European Geothermal Congress 2019

Den Haag, The Netherlands, 11-14 June 2019

A new geothermal exploration workflow for deep sedimentary basins and basement

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Keywords: Exploration, Basin, Basement, geology, geophysics, geochemical, HSA, EGS.

ABSTRACT

In order to expand the geothermal energy exploitation, we need to explore various geological contexts, particularly the sedimentary basins, which concentrate many customers. The FP7-IMAGE project (for Integrated Methods for Advanced Geothermal Exploration) was dedicated to develop a standardized workflow for geothermal exploration.

In this paper, we propose to set up a scale-dependent exploration workflow that consists in building, step by step, more and more refined subsurface models based on larger scale models. To achieve this, we highlighted the key parameters and therefore the key situations, which are favourable for geothermal fluid extraction. To detect these key situations, we defined the best methods useable at various scales. Then, we implemented a workflow of static and dynamic models in order to define the best geothermal place and reduce the financial risk of drilling.

1. INTRODUCTION

The significant growth in electricity generation, but also for heat production, from geothermal energy has occurred worldwide in recent years (Bertani, 2016) and enhances the potential of geothermal energy in the energy mix. Therefore, the high-risk cost of drilling to confirm the existence of a viable geothermal resource remains one of the key challenges facing the industry. In order to remain that, exploration is essential to better know and understand geothermal reservoirs. Then, the European Commission co-funded the IMAGE project (for Integrated Methods for Advanced Geothermal Exploration) within 7th Framework Programme for Research and Technological Development (FP7). This project involved 20 partners from 9 different countries for four years (2013-2017) and was completed in October 2017. IMAGE main aim has been to develop exploration methods for an extended resource base, including supercritical and deep basement/sedimentary geothermal reservoirs.

This paper fits into the deep basement and sedimentary context, which is particularly interesting in Europe, where less magmatic resources are present. Therefore, geothermal power production from basement and sedimentary contexts is a valuable local source of energy, produced near the consumers who may also be interested in the co-produced heat. In addition, resources with a lower temperature between 120°C and 200°C can now be used for electricity production with a better energy efficiency than before, thanks to the improvement of binary cycles for electricity production and the development of the enhanced geothermal system (EGS) technology targeting on an improved permeability of the rock mass. To exploit this temperature range from less favorable areas is a major issue for Europe, where such regions of moderate to low geothermal gradients prevail.

Geothermal resources in the sedimentary basins have some particularities in relation to volcanic resources, which have to be taking into account for their exploration. In the basins in Europe, many human activities are present, which is an advantage in terms of final consumers but also a disadvantage in terms of exploration works. Besides the social acceptance aspect, some of usual geophysical measurements can be disturbed by noise caused by industrial activity, road traffic, railways or electric fences. However, certain methods, as ambient noise interferometry, could use the human activity as source.

Another particularity of sedimentary basin context is the blind geothermal resource. Generally, a normal geothermal gradient (30°C/km) occurs and if the temperature targeted is between 120°C and 200°C, this temperature range is then reached between 4 and 6 km depth and corresponds to the deep layers of the sedimentary basins and the upper part of the basement. At this great depth, the main challenge is to find the presence of fluid, which is the main vector of the heat, and a sufficient permeability to allow economical production of this fluid. The different types of resources that can be nowadays successfully harnessed are unclear due to the lack of a significant number of running operation in this geological context. Therefore, firstly, we need to identify the geological key situations (type of lithology, type of fault network, stress field…)

which characterize the best place for geothermal fluid extraction. And, secondly, we need to develop methods to identify this type of reservoir at great depth and in a noisy environment.

In this paper, we purpose an integrative exploration method, which cost-effectively collect new geoscientific data to minimize uncertainty related to estimates of key reservoir parameters (temperature, depth, extent, permeability, etc.) prior to drilling. This exploration may start at a large scale and progressively focus on smaller target areas as data reveal the most attractive locations. In our exploration workflow, we use or develop high performance numerical hydraulically, thermal and mechanical models at the different scales in order to, firstly, determine the boundary conditions of the smaller scale models, and, secondly, identify the best hydraulic transmissivity zones. These models are based on data from surface, sub-surface and wells, if they already exist, using geological, geochemical, and geophysical methods.

2. SEDIMENTARY BASIN CONTEXT

Continental sedimentary basins host important resources such as drinking water, oil and gas, and concentrate human activities and thus the electric power and industrial heat market.

In Europe, three main types of basins exist in relation to the geodynamic setting:

- Intracontinental basins, due to sedimentary load-induced and thermal subsidence. This is the Paris Basin, the Aquitanian basin and the North German Basin;

- Rift basins, due to the tectonic stretching and thinning of the continental crust. This is mainly the case in the European Cenozoic Rift System, which includes from south to north the Catalonia basin, the Rhône valley, Limagnes, the Bresse graben, the Rhine graben and the Eger graben (Ziegler, 1992);

- The foreland and forearc basins, linked to a compressive tectonic setting and crustal load-induced subsidence. In Europe, this type of basins are related to Alpine tectonics. The Molasse basin is a foreland basin. The Pô valley and the Pannonian basin are forearc basins.

Many basins are well known in terms of geology due to oil and gas exploration activities in the 70's and 80's. In some cases, such hydrocarbon exploration campaigns provide valuable information, but they also have their limitations, notably if the wells and geophysical data do not include the basement and do not reach a sufficient depth in the sedimentary layers. Moreover, typically information is limited to the places where these kinds of resources have been explored, which does not necessarily correspond to the best areas of interest in terms of geothermal power production.

Complex interactions of different heat transfer processes (conductive, forced and free convective) characterize usually sedimentary basins (Moeck, 2014). Rift basins are hydraulically controlled by complex fault systems so that convection contributes significantly to heat transfer (Moeck, 2014). On the contrary, in the flexural and foreland basins, heat transfer is mainly conductive (Moeck, 2014). In general, conductive heat transport is overprinted by additional convective influences. Fluid convection and thus a certain degree of rock permeability are essential for tapping the geothermal fluid. In the basins, pre-existing natural fractures play a major role in this fluid flow, but natural mechanisms controlling the hydraulic performance of these fractures are not well understood, which hamper prediction of expected flow rates prior to drilling.

Therefore, generally, two types of reservoir exist and co-exist in the sedimentary basins, namely HSA for Hot Sedimentary Aquifers and fractured reservoirs. This latter is often wrongly called EGS for Enhanced Geothermal Systems, but the term EGS qualified the different technics used to improve the permeability of the reservoir. The HSA resources consist of hot water in layers of rock that easily allow the water to flow through them, called aquifers, typically sandstone layers in sedimentary basins. Conduction is the main form of heat transport in these systems, although advection and convection are likely to be a contributor in some resources. The concept for HSA usage is that permeabilities and the volume of water in the reservoir are sufficient to allow fluid extraction at high flow rates without any need for enhancement (Figure 1; Huddlestone-Homes and Russel, 2012). Fractured resources are typically related to the deeper crust or the deeper part of the basin, like the transition between the sediment and crystalline basement, deep fault zone and crystalline rocks (Figure 1). Generally, that do not naturally have high permeability and if the flow rate is not economically viable, the flow transmissivity needs to be enhanced by any engineering way (hydraulic, thermal, chemical stimulation, specific well design…).

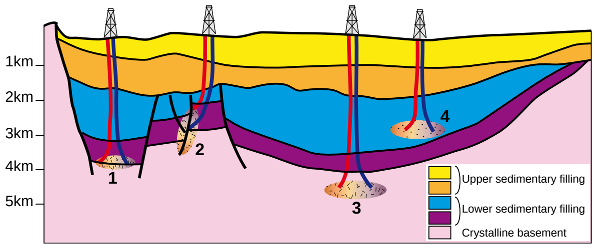

Figure 1: Schematic of geothermal reservoirs (modified from Budd *et al.*, 2015). 1: sediment/basement interface; 2: fault zones; 3: fractured basement; 4: HSA.

In the European basins, some geothermal operations already exploit the different types of reservoirs to produce heat or electricity or a combination of both (Table 1). Some projects such as Soultz, Landau, Basel and Traunreut have revealed a significant number of surprises. Soultz (France – Upper Rhine Graben) and Traunreut (Germany-Molasse Basin) encountered much (up to 25%) lower temperatures than expected from predictive models that were constrained by well data. For both settings, it appears that advective fluid flow plays a dominant role in distributing heat. Detailed studies on Soultz and Basel clearly demonstrate that pre-existing natural fractures play a key role in the flow performance of the heat exchangers (Gentier *et al.*, 2010).

Table 1: Examples of geothermal projects in Europe. Columns 1, 2, 3 and 4 refer to Figure 1. RG: Rhine graben, MB: Molasse basin, NGB: North German basin.

					Sediment/ basement interface	Faults zones	Crystalline basement	HSA	EGS
Geothermal exploitation site location		Depth (m)	Temp (°C)	Flow rate (l/s)	1	2	3	4	
Soultz	RG	5000	200	15			x		x
Landau	RG	3000	160	50-70	x				x
Insheim	RG	3600	165	50-80	x				x
Rittershoffen	RG	2700	177	70-80		x			x
Bruchsal	RG	2500	134	25				x	
Riehen	RG	1550	66	18				x	
Basel	RG	4680	174				x		x
Unterhaching	MB	3350	123	150				x	
Taufkirchen	MB	3700	135	120				x	
Sauerlach	MB	4500	140	110				x	
Traunreut	MB	5000	116	135				x	
Groß Schönebeck	NGB	4300	150	14	x				x

3. EXPLORATION APPROACH

3.1 What are we looking for?

As the geothermal resources in these kind of contexts are blind, we need to define what we are looking for in terms of physical parameters. Obviously, temperature should be highest at the shallowest depth will be targeted, i. e. at least 120°C-150°C at economically drillable depth, 3 to 5km depth. Natural permeability is the second essential parameter. Both permeability from porosity (primary permeability) and fractures (secondary permeability) should be taking into account and should allow a sufficient flow rate for an exploitation economically viable. However, this permeability could be enhanced by different technics as hydraulic, chemical or thermal stimulation or innovative well design. Then fracture network in relation to the stress field should be also taken into account. Finally, the renewable volume of brines and recharge waters should allow the sustainability of the reservoir production.

These key parameters are related to the geological patterns and subsurface phenomena, which have to be identified by relevant exploration technics. We can distinguished:

- Lithology: that plays a role both for heat and for flow. Intrusive body as heat source and/or thermally low-conductive sediments as thermal blanket could help to increase the thermal gradient (Richardson and Oxburgh, 1979; Cacase *et al.*, 2010). In another hand, high-porosity rocks allow to better fluid circulation.

- Structural patterns: that could help the fluid flow or contrary can be a barrier. Patterns of fault affected the permeability and could enhance if in such cases are fault intersections, dilational jogs, relay ramp, fault tips (Caine, 1996; Rowland and Sibson, 2004; Faults and Hinz, 2015).

- Fluid convection: that allows the heat transfer. Two type of convection exits. First, the forced convection, due to pressure gradients transports the heat from high-pressure areas to low pressure areas. This process depends on the hydraulic regime and permeability contrasts. Second, free convection or convection cells develop when the warmer and less dense fluid rises while the cooler fluid sink down.

- Stress field: that could affect the fluid circulation. The most favorable sites for fluid accumulation will occur where closed minima of mean stress contours develop (Connoly and Cosgrove, 1999).

In order to minimize the risk of a geothermal exploration, these key parameters should be find at the same place, i. e; sufficient temperature and flow at an economically viable drilling depth (Dezayes *et al.* 2016, Peter-Borie *et al.*, 2017). Althrough these best situations are no scale dependent, the exploration technics are in relation to the scale of exploration areas.

3.2 What are the main relevant scale?

As in the fields of mineral deposit exploration (i. e. Campbell McCuaig *et al.*, 2010) or petroleum exploration (i.e. Jahn *et al.*, 2008), exploration should be performed sequentially from large to local scales (Figure 2):

- The continental scale, covers at least 1000 x 1000 km including the lithospheric plate. At this scale, the objective is to consider the overall thermal field linked to the thickness of the crust and lithosphere as a result of its geodynamic history.

- The regional scale refers to an area of c.a. 100 x 100 km covering (at least parts of) a particular geodynamic setting such as a basin or a graben. Any exploration campaign should start at this scale, because the geodynamic setting controls the geology and present-day stress state of the region of interest, including average geothermal gradients, depth of sedimentary layers or deep fractured rocks. It can be compared to the province scale for ore deposit exploration.

- The local scale will correspond to a 10 x 10 km square, which is the last step of exploration before to define the field scale, or namely also the prospect area, where the location of the first exploration well can be chosen.

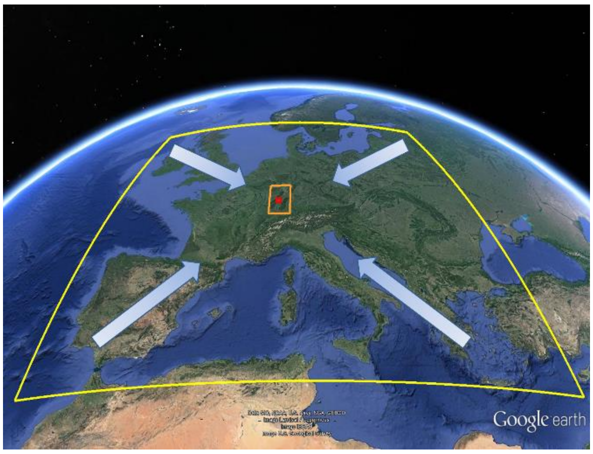

Figure 2: Crossing different scales of exploration. Yellow: continental scale. Orange: regional scale. Red: local scale.

3.3 What are the relevant exploration methods?

In this section, we have summarized the benefits and drawbacks of the main methods applicable for the assessment of favorable key situations for the development of geothermal projects i.e. a favorable heat factor (e.g. plutonic intrusion, presence of thermal blanket and/or convective heat cell) and a favorable fluid factor (e.g. fault intersection, fault jog/ramp/tip). For a more thorough description of the methods, please refer to the IGA best practice guide for geothermal exploration (2014). As the size of the exploration target depends on the exploration scale, we have first ranked the exploration methods as function of 1) the exploration scale and 2) key parameter to assess (table 2). The ranking is based on the technical feasibility of the methods, without any operational and economic considerations. It is obvious that no single method can assess the presence of all favorable key situations but rather that depending on the scale and remaining subsurface uncertainties, a combination of methods is necessary.

Table 2: Summary of main possible (in blue) and not possible (in yellow) exploration methods to use before drilling to assess the presence of favorable element for geothermal reservoir, depending on the exploration scale.

			Continental Scale				Regional Scale				Local Scale			
	Type of method	Method	Lithological setting	Structural Elements	Fluid convection	Stress field	Lithological setting	Structural Elements	Fluid convection	Stress field	Lithological setting	Structural Elements	Fluid convection	Stress field
Geophysics	Active seismic	2D seismic	■	■			■	■			■			
		3D seismic	■	■			■	■			■	■		■
		VSP									■	■		■
	Passive seismic	Microseismic				■		■		■		■		■
		Noise tomography	■				■							
	Active EM	CSEM/ERT	■				■				■			
	Passive EM	Magneto-Telluric	■				■				■			
		Streaming Potential							■				■	
	Potential fields	Gravity/Magmetism	■				■							
	Gradient Well	Temperature			■				■				■	
Geology	Structural analysis			■		■	■	■		■		■		■
	Petrography		■				■				■		■	
	Mineralogy		■				■				■		■	
Geochemistry	Rock geochemistry		■				■				■		■	
	Fluid geochemistry						■				■		■	
	Geothermometers												■	

■ Technically feasible

□ Not currently feasible or not applicable

[1] Presence and location of magmatic intrusions, thermal blanket...
[2] Presence of favorable structural elements for fluid flow
[3] Detection of fluid circulation implying convective heat transfert
[4] Determination of present-day stress tensor

To assess lithology setting and structural pattern of an exploration area at the European scale, all geophysical techniques are in principle suitable, except VSP's as the volume of investigation is limited around the borehole. Similarly, structural and petrological techniques can provide valuable information. Due to its high spatial resolution, 3D seismics combined with structural analysis is recommended to determine structural patterns but 2D seismic, passive seismic, active/passive EM and gravity/magnetism can also provide valuable information. However, the deployment of geophysical techniques at this continental scale is not really adapted except passive seismic survey, gravity and magnetism measurements, but the resolution is not enough fine to assess the structural elements. At this scale, the assessment of the fluid convection is not really possible based on these techniques. It is the same for stress field, except by analysis of seismicity and large-scale structural analysis.

To explore an area at regional scale, the use of techniques is rather the same than at continental scale. To define lithology a structural setting, all geophysical techniques are in principle suitable as well as structural and petrological method, but the resolution at this scale is not really accurate. However, 3D seismics combined with structural analysis is the best due its high spatial resolution but 2D seismic, passive seismic, active/passive EM and gravity/magnetism can also provide valuable information. The presence of convection cell is usually difficult to detect with all techniques except may be geochemistry. At this scale, the stress field can be assessed by seismicity and structural analysis (Angelier, 1990, 2002).

To assess lithological and structural setting of an exploration area at the local scale, active seismic techniques (2D/3D seismic, VSP) combined with structural and petrological analysis are best suited. VSP need borehole, but give a very accurate image of the geological structures around (Reiser *et al.*, 2017). Passive seismic, active/passive EM and gravity/magnetism will all struggle due to their limited spatial resolution as well as geochemistry methods. Fluid convection can be assessed by combination of mineralogical and geophysical analysis associated to the structure pattern to determine the fluid flow pathway. The stress field at this local scale is mainly assessed with structural analysis associated with active seismic image.

It is obvious that there are no golden rules to select the best exploration methods and, moreover, no single method can assess the presence of all favorable key situations but rather a combination of methods is necessary.

In addition to the key subsurface uncertainty that the method will address, it is necessary to select the method that will meet the best technical, operational and economical compromise (Table 3). Such information can subsequently be used to assess the value of acquiring this new information for the project and help decide whether the method is worth applying. A Value of Information (VOI) study (Trainor-Guitton *et al.*, 2017) can quickly provide the relevant elements for the decision-making based on economic criteria and help define of the appropriate exploration program.

Table 3: Main operational and financial specifications of the most commonly used geothermal exploration techniques.

		Equipment	Spatial Resolution	Crew size	Typical Price Tag	Typical Acquisition Time	Typical Analysis Time
Geophysics	Active Seismic	Vibroseis + geophones/ Hydrophones	10's m	10's people	A few k€/km (2D) A few 10's k€/km2 (3D) 100's k€/well (VSP)	Weeks	Months
	Passive Seismic	Seismometers	100's m	A few people	A few k€/km2	Months	Weeks
	Active EM (ERT/CSEM)	EM transmitter + MT stations	100's m	A few people	A few k€/km2	Weeks	Months
	Passive EM (MT)	MT stations	100's m	A few people	A few k€/km2	Weeks	Weeks
	Passive EM (SP)	Voltmeter	1000's m	1-2 people	A few k€/km2	Weeks	Days
	Gravity/ Magnetics	Land/airborne sensors	1000's m	A few people	A few k€/km2	Weeks	Days
	Heat flow/ temperature gradient	Light drill rig	10's m	A few people	A few 10's k€/well	Days	Days
Geology	Structural Analysis	Land survey equipment	1000's m to 1's m	1-2 people	A few k€/km2	Weeks	Months
	Petrography/ mineralogy	Microscope, SEM, Cathodoluminescence , electron probe	1's m to 1's mm	1-2 people	A few 10's k€/km2	Weeks	Months
Geochemistry	Solute geo-thermometers	Conductimeter, pH-meter + Laboratory	1000's m	Two people	A few 10's k€/site	Days	Weeks
	Tracers	Spectrophoto- meter and HPLC	Inter-wells	Two peoples	A few 10's k€/tracer test	Months	Weeks

4. EXPLORATION WORKFLOW

The exploration workflow presented here includes geological, geophysical and geochemical techniques as well as numerical models in order to first, integrated the data and second, predicts the geothermal target (Figure 3). The starting point is the 3D geological interpretation, which provide the structure to build thermal, mechanical and groundwater flow models.

The geological model may be the more realistic based on geological and geophysical data in order to define the subsurface structures and the lithology. The geological model could also constitute a conceptual model if no many data is available. The geological model may be the most consistent and comprehensive as possible in order to give a base for the physical models: thermal, groundwater flow and mechanical models.

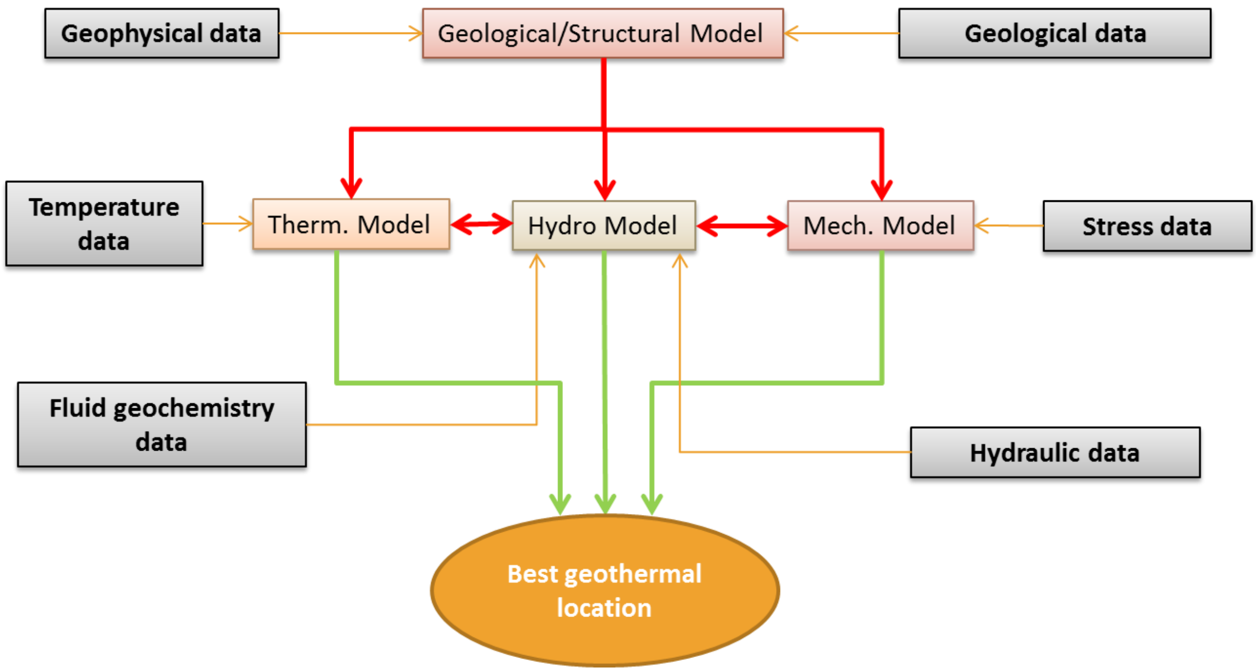

Figure 3: General geothermal exploration workflow

At all scales, the workflow is the same, but the input data and the model scales have to be adapted. At continental scale, the objective is to determine the major thermal anomalies as caused by geodynamic phenomena. The models at this scale aim to bridge the gap between large-scale geophysical models and more detailed regional models. They also provide boundary conditions for the smaller-scale models.

These continental-scale models integrate first-order contrasts in lithology, temperature and mechanical parameters. This scale is too large to numerically simulate hydraulic processes. Geological models are based on surface geological data, such as geological and fault maps, and subsurface geophysical data, as deep structures and rock properties (Table 4). At this scale, thermal models only consider conductive heat transport processes and require the integration of (i) heat flux or temperature as boundary conditions and (ii) thermal conductivity of the main rocks usually based on generic models or literature values and radiogenic heat production of the main lithological units (Table 4). The mechanical models are based on the geodynamic knowledge and the stress field, including orientation and magnitudes (Table 4). They provide boundary conditions for the smaller scale models.

The main key parameter derived from continental-scale models is temperature. Modelled thermal anomalies will be taken into account for determining preferential regions for further exploration. Thus, the regional scale defines the first relevant exploration step. Models built at this scale benefit from boundary conditions as inherent in the continental-scale models. At the regional scale, groundwater flow models can be built by integrating hydraulic and hydrochemistry data (Table 4), while generating observation-consistent images of the distribution of infiltration and exfiltration areas, deep conductivity and storage, and regional flow pathways. In general, the challenge related to this type of models lies in validating the hydraulic characteristics predicted by such models. However, indications could be brought by of geochemistry data and geothermometers (Table 4) allow interpreting which lithological units the fluids have perfused and what maximum equilibrium temperatures they thereby reached (Fouillac & Michard, 1981).

Based on geodynamic data, mechanical rock properties and stress data (Table 4), mechanical models give information about the low-stress domains, which are favorable for fluid circulation.

Table 4: Data needed for the exploration workflow at the various scale. In italic: optional data.

	Continental Scale	Régional Scale	Local Scale
Geophysical data	Remote sensing Seismic velocity structure from global tomography Density from gravimetry Magnetic field data from geomagnetic measurements	2D seismic *Gravimetry anomalies* *Magnetism anomalies* *P/S-wave velocities from seismic tomography*	2D / 3D seismic images and seismic velocity models VSP images, information on velocity and anisotropy *Electric conductivity from various EM methods* *Density from Gravimetry* *Geophysical logging from previous wells*
Geological data	Fault maps Geological maps *Stratigraphic data* *Lithofacies data*	Topography Geological map Structural discontinuities Rock type *Stratigraphic data* *Lithofacies data*	Geological map Faults map Fracture analysis *Fault zone thickness and property changes* *Facies analysis and distribution* *Thickness distribution*
Temperature data	Heat flux Themal conductivity Thermal gradient	Thermal conductivity *Heat flux* *Borehole temperature* *Thermal gradient* *Surface temperature* *Radiogenic Heat Production* *Specific Heat Capacity* *Seismology-derived temperatures*	Heat flux Themal conductivity Thermal gradient Temperature from previous borehole BHT measurements or DST *Peclet number analysis to identify convection*
Stress data	Geodynamics knowledge Stress field orientation from seismology Stress magnitudes	Geodynamics data Mechanical rock properties Stress measurements (welltests/Borehole breakouts) Seismology (Focal mechanisms) Geodesy	Geodynamics Stress measurements Pressure gradients Logs/welltests DAS logs Previous drilling reports (mud losses) (Geophy : Vp Vs paramètres élastiques)
Geochemical data		Major and trace elements analyses from thermal spring water and borehole fluid Isotope analyses from thermal spring water and borehole fluid	Major and trace elements analyses from thermal spring water and borehole fluid Isotope analyses from thermal spring water and borehole fluid *Gas anomalies*
Hydraulic data		Topography Permeability / Hydraulic conductivity from previous well tests Porosity Density *Groundwater levels* *Location of springs* *Residence time* *Flow velocity* *Rivers, Lakes* *Reservoir pressure from previous E&P wells*	Topography Location of springs *Anisotropy of hydraulic properties; e.g. horizontal vs. vertical permeability, influence of fault zones and fractures* Groundwater levels Location of circulation zones from mud losses in previous wells

At the regional scale, thermal models can be refined based on more precise data, like borehole temperature or radiogenic heat production (Table 4). Moreover, convective phenomena can be integrated into the thermal models based on groundwater flow and mechanical models, thus allowing the simulation of coupled fluid and heat transport and analyzing related thermal anomalies.

The combined analysis of the thermal, mechanical and groundwater flow models, optimally in a fully coupled way, help us to define the target at local scale. For each physical models, criteria have been defined indicating the presence of a geothermal reservoir. Based on the thermal model, we define the high temperature area at shallowest depth (Freymark *et al.*, 2017). Decharge zones or upflow areas have been determined based on hydraulical model, and less compressed areas, allowing fluid circulation, based on the mechanical model (Armandine Les Landes *et al.*, 2017). The cross-analysis of these favorable areas allows us to highlight the preferential areas for the exploration at the local scale. Then, at regional scale, temperature, stress state and fluid flow are important and this step induces the first go/no go to investigate more precisely a given region at a local scale.

At the local scale, models should be refined in order to define the area of the prospect. Data used for the regional scale models are also needed for the local scale models, if available with more details (Table 4). The data should be completed by additional, more local information such as, for example, data from existing boreholes if they are available (Table 4). At this scale, mechanical and groundwater flow models are very important to determine the best location to tap fluid.

The cross-analysis of groundwater flow and mechanical models or preferably fully coupled hydro-mechanical models allow to estimate location of upflow water plumes and deep/longest groundwater loops. The association of these both criteria allow to delineate the preferential target area for the field scale exploration. This area corresponds to the area of an exclusive license for geothermal exploration, namely prospect in ore exploration.

Even if their scope is too general to be worth of industry funding, continental and regional scale models give valuable information for industrial stakeholders. Such models integrate precompetitive geoscientific data and benefit from the practical experience acquired in past years when researchers were improving our understanding of dual geothermal systems, whether in hot sedimentary aquifers or in the basement, whether with or without the involvement of EGS technologies. For the future, a constant and frequent exchange between privately and publicly sponsored sectors should be envisaged, including the exchange of both observational data and models, in particular on the local scale.

5. CONCLUSIONS

Sedimentary basins offer an enormous but still largely unexploited geothermal potential and constitute the major part of the European territory. However, geothermal resources are located very deep in this geodynamic context and then are blind at the surface. Moreover, these highly populated territories generate a lot of noise disturbing classical geophysical exploration methods. The exploitation of resources in the basin context bears an investment risks related to insufficiently known geological and physical conditions at greater depth. The integrated modelling workflow developed by the IMAGE project has the potential to efficiently reduce these risks while making use of the huge amount of observations already available.

Future exploration campaigns can benefit from our exploration workflow. As the resources are blind, modelling is needed to better delineate the search area by simulation of fluid pathways and related thermal anomalies. These process models are based on geological and structural models, which consistently integrate all geological and geophysical data available in the modelled domain. This initial knowledge basis should be improved and complemented throughout the exploration process by adding acquisition data. The physical models, as thermal, mechanical and groundwater models, should be built based on the geological models and help to identify the fluid pathways and the place to focus the smaller-scale exploration. However, uncertainties in predictions of geothermal resource location persist and should be taken into account.

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ACKNOWLEDGEMENTS

The research leading to these results has received funding from the European Community's Seventh Framework Program under grant agreement No. 608553 (Project IMAGE).

This study was also part of the REFLET project, which received funding from the French Scientific Interest Group for carbon-free energy Géodénergies.