Technological challenges in exploration and investigation of EGS and UGR

A. Manzella,
CNR-IGG Pisa, Italy

Abstract

The most pressing technological challenges in exploration and investigation of Enhanced Geothermal Systems (EGS) and Unconventional Geothermal Resources (UGR) are considered to be those associated with the identification of the nature of geothermal heat concentrations and prospective resources prior to drill and the improvement of methods allowing a spatial and temporal reconstruction of the subsurface geothermal condition that might not only cut the time from discovery to production and improve efficiency while guaranteeing sustainability of the resource, but also reduce environmental impacts forecasting possible problems and finding solutions beforehand. A list of important research themes is provided

Introduction

The search for geothermal and tools of search have changed. In the '80s the main search focused on large reserve, high enthalpy systems with T >> 150 °C and EGS concept was at its early stage. Now that lower temperature can be exploited and EGS technology is becoming more mature there is still a hunt for high enthalpy fields - especially near known fields - to enrich the portfolio and add growth for the long term, but exploration expands to new conditions and new areas. What was considered unexploited or not economic in the past is becoming possible nowadays, if bottleneck for exploitation are overcome. Moreover, advances in technology make what is uneconomic today economic tomorrow.

In the framework of the ENGINE Coordination Action a main issue has been the definition of innovative concepts for the development of UGR or EGS. Important technical obstacles to attaining near-term and long-term EGS and UGR goals and objectives exist in the areas of resource characterization; reservoir design and development; and reservoir operation and management. In all these fields investigation and exploration provide a fundamental base. *Resource characterization* regards research in geothermal gradients and heat flow; geological structure, including lithology and hydrogeology; tectonics; induced seismicity potentials. *Reservoir design and development* includes research in fracture mapping and in-situ stress determination; prediction of optimal stimulation zones. *Reservoir operation and maintenance* includes research in reservoir performance monitoring through the analysis of temporal variation of reservoir properties. Moreover, in a new era of geothermal development, the sustainability and mitigation of environmental effects should be defined and optimized prior to major financial commitment.

Goals

During the past 50 years of exploration large amount of temperature data and significant knowledge of subsurface geology were accumulated. Based on this *a priori* knowledge several areas prospective for EGS exploration can be outlined in Europe and many regions in the World. Further exploration must prove the two most important conditions for developing an EGS: temperature higher than 85°C, and existence of permeable rocks either due to porosity in sediments or due to fractures in crystalline and volcanic rocks.
Two main goals should be addressed by exploration and investigation: to reduce the mining risk by cutting the exploration cost and increasing the probability of success in identification of EGS in prospective areas, and to provide all necessary subsurface information to guarantee the best exploitation efficiency, the sustainability of the resource and the lowest possible environmental impact.

Technological challenges targeted to these goals are mainly aimed to: 1) find improved and newly developed methodologies able to map reservoir condition suitable for EGS exploitation, in particular at local scale; 2) provide data integration (static and dynamic) and uncertainty analysis. Integration of technology and multidisciplinary evaluation of data, such as the one speeding up in the last 10-15 years for hydrocarbon exploration, must become a core competency also in the geothermal world; 3) find tools able to improve imaging between existing wells and performing real time measurements: some of these tools might be borrowed from oil and gas exploration but adapted to meet unique geothermal conditions, such as high temperature and pressure and possibly aggressive chemical composition.

1. Improve reservoir mapping

What starting conditions are necessary to develop/stimulate an EGS? What are the conditions classifying a thermally suited area for the development of an EGS? There is a need to refer to conceptual models of the main geothermal sites, from extended active geothermal sites to EGS for which heat distribution and permeability networks are available for modelling pathways for fluid circulation, gas-water-rock interaction processes (and their effects on *effective* porosity and permeability) and heat exchange. The cradle of such models should be the geometry of geology. They could be built by integrating the most significant datasets and their interpretation on reference key areas, like Larderello, Bouillante, Soultz, Groß Schönebeck. Such models must be updated as soon as new data or new experiences and results are available. Technological platforms could be promoted to develop new methods and tools, test hypotheses in situ and accuracy of conceptual models. A significant improvement of the knowledge is expected from natural analogue on which hypotheses could be tested about for example circulation of fluids in relation with seismicity and heterogeneity of the lithologies, thermal imprint of fluid circulation. The links with other investigation programmes like nuclear waste storage, capture and geological storage of CO2 and oil and gas field development will be developed to take benefit of existing installation and experiences.
Advances in exploration data acquisition, processing and workflows need continuous attention in order to provide better images in complex areas. Three main parameters should be known before drilling for exploitation of potential geothermal reservoirs: **permeability**, **temperature** and **stress field** (priority ranking). Temperature defines the energy stored in the subsurface. Permeability characterizes the flow rate that could be produced and reinjected in the system, which is directly linked with both temperature and the amount of energy that can be expected from a doublet system. The stress conditions are linked with the ability of geologists to select the most favourable sites for high flow rates and drilling and for engineers to enhance the natural permeability of the system.
Presently, at a regional scale different exploration methods are available for estimating temperature, geology and stress distribution at depth, but is very hard to map permeability. At local scale, where details of the reservoir and its potential energy need to be assessed, resolution is still rather low, while main gaps exist in combining geological, geochemical and geophysical data coming from different methods. Experiences made in hydrocarbon exploration must be modified for EGS, since EGS requires usually more knowledge about fracture and fault systems with respect to their role as potential water conduits. The reservoir imaging strategy should include large scale approaches supplemented by high-resolution experiments. Further benefit should come from adapted processing techniques.
Permeability, temperature and stress field are besides the structural inventory of the subsurface the key elements that could be put as priority for research needs.

Mapping of permeability

Even if the permeability is locally well-known from borehole measurements, it is far from evident that the permeability obtained at one given point could be extrapolated (combining surface geophysics and borehole data) to a nearby location. This can result from variations in the facies of the host rocks, to changes in the fracture network, or in the fracture properties that often control the permeability at great depths.
Workflows encompassing fault interpretation from 3D geophysics and geostatistic tools, 3D retro-deformation and fracture interpretation from well data should be further developed to give a base

for possible pathway interpretation and reconstruct the evolution with time. Palaeostress maps may also help in distinguishing between open or closed pathways.

Acoustic (compressional and shear wave) signatures of deforming rocks should be investigated with the aim to provide a database on rock physics and rock deformational properties so that high resolution 3D or 4D seismic surveys can be used to image reservoir enhanced permeability zones or to identify rock units where enhanced permeability could potentially occur. Moreover, the development of an integrated tool to handle fault and fracture analyses, drilling engineering, logging, and seismic data would provide great benefit toward a detailed permeability assessment.

Mapping of temperature

The mapping of temperature is essentially achieved by interpolating available temperature logs over a given area. In order to give a physical background to the interpolation of temperature logs, a new method was recently developed; it involves computing the temperature distribution on a numerical 3D diffusive model. Variables of the model (bottom heat flux, rock thermal conductivity and radiogenic heat production) are adjusted in order to fit temperature measurements.
However, the extension of large-wavelength heat flow anomalies at depth is often inaccurate due to the improper knowledge of the causes of the heat-flow anomaly. The existence of convective and advective cells, such as those well characterized at Soultz and in the Rhine graben area, hinder a temperature extrapolation to greater depth and can lead to wrong evaluation of thermal gradients.

It was recently pointed out that numerical modelling is important to predict the temperature distribution below the deepest temperature data of the region. Indeed, the existence of unknown local advection or convection processes due to water circulation in the host rock represent challenges for temperature prediction at these depths. Numerical models can already reproduce effects of advection and convection in geothermal reservoirs but most of them should be extended to face the complex conditions that can be met in geothermal systems. Broad thermo-hydrodynamic conditions should be incorporated in all the main reservoir simulators in order to model all parts of geothermal systems and their evolution with time.
Convective and advective cells should be also identified and characterized through detailed geochemical studies comprising definition of water chemistry, application of suitable geothermometric techniques (hydrochemical and gas geothermometers), mapping of CO_2 fluxes from soils, defining electrical resistivity variations, etc. Neural network analysis could be also useful in order to extrapolate laterally and at depth data coming from temperature logs and geothermometric data (geochemical and geophysical data)

Maps of the heat flow distribution at surface and at the crust-mantle boundary provide far-field conditions for any definition of possible targets for EGS. However, such maps require a basic knowledge of the main lithologies and their thermal properties. Thermal conductivity require proper calibration from a set of well-log parameters. With good control of thermal conductivity versus depth, the variation of heat flow versus depth can be delineated and interpreted in terms of heat-transfer processes, which is essential for the assessment of an EGS.
In order to properly define temperature and heat distribution for an EGS database thermal conductivity and the radiogenic heat production are now feasible for better constrained modelling.

It would be of great interest to produce temperature maps at regional scales plotted on some relevant geological interfaces. For example in Western Europe, temperature distribution at the top of the Trias, at the interface between sedimentary formations and basement rocks, in the uppermost 500 m of the basement, and in Eastern Europe, at the top of the Tertiary are of strong interest. Because numerical models used to compute the temperature distribution are based on the geological knowledge, there is a need to produce litho-tectonic maps at the interface between sedimentary formations and basement rocks.
There is the need to calibrate stratigraphy, reservoir fluid circulation and thermal history in underexplored areas. Measures to be taken need to involve a critical screening of thermal data, developing baseline temperature models, and investigating the modification through the time of reservoir exploitation, providing the essential thermal rock properties, and combining the

temperature field properties with reservoir properties. Analogue sites should be studied and results incorporated in the workflow in order to help the interpreters to take advantages from known similar conditions. Other investigation programmes like nuclear waste storage, capture and geological storage of CO2 and oil and gas field development may also provide useful information and experiences.

Mapping of stress

Evidences exist and show the influence of the stress field on hydro fracturing. The knowledge of spatial stress distribution (map and depth) on a local as well as on a regional scale is thus fundamental for any future experiment. Mechanisms of rupture and propagation of an existing fault system and related displacement remain debated, especially in connection with the circulation of fluids and efficiency for improving sustainable permeability.
The circulation and accumulation of fluids in the crust are fundamentally controlled by the geometry of the fault and fracture systems. The ability of these systems for the channeling of fluids is directly dependant of the stress field (orientation and intensity). Favourable and unfavourable conditions exist depending of the tectonic context and geological environment.
The mapping of stress can be obtained at various scales. At a continental scale, tectonic models provide a good estimate of the zones of different regimes. At a local scale, when exploration boreholes are available, the determination of the stress field can be done through microseismic interpretation or through hydrofracturing.
The major knowledge gap concerning stress estimation is located between regional and local scale. An important problem is that local stress variation can occur due to the existence of faults or magma bodies. Indeed, a possible objective for research could be to estimate stress at different depths, using a modelling procedure and taking in account pre-existing faults and any evidence for magma. The relationship between stress field and permeability should also be researched further.

Definition of in-situ stress, which is crucial both for understanding the dynamic of the fluid circulation and to help during exploitation, foreseeing the drilling requirements to avoid collapses, stacking and guarantee wellbore stability, as well as controlling stimulation effects including induced seismicity.

2. Integrate data

Data integration (e.g., static and dynamic) is a reoccurring theme throughout most Exploration and Reservoir Characterization elements and must be considered a key area to improve tools. There is no single software tool capable of providing a fully integrated Reservoir Model all the way from geophysics and geochemistry, through Geo Model to Flow Model due to problems with moving data, changing scales (up scaling) and common standards/workflows.
Several physical parameters (density, wave velocity, electrical resistivity…), as well as chemical and mineralogical properties are coupled with temperature and can be imaged by different geological, geophysical and geochemical methods. Thus, the definition of possible targets for EGS could be improved by the use of a 3D modelling platform, in which all solutions from geological, geochemical and geophysical modelling, direct and inverse, could be combined and analysed.

Geophysical methods are suitable to determine the architecture, geometry, and quality of target intervals. However improvement of existing methods and in particular reasonable combination of different, most sensitive techniques (passive and active seismic, MT, and others) are needed to meet the requirements of modern geophysical exploration. The interpretation of geophysical features must be supported and validated by petrophysical laboratory and borehole measurements, as well as modelling. Petrophysical studies should be extended in order to define the main relations between physical parameters, mineralogical composition, fluid chemistry and water-rock interaction effects. This would improve the knowledge of the whole resource and would allow to optimize exploitation strategy. E.g., hydro-fracturing is not the only option to enhance the permeability of reservoir rocks: selective dissolution should also be taken into account (as a

technique to increase *effective* porosity and permeability) as it could be more effective than fracturing, provided that it is applied to suitable lithological frameworks (e.g., sandstones made up of quartz and silicate minerals but also containing relevant amounts of fast-dissolving carbonate minerals) and under carefully selected conditions.
Lithology and Fluid Prediction can be improved using full wave fields. Reflection seismic through a detailed seismic attribute analysis, gravity, electromagnetic data allow to define density contrasts, porosity and permeability, nature of fluid. All these information, monitored in time, are used to make inferences about reservoir dynamic and helps in optimization of drainage. Depth migrated seismic should pay special attention on the velocity model construction. New inversion modelling tools should be defined, joining different geophysical information.

Eventually, geothermal community standards for additional data types should be developed to improve the maintenance of high quality databases and data handling and to facilitate the input of these data into simulators.

3. Improve imaging between wells

The necessity to guarantee the sustainability of the resource and zero environmental impact add focus on high availability of water including produced water injection solutions, no or reduced fluid discharge, no or reduced induced seismicity. Mapping of environmental condition before entering new areas and monitoring during operational phases is needed. This includes methods to assess impacts from discharges to shallow waters and emissions to air, the effects of compliance to a zero discharge versus a zero harmful discharge framework. A baseline should be established mapping the conditions before operation, predicting the effects of activity (risk and impact based evaluations) and monitoring actual condition during stimulation and production. To this aim a main technological challenge is the development of improved logging tools for imaging physical conditions at depth but also capable to resist at very aggressive condition (high temperature, high pressure, highly corrosive fluids) maintaining the costs as low as possible and guaranteeing a quick and reliable data transfer and storage.
As the EGS technology aims at exploiting heat in the ground at every point of the crust, the needs for mapping of permeability are more relevant at the scale of the reservoir to locate at best further boreholes. Today, various logging techniques give access to the fracture orientations and density crossing the borehole. The major issue is that the properties of the media between boreholes are poorly constrained.
In order to avoid these gaps, several geophysical tools need to be developed with the following objectives: 1) to identify the extension of a given fracture zone which intersects the borehole, and 2) to identify and characterize important fracture zones, which do not intersect the borehole. In other words, there is a need to develop a geophysical tool to image the 3D structure within the inter-well domain in hard rocks.
Here is a list of tools and real time measurements that would improve subsurface imaging and monitoring conditions during stimulation and production.

• Logging through casing should be improved. Cased-hole logging technology is a research field in oil and gas but the different casing problems of geothermal wells requires ad hoc solutions to be defined.

• A main effort should be made to design and demonstrate high temperature (> 200°C) measurement-while-drilling (MWD) tools using a unique high temperature battery system. Research projects made in the hydrocarbon exploration are focused on devices incorporating silicon-on-insulator (SOI) fabrication technology into the manufacturing process for the microchips required. The goal is to improve the reliability of high-temperature electronic components found in MWD tools needed to improve drilling efficiency and success rate at depths up to 8 km and temperatures greater than 200°C. This research should be joined and adapted to geothermal condition, especially in view of the different chemical condition often met in geothermal systems.

• The use of borehole seismic imaging supplemented with electromagnetic methods would help to map fluid content at distance of hundreds of meters from the bore hole with resolution comparable to existing logging methods. Since seismic methods provide information on the structural and mechanical properties of the medium and the conductivity provide independent information on the fluid state, these jointed measurements will provide a more complete map of the fluid distribution and matrix properties. This kind of measurements performed after the first exploratory well is drilled during an EGS project would provide precious information both for designing the subsequent wells and for defining sustainability of the system.

• Computational improvements should be made in order to obtain 3D electrical tomographs, providing the equivalent of electric logs deployed every few meters between existing wells. These high-resolution tomographs have been used with success for oil and gas formation characterization and monitoring subsurface fluid movement (i.e. tank leaks, steam floods), but should be adapted to geothermal condition where also temperature changes must be taken into account. This technique would also address the problem of tracking the fluid during stimulation or production. The ERT tomographs can be interpreted to show where the fluid saturations are changing in the field, providing insight into production and stimulation performance.

• The development of a combined microseismic receiver-tiltmeter system would provide an advanced hydraulic fracture mapping tool to measure created fracture geometry. Such system would eliminate the need for two observation wells and reduce overall costs.

Concluding remarks

The new demand for better understanding of the reservoir is setting new challenges, which are technical as well as organisational. A reservoir study project requires the availability of all the relevant prospect information, which on turn should be available to all the applications involved in the management and analysis of such a project. The improvement of the conceptual model to decrease the drilling risk of the exploitation wells needs more integration between different methods, advanced 3D modelling coupled with thermo-hydrodynamic modelling and rock physics measurements.

Integrated workflow include geophysical imaging, interpretation and earth modelling, and provides all information necessary for reservoir characterization and well design and simulation. An effective planning should incorporate all data at different scales, making the link between geology and other disciplines. The next generation of exploration tools should include an increased geological realism and representation of uncertainties, improved physics and chemistry, and should be designed for new and future computing environments.

The technical challenge is to create the systems and technologies that will streamline and optimise this sophisticated and complex workflow. The logistical and organisational challenge is to create the units and the processes within the geothermal community.

The new tools would permit the asset teams to work differently, taking advantage of a higher level of professional interaction among the various geosciences and engineering disciplines.

With the advances in geosciences knowledge we can integrate the exploration workflow, advanced volume based visualisation technology and the well design parameters, to optimise the drilling engineering process using the available information from field measurement. Establishing predicted fluid circulation and temperature distribution for optimised well design, interactively locating the optimal well path and using real-time monitoring while drilling would allow to achieve modelling-while-drilling, as well as the interactive redesign and re-engineering of the well path. All of this would save both significant time and expense in the very costly drilling process, and would allow the minimum impact to the environment while providing the sustainability of the accessed resource.