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IMAGE: the EU Funded Research Project Integrated Methods for Advanced Geothermal Exploration

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ABSTRACT

In November 2013, the four year project IMAGE (Integrated Methods for Advanced Geothermal Exploration) has been launched, harnessing research power of key research institutes in Europe and industrial players to develop novel exploration techniques for geothermal power.

The objective is to develop new methods to scrutinize and appraise geothermal systems in such a way that exploration wells can be sited with greater accuracy than before, thereby maximizing the success rate and reducing the cost of drilling associated with geothermal projects. In addition, such precision wells would reduce any potential environmental impact.

New research methods will be tested in well-known geothermal systems, both in continental sedimentary systems in Europe and in high-temperature systems related to volcanism where one might expect supercritical fluids, as in magmatic areas, such as in Iceland and Italy.

The IMAGE project will develop a reliable science based exploration and assessment method to "IMAGE" geothermal reservoirs using an interdisciplinary approach based on three general pillars:

1. Understanding the processes and properties that control the spatial distribution of critical exploration parameters at European to local scales. The focus will be on the prediction of temperatures, in-situ stresses, fracture permeability and hazards which can be deduced from field analogues, public datasets, predictive models and remote constraints. It provides rock property catalogues for 2 and 3.

2. Radically improving well established exploration techniques for imaging, detection and testing of novel geological, geophysical and geochemical methods to provide reliable information on critical subsurface exploration parameters. Methods include: a. Geophysical techniques such as ambient seismic noise correlation and magnetotellurics with improved noise filtering, b. Fibre-optic down-hole logging tools to assess subsurface structure, temperature and physical rock properties, c. The development of new tracers and geothermometers for very high temperatures and supercritical conditions.

3. Demonstration of the added value of an integrated and multidisciplinary approach for site characterization and well-siting, based on conceptual advances, improved models/parameters and exploration techniques developed in 1 and 2. Further, it provides recommendations for a standardized European protocol for resource assessment and supporting models.

The IMAGE consortium comprises eleven leading European geothermal research institutes and eight geothermal industry partners, who will perform testing and validation of the new methods at existing geothermal sites owned by the industry partners, both in high temperature magmatic, including supercritical, and in basement/deep sedimentary systems. Application of the methods as part of exploration in newly developed fields will provide direct transfer from the research to the demonstration stage The origin countries of the 19 participants include the Netherlands, Germany, Iceland, Italy, France, Switzerland, Norway, and the Czech Republic. The European Union provides € 10 million for the project.

1. INTRODUCTION

The rationale behind the IMAGE project is the application of cutting edge research based on a solid understanding of the subsurface processes and properties to significantly enhance the potential of geothermal energy in the energy mix. The uncertainty about the resource at depth, however, has been defined as one of the main bottlenecks for a more widespread use of geothermal energy. That's why initial geothermal development for power production was focused on areas with abundant high-temperature magmatic resources at shallow depth, usually associated with surface manifestations. Recent developments have targeted deep resources that are hard to detect from surface exploration. For the various countries without magmatic resources, geothermal power production from the basement and sedimentary environments 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 can now be utilized with a better energy efficiency than before, thanks to the improvement of binary cycles.

Main targets for an extended resource base are:

- Fracture dominated fluid pathways with no surface manifestations.

- Hot systems with insufficient natural permeability suitable for the development of reliable Enhanced Geothermal Systems (EGS).
- Very high temperature (400°C) “supercritical” geothermal systems marked by much higher subsurface pressure, which can result in a significant increase of geothermal development in magmatic areas. No supercritical system has been successfully explored until today.

The barriers in the utilization of these resources are primarily connected to the financial risk of drilling a non-exploitable well. The risk for such a failure is related to pre-drill uncertainty in the assessment of the following **key performance indicators**:

- Power production, depending on expected flow rates (produced and re-injected) and fluid temperature.
- Feasibility of the exploitation, linked to the presence of fluid and its geochemical composition (very acid fluids for instance are very difficult to exploit).
- Duration of the exploitation before a possible decline of temperature or ageing of the wells,
- Potential decline of productivity.
- Cost of the project, linked notably to depth or well architecture (deviated wells).
- Public acceptance, related to mitigation of induced seismicity or reinjection of produced steam.

The performance relates to critical exploration parameters:

- Resource temperature
- Resource depth
- Resource fracture permeability and connectivity
- Resource extension and recharge
- Resource quality (geochemical parameters, pressure)
- Seismogenic properties and stress

IMAGE aims to improve exploration methods for the extended resource base, which will reduce pre-drill uncertainty for the above performance indicators, based on a robust assessment of the critical exploration parameters. It goes beyond current state of the art (e.g. Bruhn et al., 2010). The best possible assessment requires exploration methods and technology able to quantify these parameters with the greatest possible accuracy. Therefore, reliable exploration technology and synthesis of existing exploration data are of critical importance for all stages of a geothermal project, from the successful targeting and drilling of the first exploration well(s), as part of a flexible drilling strategy (e.g., slimhole or conventional drillhole design), to appraisal and production drilling, and later field management and plant operation.

2. CONCEPT OF IMAGE

The main idea of IMAGE is to address the problems encountered in geothermal exploration and reservoir assessment through a three-step methodological approach (Fig. 1):

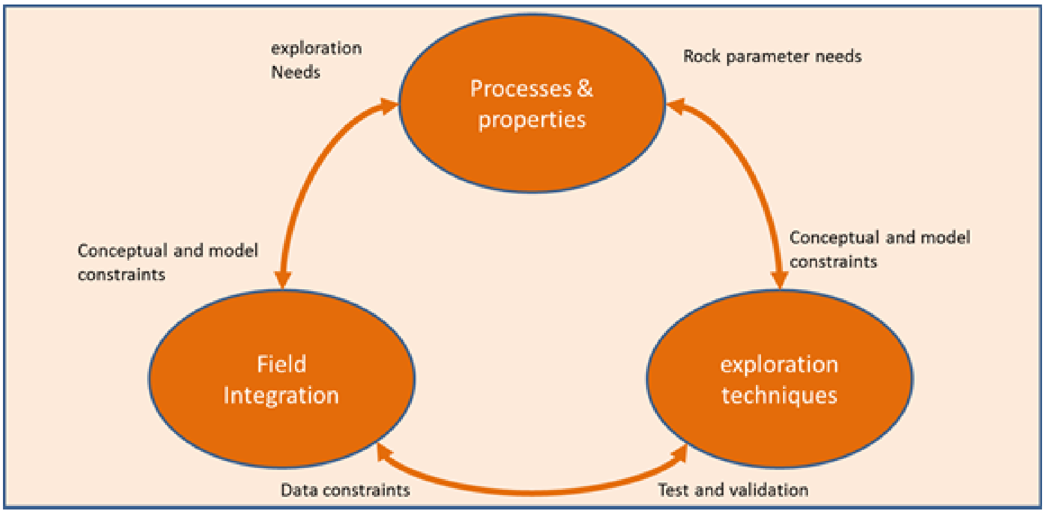

Figure 1: The concept of developing exploration methods in IMAGE: advanced understanding of processes and properties of the system - development of exploration techniques - field integration and validation as a feedback loop.

• First, understanding of underlying processes operating at European to local scales controlling the spatial distribution of critical exploration parameters. In particular, we focus on detecting and interpreting features that can be determined remotely through application of advanced or innovative exploration technologies, which can be deduced from predictive models and remote constraints, and which can directly be studied in natural analogues or laboratory condition. These studies are complemented by the establishment of European reference models and rock catalogues to be used for predictive models, and exploration techniques.

• Improving well-established exploration techniques for imaging and detection beyond the current state of the art and testing of new geological, geophysical and geochemical methods that can provide reliable information on critical subsurface exploration parameters. These methods include existing as well as novel geophysical and down-hole logging tools, to predict subsurface structure, temperature and physical rock properties, and the development of new tracers and geothermometers.

• Integrating all existing and new data derived from new exploration techniques to provide predictive models for site characterization and well-siting. These models link the novel exploration results on structures and properties with the processes and boundary conditions from regional predictive model approaches. All available information is integrated into a final model to provide the basis for development of the resource.

2.1 Magmatic and basement&sedimentary environments

The three-step structure is adapted to specific geological environments with the basic subdivision into magmatic systems and basement/sedimentary systems. IMAGE adopts this approach in two subprojects: SP2 devoted to magmatic systems and SP3 devoted to basement/sedimentary systems (Fig. 2). These two systems represent the general lines of recent development and require somewhat different approaches. For example, in most exploited volcanic geothermal systems the convective heat transport, and therefore the fluid flow, is dominant, whereas conductive heat transport plays a significant role in the usually less permeable basement and the sedimentary cover. Moreover, magmatic systems are often marked by local decoupling from regional and European scale tectonic processes. These general considerations do not only lead to different calculations for the recoverable heat but also require different approach for exploration, due to different characteristics and inner processes. The understanding of these and their detectable signatures is the basis of geothermal exploration. While major progress has been made in exploration methodologies and in our general understanding of geothermal systems, several questions remain open, related both to the general geological environment and to the application of exploration tools.

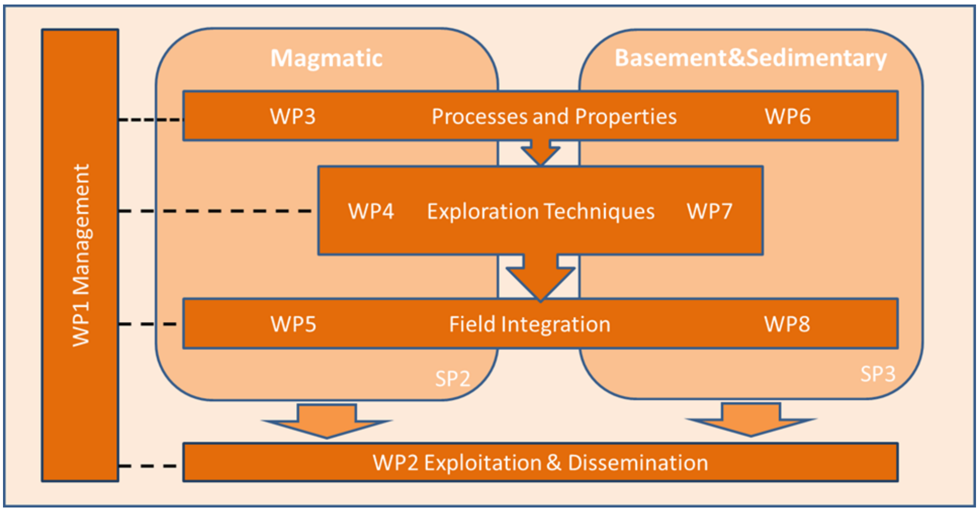

Figure 2: The concept of IMAGE.

The common aspect in both magmatic and sedimentary systems is the general need for high temperatures that drives all geothermal development. Beyond temperature, the main question is how to find and characterise the open fractures that allow fluid flow within the reservoir: their size? orientation in space? amount of fluid they transmit? The key factor to answer these questions is the local stress field and its interaction with fluid circulation, controlled by crack aperture, and rock-fluid interactions which can lead to sealing and closure of cracks. The orientation and magnitude of stress largely control the size and orientation of fractures and thus fluid percolation. While the relevance of stress has been understood for the development of EGS, it has mostly been underestimated for conventional magmatic environments.

2.2 From large to local (site) scales

IMAGE will address these issues through a systematic exploration workflow approach, from large to local scales:

• The “European scale” will cover every scale from a 1000 km x 1000 km square to the full European territory (scale of a lithospheric plate). At this scale, the objective is to consider the large stress fields or temperature fields that will constrain regional models, considering parameters such as the thickness of the crust or the movement of major geological objects (for instance mountain chains).

• The “regional scale” will mean an area with an extension of 50 to 100 km squared; this will cover the studied geological object that is considered as relevant as a first step of exploration, because of some of its characteristics (average geothermal gradient or average heat flow, depth of sedimentary layers or deep fractured rocks etc.). It also includes the immediate surroundings of this geological object to be able to constrain the regional models that will be built. The scale is therefore adapted to the studied object: this could be a slice of a graben, a part of a basin, including their borders.

- The "local scale" will correspond to the focus which is made at the last step of exploration, before drilling, when an area of interest is determined and has to be closely characterized to validate its potential and choose the location of the first well. The typical extension associated to this scale can be 10 to 25 kilometres squared. It is an adequate scale to build a model for designing and monitoring of the resource.

Purpose of prospective sites:

At the heart of the IMAGE concept is testing, validation and integration of developed methodology in a portfolio of prospective sites (Fig. 3) owned by industry partners, which is representative for the European extended resource base. This ensures:

- momentum from the geothermal industry in IMAGE, including Small and Medium Enterprises (SMEs)
- a timely and pragmatic approach, focusing exploration methodological improvements on issues which need to be resolved now and will gain the most benefit for site owners
- test and validation of methodologies based on site access and industry support
- uptake of findings and technology in the marketplace

A particular focus of the project will be on the investigation of supercritical geothermal reservoirs as part of the studies performed in the magmatic system. As available information on such systems is scarce and fairly vague, the two most known areas for shallow supercritical conditions, Tuscany in Italy and Iceland, will be studied. In Iceland, the project foresees a strong connection with the Icelandic Deep Drilling Project (IDDP2), for which drilling is scheduled in 2014, providing a basis for geophysical and downhole measurements around the site in Reykjanes. In addition, the site will allow testing the tracers developed for reservoir assessment at supercritical conditions. In Italy it will be possible to test exploration tools at large depths and in potential supercritical conditions by comparison of survey results and down- and cross-hole measurements at depth of 3.8 km.

The new exploration techniques, as described in 1.2 Progress beyond the state of the art will be tested in fields with abundant information from deep wells in a first step. In a second step, they will be applied in a new geothermal field. All testing will involve industry partners with on-going projects, either at already established sites with existing data or at sites to be developed, where demonstrative application of the tested methods will complement exploration activities by the site owners and contribute to the better understanding of the geothermal field prior to drilling. Complementary to sites used for testing and demonstration, IMAGE has selected a number of key Field Analogue sites, serving as input to the conceptual models and providing property information.

For the magmatic environment, testing will be performed in Iceland in collaboration with the Icelandic industry partners HS Orka and Landsvirkjun who provide support, information and access to existing wells, and in Larderello/Italy, where IMAGE testing is supported by Enel Greenpower, in two hot (300-350°C) deep (2.2-2.5 km) wells in an area where supercritical conditions are predicted at 3 km depth. Application of the methods, developed for supercritical systems will follow at the IDDP2 site in Reykjanes as outlined above.

For the basement/sedimentary systems, geophysical testing such as controlled source electromagnetic measurements and application of ambient noise correlation tested in Iceland will be performed in collaboration with industry partners Axpo and BKW at a site in the Alpine Molasse basin, and with Fonroche Géothermie at their site in the Upper Rhine Graben, Alsace. In addition, downhole tests will be performed with IMAGE partner Geomedia at their exploration well at Litomerice (Czech Republic).

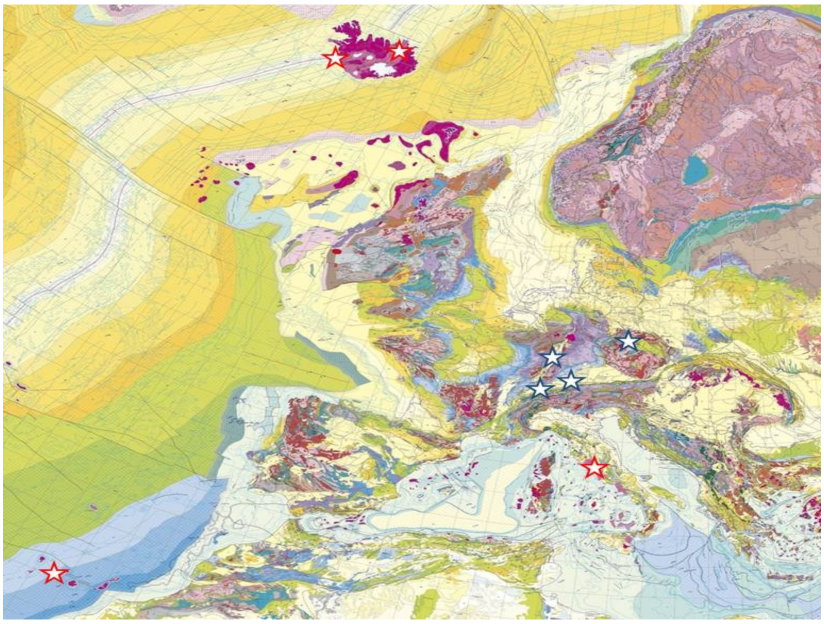

Figure 3: Magmatic sites (red) and basement/sedimentary sites (blue)

3. METHODS AND PRELIMINARY RESULTS

3.1 Processes and properties:

The past decade has been marked by a number of exploration surprises and failures, demonstrating clearly the need of better understanding processes and parameters to improve the robustness of geothermal exploration methods. Our state of understanding and major scientific and technical challenges are described below.

Internal structures and processes of supercritical systems: The IDDP1 project in Krafla -targeting supercritical fluids- has resulted in a major surprise in hitting a magma chamber at much lower depth than expected from an extensive exploration campaign. IDDP1 did not encounter expected supercritical fluid conditions. During later studies, it was demonstrated that our state of the art in conceptual models and exploration techniques had insufficient spatial resolution to predict the encountered relatively small scale magma chambers, which are most likely fault controlled. IMAGE addresses the lack of knowledge of the internal structures and processes of supercritical systems and where the processes of heat extraction from magma or very hot solidified intrusions take place. To this end, IMAGE performs detailed mapping of the exhumed ancient geothermal systems where supercritical conditions prevailed once and through comparison with presently active systems where data from deep drillholes exist. This approach requires the combination of structural geology with geochemistry (Boiron et al., 2007; Liotta et al., 2010) to investigate fracture opening in fossil systems and to understand the flow pattern of the geothermal fluid in deep systems, its flow pattern and geometry of structures that might be used to constrain the interpretation of the geophysical exploration methods.

Structural controls not only influence magma emplacement but also control strongly the spatial distribution and connectivity of fluid pathways. In Larderello and other conventional magmatic fields these pathways are dominant in the temperature distribution, marked by strong thermal anomalies in the vicinity of fault zones (Liotta et al., 2010). The formation and hydrological evolution of fractures relate to the tectonic setting, stress field and geomechanical opening and chemical sealing mechanisms of the fractures and faults in the system (e.g. Cloetingh et al., 2010). IMAGE addresses the lack of generic understanding where in Europe favourable or critical exploration parameters can be expected for geothermal power production from fractured reservoirs in basement/sediment settings. To this end, we perform a diagnostic analysis of the role of rock lithology, geodynamic setting and evolution, stress, seismogenic characterization, based on a) literature compilation of extensive knowledge on fracture permeability in the oil and gas industry and partners and b) an analysis at regional scales of dominant processes and parameters through the development of regional models (e.g. Cherubini et al., 2014).

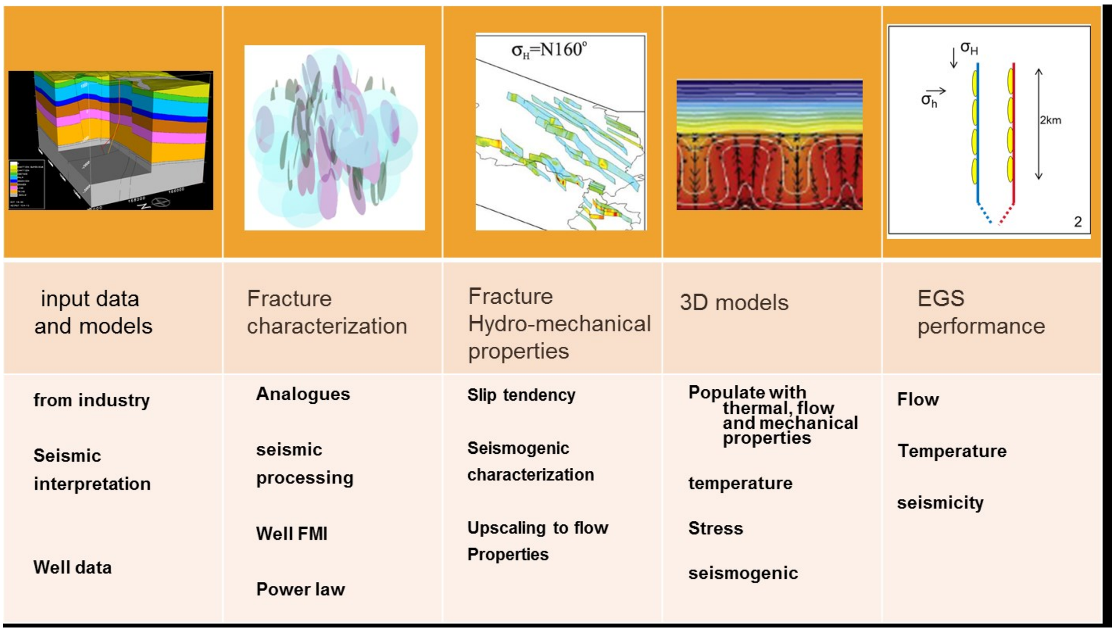

Figure 4: Image exploration workflow for natural fracture permeability assessment.

Coupled processes in fractures: In basement and sedimentary settings, the different types of resources that can be successfully harnessed are unclear, due to the lack of a significant number of running operations in these geological contexts. Exploration often relies on existing oil & gas data. In some cases these provide valuable information, but they also have their limitations, notably because the well and geophysical data do not include the basement and do not necessarily go to a sufficient depth in the sedimentary layers. Moreover, the information is limited to the places where oil and gas exploration has been performed; it does not necessarily cover the best areas of interest in terms of geothermal power production. A consistent and integrated geothermal exploration method, from a European scale to a very local one, does not really exist at the moment. The basement/sediment projects for power generation such as Soultz, Landau, Basel and Traureut have revealed a significant number of surprises. Soultz (France – Upper Rhine Graben) and Traunreut (Germany-Molasse Basin) encountered much lower temperatures than expected from predictive models (up to 25%) constrained by well data. For both settings it appears that fluid advection plays a dominant role in distributing heat. Such errors can bear a high project risk, especially for binary production systems relying on a minimum production temperature. Therefore models at regional and site scale need to address these effects prior to drilling. Detailed studies on Soultz and Basel clearly demonstrate that pre-existing natural fractures play a key role in the flow performance of the underground heat exchangers (Gentier et al., 2010; Dezayes et al., 2013). The natural mechanisms behind the hydraulic performance of these fractures are not well understood and hamper prediction of expected flow rates prior to drilling. Typically order of magnitude uncertainties in hydraulic transmissivity can occur in pre-drill assessment. Numerous studies on oil and gas migration along deep faults and recent geothermal and neo-tectonic studies indicate that relative orientation of pre-existing fractures in the natural stress field, the geometric features of the fracture network and the presence of seismogenic faulting play a key role in the distribution of fracture flow (Cloetingh et al., 2010). Geomechanical processes contributing to opening of fluid pathways compete with geochemical healing and creep. For basement and sediment systems there is a need to improve our pre-drill prediction of hydraulic performance of fractures, based on estimated rock properties, fracture geometry, temperature, stress and natural seismicity and structural studies. There is an excellent opportunity to learn from a wealth of oil and gas data in this topic (Fig. 5)

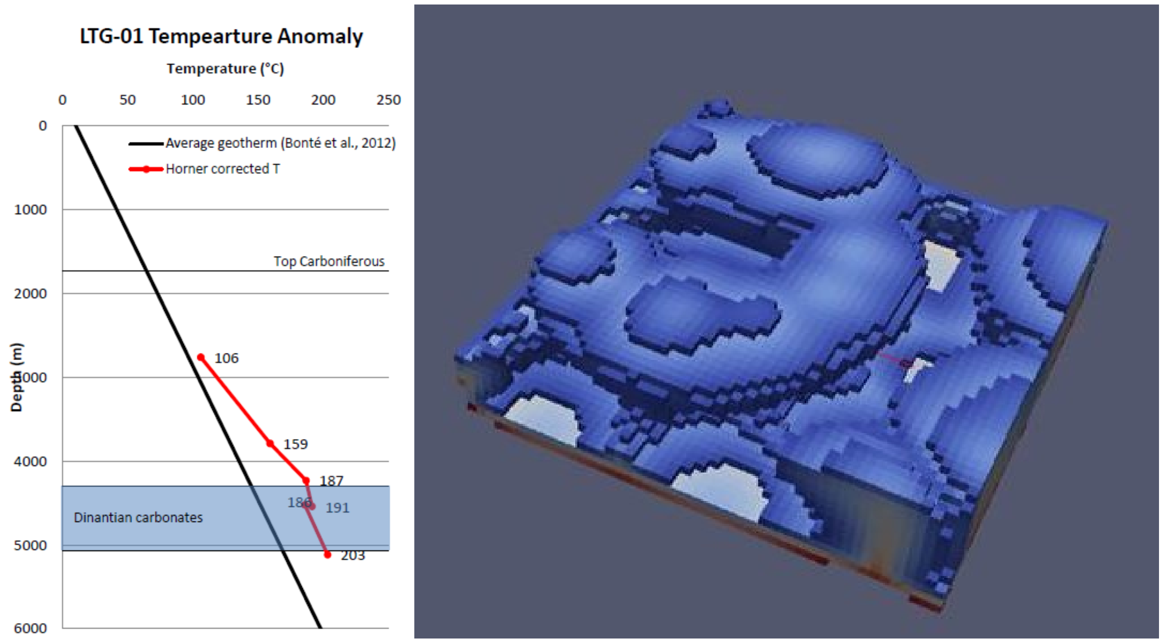

Figure 5: (Left) thermal anomaly in deeply buried carbonates inferred from borehole temperatures (Van Oversteeg et al., 2014), which can be attributed to fluid flow convection. (Right) numerical 3D model for fluid flow convection adopting a 1000 m thick convective layer, with natural permeability of 20mD and porosity of 1%.

European models and catalogues: Water injection in Landau and Basel encountered considerable problems with induced seismicity, resulting in reduced performance and postponement of the projects respectively. It is therefore of paramount importance to assess the limits of pressure which can be applied to enhance flow performance and to provide a robust estimator for the probability of induced seismicity below a required threshold. This requires a more reliable estimation of the stress field, prediction of rock mechanical properties and seismogenic characterization. IMAGE addresses the lack of European and regional models for stress, seismogenic characterisation and temperature to be used as constraints for regional and site specific models. Up to now these models have been constructed from either lithosphere constraints (e.g. Cloetingh et al., 2010) not fully constrained by direct well data, or from simple data interpolation from measurements (e.g. Bonte et al., 2010; Zang et al., 2012). IMAGE improves the resolution of European and regional models by extending physics based predictive models bridging lithosphere and basin scales (Fig. 6). These models will provide a database with generic templates for rock properties in basement/sediment settings and databases on physical properties of rocks in high temperature and supercritical geothermal conditions using advanced laboratory facilities (cf Kristinsdóttir et al., 2010) and acquiring data worldwide on the behaviour of electrical resistivity, seismic velocity, thermal and mechanical properties. A compilation of such data does not exist yet but is crucial for the further development. It involves rock samples taken from drill core of very hot and deep geothermal wells and from exposed former supercritical zones in exhumed ancient geothermal system that are now exposed on the surface. These will allow to improve model constraints and exploration techniques.

3.2 Exploration techniques:

Active and *passive seismic techniques* have been used more frequently in recent years, as they help to understand subsurface structure and controls on fluid flow in geothermal systems in various tectonic settings. This applies especially to passive seismic. Magmatic geothermal systems are more or less constantly emitting seismic energy, both in form of micro-earthquakes and in form of noise due to the geothermal activity itself, like boiling. In non-magmatic environments and areas of little tectonic activity, passive seismic methods have not been applied due to the lack of signals. Recently, the development of ambient noise interferometry, which uses permanent seismic noise as a source, often caused by human activity, makes the application of passive seismic recording feasible even in areas with little or no seismic activity (e.g. Dragonov et al., 2009; Stankiewicz et al., 2010). This method has not been used in geothermal prospecting yet. IMAGE will improve passive seismic geothermal exploration method by applying the new and promising technology of imaging by ambient noise technology to geothermal systems. Ambient noise studies have been shown to successfully characterise fluids in volcanic systems as well as in oil & gas exploration (Jousset et al., 2012). In geothermal exploration, this method has rarely been employed. Passive seismic has been shown to be a useful tool, but seismic signals are not always strong enough in all regions and are often disturbed by human activity, especially in densely populated areas. That’s why ambient noise correlation techniques will be used to solve this problem by using the noise as source for information

(Jousset et al., 2012; Fig. 7). Other downhole tools to detect seismic signals that could be relevant for geothermal applications are fibre optic cables, which allow distributed acoustic sensing (DAS), and has been demonstrated to work so far only in an oil well (Cox et al., 2012).

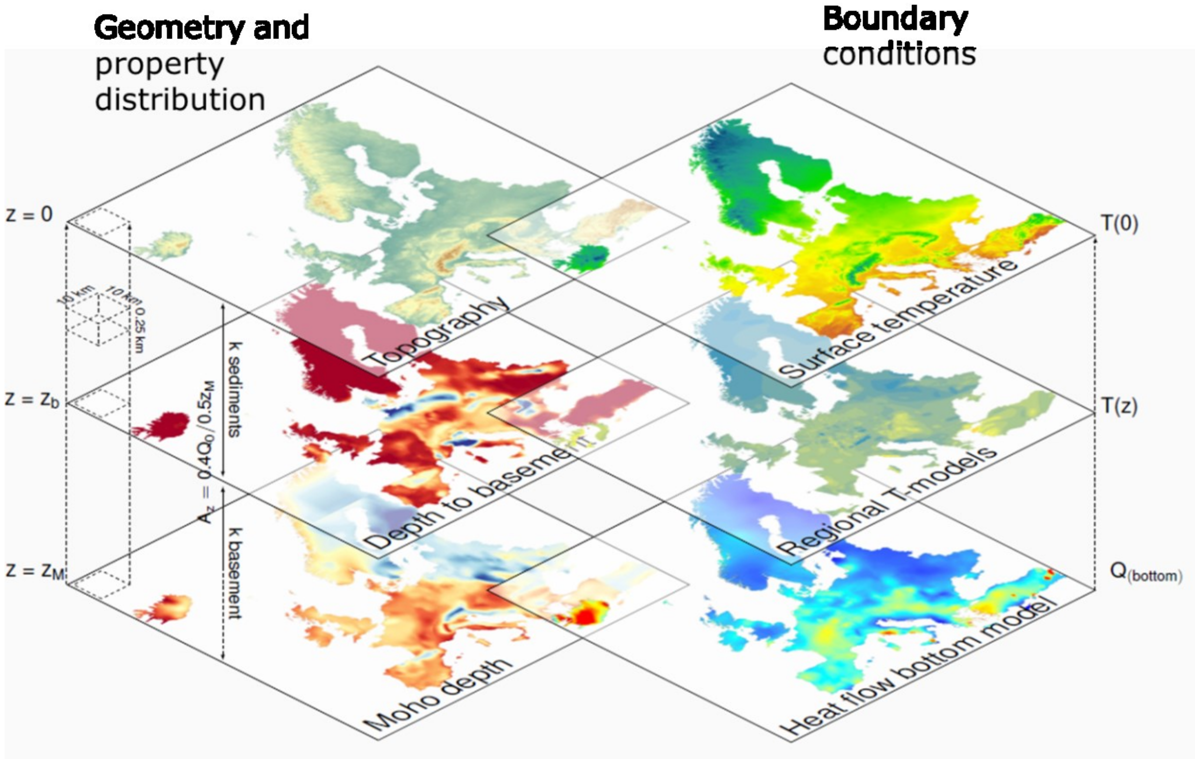

Figure 6: European thermal model based (for more details see Limberger et al., 2014)

Active seismic methods are standard tool for oil & gas exploration. They have been used in geothermal prospecting at the small scale to image the subsurface, but are not specifically directed to the exploration needs for geothermal systems. So far they have only been shown to work in areas with a sedimentary cover, whereas conventional volcanic geothermal environments were not successfully investigated by active seismic approaches. Seismic downhole methods were applied to geothermal prospecting, especially in karstified areas of the Alpine Molasse basin, including Vertical Seismic Profiling (VSP), which allows the detection of vertical structures. In volcanic geothermal systems, however, VSP has not been used so far. IMAGE addresses the problem of using seismic reflection data to image the major acoustic impedance boundaries that are expected to exist on the top and bottom of magmatic layers and porous zones filled with steam or supercritical fluid. There exists evidence that the heat extraction zone in the roots of the geothermal systems might be rather thin as well as in supercritical conditions. Hence, the importance of detecting the productive zones precisely is a major issue for designing the drilling operations. Ordinary seismic reflection surveys have turned out to give poor results in volcanic geological environment, probably due to high scattering of the seismic energy, especially at shallow depths (Planke et al., 2000). IMAGE tries to come around this problem by performing a series of Vertical Seismic Profiling (VSP) experiments and by trying several variants of the method in order to get proper reflections. The experiment will be run in Krafla where there is a good knowledge from the borehole on magma and steam zones to compare with the results of the VSP. If successful, the VSP method will be a most useful technique in volcanic areas where drilling for supercritical fluid is envisioned. State of the art seismic processing techniques developed in oil and gas exploration to detect fracture zones and fluids from reflection seismic and VSP will be further developed and applied to existing seismic data to image deep basement and flow properties.

Electro-magnetic/magnetotelluric methods MT: Among the most common exploration tools applied today are various electromagnetic methods, in particular magnetotelluric (MT). MT imaging is largely used in geothermal exploration to prospect hydrothermal anomalies at significant depths. Its sensitivity to temperature anomalies and fluid bearing pores and fractures is based on the correlation with electrical resistivity decrease. It has therefore become a standard tool for geothermal exploration in conventional geothermal environments (Spichak and Manzella, 2008). MT method, however, has two main serious limitations: lack of resolution at reservoir depth and lack of knowledge how to relate the subsurface resistivity structure to real geothermal parameters like temperature, mineralogy and pemeability. In addition, MT is highly susceptible to noise, which is caused by various human activities, including railways, electric fences and industrial applications using electricity. Methods to overcome these shortcomings are constantly improved. For example, to calculate the influence of noise, a remote reference station is commonly used at a site that is sufficiently close to the place investigated but without the sources of noise. Such stations are therefore often placed on islands. Nonetheless, the quality of the MT measurements is still limited. In addition, the use of MT as a tool for poorly permeable basement sites has yet to be tested on a well-known site to validate its efficiency for the development of EGS. IMAGE addresses the lack of resolution of the MT method by a) improving the inversion methodology, b) Controlled Source EM and c) removing noise. Improvement of inversion will be done by extending existing methodology (Árnason et al., 2010) applying external constraints (layered interface) from other geophysical (seismic/gravity) and geological data (fracture system, lithology and mineralogy) to the inversion process. In addition, CSEM will be applied to overcome the weakness of natural signal used in MT surveys (Bourgois and Girard, 2010). As their penetration depth using surface sources is generally not sufficient for depth of geothermal prospection, the borehole casing will be used to focus current line (Long Electrode Mise-A-la-Masse, LEMAM) at the targeted reservoir depth, which has been shown to work in previous field experiments. A cross-hole experiment to acquire electrical resistivity, induced polarization (IP) and self-potential (SP) data at the depth of reservoir (3.5 km) will help in defining in more detail 1) the resistivity distribution at depth also by constraining MT data inversion and 2) how resistivity distribution is influenced by fracture distribution (as defined by IP and SP data). The experiment will be done in co-operation with Enel Greenpower, which will provide access to the site and to two deep wells and well-data.

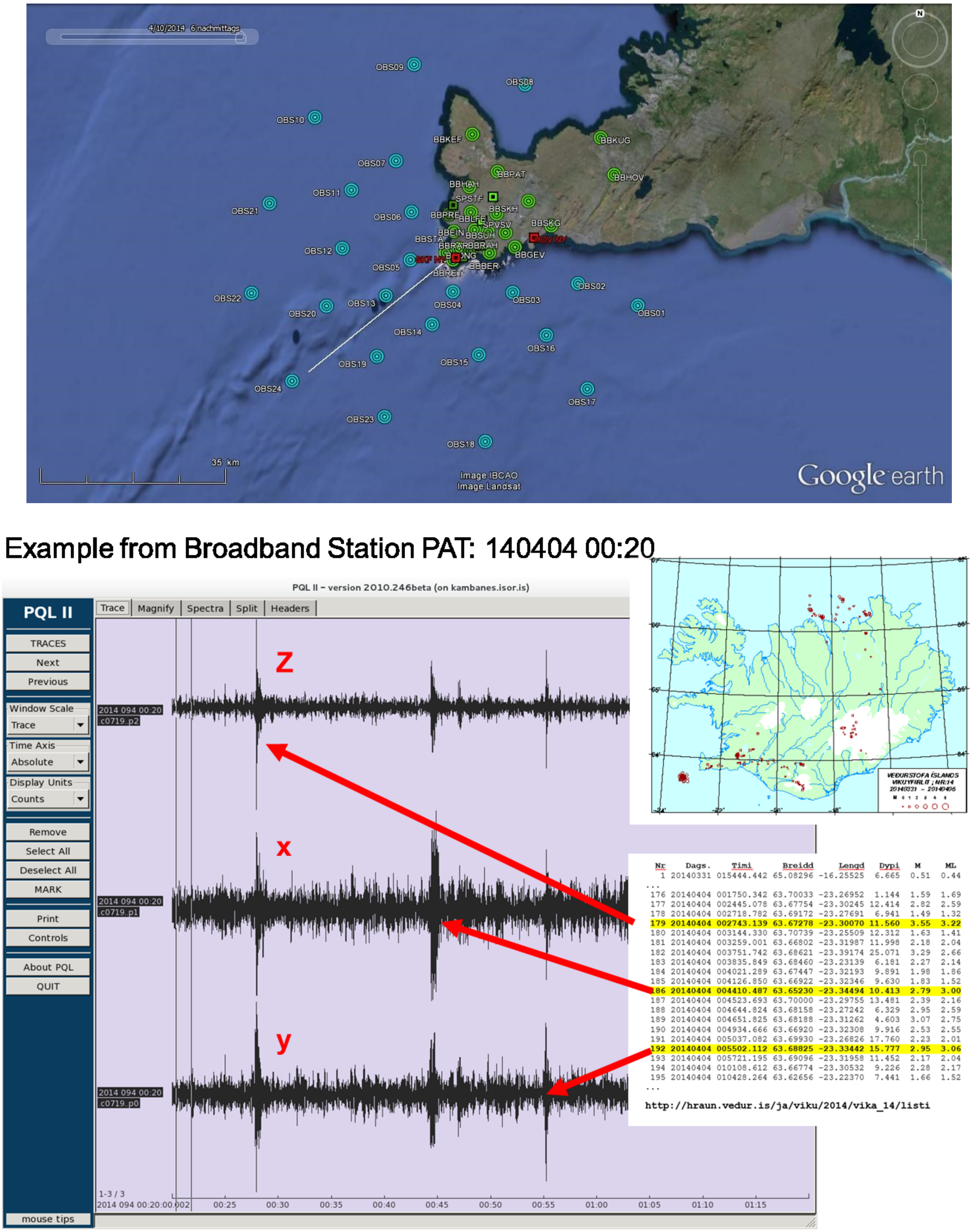

Figure 7: (Top) alignment of passive seismic seismometers surrounding the Reikjanes Area (Iceland). The onshore network is active from april 2014, whereas Ocean Bottom Seismometers (OBS) are installed in 2014. (Bottom) Seismic response from BBPAT for a natural earthquake of Magnitude 3.5 and aftershocks.

Geochemical methods, tracers and temperature monitoring: these methods have routinely been used for geothermal exploration and for reservoir assessment. Interpretation of geochemical data provides important information on the characteristics of a deep geothermal reservoir. Temperature estimates calculated from classical geothermometers, however, are not always reliable due to water mixing processes, mineral dissolution/precipitation reactions during the deep fluid rising, seawater influence, etc. For this reason, auxiliary geothermometers such as Na/Li were developed and proposed in the literature, but are poorly known and seem to be dependent on the nature of the rocks and of the fluid salinity. IMAGE addresses development and characterisation of geothermometers and tracers dedicated for the targets of the extended resource base. The lack of tracers that are stable under supercritical conditions in geothermal reservoirs limits the use of tracer tests to detect the flow path of fluid within the roots of the high temperature systems. Such tracers are needed to assess the size of the reservoirs and geometry of the flow paths and are under development in IMAGE. A similar approach is taken to develop geothermometers and tracers for determination of the temperature and origin of fluids in basement&sedimentary settings (e.g. Millot et al., 2011, Jiráková et al., 2011).

Fieldwork and stress measurement: Structural geology is a standard tool to identify favourable settings for geothermal activity. Structural analysis can be based on field work and on the interpretation of geophysical data, mainly seismic images of the subsurface. Potential settings are investigated by analysis of the 3D geometry and kinematic evolution of fault systems and fracture networks. The structural settings favouring geothermal activity generally involve sub-vertical conduits of highly fractured rock along fault zones oriented approximately perpendicular to the least principal stress. Generally, the regional stress field can be derived on the basis of several different types of data, most of them require information from wells such as the analysis of borehole breakouts and drilling induced fracturing. In-situ stress measurements can also be performed in existing wells. Methods that do not require wells include the determination of focal mechanism solutions from earthquakes of sufficiently high magnitudes occurring in the region, from which the principal stress orientations can be inferred; geological observations such as recent fault slips and volcanic alignments can also serve as first-order stress indicators. IMAGE develops novel approaches to determine stress magnitude and stress heterogeneity respectively, based on existing borehole data (cf. Evans et al., 2005), fieldwork and focal mechanisms from regional and micro-seismicity (passive seismic) to get orientation of present stress field (cf. Zang et al., 2012).

3. CONCLUSIONS

We identified a number of necessary improvements for new concepts and exploration methods to scrutinize and appraise geothermal systems in such a way that exploration wells can be sited with greater accuracy than before, thereby maximizing the success rate and reducing the cost of drilling associated with geothermal projects. In addition, such precision wells would reduce any potential environmental impact. At the heart of the IMAGE concept is testing, validation and integration of developed methodology in a portfolio of prospective sites (Fig. 3) owned by industry partners, which is representative for the European extended resource base. This ensures a timely and pragmatic approach, focusing exploration methodological improvements on issues which need to be resolved now and will gain the most benefit for site owners.

We showed that the challenges for new concepts and methods can be optimally structured in a matrix with Scientific&Technological advancement on the vertical axis and specific geological environments in the application (magmatic and basement/sedimentary systems) on the horizontal axis. This structuring allows an optimum steering of the project towards the different exploration challenges in the various geothermal systems and the practical application of the results. On the vertical axis the project is sub structured in three components with shared focus in S&T advancement:

- Understanding processes and parameters for prediction of the critical exploration parameters from European to local scales, by:
  - Improving model theory and concepts (diagnostic analysis, theoretical models, physics interaction, natural laboratories) for geological, geochemical and geophysical process-interactions underlying the geothermal system and validate these on appropriate selected datasets across Europe and selected sites of industry participants.
  - Providing European and regional models to delineate prospects and to provide constraints for site models.
  - Organizing parameterisation catalogues for site models and exploration techniques, based on compilation studies and laboratory determination of basic physical and chemical parameters.

- Development of exploration techniques to improve assessment of critical exploration parameters by data-acquisition and processing. This comprises development of:
  - Passive and Active seismic
  - Electro-Magnetic methods
  - Temperature measurement, geothermometers, and tracers
  - Fieldwork and stress measurement

The developed exploration techniques are tested on selected sites of the industry partners (Table 1).

- Development and demonstration of integrated sound methods for site characterisation and well-siting in field integration. This involves:
  - Building of 3D frameworks to represent and visualize the integrated results of exploration techniques and improved modelling of known physical processes.
  - Multidisciplinary approach for site-characterization, based on the conceptual advances, improved models/parameters and exploration techniques of IMAGE
  - Demonstrated added value in well siting

The field integration approach will be tested on extensively explored fields allowing to use downhole measurements for validation. Its added value is demonstrated in unexploited sites.

4. ACKNOWLEDGEMENTS

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