-1}. These values are good approximations; however, they are dependent on the distribution model used for heat production and thermal conductivity. Taking into account such uncertainties, but assuming reasonable confidence in extrapolating measured subsurface heat production to depth in the Beira granite, we can conclude that the surface heat flow in the Beira granite is higher than has been proposed to date.

The modelled heat flow and temperature curves, showing the effect of the metasedimentary cover, are shown in ***Figure 8***. Both profiles were modelled only to 6 km depth since this is the likely maximum acceptable depth for a potentially commercially viable EGS project.

Assuming a metasedimentary layer with 4 km thickness the surface heat flow is estimated to be around 100 mW.m^{-2}; however, with a thinner cover, the surface heat flow reaches an estimated value of near 115 mW.m^{-2} (Pereira *et al.*, 2016). At 6 km depth, the average temperature in the granitic part of the modelled segment is 210 ºC, decreasing to 205 ºC assuming a metasedimentary cover of 1 km and to 185 ºC if the metasedimentary cover has a thickness of 4 km (Pereira *et al.*, 2016). These temperatures are within the range of temperatures for potential EGS reservoirs.

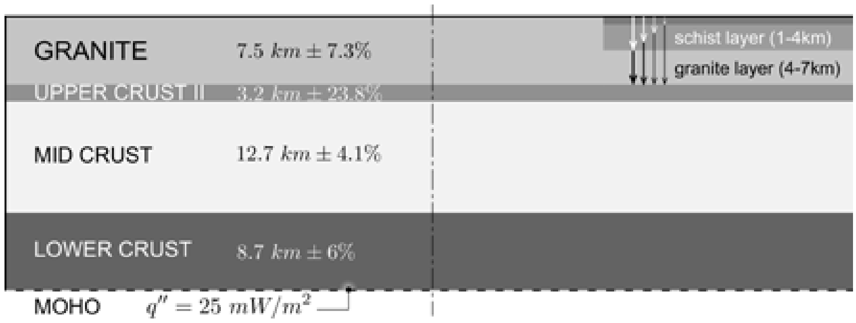

Figure 7: Conceptual crustal model for the studied segment. From Pereira et al. *(2016).*

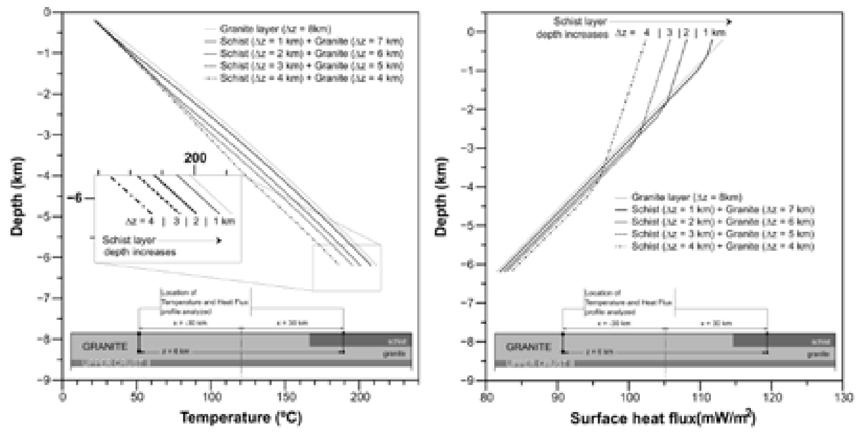

Figure 8: Temperature and heat flux curves. From Pereira et al. *(2016).*

4. Numerical modelling of EGS reservoir development in Beira granite

As discussed above, due to temperature values found, the Beira granite is the most promising scenario for an EGS reservoir in Central Portugal. Numerical simulations to assess its potential for the development of such reservoirs were carried out using the FRACSIM3D model, as is discussed in Miranda *et al.* (2017).

FRACSIM3D is a 3-D stochastic fracture network and rock mechanics model that addresses the geology and geomechanics that control the development of an EGS reservoir created by hydraulic stimulation of crystalline hot rocks. A detailed description of this model is present in the work of Jing *et al.* (2000) and the version used here is updated in respect to fracture dilation laws and the introduction of a cohesion term to mimic the strengths of compressional asperities that have to break before slip takes place. This allows crude estimates of potential microseismic event magnitudes. Briefly, FRACSIM3D uses approximations to follow the complex changes that occur within the rock mass during stimulation, and it simulates the subsequent steady state circulation of the heat exchange system created, thus helping in the design of a reservoir for the situation at hand. The model is written as a sequence of modules which, starting from available field measurements, simulates a fracture network in a cube-shaped model volume. It follows the stimulation of fractures from one and more wells at a given injection pressure and then calculates water circulation through the shear-dilated, compliant fracture network. Flow rates, water losses, heat extraction, tracer particle tracking and a frictional law allowing both slip strengthening or weakening are implemented. In summary, FRACSIM3D can analyse both the creation/ enhancement of the geothermal reservoir as well as the approximate operation of it once it has been developed.

As inputs, FRACSIM3D requires data regarding:

i. rock elastic and thermal properties;
ii. tectonic stresses;
iii. fracture orientations, frequency, and fracture length distribution;
iv. fracture friction, roughness, closure curve, macro-asperity strength expressed as a cohesion term;
v. location and properties of any possible major faults;
vi. undisturbed large scale permeability;
vii. in-situ fluid pressure (hydrostatic);
viii. rock temperature at depth.

Based on these inputs and well orientations and positions, stimulation pressures, rock volume to be treated, and the injection and recovery well pressures during circulation, it is possible to obtain as model outputs:

i. injection and recovery flow rates;
ii. thermal performance over time;
iii. tracer response curve;
iv. maps of flow, pressure, transmissivity, and temperature;
v. maps of fracture slip and unstable slip;
vi. synthetic well flow logs.

Our imperfect knowledge of the input parameters (e.g., in-situ large scale permeabilities can only be guessed, and might be set at levels 10x greater than for other EGS systems, thus representing the worst case scenario for water loss) leads to high uncertainties in the modelling process. Nevertheless, not giving too much emphasis to the absolute values of the flow rates, with progressive improvements in reservoir stimulation design and circulation conditions, our Beira granite scenario shows some quasi-commercial flow rate EGS model reservoirs (***Table 1***), bearing in mind that

Table 1: Flow rates obtained by changing circulation and stimulation pressures. Inter-well distance of 300 m; open-hole lengths of 600 m; -30º as the rotation applied to well system; -40º as the rotation applied about the y-axis and 20º as the rotation applied about the z-axis for each well mid-point. The azimuth of the maximum horizontal principal stress was considered 140º.

Case study	*Circulation pressure (MPa)*		*Stimulation pressure (MPa)*		*Flow rate (l/sec)*		*% recovery*
	Inj. well	*Prod. well*	*Inj. well*	*Prod. well*	*Inj. well*	*Prod. well*	
Base case	*9*	*0*	*16*	*16*	*-65.46*	*36.84*	*71.4*
1	*7*	*-2*	*18*	*18*	*-52.73*	*35.07*	*82.3*
2	*7*	*-2*	*20*	*20*	*-56.85*	*38.76*	*81.9*
3	*7*	*-2*	*16*	*16 + 24*	*-51.18*	*35.05*	*83.9*
4	*7*	*-2*	*20*	*20 + 24*	*-58.12*	*40.49*	*82.4*

Table 2: Flow rates for Rosemanowes and Beira granitic units.

Random number seed	*Rosemanowes*		*Beira*	
	Inj. flow (l/sec)	*Rec. flow (l/sec)*	*Inj. flow (l/sec)*	*Rec. flow (l/sec)*
-1305	*-72.44*	*71.44*	*-62.13*	*58.65*
-1306	*-97.19*	*94.47*	*-52.82*	*50.80*
-1307	*-141.05*	*139.28*	*-64.53*	*62.34*
-1308	*-107.88*	*106.91*	*-121.18*	*117.08*
-1309	*-107.53*	*106.22*	*-18.38*	*16.89*
-1310	*-114.09*	*113.30*	*-37.42*	*35.45*

a commercial EGS reservoir is expected to have flow rates higher than 10 l/sec. With the treatment options studied (reduction of circulation pressure and increase of stimulation pressure in both wells, with addition of a small extra stimulation of the recovery well) water losses were reduced from 29 l/sec to 18 l/sec. Although this still is a relatively high water loss rate, stimulation design and circulation treatments must be assessed.

A comparison study was also carried out between Beira granite and a Rosemanowes (Cornwall) scenario at the same depth using the same in-situ permeability, conservative stimulation pressures of 1 MPa below the minimum effective in situ principal stress, and assuming asperities with strength sufficient to generate micro-seismic events. The differences between the two models were the stress field orientation, fracture orientations, and fracture length distributions. Results obtained from a number of realisations are shown in ***Table 2***.

The Beira scenario shows a mean recovery flow of 95 %, while for Rosemanowes it was 99 %, with flows 54 % greater. This performance difference is due mainly to the difference in fracture orientations relative to the principal stresses. To generate equivalent flows in Beira, the stimulation pressure has to be increased, and either a second smaller high pressure stimulation of the recovery well or proppants must be introduced, or possibly both.

From multiple realisations and sensitivity studies carried out using the Beira granite scenario (to assess uncertainty and potential investment risk), we conclude that EGS reservoirs in granites in Portugal are not as easily created by stimulation as they might be in the Rhine Graben (France, Germany) or in SW England. This is mostly due to the rotation of the Iberian Peninsula in Cretaceous times that has resulted in few joints being optimally oriented for slip at the present day. These fractures, not very well-oriented for fluid flow, reduce flow by about 50 %. Necessary stimulation pressures are estimated to be about 4–5 MPa higher than those that would be required at similar depths in Soultz-sous-Fôrets or Cornwall. Nevertheless, we generated reservoirs of potential commercial interest in the majority of model realisations. Further work is required to investigate the existence of possible deep faults or hydrothermally altered zones as potential EGS reservoirs; such features may be common and may have in-situ apertures, frictional and shear dilation properties distinct from the joint-based scenario reported above.

5. Conclusions

The granitic units cropping out in Northern and Central Portugal were studied to assess their heat production potential. Amongst these, the Beira granite showed highly radiothermal heat production, and was thus selected as a target for geothermal investigations regarding EGS reservoirs.

Although we have very imperfect knowledge of the input parameters for the numerical modelling of an EGS in the Beira granite, these preliminary results show that EGS reservoirs are not as easily created by stimulation as they might be in other regions. However, reservoirs of potential commercial interest were generated in the majority of the simulations carried out.

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Geothermal use of mine water

*L.M. Lara, I. G. Colinas, M.T Mallada, A.E. Hernández-Battez, J.L. Viesca**

In the Vital Álvarez Buylla Hospital in Mieres (Asturias, Spain), the energy supply for the heating and air conditioning system relies on a geothermal facility that uses mine water from the abandoned and flooded Barredo-Santa Bárbara system of coal mines. This water is being used in the most powerful geothermal facilities in Spain and one of the biggest of its kind in Europe, where water pumped out of the Barredo mine shaft yields up to 3.5 MWt passing through a heat exchanger. The Research Building of the University Campus of Mieres (University of Oviedo, Spain) is also heated by the same geothermal resource.
An important role is played by the use of the mine water, and the energy benefits derived from it represents a rational and sustainable use of a traditional mining area after cessation of its activity, aiding environmental and economic development in places where mining activity once ruled the local economy.

A l'Hôpital "Vital Alvarez Bullya" de Mieres (Les Asturies, Espagne), la fourniture de l'énergie pour le chauffage et le système d'air conditionné dépend d'un aménagement géothermique qui utilise l'eau provenant des galeries abandonnées et noyées, des mines de charbon de Barredo-Santa Barbara. Cette eau est utilisée au sein des installations géothermiques les plus puissantes en Espagne et l'une des plus importantes de la sorte en Europe, où l'eau pompée à partir d'un puits de la mine de Barredo fournit jusqu'à 3.5 MWt en traversant un échangeur thermique. Le bâtiment de recherche de l'Université du Campus de Mieres (Université d'Oviedo, Espagne) est également chauffé par la même ressource géothermique.
L'eau de la mine joue un rôle important et le bénéfice énergétique que l'on en tire représente une utilisation rationnelle et durable d'une zone minière traditionnelle après l'arrêt de ses activités, contribuant au développement environnemental et économique de secteurs dont l'économie locale était autrefois tributaire de la seule activité minière.

La climatización del Hospital Vital Álvarez Buylla de Mieres (Asturias, España) basada en la utilización de un sistema geotérmico que emplea agua de mina, constituye la instalación geotérmica más grande de España y una de las mayores de Europa de este tipo. En dicha instalación se aprovecha el agua de bombeo procedente de la unidad Barredo-Santa Bárbara a través de un intercambiador de calor de 3,5 MWt. Además, el Edificio de Investigación del Campus Universitario de Mieres (Universidad de Oviedo, España) es también climatizado utilizando el mismo recurso geotérmico.
De esta forma, la utilización de las minas abandonadas e inundadas de la zona, adquieren un papel importante, permitiendo un uso racional y sostenible de las infraestructuras mineras una vez cesa la actividad, pudiendo ir acompañada de beneficios económicos y medioambientales que repercutan en las zonas donde la actividad minera era el principal motor económico.

1. Introduction

The Central Coal Basin of Asturias (hereafter CCBA) occupies an area of about 1400 km^2 and is the biggest outcrop of materials from the Carboniferous period in Spain. Over more than two hundred years the mining activity in the basin evolved from drift mining or "mountain mining" to mining by means of vertical shafts, with some reaching depths of 700 m or even more. These mining works have been interconnected by complex networks of galleries.

Since mining work began, 300 pits, drift mines and 73 vertical shafts have been opened, so the hydraulic system of small multilayer aquifers has evolved into a karst type hydraulic system (Pendás and Loredo, 2006) due to traditional mining methods

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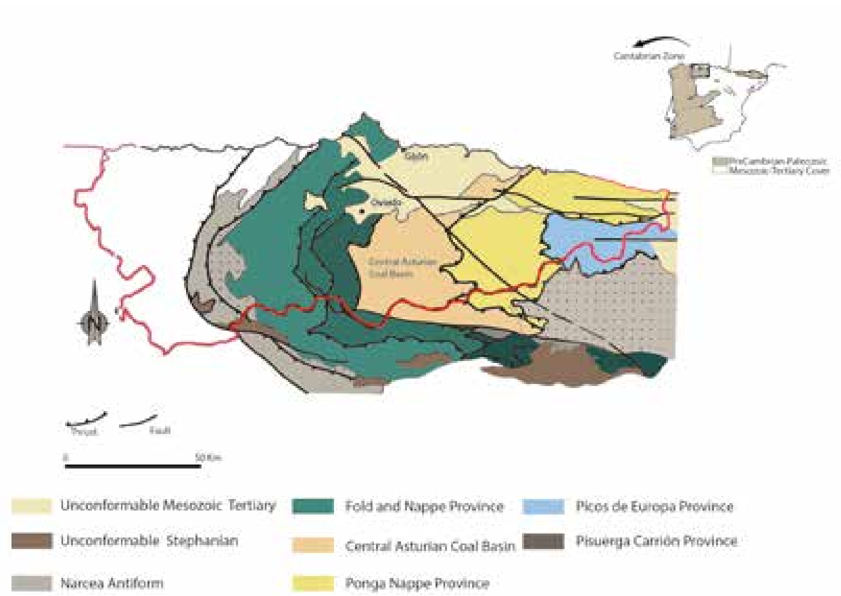

Figure 1: Location of the Central Asturian Coal Basin in the Cantabrian Zone (Iberian Masif) (Bastida et al.*, 1995).*

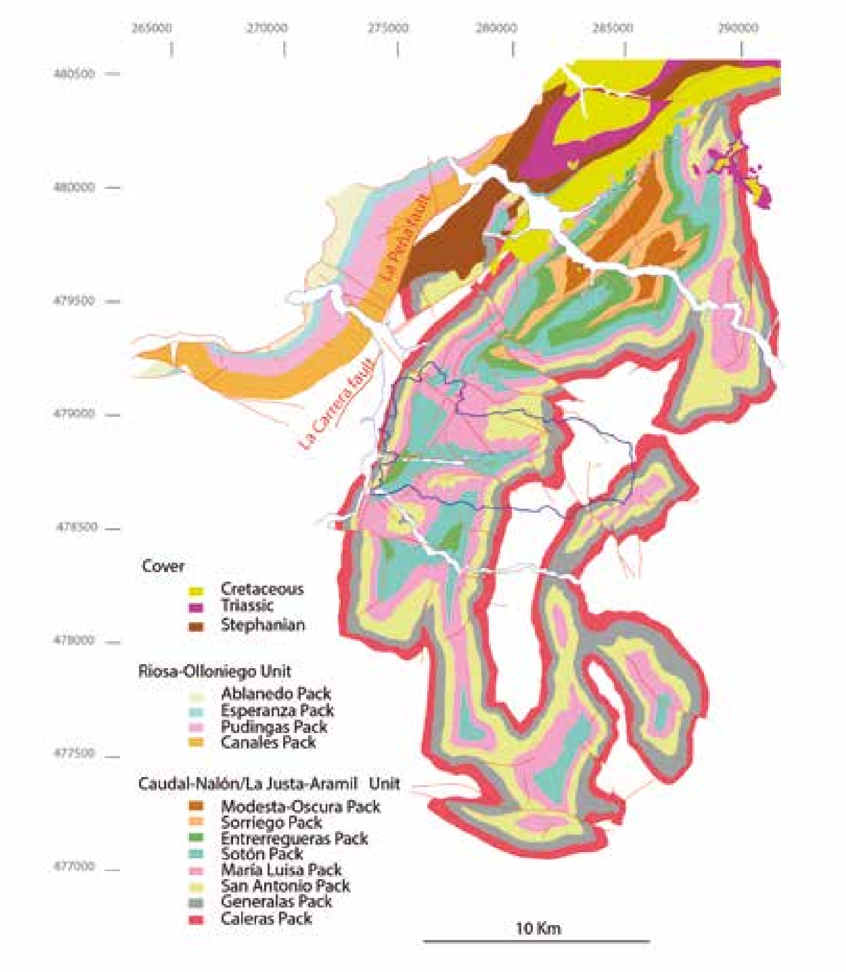

Figure 2: Geological map (Grupo Hunosa) and studied area.

and the thousands of kilometres of galleries that have cracked the surrounding rock mass.

Mining companies bear the operational and maintenance costs costs of the mine water pumping system, and these can be significantly reduced by heating and air conditioning buildings using heat pump technology that makes use of the heat energy of mine water.

The state-owned mining company Hunosa has built a Geothermal Facility that utilises the energy contained in the drainage water of the Barredo-Santa Bárbara system coal mines, extracted from the Barredo mine shaft in Mieres, Asturias, to heat and air-condition the Vital Álvarez Buylla Hospital (4.3 MWt), the Research Building on the University of Oviedo's Mieres campus (720 kWt) and a building of the Fundacion Asturiana de la Energía (125 kWt).

2. Geology

The CCBA is one of the regions defined by Julivert (1967), located in the Cantabrian Zone and inside the Iberian Masif (Lotze, 1945) (***Figure 1***). It is a synorogenic basin formed in relation to the Variscan orogeny and has been affected by several phases of deformation, which have led to an intensely folded and fractured structure.

Its western and southern boundaries are the Aramo thrust and the León fault. The Laviana thrust to the west borders with the Región de Mantos, and the northern part is covered by Mesozoic-Tertiary materials. The productive zones of the CCBA can be subdivided into different units from west to east limited by faults: the "Riosa-Olloniego Unit", the "La Justa-Aramil and Caudal-Nalón Unit" (***Figure 2***).

The Carboniferous sediments of the CCBA reach 6,000 m in thickness, aged from the Namurian B to the Westfalian D. The succession of materials has been traditionally divided into two main groups (***Figure 3***); the lower Lena Group comprises limestones and a few narrow coal seams, and the overlying Sama Group comprises a few siltstones, numerous sandstone layers, some conglomerate levels and workable coal seams. Both the Lena and Sama Groups are divided into a lithostratigraphic series referred to as "Packs" in mining terminology (García-Loygorri *et al.*, 1971) and which, arranged from bottom to top, are: Fresnedo, Levinco, Llanón, Tendeyón and Caleras (Lena Group), Generalas, San Antonio, María Luisa, Sotón, Entrerregueras, Sorriego, Modesta and Oscura (Sama Group). The section related to this project is the Caudal-Nalón Section, which includes the upper "pack" of the Lena Group (Caleras Pack) and all the "packs" of the Sama Group.

3. Hydrogeology

The Carboniferous sediments in the area studied present a monotonous succession of shales, siltstones, sandstones, many coal seams and some levels of limestone of variable thickness.

These materials have very different hydrogeological characteristics, as summarised in ***Table 1***.

Very low permeability materials: Shales and siltstones, with permeability values of 0.005 m^2/day and 2.96 x 10^{-8} m/s (ITGE, 1995). Different values of primary permeability (Fandos *et al.*, 2004) have been obtained by other researchers, estimated from pump trials and time series of potentiometric level measurements in areas without mining activity, obtaining values of below 10^{-7} m/s, and values ranging from $5x10^{-7}$ to 10^{-6} m/s in a natural fractured rock mass.

Low permeability materials: Calcareous and clay sandstones, siliceous microconglomerates (called "micro pudingas") and siliceous conglomerates (called "pudingas"). In these rocks the hydraulic conductivity

Table 1: Hydrogeological characteristics.

PERMEABILITY TYPE	MATERIALS	TRANSMISSIVITY (m^2/day)	PERMEABILITY (m/s)
Very Low	Shales or siltstone	0.005	2.96 10^{-8}
Low	Calcareous and clay sandstones, siliceous microconglomerates ("micro pudingas") and siliceous conglomerates ("pudingas")	6.5	3.92 10^{-5}
Variable due fissuring and/or karstification	Limestone and dolomites	Depending on the level of karstification and type of backfill	

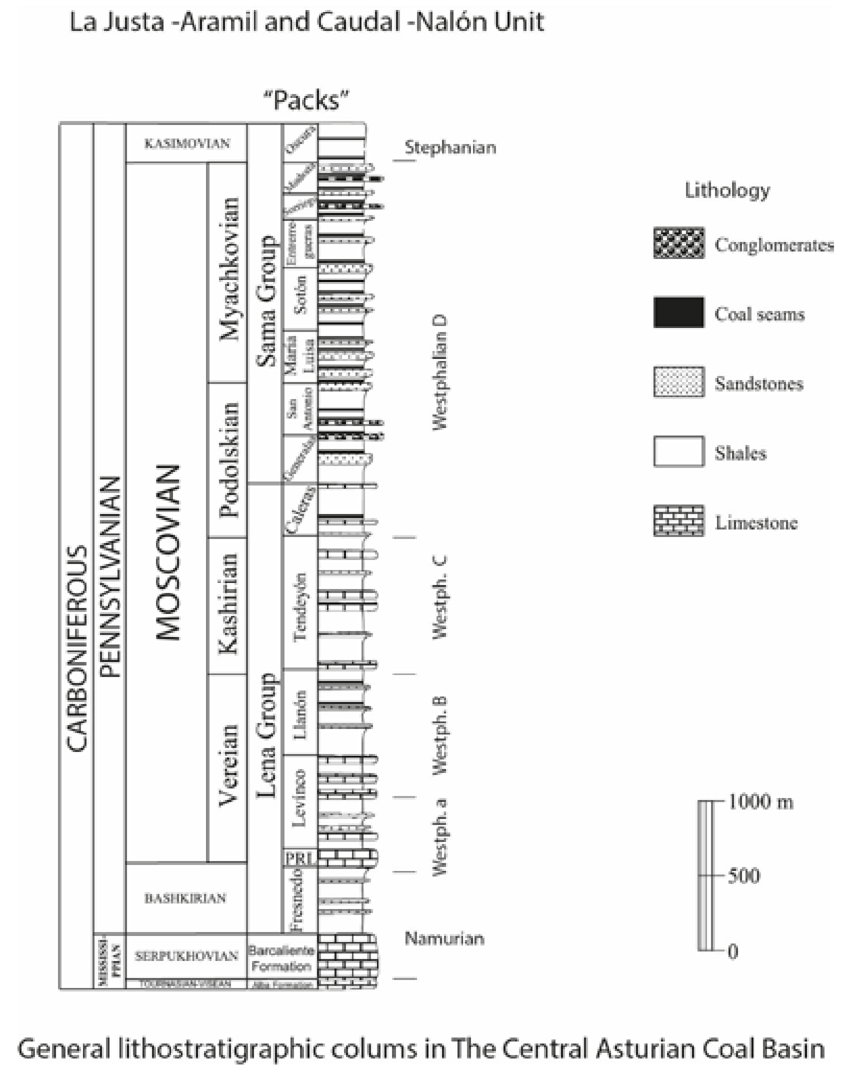

Figure 3: General stratigraphic columns in the Central Asturian Coal Basin (Sáenz de Santa María et al.*, 1985)*

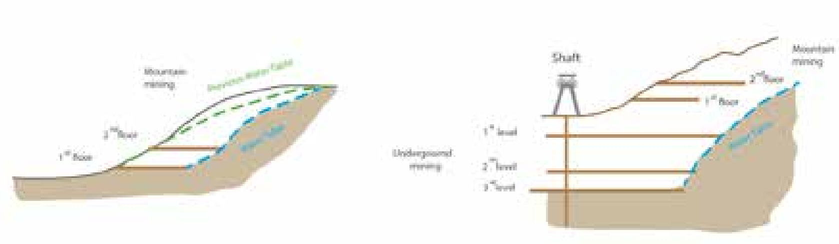

Figure 4: Drift mining and shaft mines (based on González and Rebollar, 1986).

is directly related to the degree of fissuring within the rock mass. Research carried out in areas surrounding the El Entrego and San Mamés mining works obtained transmissivity values of 6.5 m^2/day and permeability values of 3.92 x 10^{-5} m/s (Fandos *et al.,* 2004).

Variable permeability materials due to fissuring and/or karstification: Thin layers of limestone and dolomites randomly distributed between the series of shales and siltstones. These materials have developed a secondary permeability due to fissuring and/or karstification, even though their primary permeability is near zero.

4. Relief and Climate

The CCAB climate is included in the Western Europe Oceanic zone. Mild temperatures and elevated amounts of rainfall spread throughout the year are its main characteristics. Average yearly rainfall ranges from 1100 to 1300 l/m^2, the annual average maximum temperature ranges from 16 to 20 °C and the average minimum is from 4 to 9 °C.

The relief is especially uneven, the lower valley floors being at an average altitude of 280 m and the high mountains to the south of the basin rising to 1500 m. Height differences of 300 to 500 meters are very common on the steep slopes of the valleys in the mining zone, and have influenced the mining techniques used.

5. Mining Method

Mining operations have been carried out in the CCBA for the last 200 years. Drift mining or "mountain mining" was the mining method used during the mid-nineteenth century. Mining was carried out by digging tunnels at different levels from the surface (***Figure 4***) on the slope of a hill, driven horizontally into the coal seam. Coal was mined manually, in exploitation zones or panels ("talleres") with a steep slope connecting the upper and lower galleries. An inverse stair was created while mining the coal seam, and timber supports were used for protection against falls or collapse of the immediate roof. Slopes and ramps were opened to connect levels, usually in a downward direction, and were used for haulage of coal, supplies and waste.

Mining activities moved to the bottom of the valley as the coal layers worked by "mountain mining" or drift mining were depleted. Exploitation of coal seams at lower depths continued in shaft mines, underground mines in which the main entry or access is by means of a vertical shaft (called "El Pozo"). Most of the underground workings of the vertical shaft mines were finally connected with each other through galleries and some working faces, thus creating a vast network of underground galleries.

The rock mass containing the mined coal was modified substantially as a consequence of this intensive mining activity. It induced fracturing and fissuring of the rock mass, caused enlargement of existing voids, and created new man-made voids as the galleries and vent shafts were opened and other mining work was carried out. These changes allowed rain water to infiltrate the rock mass and drain through the different levels, especially through the mining voids, requiring the discharge of these waters by means of pumping to lower the piezometric level of the area. Such pumping activity had to be maintained throughout the working life of the mine shaft.

When the mining work ends and pumping is stopped, all the voids previously created gradually flood. This groundwater flow raises the piezometric watertable level, whose position may not coincide with the initial one (Younger *et al.*, 2002) making it necessary, in some cases, to maintain permanent pumping in order to avoid flooding connected active mining zones or populated areas.

The Barredo-Santa Bárbara system coal mines comprise the Barredo, Figaredo (which has two shafts: San Inocencio and San Vicente), San José and Santa Bárbara shaft mines (***Figure 5***). They are connected at a number of locations (***Figure 6***).

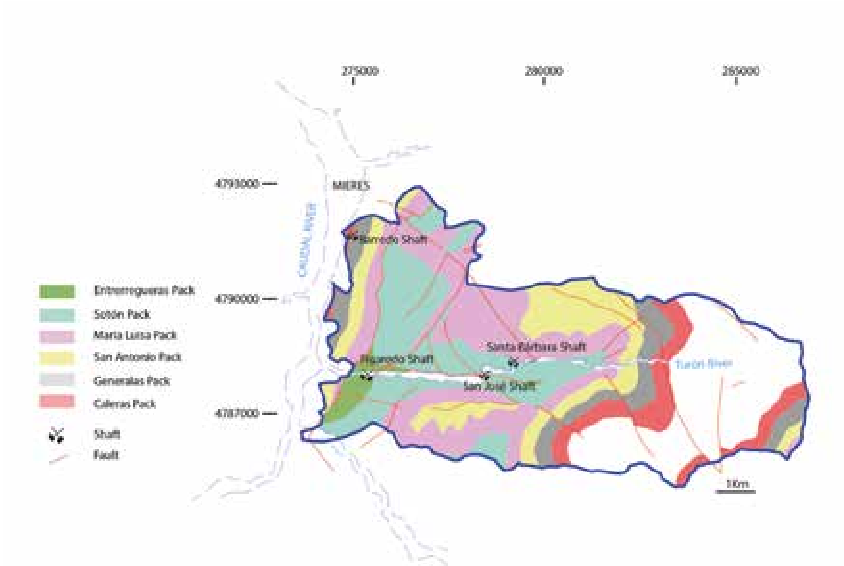

Figure 5: Delimited study area.

6. Barredo-Santa Bárbara Water Reservoir

In order to determine the volume available in the Barredo-Santa Bárbara system (***Table 2***), both the volume corresponding to the mine galleries and the corresponding voids generated by the coal operation (exploited coal seams, backfill zones, etc.) have been taken into account. The mine gallery volume was obtained from the plans of the mining work in the different mines, supposing an average section of 10 m². The voids volume generated by coal mining (exploiting the coal seam) has been estimated from coal production data. Estimates consider that 40% of the volume of coal exploited is void space that allows water flow, and that the remaining 60% has been filled by backfilling or controlled roof collapse, depending on the coal mining method used.

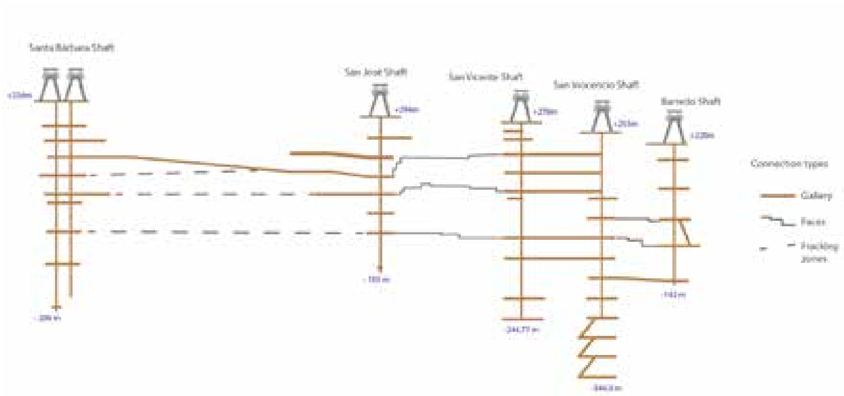

Figure 6: Connecting locations in the Barredo-Santa Bárbara system coal mines.

Table 2: Barreo-Santa Bárbara Water Reservoir.

MINE SHAFT	GALLERY VOLUME (Mm³)	MINED VOLUME (Mm³)	TOTAL VOLUME (Mm³)
Barredo	1.48	0.47	1.95
Figaredo	2.54	0.42	2.96
San José	1.71	0.45	2.15
Santa Bárbara	3.47	0.42	3.90
	9.20	1.76	10.96

7. Assessment of Mine Water as a Geothermal Resource

The Barredo-Santa Bárbara system coal mines have an average usable flow rate of about 6.2 hm³/year (pumping average flow rates), a regulation volume (mining voids) of more than 10 Mm³ with a stable all-year-long temperature above 20 °C (***Figure 7***). The mine water is usable for energy purposes (Gutiérrez *et al.*, 2016) and its quality is suitable for public water supply after being treated. Nevertheless, the elevated hardness of these mine waters is a drawback; this prevents its direct use in the heat pump, and therefore the use of heat exchangers is necessary.

8. Vital Álvarez Buylla Hospital Heating and Air Conditioning

This hospital serves more than 70,000 inhabitants, mostly from the Caudal River Basin, including the nearby urban settlements of Mieres, Aller and Lena. The hospital facilities have 120 rooms for patients and 28,000 m² floor space.The stable temperature and high available pumping flow of the mine waters allowed them to be used for geothermal heating and air conditioning.

The water flow to meet the demands of the hospital facilities, which varies due to the heating exchange demand, is pumped from the drainage system of the Barredo-Santa Bárbara system coal mines. The pumping station facility comprises four submersible pumps, each with a nominal flow of 215 m³/h and a head of 60 m.

The heat exchange system is located at the Barredo vertical mine shaft. It has a tubular heat exchanger, with three circuits and three manifolds made of AISI 316 stainless steel, designed for a flow rate of 400 m³/h in the primary circuit and 520 m³/h in the secondary circuit. It performs a heat exchange of 3500 kW, as the mine water transfers its energy to a closed loop circuit of "clean" water, which is piped to the hospital, located 2 km from the mine shaft (***Figure 8***).

The 2-km closed loop circuit is made of 400 mm diameter high density polyeth-

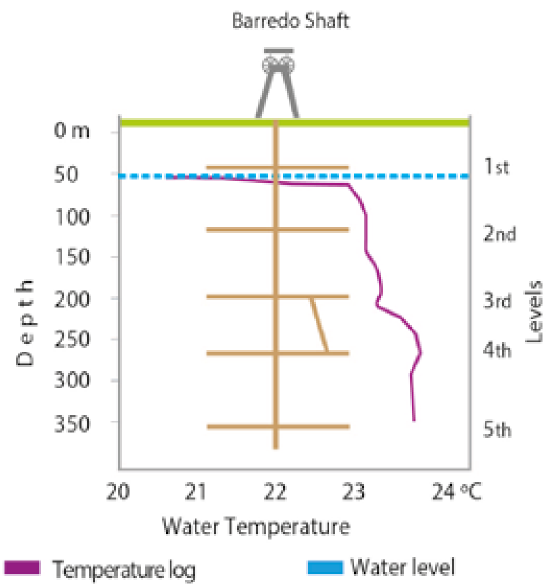

Figure 7: Water temperature vs. depth below surface.

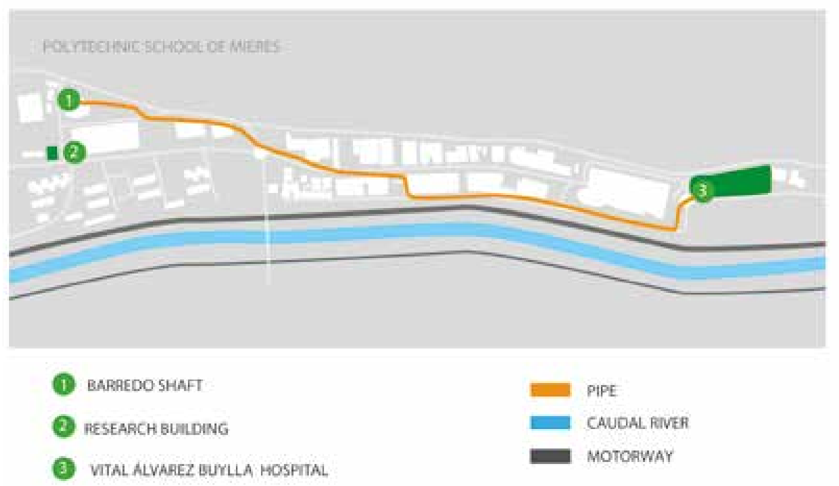

Figure 8: Map of the pipeline to the hospital.

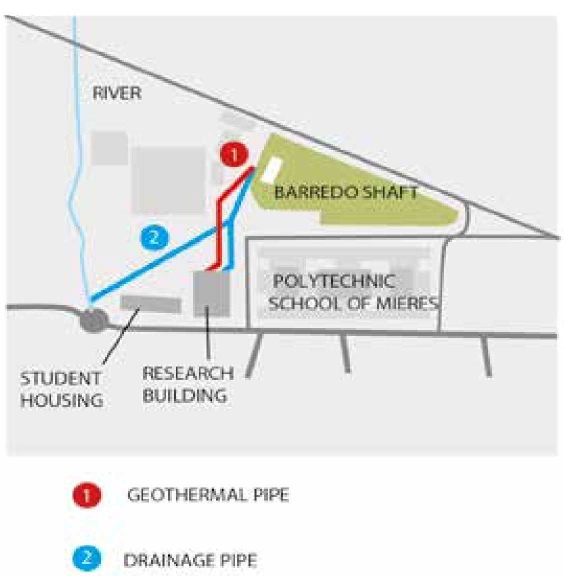

Figure 9: Pipeline layout.

ylene pipes, and 2+1 pumps that supply a 260 m^3/h flow rate with a head of 55 m to the hospital facilities. These pumps are equipped with variable frequency drives to regulate the water flow and therefore the energy that is transported to the hospital.

The hospital machine room comprises three heat pumps, two of which can work either in heating mode or refrigerating mode (1509 kW power each) and another one can operate in both modes simultaneously, generating both heat and cold at the same time (1298 kW).

Whenever the demands for heating and refrigerating are unbalanced, mine water is used as a compensation fluid, i.e., when the cooling demands exceed the heating demands, mine water is used to lower the temperature of the returned hot water by means of a plate heat exchanger. In the opposite case, during the winter the building is not able to consume all the refrigerated water that the heat pump requires to operate in equilibrium, so the mine water provides the necessary heat (using a second plate heat exchanger), allowing the heat pump to operate at the optimal temperature difference.

During 2015 the total useful energy supplied (heating and refrigerating) totalled 7,654,862 kWht (5.5 MWht of heat and 2.15 MWht of cold). In order to provide all this energy, there was a consumption of 1,343,780 kWh of electric energy (operation of heat pumps + closed loop circuit pumps).

A resulting reduction in CO_2 emissions of more than 80% and an economic saving of 10% (Gutiérrez *et al.*, 2016) is achieved compared with the traditional heating and refrigeration systems originally planned in the hospital.

9. Heating and air conditioning of the Research Building of the University Campus of Mieres

The drainage system of the Barredo-Santa Bárbara system coal mines provides the water flow demanded (120 m^3/h), as in the case of the Vital Álvarez Buylla hospital facilities. A multilayer polypropylene pipeline transports the mine water to the Research Building (***Figure 9***), where it gives up some of its energy, and then leads it to the nearby stream.

The building is equipped with two heat pumps, each with 362 kWt capacity and capable of producing hot water at 45 °C and cold water at 7 °C at the same time. A four-pipe fan coil system is used for heating and air conditioning. In 2015 the heat pumps required 61,605 kWh of electric energy and produced 235,747 kWht, used mainly for heating purposes. The use of this system results in important economic savings and a reduction of up to 70% in CO_2 emissions.

10. Conclusions

The Central Coal Basin of Asturias contains a large number of closed and flooded underground mines that make up "underground reservoirs" capable of being reused as water energy resources. Until now, mine water was being wasted but through the heat pump technology it can be successfully reused, reactivating the economy of the mining areas and allowing us to carry out a sustainable cessation of the traditional mining activity.

Mine water has enormous geothermal potential, with a stable all-year-long temperature and flow. Heat pump technology is now being applied to singular buildings located in Mieres using water from the Barredo-Santa Bárbara mine reservoir, reducing energy consumption, CO_2 emissions and contributing to economic savings when compared with a conventional system.

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ThermoProVal: towards improved guidelines for the realisation of borehole heat pumps in alpine geological settings

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Project ThermoProVal aims at promoting the use of shallow geothermal energy in alpine areas with a particular emphasis on the correct execution of geothermal boreholes. This is not only important to ensure sound performance of the borehole heat pump (BHP) during its life-cycle but also mandatory, as laid down in the Swiss Federal Waters Protection Ordinance. The ski resort of Verbier in the Swiss Alps is used as a case example. The study systematically compares the dimensioning of BHP based on a priori *parameter values (deduced from knowledge of the local geology and the SIA 384/6 Swiss codes) with results from* a posteriori *values obtained from thermal response tests (TRT). First observation indicates that BHP designs are generally significantly oversized by about 30 per cent. This discrepancy is a direct result of groundwater flows at depths that are easily evidenced by mean of TRT but rarely taken into account in conventional design. Groundwater flows, despite improving the effective ground thermal conductivity, represent also a serious challenge for drilling operations, leading to overbreaks, injection washouts and increased risks due to potentially confined groundwater conditions. ThermoProVal recommends establishing a set of specific survey and drilling guidelines for the realisation of BHP in alpine geological settings with a strong focus on optimising cooperation between geologists, drilling companies, heating engineers and the authorities.*

Le Projet ThermoProVal a pour but de promouvoir, en région alpine, l'utilisation de l'énergie géothermique à faible profondeur en insistant particulièrement sur la bonne exécution de forages géothermiques. Cela est non seulement important pour garantir le bon fonctionnement de la sonde géothermique verticale (SGV) pendant son cycle de vie, mais également une obligation découlant de l'Ordonnance Fédérale sur la protection des eaux. La station de ski de Verbier dans les Alpes suisses sert de cas d'école. L'étude compare de façon systématique le dimensionnement de la SGV à partir de valeurs choisies a priori *(valeurs déduites des données géologiques locales et des codes suisses SIA 384/6), avec les résultats obtenus* a posteriori *à partir de tests de réponse thermique (TRT). Les premiers résultats indiquent un surdimensionnement des SGV est en général surdimensionnée d'un facteur de l'ordre de 30%. Cet écart est dû à des circulations d'eau souterraine en profondeur qui sont facilement mises en évidence par moyen de TRT, mais rarement pris en compte lors d'une conception conventionnelle. Si ces circulations améliorent de fait la conductivité thermique réelle, elles représentent un défi important lors des opérations de forage conduisant à des hors-profils, des affouillements et des risques accrus en cas de conditions artésiennes. ThermoProVal vise l'établissement d'une série de recommandations spécifiques pour les études et les forages destinées à l'implantation de SGV en milieux géologiques alpins ainsi que l'amélioration de la coopération entre les géologues, les compagnies de forage, les ingénieurs en géothermie et les autorités.*

El proyecto ThermoProVal tiene como objetivo promover el uso de energía geotérmica superficial en áreas alpinas con un énfasis particular en la ejecución correcta de los pozos geotérmicos. Esto no sólo es importante para garantizar el buen funcionamiento de la bomba de calor del pozo (BHP) durante su ciclo de vida, sino también obligatorio, tal como se establece en la Ordenanza Federal de Protección de Aguas Federales Suiza. La estación de esquí de Verbier en los Alpes suizos se utiliza como ejemplo. El estudio compara de manera sistemática el dimensionamiento de BHP basado en valores de parámetros a priori *(deducidos del conocimiento de la geología local y de los códigos suizos SIA 384/6) con los resultados de los valores* a posteriori *obtenidos de las pruebas de respuesta térmica (TRT). Una primera observación indica que los diseños BHP son, en general, significativamente sobredimensionados en alrededor del 30 por ciento. Esta discrepancia es un resultado directo de los flujos de agua subterránea que se evidencian fácilmente por la media de TRT, y que raravez se tienen en cuenta en el diseño convencional. Los flujos de aguas subterráneas, a pesar de mejorar la conductividad térmica efectiva del suelo, representan también un serio desafío para las operaciones de perforación, lo que genera sobrecargas, fracasos de inyección y mayores riesgos debido a condiciones de aguas subterráneas potencialmente confinadas. ThermoProVal recomienda establecer un conjunto de guías específicas de prospección y perforación para la realización de BHP en entornos geológicos alpinos con un fuerte enfoque en la optimización de la cooperación entre geólogos, empresas de perforación, ingenieros de calefacción y las autoridades.*

Requirements for geothermal boreholes in Switzerland - a short overview

In Switzerland, the trend of implementing individual geothermal heating solutions for domestic purposes (borehole heat pumps – BHP) has steadily increased since the 2000s. Accordingly, in 2009 the Swiss Federal Office of the Environment (FOEN) released general recommendations (FOEN, 2009) to ensure harmonious practice between cantons[1] and application

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1 The Swiss Confederation consists of 26 cantons that all have a permanent constitutional status and, in comparison with the situation in other countries, a high degree of independence. The individual cantons have very different locations – the Alps, the Swiss Plateau and the Jura mountains – and differ not only in topographical characteristics but also in population and degree of urbanisation. In terms of resource management, the Swiss cantons remain sovereign over their underground resources, which is also the case for geothermal energy.

of the legal requirements relevant to the authorisation procedure. These are briefly described as follows.

Land planning and construction requirements:

With respect to the Swiss Constitution, land owners have the right to freely use the underground space to the depth required to cover their needs. Some limitations are however introduced regarding how the public domain is defined, limiting accordingly the available depth, or if the used resource has economic value. To gain a construction permit, every project inquiry requires a public consultation phase where potentially affected citizens can make use of their right to oppose the project. If there is no opposition, the construction authority delivers a permit.

Environmental and water protection requirements:

The construction permit includes a set of general conditions that address overall quality prescriptions aimed at ensuring sound execution of the project and proper initial evaluation of environmental impacts. Implicitly, geothermal boreholes are to be executed by well-trained professionals applying the most recent technical standards. Specific conditions are moreover defined in the Swiss Federal Legislation on Water Protection (Water Protection Ordinance): the use of shallow geothermal heat, i.e. in Switzerland to a depth generally not exceeding a few hundred of meters, must not affect groundwater quality or its dynamics, and a local thermal equilibrium of aquifers is to be maintained.

Energy planning requirements:

The Swiss Energy Strategy calls for the promotion of indigenous renewable energies in the energy mix of Switzerland. With this regard, federal subsidies are allotted to support the development of individual heating solutions based on renewable energies, as well as for the replacement of electric or fossil-fuel based heating. This explains in part the interest in BHP in the last decade. In this context, it is the task of the cantons to develop a rational and efficient energy planning at the local and regional scale. How to realise these objectives in very disparate settings (urban vs. rural, lowland vs. highland areas) is left to the judgement of cantonal or in some cases local authorities. As such, they are implicitly responsible for adequately monitoring and anticipating the cumulative effect induced by the multiplication of BHP projects.

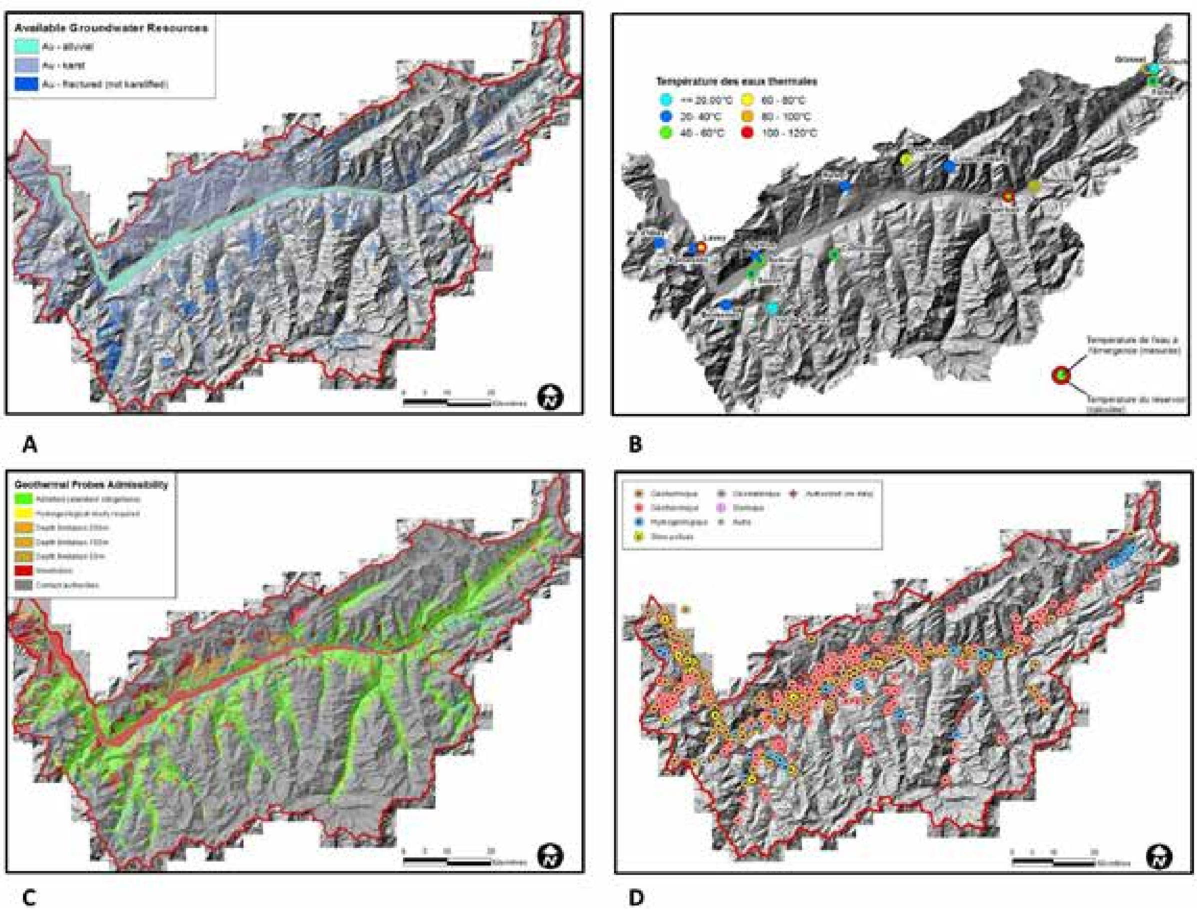

*Figure 1 : A) Spatial extent of the major hydrogeological reservoirs in Canton of Valais: alluvial (green), karst (pale blue) and fractured (blue). Currently, the extent of fractured rock type aquifers are affected by the biggest uncertainty in terms of structure and geometry. As such, potentially available groundwater ressources in these settings are still roughly estimated. B) Hot springs in Valais with indication of the measured spring temperature and the inferred temperature of the associated geothermal reservoir. Courtesy of CREALP. C) Availabilty map for geothermal boreholes (used to study the feasibility of a BHP project). Within the construction zone, a set of general and specific conditions apply for boreholes, as defined by the current geological knowledge. There is a general interdiction on geothermal probes in the Rhone Valley due to protection requirements of the Rhone aquifer. In the Rhone Valley, extensive use of open loop groundwater heat pumps is performed (not discussed in this paper). D) Borehole Database of Canton Valais (**https://geocadast.crealp.ch**). At the end of 2016, about 5,500 logs were publicly made available through the internet.*

To simplify the evaluation of projects, FOEN recommends the canton to develop "admissibility maps", which are land planning instruments aiming at reliably assisting land owners and contractors in the initial feasibility assessment of geothermal boreholes. Such instruments compile available information in a risk assessment and management perspective, defining "open" and "closed" zones for boreholes, as well as sectors where a maximum borehole depth has to be respected or where additional geological investigations are required. Layers of information that are generally compiled are water protection measures, maps of contaminated sites, interpreted geological data (i.e. derived from 1:25,000 geological maps & cross-sections, maps of geological hazards, past surveys, research …), and underground infrastructures such as tunnels, hydroelectric/gas pipes, etc.

To address the dimensioning and design requirements of BHP, in 2010 and 2015 the Swiss Society of Engineers and Architects (SIA) released two dedicated codes: 384/6 for geothermal probes (i.e. BHP) and 384/7 for groundwater heat pumps. They provide a set of standard technical recipes and introduce calculation schemes accounting for the thermal response of common geological ground materials. Specific recommendations for individual projects are given based on the predicted energy needs, broadly differentiating between "regular" and "complex" projects. For a complex design, the use of numerical computation is mandatory. However, a lack of accurate data about site condition and detailed underground structure challenges model parameterisation, often resulting in overestimation and the introduction of conservative security factors.

Recently, conflicts among neighbours related to interfering BHP are increasing in densely constructed areas, leading authorities and professionals to evaluate potential adjustments of the SIA codes and question long-term resource management issues. This problem is twofold: on one hand, improvement of the overall design of BHP is addressed. On the other hand, potential improvement in the execution of geothermal boreholes by the drilling companies is evaluated. Especially since 2015 a more holistic approach has been promoted to avoid the risk of a loss of confidence in the BHP technology. Case studies have been carried out in the city of Zürich (Wagner *et al.*, 2015). An evaluation of analysis techniques to document more accurately the correct implementation of geothermal boreholes has been moreover published under the support of the Swiss Federal Office of Energy (Energie Schweiz, 2015).

Confronted with the challenges of underground planning, several Swiss cantonal administrations are currently reinforcing their geological data recovery policies. A recent document from the Swiss Federal Office of Topography (swisstopo) provides a legal framework for a standardised geological data collection, management and processing for broad and effective public access (Kettiger, 2016). Such progress should make it easier in the future to constantly actualise admissibility maps for geothermal projects, minimising risk of potential conflicts, reducing uncertainties in geothermal resource assessment and management, and promoting more efficiently the use of both shallow and deep geothermal energy in a long-term perspective.

Geothermal potential of the canton of Valais

Despite a particularly contrasted geological setting hosting some of the most emblematic mountains across the country, a common quote inherited from the mining rush in the 19th century refers to the Canton of Valais as a land "rich in poor raw materials". However, from a 21st century perspective, generalised availability to water resources in Valais represents one of the major economic values of the Canton, with a strong contribution to national hydropower production and facilitated access to high standard drinking water. In the current energy debate in Switzerland, geothermal energy as a contributor to the indigenous production of renewable energy (heating + power) should gain attention very soon. Potential targets in Valais have been defined already since the early 1990s (Bianchetti *et al.*, 1992; Sonney and Vuataz, 2008).

For groundwater protection issues (but also geothermal resource assessment), three major typologies of reservoir are delimited on the hydrogeological map of the Canton of Valais (***Figure 1A***). Based on information from thermal springs, each of these reservoirs is potentially attractive for geothermal prospection (***Figure 1B***) and would benefit from exploration programmes as they are still poorly documented.

Geothermal heating in Valais is currently restricted to shallow potentials, mainly through vertical BHP but also open loop groundwater heat pumps. ***Figure 1C*** depicts the admissibility map for geothermal boreholes of Valais. Each year, information from newly realised boreholes assists the actualisation of the map. In recent years, the Canton of Valais has focussed on gathering information about groundwater flow paths at depth. A major contribution to geological knowledge and resource management is therefore borehole data. The Canton of Valais has been maintaining a borehole database since 2013, with about 5,500 logs made accessible online at the end of 2016 (***Figure 1D***).

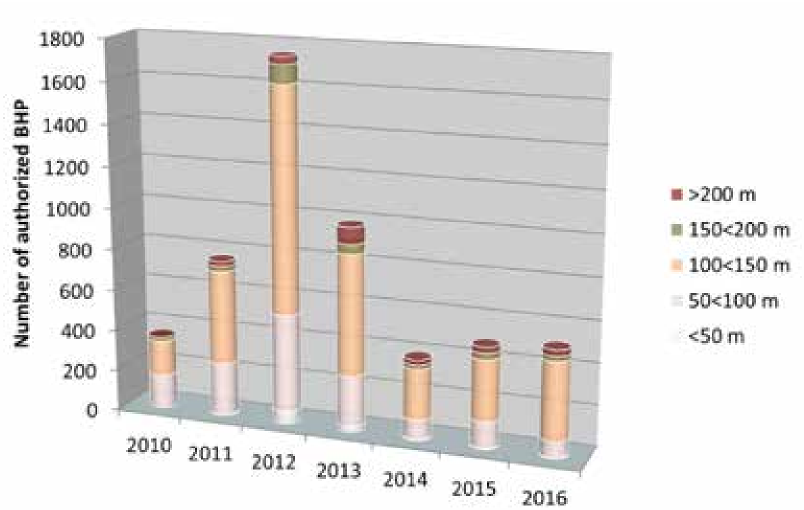

Figure 2: Changes in BHP demand in the Canton of Valais between the years 2010 and 2016 highlighting typical borehole depths. Data represents the total number of authorised boreholes. A peak in demand was observed in 2012, related to a 2011 modification in the land planning policy that introduced a limited construction quota for municipalities outside urbanised areas. Accordingly, an excess amount of BHP projects were submitted to the cantonal authority to be delivered a permit before these new rules became effective. Note that the majority of BHP projects are realised at a depth between 50 and 150 m. Data do not differentiate between individual BHP and BHP fields.

It is expected that the continuous documentation of underground resources will strongly benefit and assist the economic development of Canton Valais in the 21st century and facilitate project planning through high-level risk assessment and thorough evaluation of environmental impacts.

BHP in Valais: Trend and challenges

On average, 400 borehole authorisations are issued every year in Canton Valais by the Service of Environmental Protection. More than 50% are BHP (open loop groundwater heat pumps included). In this context, individual projects often need multiple boreholes (BHP fields), assuming sometimes very complex design with up to 30 boreholes per project. Over time, improper (i.e. inaccurate) design increases the risk of resource overuse and damage to the system, potentially leading to groundwater contamination issues. The evolution of BHP in Valais between the year 2010 and 2016 is illustrated in ***Figure 2***, highlighting typical drilling depths.

Despite fairly harmonised authorisation conditions, among which is the obligation to transmit to the authorities a documented borehole report including geological log, transmission of geological information unfortunately still occurs in less than 20% of the cases.

The Service of Environmental Protection of Canton Valais is currently working on the release of a practical guideline for professionals and construction authorities, informing them about BHP standards and communicating about related hazards. ***Figure 3*** summarises possibly affected objects with BHP and depicts principles for more sustainable resource management at the local and regional scale, used to proactively limit neighbourhood conflicts and damage to existing construction and infrastructures.

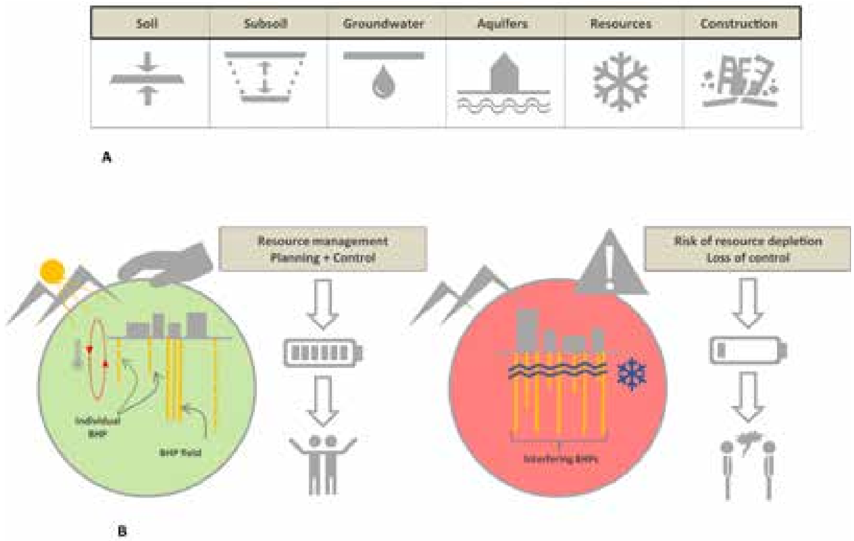

Figure 3: A) Depiction of common risks and impact patterns associated with the realisation of BHP in alpine geological settings and generally taken into account to compile "admissibility maps". To assess the effect of a new BHP project on the local geothermal resource, knowledge about existing projects in the neighborhood is of paramount importance. The pictograms were developped by the Service of Environmental Protection as a mean to stimulate communication and understanding of the problems inherent to BHP in Valais. Practical Guidelines for practitioners and authorities are in preparation. B) "Good" and "bad" behaviours in the use of shallow geothermal energy in alpine geological settings. The lack of planning and an uncoordinated realisation of individual projects seiously increase the risk of interference between nearby BHPs, resulting in faster depletion of the available geothermal heat and increasing the occurrence of neighbourhood conflicts. Coupling BHP with solar energy, surrounding or exhaust air, can be used to ensure an active regeneration of geothermal heat and might provide a viable practice to solve existing conflicts, especially in alluvium. See Wagner et al. *(2015) for a complete discussion.*

Project ThermoProVal - A case study in the Swiss Alps

Project ThermoProVal aims at promoting the use of shallow geothermal energy in alpine areas with a particular emphasis on the correct execution of geothermal boreholes. A key aspect of the project is therefore to help improving project design based on an initial approval of ground thermal response and more careful consideration of both geology and hydrogeology at the local scale.

According to the SIA 384/6 Swiss codes, the design of BHP is mainly influenced by the thermal properties of soils, especially their thermal conductivity (i.e. their property to conduct heat). Thermal parameters of soils are mainly determined by laboratory tests on homogeneous samples, though they are strongly influenced by their water content. In rocks, water content depends essentially on the degree of disturbance of the rock mass, i.e. fracture network development. There is therefore a strong scale effect to take into account when extrapolating those values to real project conditions.

Several mathematical relationships make it possible to correct the laboratory value of thermal conductivity using various parameters characterising, for instance, the mineralogical composition of the soil or its water content (Reiffsteck *et al.*, 2013). Nevertheless, due to the number of required parameters and the difficulty of assessing them, tabulated values – like those proposed by the SIA 384/6 codes – are commonly used for designing BHP projects. This approach has proved to be suitable for fairly homogeneous geological conditions, but is challenged in the presence of complex ground conditions, especially where groundwater flow patterns are inferred or overlooked. Water circulation at depth not only strongly increases thermal ground response, but requires particular care during drilling operations to secure clean borehole execution and ensure the level of groundwater protection required by the Swiss Water Protection Ordinance.

Based on an analysis of current practice, three steps have therefore been defined in the framework of the project, using the densely constructed ski resort of Verbier (Bagnes municipality) as a case example.

Critical analysis of a priori BHP design

SIA Code 384/6 code requires ensuring a life cycle for BHP of at least 50 years. A mapping of known projects across the Val de Bagnes territory has therefore been conducted (***Figure 4***). Based on available data, typical expected lithological columns were defined to help characterise geological heterogeneity within three main sectors assumed to have contrasting ground thermal response (***Figures 4 and 5***).

Thermal parameters are assessed according to the values tabulated in the SIA 384/6

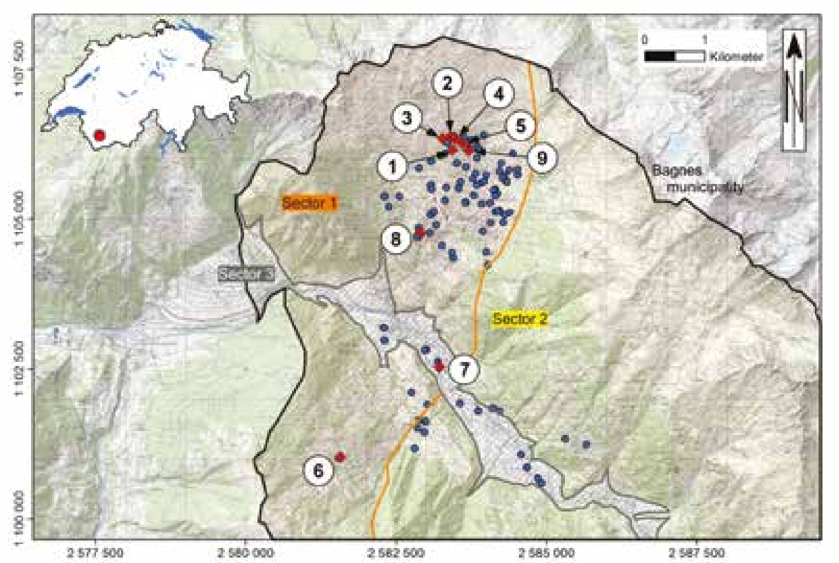

Figure 4: Bagnes municipality (reproduced with authorisation of swisstopo nr. JA100035): localisation of known BHPs (blue dots) and subdivision of the territory based on geological characteristics. Sector 1: predominance of shale (flysch, carbonaceous shale), partially covered by Quaternary deposits; Sector 2: crystalline rocks (mainly quartzite or gneiss), partially covered by Quaternary deposits; Sector 3: Quaternary glacial and fluviatile deposits (alluvium). BHP projects where a TRT could be performed in the framework of project ThermoProVal are highlighted in red. Indicative numbers refer to selected projects for which a simplified lithological columns and thermal conductivities are given in ***Figure 5.*** *The majority of BHP data are clustered around the village of Verbier in the northern part of sector 1. Please note that currently no TRT data is available for sector 2.*

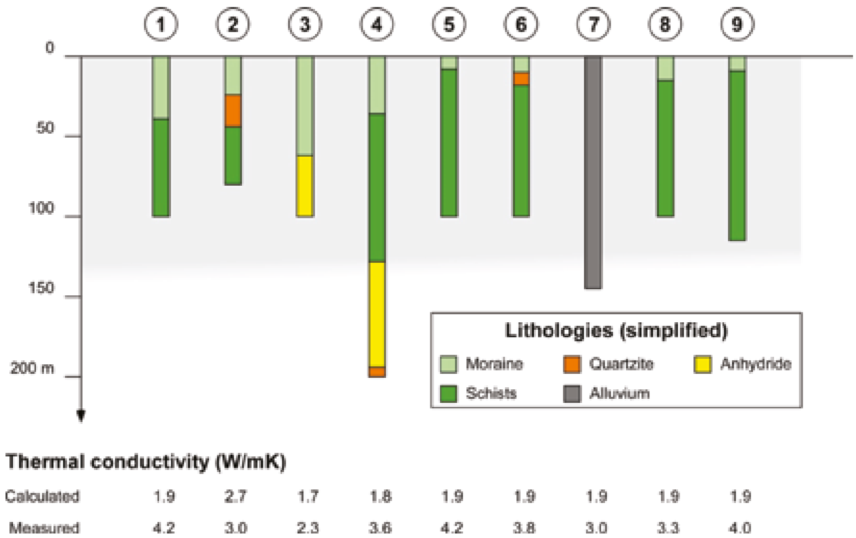

Figure 5: Simplified lithological columns for 9 BHPs realised on the territory of the municipality of Bagnes as depicted in ***Figure 4.*** *For each project, the* a priori *calculated thermal conductivity (derived from SIA 384/6 codes) is compared with the a posteriori calculated thermal conductivity (based on TRT results). This synthesis for various BHP analysed within the ThermoProVal project indicates a discrepancy of about 30% between theoretical and real ground thermal parameters.*

codes. Based on single values, a theoretical thermal conductivity along the entire borehole can be calculated. As can be seen in ***Figure 4***, the density of available geological data in the case of Bagnes is quite disparate. This makes it currently difficult to assess the thermal potential of each geological sector with the same level of accuracy. The ski resort of Verbier (Northern part of sector 1 in ***Figure 4***) can be predicted with better confidence.

Confronting a priori design with real ground conditions

In situ thermal response tests (TRT) (Gehlin, 2002; Energie Schweiz, 2015) on selected BHP projects under construction provide a mean to *a posteriori* compare BHP designs with in situ measured thermal conductivity along the entire borehole length. In the ThermoProVal project, TRT are performed about 10 days after the installation of the BHP by the drilling company; the delay is in order to avoid effects of exothermal reaction induced by grouting. TRT duration is about 3 days.

To help assess groundwater flow paths and conflicting situations along the borehole length, thermal profiles are made before and after the completion of a TRT (***Figure 6***). Such information is pivotal to assess the quality of the drilling execution and the quality of the grouting operations. Volumes of injected bentonite-cement mixtures have to be cautiously documented by the drilling company to allow for a critical comparison with the TRT interpretation by the geologist.

Case by case interpretation of BHP performance

The comparison of *a priori* (theoretical) parameters with *a posteriori* (measured) parameters allows better anticipation of the expected short and long-term behaviour of BHPs. Any data provided by the drilling company and – if available – by the geologist supervising the project are essential in this context, and should be collected and analysed properly by those responsible for any BHP project.

With a multiplication of individual projects on an already densely constructed area, neighbouring BHPs can negatively interact over time. With heterogeneous geological conditions that can significantly affect ground thermal response, performance bias can very easily be introduced, increasing the risk of conflicts with concurrent BHP or accelerating depletion of the geothermal resource (***Figure 3B***).

Surprisingly, it has proven difficult to convince architects and engineers responsible for individual BHP projects to engage in critical design analysis – even in the framework of Project ThermoProVal, which gave them an opportunity to carry out a TRT without additional costs.

This challenge would have therefore to be directly addressed by the different authorities in charge (construction, energy and environmental protection). Within the

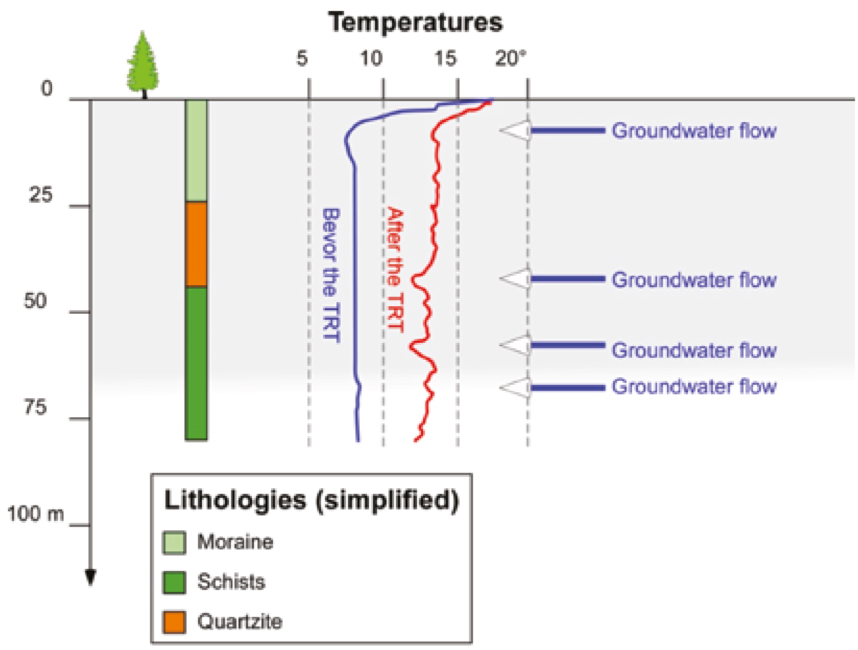

*Figure 6: Example of thermal profiles realised as part of TRT, illustrating the presence of groundwater flows (case no. 2 in **Figures 4 and 5**). Based on the available borehole report, data are sparse in terms of groundwater characterisation (flow rate, temperature, chemistry, etc.). The geological information system of Canton Valais should be dedicated in the future to allow access to such information at an early stage of the feasibility assessment for new BHP projects.*

ThermoProVal project, it is accordingly proposed to monitor a set of selected BHP projects representative of the geological sectors depicted on ***Figure 4*** in order to progressively gain knowledge on the seasonal variation in ground thermal response and to help promote and optimise resource management at the local to regional scale through effective and binding recommendations.

Application of geological knowledge: recommendations for BHP in alpine geological settings

Project ThermoProVal is conducted on the Bagnes territory of Canton Valais and takes the ski resort of Verbier as a case example to perform a critical analysis of the development of BHP in alpine geological settings. The observations made in this context are representative of other Swiss alpine municipalities facing similar development trends, both in terms of construction and shallow geothermal energy consumption. They confirm that there is a high level of uncertainty prevailing during the design of BHP projects. In the case of Verbier, ground thermal parameters based on Swiss codes and used for the design of BHPs are generally significantly underestimated by about 30 per cent (***Figure 5***). As a consequence, the length and/or number of BHPs – and therefore the costs of installation – are overestimated by the same amount.

This discrepancy is a direct result of (sub)-horizontal groundwater flows that are easily evidenced by means of the thermal profiles carried out as part of TRT, but rarely taken into account by the geologists during the design stage – and surprisingly rarely pointed out by the drilling companies, likely because they are subject to severe financial and time constraints. The existence of these localised groundwater flows, part of the hydrogeological systems supplementing drinking water resources, often go together with abnormal high grout consumption reported by the drilling companies, and signal the likely presence of overbreaks and grout washouts. In such cases, optimal thermal contact between the BHP and the soil is difficult to ensure, especially in the long run. Some thermal profiles even demonstrate the existence of vertical groundwater flows, indicating a real risk of interconnecting superimposed aquifers. This situation might lead at depth to progressive contamination of drinking water resources and clearly contravenes the Swiss Federal Water Protection Ordinance.

Facing suboptimal practices, one of the main motivations to initiate Project ThermoProVal was therefore to demonstrate that the sound, performance-oriented planning of BHP could be relatively easily addressed if closer collaboration between geologists (evaluation and projection of in situ conditions), engineers (BHP design and requirements) and drilling companies (correct execution of BHP boreholes) could be ensured.

In the case of BHP, local but also regional hydrogeological conditions largely control thermal ground parameters but short- and long-term effects are often difficult to anticipate, because the influence of groundwater flow paths on the effective performance of the geothermal installation is unknown. Long-term monitoring – for instance as suggested in ThermoProVal by equipping selected boreholes with fibre optics and making regular thermal profiles – could provide an interesting mean with this respect. Unnoticed groundwater flows represent also a huge challenge for drilling companies, because of the aforementioned problems of grouting, instability or interconnecting aquifers. Here again, access to better initial geological input can massively help reduce potential risks and define protective measures for drilling operations. For instance, the systematic use of a geotextile wrap in order to avoid grout washouts could be a simple and low-price solution, if washout is anticipated.

Based on these considerations, availability maps for geothermal boreholes can be improved by adding information accounting for groundwater occurrence at depth in order to lower the level of uncertainty. In the case of Bagnes, zones of *"possible groundwater flows"* (for highly fractured and permeable rocks), *"probable groundwater flows"* (near boreholes that show the presence of water) and *"confirmed groundwater flows"* (in or close to groundwater protection zones) are currently being discussed. Because feasibility studies in alpine geological settings are still very often confronted with a substantial lack of initial information about geological and hydrogeological conditions, authorities have a key role to play in order to promote a geological information system that would be accessible to professionals and where integrated data from previous BHP projects could be consulted. This is relevant not only for heating engineers but also for drilling companies.

With this in mind, Project ThermoProVal wishes to establish applicable guidelines for drilling operations in regions with a partly unknown and highly heterogeneous geology. In order to ensure resource management in the long-term, one of the biggest challenges remaining is the need to facilitate communication between the different protagonists involved at the administrative and practical levels. It still seems therefore quite fair to remind all those involved that correctly executed projects not only lead to longer-term efficiency of BHP but also to improved protection of public resources, both from an energetic and environmental perspective.

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Hydrogeological modelling of geothermal waters in Pamukkale, western Anatolia, Turkey

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The study area, located in the eastern part of the continental rift zone of the Büyük Menderes within the Menderes Massif, western Anatolia, is composed of Paleozoic metamorphic rocks, Mesozoic limestones and Eocene via Pliocene to Quaternary sediments. Paleozoic marbles, quartzites and carbonate schists, Mesozoic limestone, Pliocene sediments and Quaternary alluvium and travertine serve as permeable rocks for the geothermal waters. The geothermal waters in Pamukkale and environs with outlet temperatures of about 35 °C and reservoir temperatures up to 250 °C can be considered as Ca-Mg-SO_4-HCO_3 type waters. The formation of the travertine in Pamukkale is one of the world's wonders, directly connected with decreasing temperatures and CO_2 partial pressures. The formation of travertine deposits depends upon the solubility of $CaCO_3$ controlled principally by CO_2 partial pressure, temperature and pH values, in which reaction equilibriums play an important role. Moreover, the travertine deposits, which show a U-series age of at least 400 ka form one of the important world wonders. The geothermal waters of Pamukkale, with its high sulphate contents up to 650 mg/l and Rn concentrations up to 20 Bq/l, were modelled hydrogeologically from schematical points.

La zone étudiée, localisée dans la partie orientale de la zone de rift continentale du Büyük Menderes, à l'intérieur du massif de Menderes, en Anatolie occidentale, est constituée de roches métamorphiques paléozoïques, de calcaires mésozoïques et de sédiments d'âges éocène, pliocène à quaternaire. Les marbres du Primaire, les quartzites et les calcaires schisteux, les calcaires mésozoïques, les sédiments pliocènes et les alluvions et travertins quaternaires représentent des formations perméables pour les eaux géothermales. Celles-ci à Pamukkale et ses environs, présentant, à la sortie, des températures d'environ 35° C et des températures de réservoir pouvant atteindre 250° C, peuvent être considérées comme des eaux de composition contenant les éléments Ca-Mg-$S0_4$-$HC0_3$. La formation de travertin à Pamukkale est l'une des merveilles du monde, directement liée aux baisses de température et, en partie, de pression du $C0_2$. La formation des dépôts de travertin dépend de la solubilité du $CaC0_3$, contrôlée principalement par, pro parte, la pression de CO_2, la température el les valeurs de pH, solubilité pour laquelle les équilibres de réaction jouent un rôle important. De plus, ces dépôts, d'âge minimum 400 000 ans -datation à l'uranium- constituent aussi une merveille du monde, significative. Les eaux géothermales de Pamukkale avec leur haute concentration de sulfate (jusqu'à 650 mg/l), et de radon (jusqu'à 20 Bq/l) ont fait l'objet d'une modélisation hydrogéologique à partir d'un échantillonnage de points.

El área de estudio, situado en la parte oriental de la zona del rift continental de los Büyük Menderes dentro del Macizo de Menderes, Anatolia occidental, está compuesta de rocas metamórficas paleozoicas, calizas mesozoicas y eoceno a través de pliocenos a sedimentos cuaternarios. Los mármoles paleozoicos, las cuarcitas y los carbonatos esquistos, la piedra caliza mesozoica, los sedimentos del Plioceno, el aluvión cuaternario y el travertino sirven como rocas permeables para las aguas geotérmicas. Las aguas geotérmicas de Pamukkale y sus alrededores con temperaturas de salida de aproximadamente 35 ° C y temperaturas de depósito hasta 250 ° C pueden considerarse como aguas de tipo Ca-Mg-SO_4-HCO_3. La formación del travertino en Pamukkale es una de las maravillas del mundo, directamente conectado con la disminución de las temperaturas y las presiones parciales del CO_2. La formación de depósitos de travertino depende de la solubilidad del $CaCO_3$ controlado principalmente por la presión parcial del CO_2, la temperatura y los valores de pH, en los cuales los equilibrios de reacción juegan un papel importante. Por otra parte, los depósitos de travertino, que muestran una edad de la serie U de al menos 400 ka forman una de las maravillas mundiales importantes. Las aguas geotérmicas de Pamukkale, con su alto contenido de sulfatos hasta 650 mg/l y concentraciones de Rn hasta 20 Bq/l, fueron modeladas hidrogeológicamente desde puntos esquemáticos.

In Turkey, geothermal waters are located in large areas in connection with tectonic features and volcanism from the Middle Miocene to recent in age. The high-enthalpy geothermal waters form in the continental rift zones of the Menderes Massif, which suffered compression and later extension tectonics. The study area of Pamukkale is located 20 km NW of the provincial capital of Denizli (***Figures 1 and 2***) which is 360 m above sea level. The geothermal waters of Pamukkale are located in the southern shoulder of Çökelez Mountain, in the travertine platform and within the travertine mass forming an unrivalled example in the world. The area of travertine and the antique ruins of the Hierapolis City form an important centre due to its original natural structures and historical value. The study area of Pamukkale has an area of 44 km^2 and is a Special Environment Protection Region with five residential areas: Develi, Karahayit, Pamukkale, Yeniköy and Akköy. The aim of this study is (i) to update geological mapping of the geothermal areas in Pamukkale and environs, (ii) to describe the water-rock interaction by mineralogical, petrographical and geochemical working methods, (iii) to investigate the formation and development of geothermal waters by hydrogeological, hydrogeochemical and isotope geochemical methods and (iv) to create an conceptual hydrogeological model of the Pamukkale geothermal field.

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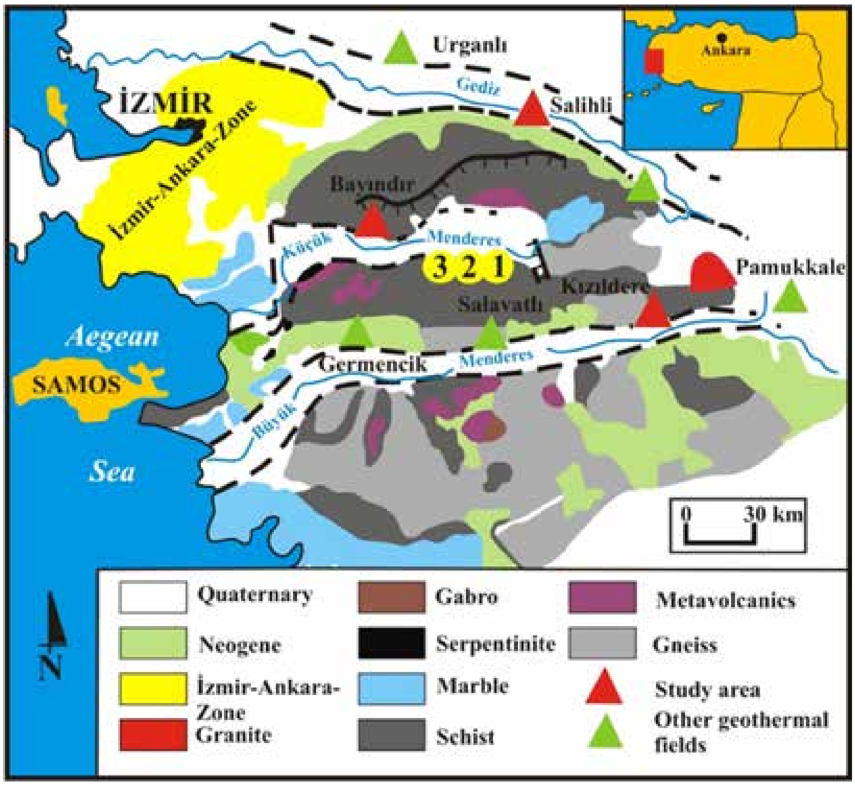

Figure 1: Geological map of the Menderes Massif and the location of the study area of Pamukkale. 1: Mercury deposit of Haliköy, 2: Antimony deposit of Emirli, 3: Arsenopyrite and gold deposit of Küre (modified from Özgür, 1998).

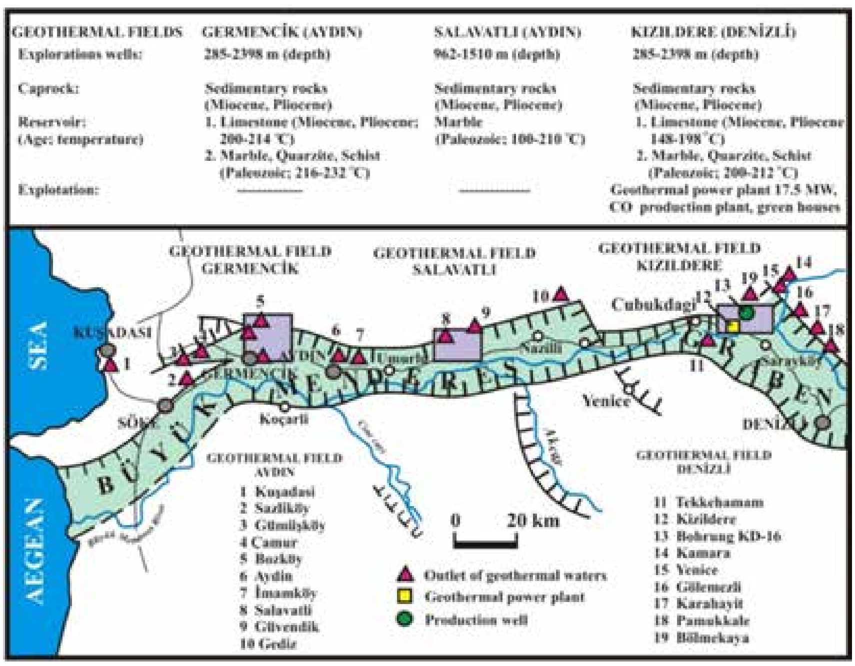

Figure 2: Geothermal waters in the rift zone of the Büyük Menderes and the location of Pamukkale (modified from Özgür, 1998).

Material and methods

In order to understand the hydrogeochemical features of the geothermal waters in Pamukkale and environs, 16 samples were collected (Kıymaz, 2011; Kutlu, 2015; Uzun, 2017) (***Figure 3; Table 1***). During this sampling campaign, in-situ measurements such as temperature, pH, Eh, electrical conductivity and alkalinity were taken (***Table 1***). The cations of Na^+, Ca^{2+}, Mg^{2+}, K^+, Si^{4+} and B^{3+} were analysed by ICP-OES methods, while the analyses of anions such as F^-, SO_4^{2-}, Cl^- and NO_3^- were performed by IC methods. The values of HCO_3^- and CO_3^{2-} have been calculated by the alkalinity measurements in the field. The evaluation of the hydrogeochemical data was carried out using Aquachem 3.7 (Calmbach, 1999).

Results

Geologic setting

Denizli Basin is located in the Aegean Region, where the E-W trending continental rift zone of the Büyük Menderes – limited by active and normal faults – and the NW-SE trending continental rift zone of the Gediz incorporate (***Figure 4***). In the study area, Paleozoic metamorphic rocks of the Menderes Massif form the basement rocks which are overlain by Mesozoic limestones, Eocene to Pliocene sedimentary rocks and Quaternary alluvium and travertine. The travertine of Pamukkale precipitates on the falling block of the Pamukkale fault, which is located in the eastern part of the basin and constrains the basin in the North (Altunel, 1996). In the areas with intensive fissures of the main fault, intensive precipitations of travertine can be observed. Parallel to oblique fissures were generated in connection with main Pamukkale fault. In the study area, opening fissures were observed, and ridge type travertine has been observed in some of the fissures. With the exception of Pamukkale, the travertine of Denizli can be observed in localities such as Yeniköy, Küçükdereköy, Irlıganlı, Kocabaş, Koyunaliler and Karateke in the eastern direction. The factors affecting the precipitation of travertine are (i) the compositions, saturation indexes and partial CO_2 pressures of geothermal and mineral waters, (ii) the temperatures, flow regimes and flow rates of the geothermal waters and (iii) the temperature of the geothermal waters during flow.

Hydrogeology

In the study area, Paleozoic marbles, Mesozoic limestones, Pliocene sediments and Quaternary alluviums and travertine occur as permeable rocks in general. Paleozoic marbles can be observed between Karahayıt and Pamukkale and in the NE part of the Pamukkale main springs, whereas Mesozoic limestones occur to the north of Pamukkale main springs. Pliocene sediments are found in the environs of Pamukkale main springs and in the upper part of Yenice horst between Pamukkale and Karahayıt.

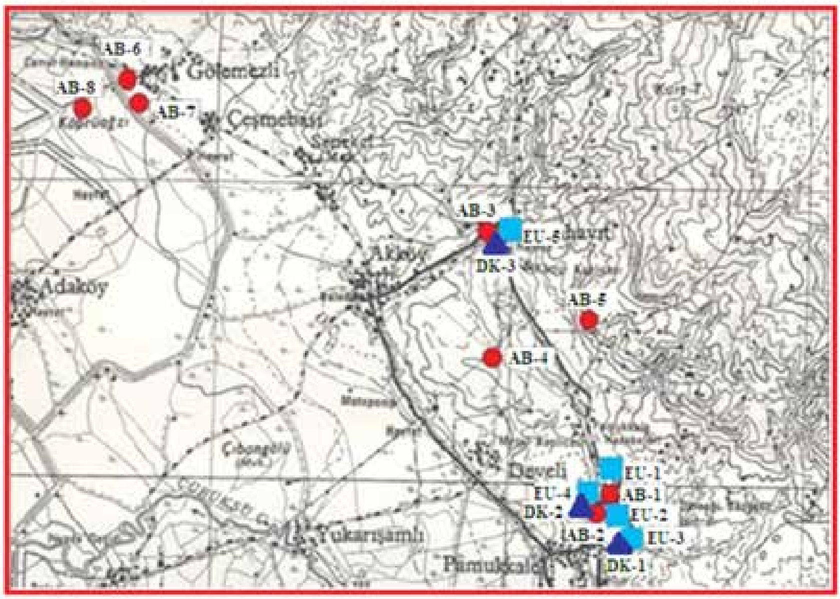

Figure 3: Sample locations of the geothermal field of Pamukkale (modified from Kıymaz, 2011; Kutlu, 2015; Uzun, 2017).

The Kolonkaya and Tosunlar formations on the first shallow reservoir rock form an intercalation of claystones, marls and sandstones and are good cap rocks for the first reservoir rocks. These cap rocks have a thickness of 350– 600 m.

Hydrogeochemistry

The geothermal waters of Pamukkale and environs can be considered as Ca-Mg-(SO_4)-HCO_3 type waters in the Piper diagram (***Figure 5***). Hydrogeochemically, the geothermal waters in the study area display the dominant cations Ca>Mg>Na+K and dominant anions HCO_3>SO_4>Cl. These show an environmental and shallow origin according to the Cl-SO_4-HCO_3 ternary diagram (Kutlu, 2015). Accordingly, the geothermal waters have high sulphate contents, which might be attributed to gypsum and pyrite mineral phases in impermeable cap rocks. The waters are

Table 1: In-situ measurements and hydrogeochemical analyses of the geothermal waters in Pamukkale and environs (Kıymaz, 2011; Kutlu, 2015; Uzun, 2017).

Sample	Location	T(°C)	pH	Eh (mV)	EC (µS/cm)	Na^+ (mg/l)	K^+ (mg/l)	Ca^{+2} (mg/l)	Mg^{+2} (mg/l)	B^{+3} (mg/l)	F^- (mg/l)	SO_4^{-2} (mg/l)	Cl^- (mg/l)	Si+4 (mg/l)	NO_3^- (mg/l)	HCO_3^- (mg/l)
EU-1	Plüton-yum spring	34.8	6.61	155	2420	42.10	5.52	442	94.10	0.80	1.82	706	14.10	30.10	1.20	1176.1
EU-2	Gelin Hamamı	34.7	6.69	157	2410	42.40	5.60	434	90.40	0.90	1.40	661	14.60	30.50	1.10	1125
EU-3	Beltes spring	34.1	6.91	144.3	2410	42.50	5.45	445	96.10	0.80	1.35	662	14.70	30.40	1.00	1147.3
EU-4	Jan-darma spring	34.1	6.96	128.7	2410	42.5	5.45	325	95.50	0.80	1.34	661	12.90	30.50	0.90	1164.2
EU-5	Karahayıt spring	44	6.67	136.8	2540	117	24.3	367	118	1.60	1.85	915	38.8	29.70	5.60	1196.3
DK-1	Pamuk-kale spring	35	6.56	259.9	2430	44.2	5.45	99.4	401	1.0	0.8	649	13	15.8	1.56	1098
DK-2	Plüton-yum spring	35.1	6.44	282.1	2400	40.1	5.08	95.4	479	0.9	1.8	642	14.1	15.2	1.88	1079.7
DK-3	Karahayıt spring	46.6	6.52	63	2680	107	21.1	124	414	1.6	2.2	905	31.8	26.8	0.65	927.2
AB-1	Özel İdare spring	35	6.22	210	2410	48.85	15.55	455.05	69.90	0.71	1.35	624.8	12.29	19.19	0.51	1128.5
AB-2	Jan-darma spring	33	6.24	229	2420	42.95	3.10	449.90	71.25	0.46	1.39	611.9	12.64	19.12	0.58	1159
AB-3	Karahayıt spring	52	6.39	113	2790	131.65	21.80	528.5	123.15	0.96	1.88	872.3	27.23	28.94	0.01	1189.5
AB-4	Karahayıt Rich-mond Hotel	48	6.18	161	2810	124.3	17.25	440.75	95.30	1.60	2.21	879.7	51.61	21.32	0.05	1128.5
AB-5	Karahayıt groun-dwater	23.9	8.01	287	448	86.4	0.65	3.77	0.48	0.22	0.34	11.12	5.57	5.10	13.53	231.8

AB-6	*Gölemezli well 1*	*67*	*6.89*	*194*	*2420*	*247.7*	*52.2*	*148.75*	*72*	*3.40*	*0.99*	*377.7*	*31.41*	*29.92*	*<0.01*	*1159*
AB-7	*Gölemezli well 2*	*69*	*6.69*	*144*	*3470*	*207.85*	*42.95*	*555.5*	*84.25*	*2.99*	*1.20*	*431.9*	*27.44*	*24.31*	*<0.01*	*2074*
AB-8	*Gölemezli Hamam*	*59*	*6.28*	*253*	*4460*	*431.6*	*45.05*	*464.15*	*109.5*	*5.74*	*2.45*	*1664*	*70.84*	*59.03*	*<0.01*	*1250.5*

immature waters according to the ternary diagram of Na/1000-K/100-√Mg (***Figure 6***; Giggenbach, 1988). Moreover, geochemical thermometers of Na-K and Na-K-Ca show calculated temperatures ranging from 200 to 280 °C in the study area.

The abundant travertine deposits of Pamukkale are related to the unusual geological, tectonic and geomorphological setting in the study area (El Desouky *et al.*, 2015; ***Figure 7***). The study area is characterised by abundant carbonate successions in its substratum, which provide the necessary parent carbonate sources for the formation of travertine deposits. According to El Desouky *et al.* (2015), Miocene to Pliocene subvolcanic activities in the area probably play a major role in the formation of travertine deposits by (1) acting as a heat source for the geothermal fluids, (2) enhancing decarbonation processes in the deep subsurface and (3) contributing to the CO_2 source via mantle degassing. The extensional tectonic features associated with the development of the study area cause a network of faults and fissures that enhance circulation of geothermal waters. In the area, the rain fall rates of up to 600 mm and the presence of high mountains (1500–2000 m) ensure the necessary meteoric waters and hydraulic head for the travertine-precipitating geothermal waters. The formation of travertine deposits depends upon the solubility of $CaCO_3$ controlled principally by CO_2 partial pressure, temperature and pH values in which reaction equilibriums play an important role:

(1) $H_2O + CO_2 <=> H_2CO_3$

CO_2 is dissolved in waters as H_2CO_3

(2) $CaCO_3 + H_2CO_3 <=> Ca^{2+} + 2HCO_3$-

The process that increases the CO_2 proportion enhances the solution of $CaCO_3$, whereas each reduction in CO_2 proportion preludes the precipitation of $CaCO_3$. Under lower pH values, in which the most carbonates are solved as H2CO_3, the reaction proceeds to the right side; under higher pH values, the reaction proceeds to the left side due to the precipitation of $CaCO_3$. CO_2 is less soluble in hot waters than in cold waters. The solubility of $CaCO_3$ decreases slightly with increasing temperatures.

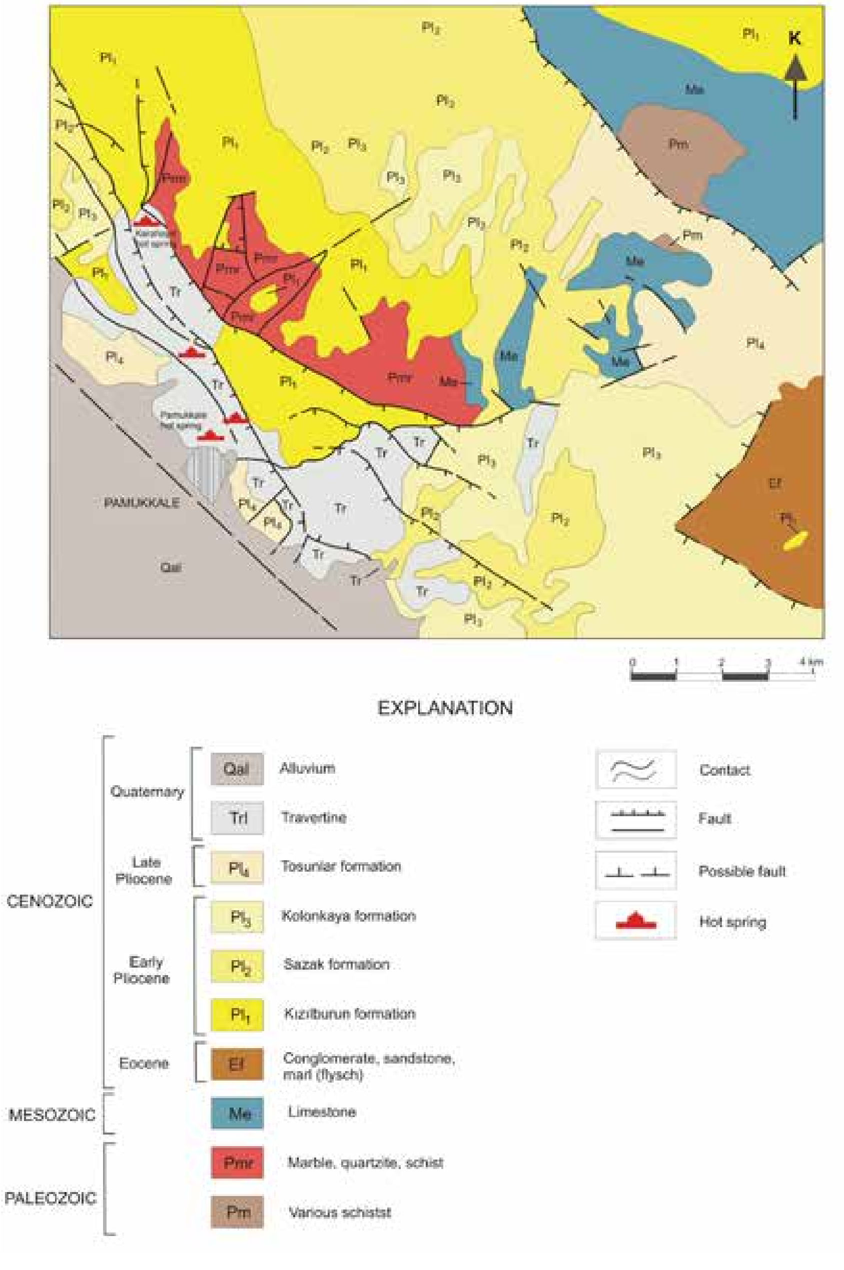

Figure 4: Geological map of the geothermal field of Pamukkale and environs (modified from Akkuş et al.*, 2005).*

(3) $CaCO_3 + H^+ <=> Ca^{2+} + HCO_3$-

HCO_3- ions are derived from the reaction of H^+ with the carbonates.

For the formation of travertine deposits in Pamukkale and environs, the temperature and CO_2 partial pressure are two rival parameters. In Pamukkale, the important parameter is the decrease of CO_2 partial pressure, and probably the temperature plays a secondary role. The strong temperature decrease in the ascending geothermal waters increases $CaCO_3$ solubility in waters. Moreover, the pressure release due to escape of CO_2 at the surface encourage carbonate precipitation. In volcanic activities in

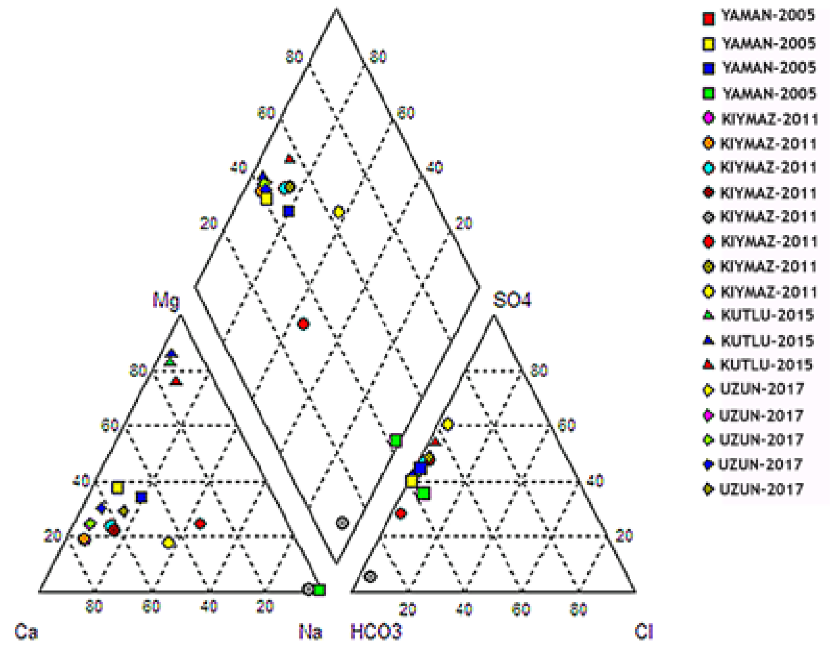

Figure 5: Piper diagram of the geothermal waters in Pamukkale and environs.

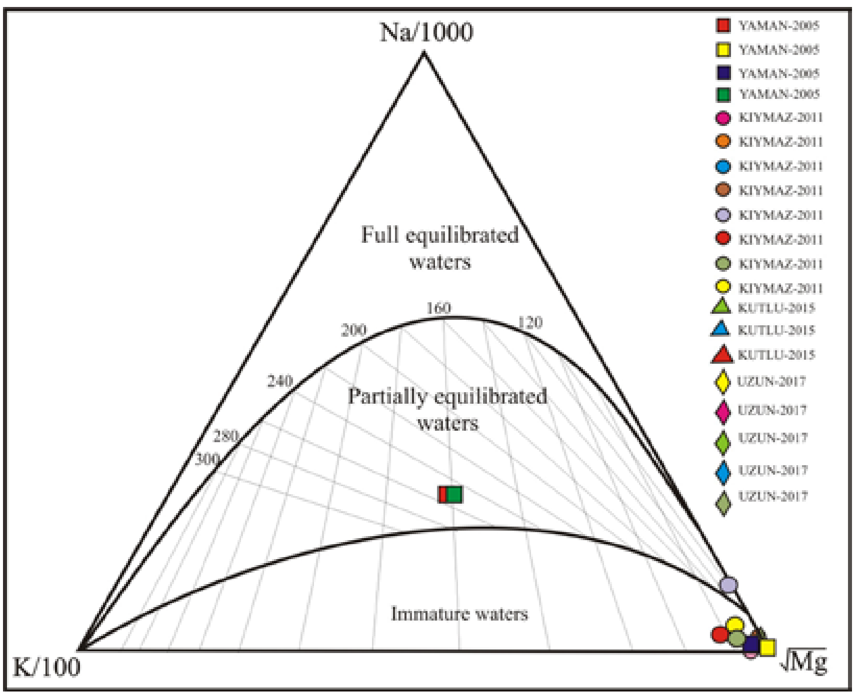

Figure 6: Na/1000-K-100-√Mg ternary diagram of the geothermal waters of Pamukkale and environs.

depth, i.e. volcanic rocks in Denizli (Semiz, 2003), the partial pressure of CO_2 in which $CaCO_3$ is solved is high. With the additional carbonate dissolution in the reservoir, CO_2 is consumed. However, the CO_2 partial pressure decreases insignificantly. Moreover, the geothermal waters are supersaturated due to $CaCO_3$ if the waters reach the reservoir. The carbonates precipitate if temperature equilibrium by the fast ascending geothermal waters does not take place in the same proportion as the pressure decrease at outflow. In addition, it is well known that blue-green seaweeds are involved in carbonate precipitation: the seaweeds extract CO_2 from the system in the microenvironment and thus encourage carbonate precipitation as aragonite (Ramon, 1983).

In Pamukkale, the formation of travertine deposits was generated in five phases (Eşder and Yılmazer, 1991):

1. formation of the Çökelez fault, which strikes in NW-SE direction. The outflow of the geothermal waters is controlled by the faults directly. Today, the travertine deposits of this phase are noticeable in high elevation spheres. For these travertine deposits of the first phase, a U-series age of 400 ka can be accepted (Altunel, 1996).
2. The formation of travertine deposits is of modern origin. An option of an outflow of hot spring was developed by the formation of the Karahayıt fault. The travertine of the second phase is widespread in accordance with foothill slope.
3. There is a stairway fault in the area. The travertine of this phase is observed in SE part of Pamukkale and was utilised in the construction of the ancient city Hierapolis.
4. In this phase, the stairway faults were generated widespread.
5. The last phase shows the landscape as it is nowadays. Great parts of the formation of travertine deposits in higher elevation areas have been eroded. Recent travertine forms modern carbonate precipitations as travertine consisting particularly of aragonite.

Isotope geochemistry

In the study area, the stable isotope compositions ($\delta^{18}O$ and $\delta^{2}H$) in the geothermal waters are shown in ***Figure 8*** (Kıymaz, 2011; Kutlu, 2015; Uzun, 2017: Yaman, 2005). $\delta^{2}H$ values in geothermal waters vary between -61.9 and -51.8 ‰, whereas $\delta^{18}O$ values range from -9.23 to -5.84 ‰. The tritium contents of the geothermal waters vary between 0.7 and 3.3 TU. The samples of the geothermal waters of Pamukkale lie along the global meteoric water line (GMWL), whereas the samples of the high temperature geothermal waters in Kızıldere (Özgür, 1998; Yaman, 2005) deviate from GMWL, indicating intense water-fluid interaction under high temperature conditions. ^{3}H values up to 3.3 TU show an atmospheric or anthropogenic origin. Therefore, there is a mixing process between fresh groundwaters and geothermal waters in the area of Pamukkale.

Discussion

The geothermal waters of Pamukkale and environs were modelled hydrogeologically (***Figure 9***). The meteoric waters in the drainage area percolate at fault and fracture zones and through permeable clastic sediments into the reaction zone of the roof area of a magma chamber. The chamber is located at a probable depth of 4-5 km, where meteoric fluids are heated by the cooling magmatic melt and ascend to the surface due to their lower density caused by convection cells. The volatile components of CO_2, SO_2, HCl, H_2S, HB, HF, and He from the magma reach the geothermal water reservoir, where an equilibrium forms between altered rocks, gas components, and fluids. Thus, the geothermal waters ascend along the tectonic zones of weakness at the continental rift zones of the Menderes Massif in the form of hot springs, gases, and steams. These fluids are characterised by high to medium CO_2, H_2S and NaCl contents. It is very important to note that the fluids indicate a reduced pH-neutral environment after equilibrium adjustment with hard rocks in the reaction zone, namely in the roof area of magma chamber (Giggenbach, 1992).

The formation of travertine deposits depends upon the solubility of $CaCO_3$, controlled principally by CO_2 partial pressure, temperature and pH values, in which reaction equilibriums play an important role. Recent travertine deposits form the modern carbonate precipitations consisting of aragonite. In the study area, the travertine can be considered as terrace, ridge and channel type travertine (Altunel, 1996). Additionally, the geothermal waters of Pamukkale have high sulphate contents of up to 650 mg/l (Özgür *et al.*, 2004) and Rn concentrations of up to 20 Bq/l (Kulalı, 2016). These features are connected with the decay of uranium minerals in the metamorphic rocks of the Menderes Massif as in which the high sulphate contents ara associated with sulphide contents such as pyrite as well as gypsum minerals in reservoir and cap rocks.

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Figure 7: Sinter terrace of the travertine deposits in the study area of Pamukkale.

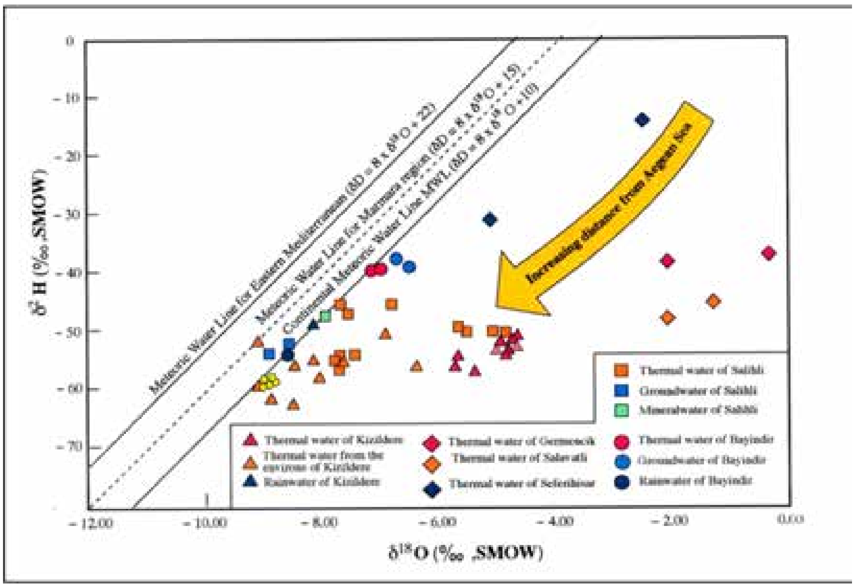

Figure 8: Plot of δ18O versus δ2H of the geothermal waters in Pamukkale and environs. For the data of stable isotopes see Özgür (1998), Yaman (2005) and Kıymaz (2011).

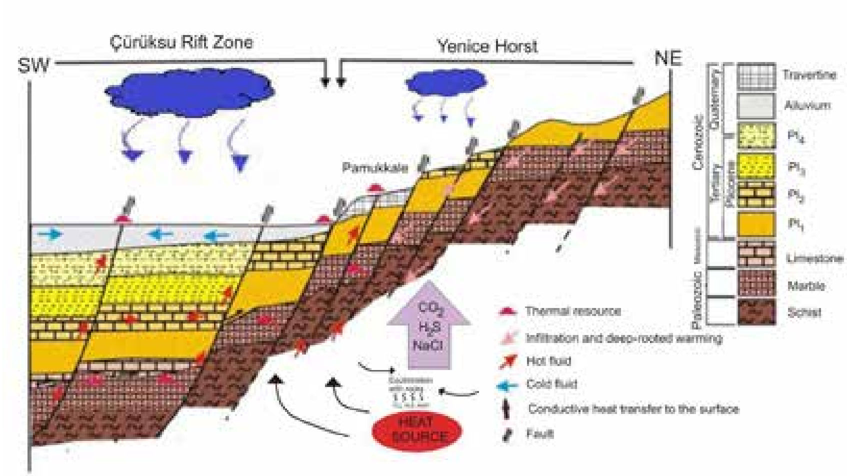

Figure 9. Hydrogeological modeling of the geothermal waters of Pamukkale and environs (Pl4: Tosunlar formation; Pl3: Kolonkaya formation; Pl2: Sazak formation; Pl1: Kızılburun formation) (modified from Dilsiz et al.*, 2004).*

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Rock power: Geothermal power simulations for schools

Earthlearningidea Team: Elizabeth Devon, Chris King and Peter Kennett*

Earth Learning Idea is a web-based, global teaching resource. It provides freely-downloadable activities for teachers of science, geography and related subjects. All are written in the same format, with the activity described first, followed by full teacher back-up, including context, pupil learning outcomes, underlying principles and thinking skills. The activity described here models geothermal power sources and challenges pupils to say whether they are renewable or not. The apparatus, involving a density can and gravel, is simple to assemble and can be used to simulate 'hot dry rocks', 'hot wet rocks' and hydrothermal power. Ground source heat pumps are also discussed. The statement, found in many science textbooks, that 'geothermal energy is renewable' is debated.

"Earth Learning Idea" ou le concept d'éducation en Géosciences représente une ressource globale d'enseignement avec support numérique (web). Il fournit gratuitement des sujets d'activité téléchargeables à l'intention de professeurs de sciences, de géographie et de thèmes associés. Les sujets sont tous écrits avec le même format, le type d'activité décrit en premier, suivi du soutien et du contrôle du professeur concerné, incluant le contexte, ce qu'a retenu l'élève, en soulignant les principes et les manières de penser. Le sujet décrit ici représente les différents modèles d'énergie géothermique et teste les élèves pour savoir s'il s'agit d'énergies renouvelables ou pas.
Le dispositif, impliquant un densitomètre et du gravier, est simple à assembler et peut servir à simuler l'effet de roches chaudes, sèches ou humides et d'énergie hydrothermale. Les pompes à chaleur air-eau sont également étudiées. L'affirmation, rencontrée dans nombre de manuels scientifiques selon laquelle l'énergie géothermique est renouvelable, fait partie du débat.

"Earth Learning Idea" es un recurso de enseñanza global basado en la web. Proporciona actividades que se pueden descargar de forma gratuita para profesores de ciencias, geografía y temas relacionados. Todos están escritos en el mismo formato, en primer lugar se describe la actividad , el profesor tiene un apoyo completo incluyendo el contexto de la actividad, los resultados del aprendizaje por parte delalumno, los principios subyacentes y las habilidades de pensamiento. La actividad descrita aquí modela fuentes de energía geotérmica y desafía a los alumnos a decir si son renovables o no. El aparato, que implica una capa de densidad y grava, es fácil de montar y puede ser usado para simular 'rocas calientes secas', 'rocas calientes húmedas' y energía hidrotérmica. También se discuten las bombas de calor. Se debate la declaración que se encuentra en muchos manuales de ciencias, según la que "la energía geotérmica es renovable".

Earth Learning Idea, accessible at ***http://www.earthlearningidea.com/***, was set up in May 2007, for the International Year of Planet Earth, with the intention of reaching as many children throughout the world as possible, particularly those who suffer from lack of resources and from lack of thought-provoking teaching. The aim is to foster a better knowledge of the natural world and how it works, encouraging the joy of knowledge about the Earth in those who may not otherwise have the opportunity to receive it.

Earth Learning Idea publishes a new Earth science teaching activity every two weeks. By the end of 2016, 251 activities had been published in English and another 20 activities were in preparation. All are written in the same format, with the activity described first, followed by comprehensive teaching notes, including context, pupil learning outcomes, underlying principles and thinking skills. All activities are made available as free-to-download pdf files with a download rate of more than 40,000 per month and the total number of downloads approaching 3 million (King, 2017; King *et al*, 2007, 2010, 2013, 2014). The website carries, or links to, more than 820 translations of activities, facilitated through a voluntary collaborative global network. The translations are chiefly in Spanish, Catalan, Portuguese, Norwegian, Italian, Japanese and German, but also in Polish, Slovakian and South Korean. We are hugely grateful for the efforts of our colleagues around the world in translating all these Earth Learning Ideas.

The activity below describes an edited version of just one of the 250+ Earth Learning Idea activities – focussed, in this case, on geothermal power.

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Rock power: geothermal power simulations

Modelling geothermal power sources – renewable or not?

Add water to a heated gravel-filled density can, to model three types of geothermal power source, like this:

Fill the density can with coarse permeable gravel and carefully insert a vertical Pyrex™ tube until it nearly reaches the bottom, as shown in the diagram, ***Figure 1***.

Then heat the apparatus up in an oven or on a hot plate (e.g. to 100 oC); be aware of the safety risk from the hot can. Once hot, add a thermometer or temperature probe to the top of the gravel, and get a container

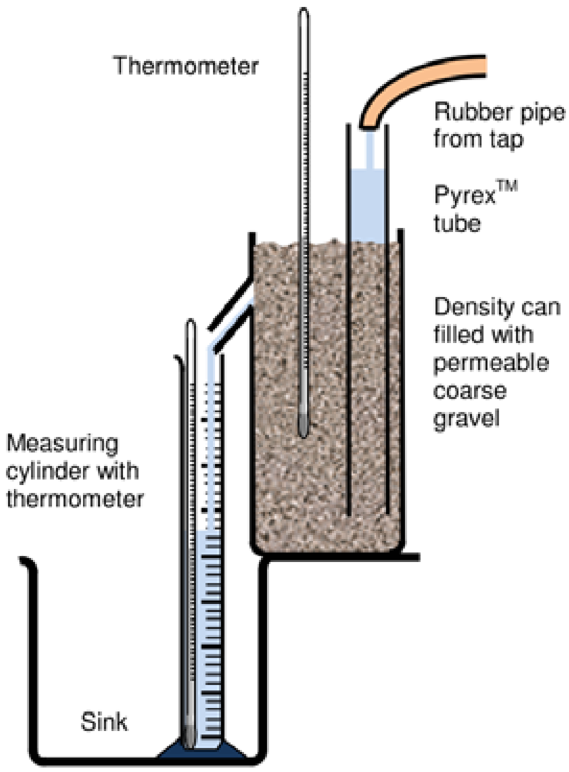

Figure 1: The apparatus (photo courtesy of Chris King).

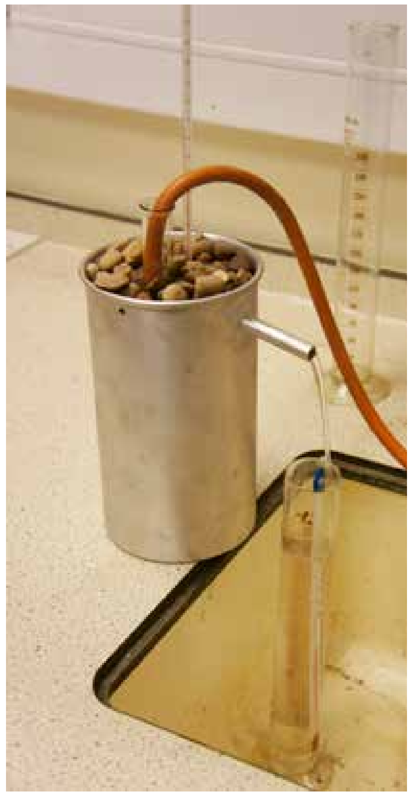

Figure 2: The geothermal power model 'in action' (photo courtesy of Chris King).

ready with a thermometer to catch overflowing water and measure its temperature.

Then use this apparatus to model the following forms of geothermal power source, (see ***Figure 2***).

'Hot dry rocks'

Model this by adding water steadily to the Pyrex™ tube and catching the overflow, whilst monitoring the temperature of the gravel and overflow water. 'Hot dry rocks' are rocks like granite that have become warm over millions of years of decay of the radioactive minerals they contain. The heat can be extracted by drilling two boreholes into the granite, ensuring these are connected by cracks, then pumping water around the system.

'Hot wet rocks'

Simulate this as described above, but first, fill the hot can with water until it just overflows, then leave it for some time (e.g. 5 minutes). This models how water trapped in deep permeable rocks (aquifers) that are insulated by thick sequences of overlying rocks, can accumulate geothermal heat. 'Extract' the heat by adding water to the Pyrex™ tube, as above, monitoring the gravel and overflow water temperatures.

'Hydrothermal power'

To model this, stand the density can on a hot plate and repeat the activity. Hydrothermal power is extracted where there is a source of geothermal heat near the Earth's surface, as found in places like Iceland, Italy, Japan, New Zealand and the Yellowstone area of the USA. 'Extract' the heat from the model by adding water down the Pyrex™ tube, as above.

Alternatively, run just one of these models, and use the findings to discuss how the other two might work.

Now **ask the pupils** to use what has been found from these simulations to discuss which, if any of these geothermal power sources is renewable.

Finally, discuss the proposition, found in many science textbooks, that 'geothermal energy is renewable'.

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Teaching notes

Title: Rock power: geothermal power simulation.

Subtitle: Modelling geothermal power sources – renewable or not?

Topic: Using a density can filled with gravel to model different forms of geothermal power source.

Age range of pupils: 14-19 years.

Time needed to complete activity: 15 minutes per run.

Pupil learning outcomes: Pupils can:
- describe the different situations in which geothermal power can be extracted from rocks;
- explain how a density can of hot gravel can be used to model these forms of geothermal power;
- discuss whether or not these forms of geothermal power can be regarded as renewable.

Context:

These simulations clearly show that:

- **'hot dry rocks'** geothermal power is not renewable, since the temperature of the gravel steadily falls as heat is extracted by the overflowing water, so that the temperature of the overflowing water also falls, over time. This is because the heat is extracted much more quickly than it is being generated by radioactive decay in the rock.

- **'hot wet rocks'** geothermal power is not renewable because it taps into 'fossil heat' accumulated over recent geological time, as a rate much faster than it is being accumulated.
- **'hydrothermal power'** can be extracted renewably, if heat is removed at a slower rate than it is accumulating from the heat source below. However, most hydrothermal power stations extract heat more quickly than it is accumulated, so they only have a finite life and will eventually close. In these cases, heat is being extracted at non-renewable rates.

Note: You can do the first demonstration just by pretending the density can has been heated, by touching it and pretending to burn your fingers – whole classes have been convinced by this!

A fourth source of power, which is sometimes described as 'geothermal', is **'ground source heat pumps'** where water from an underground or surface source has its heat extracted for warming buildings and is recycled. However, since some 98% of the power in these systems comes from solar heating of the Earth's surface, and only around 2% is true geothermal power from the Earth, this is not geothermal power in the sense described above. Air-source heat pumps are also available, where heat is extracted from the air, rather than from the ground.

Following up the activity:

Ask pupils to research how 'ground source heat pumps' work, and whether or not this power source can be described as 'renewable'. It can, since heat can only be extracted at the same rate as it accumulates.

Underlying principles:

- The Earth generates heat, called geothermal heat.
- The Earth's heat is generated by radioactive decay in the rocks of the Earth (with a component of original heat from the formation of the Earth).
- Earth's heat flows to the surface and can be tapped through the three forms of geothermal power, described above.
- Such power is usually not renewable, because the heat is normally extracted at a faster rate than it accumulates.

Thinking skill development:

If one run of the activity is carried out, and pupils are asked to use this to discuss how the set-up might behave in the two other circumstances, they will use the mental 'construction' of one model and apply it to the two other models. This will provoke pupils into considering and reworking their pre-conceived ideas of how geothermal power is generated. Discussions around the models, and their links with reality, involve more powerful knowledge of the principles and processes. Linking each model with its 'real world' operation develops a greater awareness of how geothermal power works in different geological contexts.

Resource list:

- a large density or displacement can (density cans are also called 'Eureka cans' because they are designed to use the Archimedes method of measuring density)
- permeable coarse gravel to fill the can to above spout level
- a Perspex™ tube long enough to penetrate nearly to the bottom of the gravel, and stick out of the top
- an oven or hot plate (a hot plate is needed for the 'hydrothermal power' simulation)
- heat-proof mitts or gloves to be used in moving the hot container
- a thermometer or temperature probe to go in the gravel (reading to higher than 100 oC in case the can is heated to over 100 oC)
- containers to catch the overflow (e.g.. several measuring cylinders)
- a thermometer to go in the overflow containers
- a sink or basin
- a source of flowing water

Useful Links:

Earthlearningidea: 'Power through the window: which power source might be built in the view you can see from your window?'

Source:

The model was described by Adrian Cook in the Earth Science Teachers' Association's 'Science of the Earth', 'Rock power! – geothermal energy resources' unit (1991), published by Geo Supplies, Sheffield. It was based on an activity originally described in 'Introducing Earth Science' by James Bradbury (1986) published by Blackwell, who gave permission for its use.

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The Development and Deployment of Deep Geothermal Single Well (DGSW) Technology in the United Kingdom

Michael A. Collins[1] and Ryan Law[2]

Deep geothermal heat has not, to date, contributed meaningfully to the overall renewable heat supply in Europe. This is particularly true in the United Kingdom (UK), where there is only one geothermal heat network in operation. This lack of deployment has been due to the geographical distribution of suitable geothermal aquifers, the high cost of drilling to suitable depths, the paucity of deep geological data and, more recently, permitting/ seismicity issues. To enhance the overall development of the deep geothermal resource, Geothermal Engineering Ltd (GEL) and Arup have pioneered the development of single well technology. Progress to date includes a successful field trial in 2014 and the ongoing development of high profile demonstrator projects across the UK via 'Geon Energy Ltd', a joint venture between GEL and Arup.

Les sources géothermales profondes n'ont pas, à ce jour, contribué de façon significative à un gain général et renouvelable de chaleur en Europe. Cela est particulièrement vrai au Royaume Uni (UK) où il n'existe qu'un seul réseau de chaleur géothermale en opération. Ce défaut de développement est lié à la répartition géographique des aquifères géothermaux convenables, au coût élevé du forage pour atteindre les profondeurs requises, le manque de données géothermales profondes et plus récemment, les problèmes concernant les autorisations d'accès et la séismicité. Pour accroître le développement global de la ressource géothermale profonde, les entités Geothermal Engineeering Ltd (GEL) et Arup ont été parmi les premieres à développer la technologie du forage unique. Un progrès marquant inclut un forage d'essai positif en 2014 et le développement en cours de projets de démonstration de haut niveau sur toute la Grande-Bretagne à travers Geon Energy Ltd, un Projet d'Association entre GEL et Arup.

Al día de hoy, el calor geotérmico profundo no ha contribuido de manera significativa al suministro de calor renovable en Europa. Esto es particularmente cierto en el Reino Unido, donde hay solamente una red de calor geotérmico en funcionamiento. Esta falta de despliegue es debida a la distribución geográfica de los acuíferos geotérmicos adecuados, al alto costo de la perforación a profundidades apropiadas, a la escasez de datos geológicos profundos y, más recientemente, a los problemas de permisos y sismicidad. Para mejorar el desarrollo global del recurso geotérmico profundo, Geothermal Engineering Ltd (GEL) y Arup son pioneros en el desarrollo de la tecnología de pozo único. Los avances hasta la fecha incluyen un exitoso ensayo de campo en 2014 y el desarrollo continuo de proyectos de alto perfil en todo el Reino Unido a través de "Geon Energy Ltd", una empresa conjunta entre GEL y Arup.

1. Introduction

According to recent studies (SKM, 2012), the deep geothermal heat resource in the United Kingdom is much greater than the total current annual heat demand. However, the development of deep geothermal energy as a source of renewable heat has been slow. In an attempt to speed up development of the deep geothermal resource, Geothermal Engineering Ltd was funded by the Department of Energy and Climate Change (DECC) in 2013 to design, test and develop so called 'deep geothermal single well' (DGSW) systems, the ultimate aim being to have an *'off the shelf'* technology that can be installed in almost any geological environment, irrespective of permeability. This paper reports on the reasons for the design and development of the single well system, the basic elements of the system, the installation and field trial in an existing deep well and the thermal modelling approaches applied to current projects that the new joint venture company Geon Energy Ltd is working on.

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2. Barriers to deep geothermal development in the UK and reasons for the single well concept

There are a number of well-documented reasons why development of deep geothermal resources in the United Kingdom has remained 'largely untapped'. The principal problem is the high risk/ low financial reward associated with deep geothermal heat supply. These barriers are compounded by the lack of knowledge of UK deep onshore geology, an established geothermal industry and the absence of a legal framework. These barriers have meant that, despite a number of deep geothermal heat and power projects being planned over recent years, none have drilled wells and delivered heat or power to an end user or the grid.

For the deep geothermal industry (heat and power) to develop in the UK, there are 5 key constraints that we consider need to be overcome, namely exploration risk, high capital project cost, geographical reach, induced seismicity risk and proximity of heat demand.

3. How the DGSW addresses these issues

Over the past three years, Geothermal Engineering Ltd and Arup have been work-

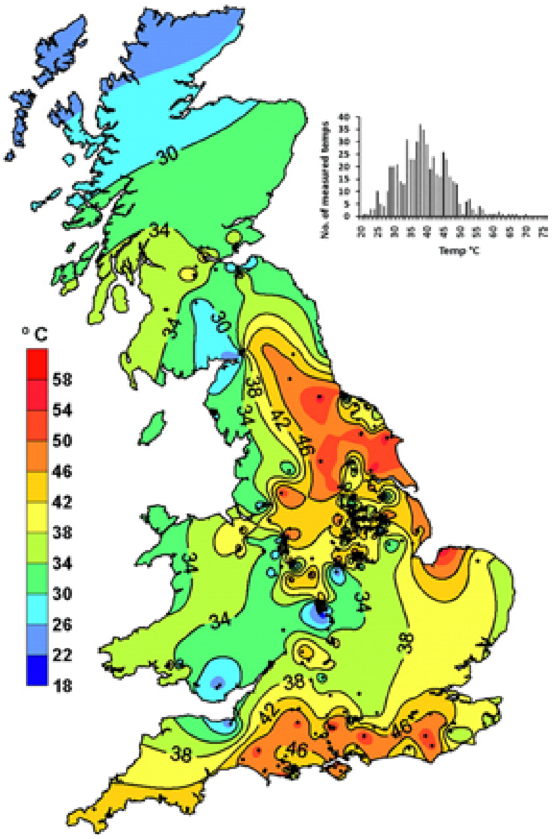

Figure 1: Measured temperatures at 1 km below ground level in the UK (from Busby et al., *2011).*

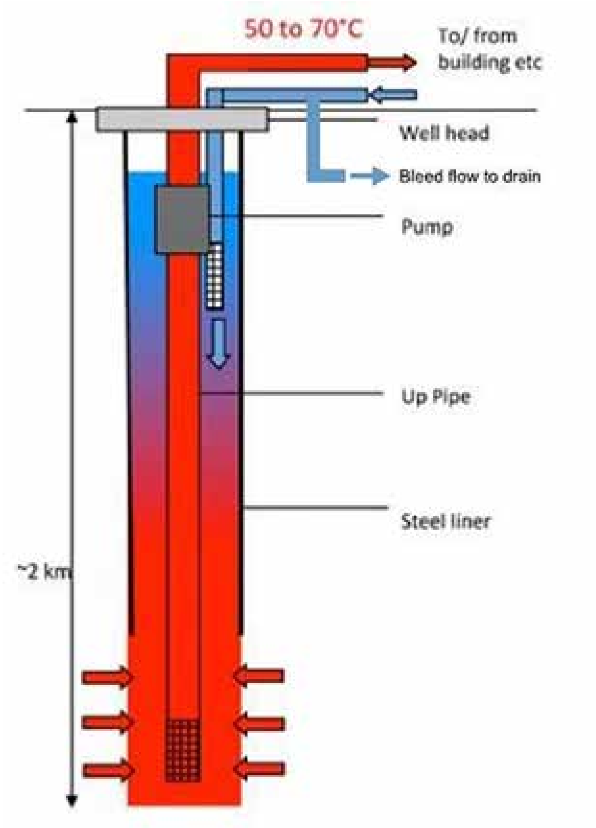

Figure 2: Schematic of the Deep Geothermal Single Well.

ing on the design of a deep geothermal system to address some of the problems that are distinctive to the UK in order to kick-start the delivery of commercially viable geothermal heat. The resulting Deep Geothermal Single Well (DGSW) system addresses each of the challenges listed above in the following ways:

3.1 Exploration risk

The DGSW technology is not dependent on abstracting large quantities of water from the sub-surface. Instead, much like standing column well technology, the majority of the water is re-circulated within the well. This means that a successful project does not rely on identifying, targeting and hitting a highly permeable rock at a specific depth. The only requirement is that the temperature at depth is within the operational range for the building or plant.

A range of temperature at depth maps for the UK have been developed (Busby *et al.*, 2011) which have used deep borehole temperature data sets to create temperature contours to 1 km below the ground surface. These maps indicate that significant areas of the UK have a good thermal gradient (***Figure 1***) that is suited to the circulatory DGSW technology, meaning that renewable heat delivery can be delivered in areas with a heat demand.

3.2 High capital cost per project and delivery times

Drilling single vertical wells substantially reduces the upfront capital expenditure of a deep geothermal heat project. The well design is as simple as possible and the drilling operations run under a Turn-Key contract to reduce cost over-runs. Further, as the DGSW only consists of one vertical well and no plant at the surface, the project delivery time is reduced to between 12 and 18 months.

3.3 Geographical reach

Because the DGSW system is not dependent on a geothermal reservoir (whether existing or artificially created), it has a much greater geographic reach than traditional systems and can be deployed in almost any geological environment where there is a heat demand at the surface. This is important as, in the UK, heat demands are often not located above ideal geothermal conditions.

3.3 Induced seismicity

The DGSW system does not need to inject fluid into the ground at high pressure and does not need to create a reservoir at depth, which is always required in projects utilising doublet systems. In a hard rock such as a granite, some degree of stimulation or 'fracking' will always be required to engineer a reservoir between two wells. The need of fracking for two-well projects leads to costly and lengthy planning and project delays. There is therefore no risk of induced seismicity when a DGSW is installed and no risk of negative community perceptions of the technology.

3.4 Heat demand

The heat output of the DGSW is suited to sites where small heat networks can be developed quickly or are already in place (such as universities, schools, sports centres, multiple apartment blocks, etc.). Larger scale networks with multiple end users are not required. This enables projects to be developed much faster, as the number of parties involved in the Heat Purchase Agreement (HPA) and network operation/ management/ liability is normally one.

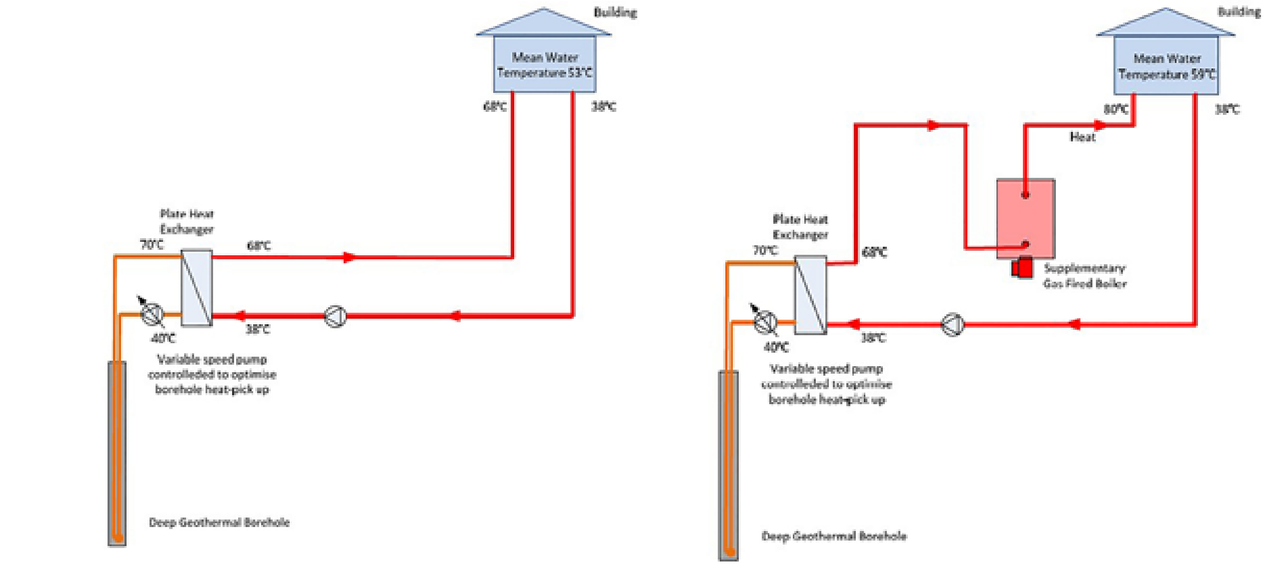

Figure 3: Monovalent and bivalent modes of operation.

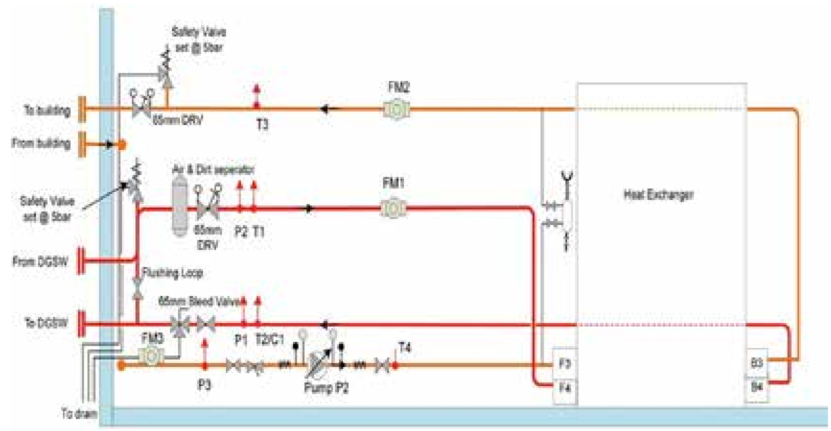

Figure 4: Schematic plan of plant room and heat exchanger connections.

Figure 5: DGSW pipework being installed at the trial site.

4. DGSW system design and operational modes

The DGSW is a simple co-axial design that is similar to that deployed in a standing column well Ground Source Heat Pump system that would typically be found on the East Coast of the United States. The only difference between the two is the materials used for the pipework and the depth of the installation. A schematic of the system is shown in ***Figure 2.***

Figure 6: 400 kW Thermal Response Test (TRT) rig with "air blaster" – external and internal viewpoints.

The system has been designed to operate in two principal modes (***Figures 3 and 4***):

- Monovalent System – DGSW sole source of heat
- Bivalent System – DGSW using gas-fired boilers for supplementary heat

In a standard project, to maximise the thermal output of the DGSW, the operation of existing heating systems would be adapted to run on a lower mean water temperature (MWT) than the norm. The MWT is very well suited to modern buildings that deploy underfloor heating or warm air systems. For retrofits, the secondary circuits will be configured to deliver space heating for longer time periods to accommodate the lower MWT.

5. Installation and field trial

For the field trial, the DGSW equipment was installed in an existing 2.6 km well that was drilled in the granitic rock in Cornwall during the 1980s as part of the Hot Dry Rock project. The pipework was installed and fitted with a fibre optic temperature cable along its length to enable an accurate temperature profile to be recorded every 5 seconds during a range of energy abstraction tests that were carried out on the well (***Figure 5***).

The energy abstraction tests were conducted using a 400 kW 'Thermal Response Test' rig that was designed and built for this project (***Figure 6***).

In brief, a wide-range of tests were conducted on the well, which included flow rate variations, energy abstraction rate variations and durations and 'bleed flow' tests. High quality data was recorded from the pipework installed using a fibre optic cable in the well to enable calculations to be made on the thermal performance of the well under different conditions. The results were also used to validate the numerical models that had been created using the USGS SUTRA code during the design process.

In summary, the field trial proved that the DGSW system could deliver heat with a very high co-efficient of performance (COP). The pump input power was approximately 7 kW to deliver a total flow rate of 3 l/s. The total heat energy output from the well was dependent on the total flow rate, the delivery temperature and the return temperature. With the current configuration, it was shown that a 2 km system would achieve a delivery temperature of 69°C. Using the assumed return temperature of 40 °C, the well would deliver a peak load of 363 kW with a 7 kW input: an equivalent COP of 52.

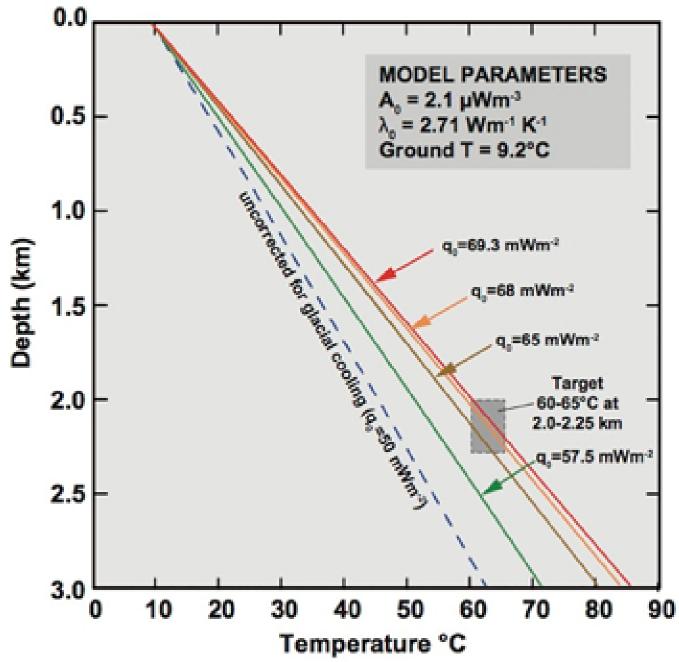

Figure 7: One-dimensional thermal model developed for Aberdeen Granite pluton incorporating surface heat flow q_0 corrections for glacial cooling.

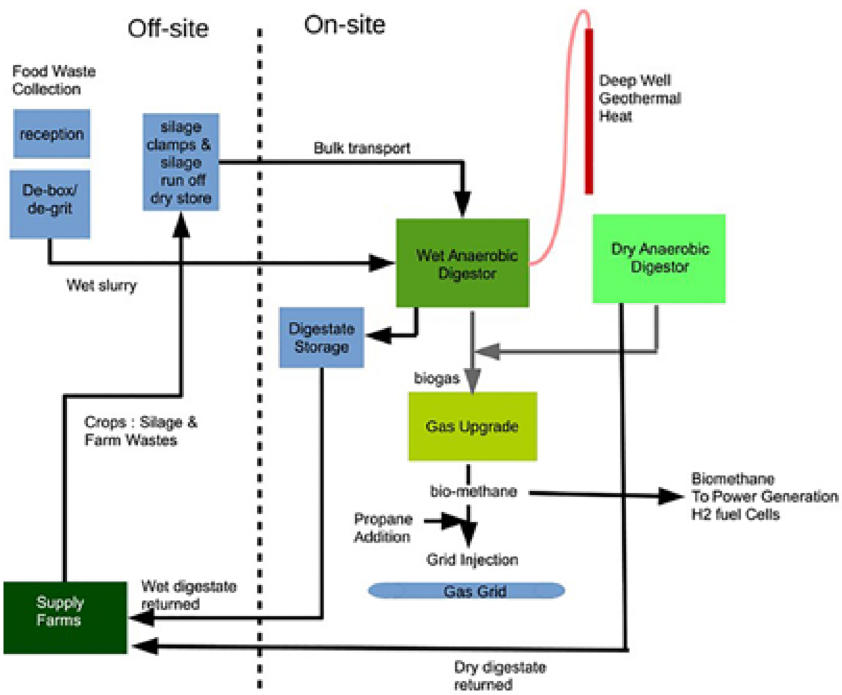

Figure 8: The proposed DGSW integration with the Anaerobic Digestion unit at the new Aberdeen Exhibition and Conference Centre.

5. Current projects

5.1 Jubilee Pool, Penzance

One of the first projects will be to develop a deep geothermal single well (DGSW) to supply heat to a portion of the Jubilee Pool, Penzance. The geothermal well will be installed to help attract more visitors to the pool and to assist the wider redevelopment of the area. The deep geothermal work will be partially funded by the European Regional Development Fund (ERDF) and the planning process for the well has recently commenced. The project aims to drill the DGSW in late 2017.

5.2 Aberdeen Exhibition and Conference Centre (AECC)

Geothermal Engineering Ltd, Arup and St Andrews University recently completed a feasibility study for the Scottish Government's *'Deep Geothermal Challenge Fund'* call, which was coordinated through the Scottish Government's Low Carbon Infrastructure Transition Programme (LCITP). The feasibility study (GEL *et al.*, 2016) proposed the installation of a deep geothermal single well (DGSW) demonstrator at the new Aberdeen Exhibition and Conference Centre (AECC) and provided a technical, environmental and economic appraisal of the well delivering heat innovatively to an onsite Anaerobic Digestor (AD) unit.

The site is located on the foliated Aberdeen Granite, which is a substantial pluton-shaped body approximately 16 km in its longest dimension and 6 km in its shortest which was emplaced approximately 470 million years ago (Kneller & Aftalion, 1987).

In assessing the geothermal potential of the Aberdeen granite, a one-dimensional thermal model was created by St Andrews University following the approach taken by Lee (1986) and Wheildon & Rollin (1986) with the unique difference of taking into account glacial cooling effects on predicting temperature at depth. Recent studies have suggested that surface heat flows q_0 in the NE of Scotland have been underestimated by 15 mWm^{-2} (Majorowicz & Wybraniec, 2011) and 16.8 to 21.7 mWm^{-2} (mean 19.3 mWm^{-2}) (Busby *et al.*, 2015) leading to potential underestimates of thermal resources. Heat production A_0 was estimated from 9 samples of Aberdeen Granite tested for density and presence of the radioactive elements Uranium (U), Thorium (Th) and Potassium (K) using empirical formulae (Rybach, 1988) with a mean value of 2.1 µWm^{-3} used for heat production in the modelling. Four samples of the Aberdeen Granite were tested for thermal conductivity with a mean value of 2.71 Wm^{-1}K^{-1} used for surface thermal conductivity (λ_0) in the modelling.

The graph presented in ***Figure 7*** shows the range of steady state temperature profiles generated in the model outputs based on a range of surface heat flows q_0 and the parameters discussed. The application of q_0 corrections clearly has a significant impact on predicted temperatures at depth within the Aberdeen Pluton.

The DGSW proposal for the Aberdeen AECC is to use the well for the provision of parasitic heat load to the AD plant (***Figure 8***), which would replace the need for a 500kW Combined Heat and Power (CHP) unit. The parasitic heat requirement for the AD unit is for a temperature of between 38-42 °C at 500 kW which, as identified in the modelling undertaken, could be delivered offering the opportunity for 'renewable to heat renewable'. The use of the DGSW would translate to a significant carbon reduction and operational expenditure (OPEX) saving from not needing to import gas for the CHP (c. £1.7 m over a 50 year operational period).

The AECC study also identified a significant opportunity for skills crossover, job creation and supply chain development from the existing oil and gas industry in Aberdeen into deep geothermal development. In particular, the opportunity for synergistic skills diversification was warmly welcomed from the service and supply industries.

The AECC deep geothermal feasibility study has recently completed the third-party technical and economic due diligence which was requested by Scottish Government and it is hoped can form a blueprint for deep geothermal development in Scotland and indeed other locations impacted by glacial cooling.

5.3 The Science Central Borehole (Newcastle University)

The Science Central borehole in Newcastle was drilled to a depth of 1,821 m in 2011 and following significant workover operations including airlifting and recovery testing the target Fells Sandstone formation was reported to have a low conductivity of c. 7x10^{-}5md^{-}1 (Younger *et al.*, 2016) preventing its development as either a demonstration or operational abstracting geothermal well.

In 2016, Arup and Geothermal Engineering Ltd were appointed by Newcastle University to undertake a technical and economic feasibility study on the use of the DGSW technology within the Science Central borehole. Despite the reported low natural permeability, the measured temperature of 73 °C at 1740 m and estimated surface heat flow q_0 of 88 mWm^{-2} (Younger *et al.*, 2016) highlighted that a circulatory deep geothermal system in conjunction with a high temperature heat pump could potentially provide a thermal output from the well that could be used to provide low carbon heat to proposed building units within Newcastle University's Science Central development.

The study included a technical appraisal of the existing well construction, which despite a small 101mm internal well diameter at depth was found to be technically compatible for the installation of the DGSW technology. To evaluate the thermal interaction between the surrounding formation and the well, a two-dimensional axisymmetric model was developed using the USGS SUTRA code. SUTRA was developed to simulate fluid movement and transport of energy in the subsurface environment and can be used to evaluate coupled processes such as fluid density-dependent groundwater flow and transport of thermal energy in the subsurface.

The modelling performed produced likely thermal output ranges for the delivery of heat from the Newcastle well assuming 2 l/s flow (80 to 100 kW) and 3 l/s flow modelled to range between 88 to 138 kW. The models identified that continuous heat delivery over a 24 hr period (with no bleed) would reduce the delivery temperature to approximately 34 °C (***Figure 9***). It was proposed that operating the well for a period of 10 hours per day delivering heat to a building would permit temperature recharge during building non-operational periods, which would have an increased environmental benefit through efficient heat delivery and reduced electricity use.

The results of the evaluations imply that the potential thermal delivery capacity from the well is at least 100 kW at 30 °C (assuming a temperature difference ΔT of 10 °C) and a flow rate of 3 l/s over a period of 10 hours per day. To increase the temperature for use in a building heating system (70 °C), the geothermal well water will require to be passed through a high temperature heat pump. This innovative approach would increase the thermal output of the combined system to be approximately 160 kWh (590,000 kWh/yr).

The study undertaken demonstrated that the installation of the DGSW technology provides a genuine opportunity for the delivery of deep geothermal heat from the Newcastle Science Central well despite the very low natural permeability and the well's technical constraints.

5.4 Future Projects

Discussions are currently being undertaken for the utilisation of DGSW heat delivery to a renewable low temperature district heat network project in East Ayrshire in Scotland and also with the School of Geosciences, University of Edinburgh.

6. Conclusions

The Deep Geothermal Single Well system (DGSW) has been developed to kick-start the geothermal heat sector in the UK. It addresses a number of challenges that are distinctive to the United Kingdom.

The system was extensively field trialed in 2014 in an existing deep well in Corn-

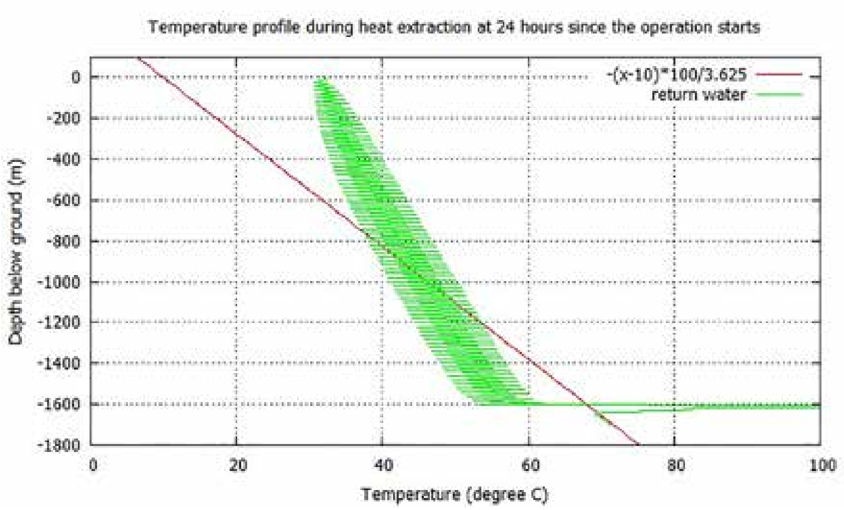

Figure 9: Modelled temperature profile at 24 hrs after heat extraction commences.

wall. The results showed that, if managed correctly, the system can deliver circa 400 kW with a 7 kW electrical pumping input.

Following on from the trial, a joint venture company has been formed between Geothermal Engineering Ltd and Arup to roll out the technology in the United Kingdom – Geon Energy Ltd. Current projects are ongoing in a range of geological conditions and the paper has described the modelling approaches taken to estimate deep temperature at these sites. Two high profile demonstrator projects are planned for 2017-18 in Cornwall and Scotland with further commercial opportunities to follow.

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Social changes and Geosciences

*Gian Vito Graziano**

In a context in flux, where to the well-established movement of goods a more intense movement of persons is added, including different forms of immigration, the needs of society consequently change. Even the increase in population is expected to change the social landscape structurally in the medium to long term. The world population, today just over 7 billion, is growing rapidly, and by 2050 the UN estimates that it will have reached 9.1 billion people. According to the *"World Population Prospects"* nine countries – India, Pakistan, Nigeria, Ethiopia, the United States, the Democratic Republic of Congo, Tanzania, China and Bangladesh – alone are expected to account for half of the estimated increase worldwide, with a growth forecast that reaches 95% (UN, 2013).

In this context of global change, climate change represents the most commonly perceived challenge for humanity, but not the only one; in fact there are additional challenges, no less demanding, from food supply to the development of a more orderly and socially-acceptable world economy. We think first of all of the basic needs of food and water, but there is also a growing demand for energy, housing, and infrastructure, and the resulting industrial and educational requirements. Meeting these needs will take natural resources, energy, transport, homes. This will most likely lead to the emergence of new practices and new occupational needs, linked to a demand for services that will be shaped by changing global needs.

In order to meet these increased human needs, it is necessary to immediately implement interventions in response to the special features of social change. These interventions should be characterised by the contributions of science, increasingly relevant and specific; for this, scientific skills are certainly necessary, but also the professional and organisational ability to integrate and strengthen them to meet global needs (Tellus Institute, 1998). In this sense the Geosciences are among the disciplines that are best able to respond to many of the social goals that we will have to confront in the future. The Geosciences also represent a deterrent against any forms of the future tied to an economic vision based solely on market forces and a consumer society, which undoubtedly represents a dangerous development model. If we continue in this direction, it will expand the risk of social monopolisation already in place, the continuation or worsening of poverty and the persistence or the aggravation of environmental degradation, all of which not only affect the resilience of ecosystems and the global economy, but may even erode social cohesion. In the coming years an analysis of global scenarios will have to define a priority of shares, or a strategy where scientific research, technological innovation and education will all play a key role.

In the report "Geologist 2.0" presented at the 2014 Summer Council Meeting of the European Federation of Geologists (EFG), Prof. Manuel Regueiro from *Ilustre Colegio Oficial de Geologos de Espana* pointed to studies on the various scenarios as a platform from which to begin to address these challenges, and pointed out that in this approach the geosciences have a feature that makes them different from other scientific disciplines and makes them unique in the general panorama, that is, to know and conceive of the past as a prelude. The geosciences, showed Regueiro, are one of the few disciplines, if not the only, to base their ability to read and understand the evolutionary phases and transformations – from the earth's crust to those of natural habitats – on the time factor. But not only this; in a possible transition to forms of development based on sustainability, the geosciences are a necessary condition to guarantee a global future, not only ecological, but also human.

Supported by the testimonies of past climate changes, geologists are convinced that CO_2 is one of the main factors of change in the climate system. The evidence confirms the basic physical principle that the placing of large amounts of greenhouse gases, such as CO_2, into the atmosphere causes an increase in the temperatures of the planet. These findings also show that this is likely to lead to a rise in sea levels, increasing acidity of the oceans, a decrease in sea water oxygen levels and significant weather changes.

If then we go back to the basic needs of food and water, we are all well aware that thousands of people on our planet are still dying because they have no access to water or because they drink contaminated water, and that water resources can be universally guaranteed not only by hydrogeological exploration and with the proper use of resources, but also with civil management and water distribution. Similar reasoning applies to the food supply, where agriculture needs to protect productive soils and enhance their fertility, through the knowledge of rocks and minerals, the direct application of this knowledge, and implementation of technical protection and conservation of territories.

It is no coincidence that the Council of Europe, in promulgating the Water Charter, has stressed the need that water management is framed "in the natural catchment area, rather than within administrative borders and policies", a concept dear to geology and taken up in the current international model of water management, the "water resource management" that inspired the water policies of the European Union. This stresses the essential value of the catchment area for the coherent and integrated management of water resources. The issues related to water and food should be incorporated into a broad framework encompassing the qualitative and quantitative water needs of the population and for production and agricultural activities, protecting against threats linked to hydrogeological and climate change.

The social demand for energy, infrastructure and housing or shelter is a major factor in the progressive growth in the demand for geological culture and the professional services related to it. Activities such as providing rocks and materials for construction, urban planning and natural systems, disposing of waste, searching for energy resources, and seismic micro-zoning all depend on the geosciences and requiring

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geologists. There are not many in the world: about 500,000 earth scientists, 0.007% of all scientists (MEAB, 2005). It is estimated that there will be demand for another 10,000 new geologists around the world over the next 10 years (MEAB, 2005), but the trends of the geological profession have often been irregular, employment-related and more often tuned to the cyclicality of the industries employing the geoscience.

And in turn, industry (especially the mining industry), policies for the environment and water resources, and universities are driven by politics and markets, as indeed are governments (Landon, 2003). Thus, we must draw the attention of public institutions, finding ways to touch the daily life of the people, to realise the value of our work, recognising that we can improve their lives – sometimes even save them – or more generally be aware of the fact that geological knowledge can undoubtedly count. The recognition of geology as a field safeguarding public interests is an alternative paradigm (Graziano, 2012), but it is perhaps the one that will bring the geosciences to attain the place they deserve in global policies for a more secure and sustainable world, helping to create effective role models both in the aspect of environmental sustainability and in economics.

In the philosophy of science, a paradigm is the disciplinary matrix of a scientific community that is concentrated in a global vision and generally accepted in the world where it operates. The disciplinary matrix of a part of the geological community (including the Italian one) is developing into a global vision of society.

This is a responsibility that the community itself has taken on, tending to "... encourage the use of critical analysis of natural resources, the promotion and protection of the Geosphere, accurate information about the risks, the involvement of the society in the idea of a common and shared geological heritage, which favors a social construction of knowledge" (Manifesto of "Geoethics and geological culture" as reported in Peppoloni and Di Capua, 2011; see also Peppoloni and Di Capua, 2015).

But local responsibility remains, which we are struggling to extend to the entire community, especially in those countries where the geosciences are historically and inextricably linked to strong economic powers. But this is the only way forward, one which requires closer cooperation between the European and world geological associations: the daunting task is to take the path of responsible development. The world needs science and science is undoubtedly on the side of geologists: we must walk on this road – we cannot afford to choose another.

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News corner:
Compiled by Isabel Fernández Fuentes and Anita Stein, EFG Office

Horizon 2020 projects

Horizon 2020 is the biggest EU research and Innovation programme ever, with nearly 80 billion euros of funding available to secure Europe's global competitiveness in the period 2014–2020. Beginning in 2015 the Federation was already involved in four Horizon 2020 projects: INTRAW, KINDRA, MINATURA2020 and ¡VAMOS!. Four new projects started in 2016 (UNEXMIN, CHPM2030, MICA and FORAM). Below you will find descriptions of the topics and aims of the current projects.

INTRAW

642130 - INTRAW
International cooperation on Raw materials
START DATE: 1 February 2015
DURATION: 36 MONTHS

INTRAW, which started in February 2015, aims to map best practices and develop new cooperation opportunities related to raw materials between the EU and technologically advanced countries (Australia, Canada, Japan, South Africa and the United States) in response to similar global challenges. The outcome of the mapping and knowledge transfer activities conducted in the first two years of the project will be used as a baseline to set up and launch the European Union's International Observatory for Raw Materials as a permanent raw materials knowledge management body.

The European Federation of Geologists (EFG) is the coordinator of a consortium of 15 partners from different countries including Australia, the United States and South Africa. Most of EFG's members are also part of the consortium as EFG Linked Third Parties.

For more information: ***www.intraw.eu***

KINDRA

642047 - KINDRA
Knowledge Inventory for Hydrogeology Research
START DATE: 1 January 2015
DURATION: 36 MONTHS

Groundwater and hydrogeology-related research activities cover a wide spectrum of research areas at EU and national levels. However, groundwater issues are quite often either ignored or considered only in insufficient detail and separated from the associated surface water bodies, despite groundwater's critical importance as a renewable, high-quality, naturally protected (but still vulnerable) resource that has significant impacts on both surface water bodies and ecosystems. The EU-funded KINDRA project seeks to take stock of our current knowledge of hydrogeology through an inventory of research results, activities, projects and programmes.

EFG is the leader on data collection and processing to carry out an EU-wide assessment of existing practical and scientific knowledge (using the developed HRC-SYS) focussing on EU, national, regional, international and EU-third party scientific activities. This assessment is implemented with the help of the national members of EFG. EFG is also involved in the dissemination activity.

More information: ***www.kindraproject.eu***

¡VAMOS!

642477 - VAMOS
¡Viable and Alternative Mine Operating System!
START DATE: 1 February 2015
DURATION: 42 MONTHS

The aim of the EU-funded ¡VAMOS! (Viable Alternative Mine Operating System) project is to design and build a robotic underwater mining prototype with associated launch and recovery equipment, which will be used to perform field tests at four EU mine sites. The project consortium passed a major milestone in September 2015 with the successful delivery of conceptual design plans of the prototype and all associated equipment.

EFG supports the project through stakeholder engagement and dissemination activities.

More information: ***http://vamos-project.eu***

MINATURA2020

642139 - MINATURA 2020
Developing a concept for a European minerals deposit framework
START DATE: 1 February 2015
DURATION: 36 MONTHS

MINATURA2020 was launched in February 2015 as a response to social needs to safeguard mineral deposits of public importance for the future. The overall objective of this three-year project is to develop a concept and methodology for the definition and subsequent protection of "Mineral Deposits of Public Importance" (MDoPI) in order to ensure their best use in the future. EFG is involved in the establishment of the Council of Stakeholders and leads the Work Package on Dissemination (WP6).

More information: ***www.minatura2020.eu***

UNEXMIN

690008 - UNEXMIN
Autonomous Underwater Explorer for Flooded Mines
START DATE: 1 February 2016
DURATION: 45 MONTHS

Thirteen organisations from seven countries across Europe are collaborating in this ambitious project to develop a submersible robotic system for surveying and exploring flooded mines. The €5M project, funded by the European Union's Horizon 2020 research programme, will include the development of a Robotic Explorer (UX-1) for autonomous 3D mine mapping to gather valuable geological information that cannot be obtained in any other way: in general the mines are too deep and dangerous for access by human divers.

Some of EFG's national associations participate in this project as Linked Third Parties and support the consortium through data collection for the inventory of flooded mines. EFG also supports the Work Package on dissemination and EFG's Third Parties disseminate the project results at national level in web portals, newsletters, conferences, workshops, educational activities, exhibitions or by any other relevant means.
More information: ***www.unexmin.eu***

CHPM2030

654100 - CHPM
Combined Heat, Power and Metal extraction from ultra-deep ore bodies
START DATE: 1 January 2016
DURATION: 42 MONTHS

The CHPM2030 project aims to develop a novel, pilot level technology that combines geothermal resource development, minerals extraction and electro-metallurgy in a single interlinked process. In order to improve the economics of geothermal energy production, the project will investigate possible technologies for manipulating metal-bearing geological formations with high geothermal potential at a depth of 3–4 km in order to make the co-production of energy and metals possible; potentially this could be optimised according to market demands in the future. Led by the University of Miskolc (Hungary), the project will be implemented through the cooperation of 12 partners from 10 European countries.

EFG supports the activities relating to the CHPM2030 methodology framework definition (WP1), particularly European data integration and evaluation: during the first months of the project, EFG's Linked Third Parties (LTP) collected publicly available data at a national level on deep drilling programmes, geophysical and geochemical explorations and any kind of geo-scientific data related to the potential deep metal enrichments. They also collected data on the national geothermal potential. Guidelines and templates for data collection were provided by EFG.

During the second year, EFG will support the road mapping and preparation for Pilots (WP6), European Outlook. EFG's Linked Third Parties will assess the geological data on suitable ore-bearing formations and geothermal projects collected in WP1, in relation with the potential application of the CHPM technology. This work will combine these data with the outcomes of the most recent predictive metallogenic models. Only existing datasets will be utilised; no new surveys will be carried out.

EFG also leads the Work Package on dissemination and has produced so far the following deliverables: Final project web site; Project image and stylebook; Communication and dissemination plan; Brochure (1st edition); Newsletter 1 and Press release and media kits.
More information: ***http://chpm2030.eu***

MICA

689648 - MICA
Mineral Intelligence Capacity Analysis
START DATE: 1 December 2015
DURATION: 26 MONTHS

The MICA project brings together experts from a wide range of disciplines in order to ensure that raw materials information is collected, collated, stored and made accessible in the most useful way in order to respond to stakeholder needs. Hence, the goal for MICA is to provide stakeholders with the best possible information in a seamless and flexible way using an ontology-based platform, the European Union Raw Materials Intelligence Capacity Platform (EU-RMICP). To accomplish this goal, MICA will assess sources of relevant data and information and conduct analyses of appropriate methods and tools in order to provide guidelines and recommendations.

EFG supports the Work Package on communication, outreach and linkages. In collaboration with EuroGeoSurveys, EFG will be involved in the development of the communication strategy, the engagement with geosciences data providers, and professionals and public outreach.

More information: ***http://mica-project.eu***

FORAM

730127 – FORAM
Towards a World Forum on Raw Materials
START DATE: 1 November 2016
DURATION: 24 MONTHS

The project Towards a World Forum on Raw Materials (FORAM) will develop and set up an EU-based platform of international experts and stakeholders that will advance the idea of a World Forum on Raw Materials and enhance the international cooperation on raw material policies and investments. This platform will work on making the current complex maze of existing raw material related initiatives more effective. As such, the FORAM project will be the largest collaborative effort for raw materials strategy cooperation on a global level so far. Synergies with relevant EU Member State initiatives will be explored and fostered. Particularly, the project will seek to engage the participation of G20 member countries and other countries active in the mining and other raw materials sectors, so that experiences will be shared and understanding of all aspects of trade in raw materials will be increased.

The FORAM project is coordinated by the World Resources Forum Association (WRFA) and supported by eleven additional leading organisations (EuroGeoSurveys, European Federation of Geologists, United Nations University, Leiden University, University of Kassel, Clausthal University of Technology, ESM/Matsearch, Gondwana Empreendimentos e Consultorias, Servicio Geológico Colombiano, MinPol GmbH and La Palma Research Centre for Future Studies SL), which compose the FORAM consortium.

EFG leads Work Package 3 on "Strategic Planning", which will set the stage for the World Forum on Raw Materials (WFRM) using a highly participative process. WP3 will define and present a long-term vision and its strategic positioning, as well as an appropriate framework to measure performance and to respond to geo-political, technological and economic changes.

More information: ***http://foramproject.net/***

EFG and the UNECE gather international experts to discuss cooperation on natural resources

The European Federation of Geologists (EFG) and the United Nations Economic Commission for Europe (UNECE) co-organised, the conference "International cooperation on natural resources: geoscientists' contribution to enhanced governance, policy making and attainment of the Sustainable Development Goals". The event was held on 9–10 February 2017 at the Royal Belgium Institute of Natural Sciences, a venue located only a few hundred metres away from the European Parliament, and was supported by a broad range of European and international organisations. Nearly 100 participants from across Europe and abroad attended the event, whose international character was also displayed through a broad geographical representation on a programme conveying views from Europe, South Africa, the United States of America and Canada.

The continuing rise in global population and living standards, as well as technological innovation, is increasing global demand for energy and minerals with consequent requirements for a broader and more diversified range of natural resources, including conventional fossil or nuclear fuels and renewable energy. Therefore, a transparent and consistent estimation and classification methodology for mineral and renewable energy resources is vital to support international and national resources management and forecasting and to advance global cooperation. In this context, the aim of the conference was to contribute to the creation of a solid European Knowledge Database on mineral and energy resources by fostering the convergence of terminology and the comparability of data. During the two days almost 30 speakers – representing relevant UNECE and European policy areas, as well as international and European regulatory authorities, industries, non-governmental organisations and academia – discussed a transparent and harmonised European classification framework and the possibility for such framework to be based on the United Nations Framework Classification (UNFC).

This event was supported by the Committee for Mineral Reserves International Reporting Standards (CRIRISCO), the European Association of Geoscientists and Engineers (EAGE), EuroGeoSurveys, the Geological Society of Africa (GSAf), the Pan European Mineral Reserves and Resources Reporting Committee (PERC) and the Royal Belgian Institute of Natural Sciences.

More information: ***http://eurogeologists.eu/2017/02/14/efg-and-the-unece-gather-international-experts-to-discuss-cooperation-on-natural-resources/***

TAEG constitutes National Vetting Committee for EurGeol title applications

EFG's Turkish member TAEG, the Turkish Association of Economic Geologists, successfully applied to establish a National Vetting Committee (NVC) for European Geologist title applications. This new status allows TAEG members to apply for the European Geologist (EurGeol) title directly through their association.

The EurGeol title is a professional title created by the European Federation of Geologists that recognises the ability to deliver a high quality of services within the practice of geology. EurGeol title holders also undertake continuing education and training activities, thus demonstrating their personal commitment to stay up to date and informed within the sphere of their professional work.

More information about the European Geologist title and how to apply: ***http://eurogeologists.eu/eurgeol-title/***

EFG signs Agreement of Association with EAGE

EFG and EAGE (the European Association of Geoscientists and Engineers) have officially signed an Agreement of Association. EFG thus becomes an Associated Society of EAGE, a status that will strengthen the close relationship between EFG and EAGE and facilitate further collaborative communication, including mutual promotion of events and publications. The Agreement of Association consolidates the collaboration with EAGE established through a first Memorandum of Understanding in 2013.

The signing took place in Brussels during the EFG/UNECE conference on 10 February 2017. The Agreement was signed by EFG Executive Director Isabel Fernandez, EFG President Vitor Correia and EAGE Executive Director Marcel van Loon.

EFG becomes partner of ENSQM

The European Network for sustainable quarrying and mining (ENSQM) is a neutral network aiming at boosting sustainable mining and quarrying at national level by creating a culture of cooperation among all the stakeholders in the mining and quarrying sector at national level to open and manage mines and quarries in a sustainable way. At national level, this commitment could be materialised in a national/local/regional forum within the framework of jointly agreed objectives and procedure between the stakeholders of the mining and quarrying sector. The ultimate goal would be that the European Network for Sustainable Quarrying and Mining becomes a reference for the sector because it takes into account economic, social and environmental values.

More information: ***http://ensqm.weebly.com/***

EuroWorkshops: EFG launches a new cross-boundary training programme

Shaping and strengthening a European community of better-trained geologists who exchange and collaborate beyond national boundaries is one of EFG's major missions. In order to achieve that mission, the EFG has launched a new form of professional training: the EuroWorkshops.

Every year, one or two National Associations (NAs), members of EFG, will select a theme, provide speakers and location close to the geological point of interest, and will organise the EuroWorkshop, as well as a field trip. Organised all across Europe, the EuroWorkshops will allow geologists to receive professional training and exchange ideas; and will thus reinforce their skills, knowledge as well as the European idea among them. The EuroWorkshops will also provide a unique opportunity for students and young professionals to receive applied training and familiarise themselves with the missions and vision of EFG.

All EuroWorkshops are accepted within the Continuing Professional Development Program (CPD) of the EFG under the activity category of FLT ("Enhancing and maintaining skills and knowledge – Formal Learning") and will be honoured with 1 point/hour.

The first EuroWorkshop will take place in Fira, on the island of Santorini (Greece), on 18¬– 19 May 2017. Co-organised by EFG and the Association of Greek Geologists (AGG), the "EuroWorkshop on Geothermal Energy" will provide a glimpse into the future of geothermal energy, facilitate cross-fertilisation between different scientific areas and contribute to bringing society a step closer to reaching the goal of zero CO_2 emissions.

More information: ***http://eurogeologists.eu/santorini-2017/***

EAGE/EFG Photo Contest 2017

The theme of the Photo Contest 2017 is again 'Geoscientists at work'. At the beginning of the year, all EAGE members and members of EFG's national associations were invited to submit their photos relating to the following five sub-categories:

- Education & training
- Landscapes & environment
- Fieldwork
- Energy
- Women Geoscientists

EAGE and EFG members currently can vote online for their favourite photograph among nearly one hundred entries. The 12 most stunning photographs coming from different continents will be printed and exhibited during the 79th EAGE's Annual Conference & Exhibition 2017 (12– 15 June, Paris, France).

On 1 May the voting for the Top 3 will open. The winners will receive some fantastic prizes.

More information: ***http://houseofgeoscience.org/photocontest***

Submission of articles to European Geologist Journal

Notes for contributors

The Editorial Board of the European Geologist journal welcomes article proposals in line with the specific topic agreed on by the EFG Council. The call for articles is published twice a year in December and June along with the publication of the previous issue.

The European Geologist journal publishes feature articles covering all branches of geosciences. EGJ furthermore publishes book reviews, interviews carried out with geoscientists for the section 'Professional profiles' and news relevant to the geological profession. The articles are peer reviewed and also reviewed by a native English speaker.

All articles for publication in the journal should be submitted electronically to the EFG Office at ***info.efg@eurogeologists*** according to the following deadlines:

- Deadlines for submitting article proposals (title and content in a few sentences) to the EFG Office (***info.efg@eurogeologists.eu***) are respectively 15 July and 15 January. The proposals are then evaluated by the Editorial Board and notification is given shortly to successful contributors.
- Deadlines for receipt of full articles are 15 March and 15 September.

Formal requirements

Layout

- Title followed by the author(s) name(s), place of work and email address,
- Abstract in English, French and Spanish,
- Main text without figures,
- Acknowledgements (optional),
- References.

Abstract

- Translation of the abstracts to French and Spanish can be provided by EFG.
- The abstract should summarise the essential information provided by the article in not more than 120 words.
- It should be intelligible without reference to the article and should include information on scope and objectives of the work described, methodology, results obtained and conclusions.

Main text

- The main text should be no longer than 2500 words, provided in doc or docx format.
- Figures should be referred in the text in italic.
- Citation of references in the main text should be as follows: 'Vidas and Cooper (2009) calculated…' or 'Possible reservoirs include depleted oil and gas fields… (Holloway *et al.*, 2005)'. When reference is made to a work by three or more authors, the first name followed by '*et al.*' should be used.
- Please limit the use of footnotes and number them in the text via superscripts. Instead of using footnotes, it is preferable to suggest further reading.

Figure captions

- Figure captions should be sent in a separate doc or docx file.

References

- References should be listed alphabetically at the end of the manuscript and must be laid out in the following manner:
- Journal articles: Author surname, initial(s). Date of publication. Title of article. Journal name, Volume number. First page - last page.
- Books: Author surname, initial(s). Date of publication. Title. Place of publication.
- Measurements and units
- Measurements and units: Geoscientists use Système International (SI) units. If the measurement (for example, if it was taken in 1850) was not in SI, please convert it (in parentheses). If the industry standard is not SI, exceptions are permitted.

Illustrations

- Figures should be submitted as separate files in JPEG or TIFF format with at least 300dpi.
- Authors are invited to suggest optimum positions for figures and tables even though lay-out considerations may require some changes.

Correspondence

All correspondence regarding publication should be addressed to:
EFG Office
Rue Jenner 13, B-1000 Brussels, Belgium.
E-mail: ***info.efg@eurogeologists.eu***

Note

All information published in the journal remains the responsibility of individual contributors. The Editorial Board is not liable for any views or opinions expressed by these authors.

Subscription

Subscription to the journal:

15 Euro per issue

Contact

EFG Office
Rue Jenner 13, B-1000 Brussels, Belgium.
E-mail: ***info.efg@eurogeologists.eu***

Advertisements

EFG broadly disseminates geology-related information among geologists, geoscientific organisations and the private sector which is an important employer for our professional members, but also to the general public.

Our different communication tools are the:

- EFG website, ***www.eurogeologists.eu***
- GeoNews, a monthly newsletter with information relevant to the geosciences community.
- European Geologist, EFG's biannual journal. Since 2010, the European Geologist journal is published online and distributed electronically. Some copies are printed for our members associations and the EFG Office which distributes them to the EU Institutions and companies.

By means of these tools, EFG reaches approximately 50,000 European geologists as well as the international geology community.

With a view to improving the collaboration with companies, EFG proposes different advertisement options. For the individual prices of these different advertisement options please refer to the table.

Prices for advertisements

EGJ	**One Insertion**	**Two Insertions**
Full page (colour)	820 Euro	1320 Euro
Half page (colour)	420 Euro	670 Euro
Quarter page (colour)	220 Euro	350 Euro
Full page (black and white)	420 Euro	670 Euro
Half page (black and white)	220 Euro	350 Euro
Quarter page (black and white)	120 Euro	200 Euro
Business card size	90 Euro	150 Euro
Preferential location	25% plus	
Price for special pages:		
Outside back cover (colour)	1200 Euro	1900 Euro
Second page (colour)	1000 Euro	1600 Euro
Second last page (colour)	1000 Euro	1600 Euro

Geonews	**Annual Price**
Ad and regular newsfeed	1500 Euro
EFG Homepage	
Ad and regular newsfeed	1500 Euro
University ad	
Ad for training opportunities in the job area of the homepage	500 Euro
Annual package	
Business card size ad in EGJ, GeoNews and homepage.	3000 Euro