IMAGE

Integrated Methods for Advanced Geothermal Exploration

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Day 1

OPENING SESSION

(Chair: Jan Hopman, IMAGE Coordinator, TNO)

Novel drilling technology and investigation of supercritical condition in continental Europe: the DESCRAMBLE project

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[1]ENEL GP, I.

The aim of the DESCRAMBLE (Drilling in dEep, Super-CRitical AMBients of continentaL Europe) project is to develop novel drilling technologies for a proof-of-concept test of reaching deep geothermal resources and to contribute to a low-carbon European society. The project proposes to drill in continental-crust, super- critical geothermal conditions, and to test and demonstrate novel drilling techniques to control gas emissions, the aggressive environment and the high temperature/pressure expected from the deep fluids. The project will also improve knowledge of deep chemical-physical conditions for predicting and controlling critical drilling conditions. To achieve this target the first drilling in the world in an intra-continental site at a middle-crustal level will be performed. The test site is an existing dry well in Larderello, Italy, already drilled to a depth of 2.2 km and temperature of 350 °C, which will be further drilled to 3-3.5 km to reach super-critical conditions unexpectedly experienced, and not controlled, in a nearby well in 1979. The site is perfect for such an experiment, as it is representative of most deep crustal levels in Europe, cost effective since drilling to reach the target is reduced to a minimum, practical due to the high probability of encountering super-critical conditions. The productivity and efficiency of the project are guaranteed by the combination of industrial and research participation and by the recognised expertise of the consortium in geothermal R&D as well as oil and gas drilling, bringing together excellence in the respective sectors. DESCRAMBLE will explore the possibility of reaching extremely high specific productivity per well, up to ten times the standard productivity, with a closed loop, zero emission, and reduced land occupation. Specific Objectives are 1) Demonstrate safe drilling of a deep super-critical geothermal well, 2) Reduce the technical and financial risks of drilling and exploiting deep geothermal wells by improving knowledge of the physical and chemical conditions in deep geothermal formations, 3) Reduce pre-drill uncertainty in the exploration of deep geothermal wells, 4) Investigate the economic potential of exploiting chemicals and minerals by analysing fluid samples for valuable materials. The project is organized into two main phases: (1) Drilling in supercritical conditions, including drilling components, well materials, design and control; (2) Geo-Scientific activities for predicting and controlling critical conditions, which considers petrological, physical and chemical characterization, simulation and monitoring, including high temperature and pressure tools. DESCRAMBLE will be performed in 36 months (3 years) and the project can be divided into the following main phases:

Year 1: General preparation activities for drilling, data reviewing and new data acquisition, design and execution of seismic surveys, development of the new instrument and tool, software activity for modeling;

Year 2: Execution of the drilling and testing;

Year 3: Testing, validation and assessment of results.

The information exchange with IMAGE project will be extremely important: through the common partners of the two projects it will be possible to have access to relevant information and a fruitful scientific cooperation.

Challenges in geophysical exploration of geothermal systems in magmatic environment

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High temperature geothermal systems are linked to recent volcanism. They extract their heat from cooling intrusions and the geothermal fluid is mostly confined to fracture network in low permeability rocks. These systems are found at the plate boundaries but in different tectonic and geological environment. Presently, a great majority of the power produced by geothermal comes from these systems but only a very small proportion of their total energy potential onshore has yet been harnessed. The properties of these systems are quite variable which requires that exploration techniques must be tailor- made for each case. The main tasks of geophysical exploration are: a) to detect and map the overall volume of the reservoir, b) to estimate the reservoir temperature distribution and find the permeable fracture zones, c) detect and map the heat source and d) unravel the physical and geological processes in the volcanic geothermal systems. The objective is to develop a geothermal field for economical and sustainable power production and reduce the associated drilling risk. Two the most diagnostic methods for geothermal exploration in magmatic environment are resistivity measurements (mainly Magnetotellurics (MT)) and passive seismics. Application of both methods yield a model of distribution of physical parameters in the underground that consequently have to be interpreted in terms of geothermal parameters like temperature and permeability. This process involves two types of challenges; to build models that are likely to reflect the real distribution of physical parameters and to establish relationship between the models and geothermal parameters of interest, primarily the temperature. Both challenges are dealt with in IMAGE. Conventional 3D modelling of MT data does not result in unique models as the inversion process is highly underdetermined – model parameters are much greater than the data points. The consequence is that the resulting model depends on the initial model used in the inversion and how the inversions is carried out as well as on the inversion parameters selected by the geophysicist. The challenge is to find out how constraints from other data could be applied during the modelling process to counteract this uncertainty. High temperature fields usually show micro-seismic activity that form the basis for the exploration by passive seismics. The challenges, include improvement of data collection and modelling methods to obtain the distribution of the elastic parameters in the underground as well as exact location of faults and their focal mechanisms and the depth to the brittle-ductile boundary. Improvement of recording methods, including the revolutionary DAS technique, is also a new challenge. Based on models of resistivity and the elastic parameters, a model of the reservoir can be derived. This requires the knowledge of the physical relationship between resistivity and the geothermal parameters; temperature, porosity, density and cation exchange capacity (CEC) that reflects the degree of hydrothermal alteration. This also requires the relationship between the elastic parameters and density, porosity and temperature, especially for the temperature range from reservoir temperature to melting of the rock. Long term research in conjunction with development of high temperature fields around the world is required to reach the above mentioned challenging aims. It is a long distance run where contribution comes from many projects, researchers and developers. IMAGE makes a significant contribution.

Understanding of magmatic geothermal systems from studies of exhumed systems in continental and oceanic settings

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The understanding of the relationships between geothermal fluid flow and geological structures represents one of the main task to improve exploration and exploitation of geothermal resources. We have contributed to this issue studying analogous exhumed examples of geothermal systems developed in continental (Elba Island, Italy) and oceanic settings (Geitafell, Iceland). The adopted methodology follows the classical approach of structural geology, petrography and fluid inclusion studies. Eastern Elba Island is characterized by a widespread Fe-oxides, Fe-hydroxides and sulphides deposits exploited for centuries and deriving from the hydrothermal activity occurred during the mid-crustal Porto Azzurro monzogranite (5.9 Ma) cooling. Hydrothermal circulation is accompanied by extensional tectonics, developing low-angle normal faults and NE-trending oblique-slip to normal shear zones, defining parallel sets of localized deformation, each other connected by linkage structures. The field mapping highlighted that the damage zones and the slip-surfaces of both low-angle normal faults and NE-trending shear zones are characterized by extensional and shear veins filled up with the same hydrothermal minerals, thus indicating a contemporaneous faults activity. Furthermore, the main ore deposits are located along the NE-trending shear zones or in the permeable geological bodies hydraulically connected to these structures. We therefore envisage a dominant role of the NE-shear zones in controlling the geothermal fluid paths. Fluid inclusions studies were carried out at different structural levels. At the deepest outcropping levels (tourmaline+quartz veins in Paleozoic micaschist), the results indicate occurrence of fluids with T of about 370-650°C and salinity encompassed between 19% and 48% wt. NaCl eq.; differently, at shallow structural levels (hematite+quartz veins in Triassic quartzite), T tends to decrease (T<350°C) whereas isotope analyses and salinity values (0-25 wt. % NaCl eq.) indicate a progressive contribute of meteoric water, leaching of the Late Triassic evaporitic level and/or mixing with magmatic fluids. Estimated fracture permeability from field data resulted in the range 10^{-11} - 10^{-17} m^2, mostly depending on fracture width rather than its length. The Geitafell volcano (5-6Ma) is an extinct central volcano that is believed to have been active in the rift zone during Late Miocene, and later migrated southeastwards as a consequence of the accretionary crustal processes at divergent margins. The magmatic chamber is represented by a gabbro pluton emplaced in Miocene flood-basalts hosting rocks. The field activity was based on collection of: (a) field-samples for laboratory analyses; (b) structural and kinematic data from the surrounding of the gabbro; (c) core-samples for petrographic and fluid inclusion studies from seven slim- boreholes (down to 30 m, as a maximum) drilled at the boundary between the gabbro and its hosting rock. Field mapping highlighted the occurrence of two systems of faults, NE- and NW-trending respectively, and dissecting both the gabbro and its hosting rocks. NE-trending faults are dominantly oblique-slip faults, whereas the NW-trending faults are mostly with a significant normal component. Their damage zones and slip surfaces are characterized by shear veins with synkinematic hydrothermal minerals (andradite, epidote and quartz, mostly) indicating their coeval activity during hydrothermal fluid flow. Estimated fracture permeability from field data resulted in the range 10^{-11} - 10^{-17} m^2. Fluid inclusions studies, carried out in samples from boreholes, clearly indicate that the hydrothermal fluids were characterized by boiling at T around 270-280°C and very low salinity (<1 wt. % NaCl). As a result of passive enrichment in solute species due to boiling, salinity up 10 wt. % NaCl eq. was locally registered in fluid trapped by calcite, and minor in quartz. In garnet, fluid inclusions indicate fluids with T up to 420°C. Concluding, the whole collected data indicate that meteoric fluids were channelled to depth through the structural paths defined by the fault zones; the continuous interaction between meteoric water and cooling rocks determined an open geothermal system characterized by convective heat transfer, without fluids deriving from a magma source.

Rationale behind the IMAGE approach for geothermal exploration

Jan-Diederik Van Wees[1,2], Jan Hopman[1], Chrystel Dezayes[3], Adele Manzella[4], David Bruhn[5,8], Judith Sippel[5], Ólafur G. Flóvenz[6], Gylfi Páll Hersir[6], Sæunn Halldórsdóttir[6] and Domenico Liotta[7]

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

- 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. Integration of all available information into a final model to provide the basis for development of the resource.

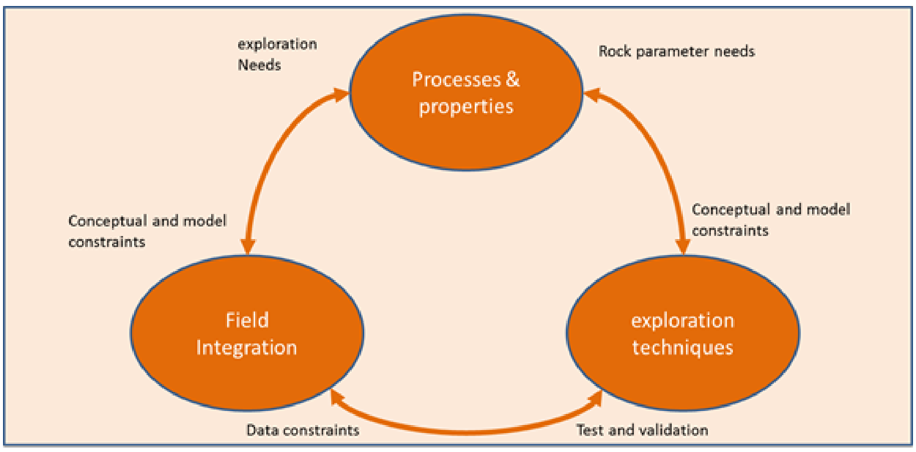

Fig. 1: The concept of developing exploration methods in IMAGE: advanced understanding of processes and properties of the system - development of exploration techniques - field integration and validation as a feedback loop.

Session 1.1

Modelling approach and application

(Chair: Jörg Uhde, Stadtwerke Bad Waldsee GmbH)

SP3 Sedimentary and basement field exploration

Chrystel Dezayes[1], Sylvie Gentier[1], Magdalene Scheck-Wenderoth[2] and Jan Hopman[3]

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Often dedicated to volcanic regions, geothermal power generation is now also being developed in non-magmatic areas. The exploitation of temperatures between 120°C and 200°C for electricity production in sedimentary and basement rocks, out of the active volcanic context, is nowadays available because of the improvement of the binary power plant productivities and the development of the EGS technology depending on the initial permeability of the rock mass. This temperature range exploitation in less favourable areas is a major issue for Europe, where these geographical areas represent the major part of the territory. For an average thermal gradient (30°C/km), the temperatures are reached between 4 and 6 km. This leads to locate the temperature range on deep layers of sedimentary basins (aquifers more or less permeable, namely HSA) and the upper part of the basement. However, thermal anomalies are present in relation to specific geological contexts and fluid circulations. At these places, the temperatures are reached at lower depth, then the drilling costs are cheaper and the risks are reduced. However, in addition to the temperature, two other conditions should be assembled to allow the exploitation of the geothermal energy: the presence of fluid, which is the vector of the heat, and a sufficient permeability, which allows the production and the re-injection of the fluid. For all these reasons, the overall objective of the IMAGE sub-project 3 is to set up and validate an integrated methodology that consists in building conceptual local models based on regional models and key situations identifiable by innovative and validated exploration methods. This objective induces a 3-step approach in the way to conduct research and development inside the SP3: **(1)** WP6 first aims at building regional models that will be used later in the sub project to characterize the geothermal resource at a closer scale. This kind of regional models are made as a precompetitive approach: the other regional models that will be developed after this project using the same methodology are supposed to be paid rather by the public authorities than by industry. Even if these models are too general to be paid by industry, these give a valuable information for industrial stakeholders, made from precompetitive geoscience data and practical experience acquired in past years by trying to understand dual geothermal systems, in hot sedimentary aquifers or in the basement, having potentially used EGS technologies. **(2)** To go at a local level, which will be the issue of the last WP, additional data and more specific data acquisition (exploration techniques) will be necessary. The objective of this WP 7 is to identify existing exploration methods, develop and validate innovative ones, which will be relevant to identify the local key situations that are favorable for a geothermal operation and to refine the regional models at the neighborhood of the selected areas of interest. **(3)** At this stage, all the tools are ready to build a local, integrated model, which is the main activity within WP8. This kind of model will be the tool used to determine the location and design of the first drilled well. It will be applied on sites, in connection with industrial operation, for the validation of innovative methods and the validation of the building of the local integrated models. At the end, the project leads to an integrated exploration methodology that relies on two classical successive steps: **(1)** The building of enhanced regional models, for different parameters (temperature, stress, geology and hydrogeology), using public data and generally made with a precompetitive approach thanks to public funding; this step induces a first go/no go to investigate more precisely a given region. **(2)** The identification of the areas of interest through the use of local available data (that can be free or not) from surface, existing wells and sites and through additional data acquisition (using when necessary innovative exploration techniques), in order to identify the relevant key situation favourable for a geothermal project and to build of local integrated model useful for the industrial project owner; this is the second go/no go before drilling. This methodology aims at deciding at the end the best location (in terms of risk and cost) for the first well which is at the same time an exploration well and – hopefully – a future production/injection well.

Conceptual models for numerical modeling of the key situations

Mariane Peter-Borie[1], Arnold Blaisonneau[1], Sylvie Gentier[1] and Théophile Guillon[1]

BRGM, Orléans, F.

The definition of key situations, *i.e.* patterns that suggest that there is a potential to have sufficient temperature and flow at an economically viable depth for a geothermal exploitation, may provide useful guidance for exploration. In order to understand why some patterns constitute key situations and to understand the processes occurring in these key situations, conceptual models are built. They constitute basis for numerical modeling (mechanical, thermal, hydraulic…) that allow quantitative evaluations of the favorable characteristics of the patterns for which key situations prove to be a guide for exploration. Thanks to this approach, the range of application and the interest of key situations are increased. The understanding of several key situations may allow, in a second phase, the study of combinations of the different favorable patterns in order to understand interactions between the key situations. The thorough understanding of the key situations and their interaction will help to develop leads for exploration methodology and in particular should constraint the exploration methods as geophysical measurements, by defining objects that have to be identified (constraint on the method) and their size (resolution constraint).

Here, we present a first conceptual model of the "aborted intercontinental rift" key situation. The aim of this model is to study the influence of the faults network architecture on the local stress state, which may have an impact on fluid flow.

Permeability around fault zones in geothermal reservoirs: Predictions based on limited available data during exploration

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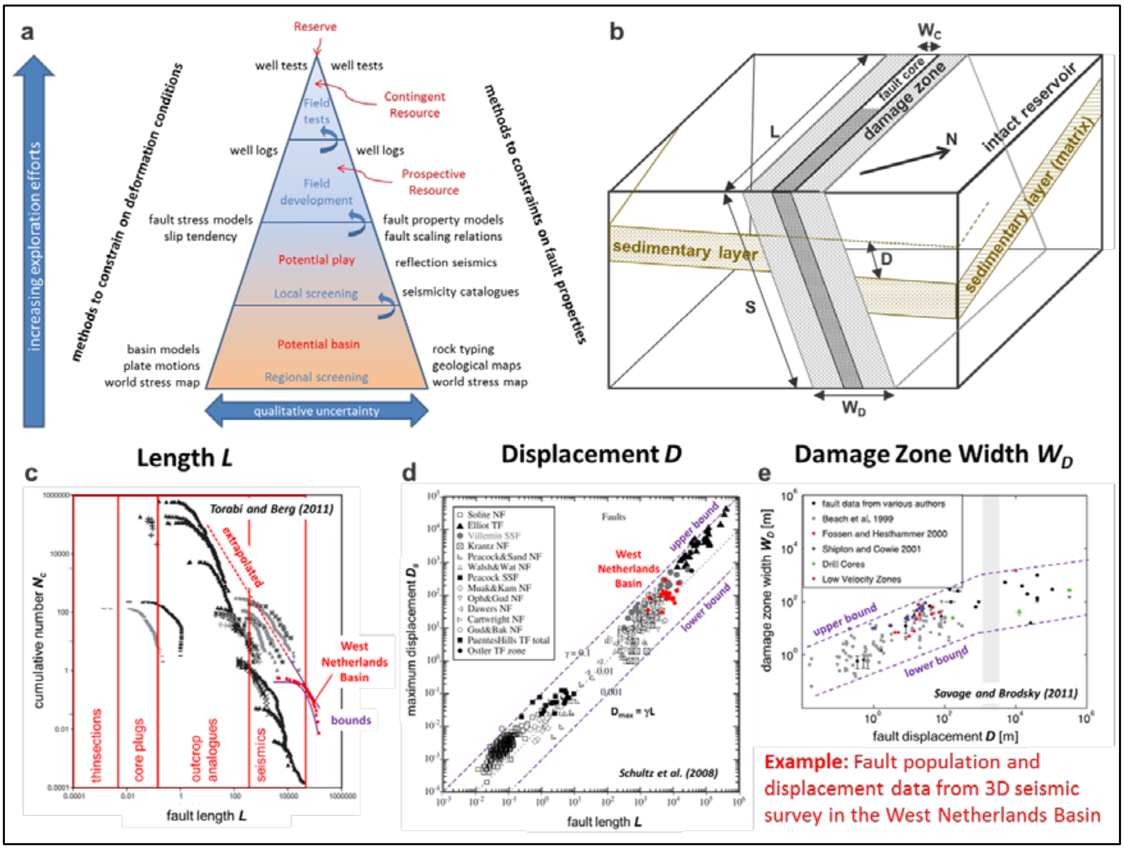
The occurrence and properties of natural faults and fractures in deep geothermal reservoirs are key in determining reservoir flow properties, and thereby the success of many geothermal projects. Factors like fracture density, connectivity and permeability should be taken into account when exploring for new geothermal sites. In most cases, exploration occurs upfront with limited available data (a). Accordingly, methods to predict fracture-related reservoir properties can de-risk geothermal exploration efforts. Fault zones generally exhibit a specific architecture with a fault core and damage zone, surrounded by intact reservoir rock. In this study, an analytical model of permeability around fault zones has been derived based on 3D permeability tensors that describe non-isotropic permeability in each of these structural units (b). In order to address the variation or uncertainty in data, distributed fault properties from different data sources are described by a power law or lognormal distribution in the model (c). Fault scaling relations based on compilations of existing data are used to constrain the dimensions of the different structural units (d, e). Experimental data for permeability of fault gouges are used to constrain fault core permeability. Damage zone permeability is based on fracture density and orientation, and includes the effect of decreasing fault density with increasing distance from the fault core. Permeability of intact reservoir rock includes anisotropy due to heterogeneity of sedimentary layers and internal structures such as channels or cross bedding. The model is used to analyze (1) the interplay between matrix, damage zone and fault core permeability in determining flow around fault zones, (2) the effect of fault and fracture distributions, orientations and interactions on damage zone permeability by incorporation of fault population data, (3) the use of fault scaling relations to characterize fault zones and describe permeability around fault zones on the basis of limited data, and (4) optimum configuration of geothermal doublet systems around fault zones.



Thermo-mechanical model of the European lithosphere

Jon Limberger[1], Jan-Diederik van Wees[1,2], Magdala Tesauro[1], Damien Bonté[1], Lindsay Lipsey[1,2], Fred Beekman[1] and Sierd Cloetingh[1].

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One of the critical exploration parameters for geothermal systems is the subsurface temperature. Temperature data are reliable up to a depth of 1 km in most parts of Europe. Accordingly, the robustness of temperature estimation rapidly decreases with depth, as temperature data from wells become sparser and unevenly distributed. As part of the EU FP7-funded Integrated Methods for Advanced Geothermal Exploration (IMAGE) project we developed a methodology to obtain an improved, physics-based thermal model of the European lithosphere. Using geophysical data the model is divided into a four layer geometry consisting of sediments, upper crust, lower crust and lithospheric mantle. The horizontal resolution is 20 by 20 km, while the vertical resolution decreases progressively from 250m within the sediments to 2.5km within the lithospheric mantle. The steady-state temperature distribution within the model is calculated based on vertical heat flow only, imposing the temperature at the surface and the 1200 °C isotherm of the thermal lithosphere-asthenosphere boundary as boundary conditions for the top and bottom of the model, respectively. Thermal properties, including radiogenic heat production and temperature- and pressure-dependent bulk thermal conductivity, follow the broad-scale lithological variation within the European crust. Further improvements of the thermal model, aiming at consistency between temperature and heat flow observations and tectonic model predictions, are obtained by adopting data assimilation techniques derived from reservoir engineering best practices. If publically available, borehole temperature data are used for this calibration. For other areas temperature maps derived from borehole data are used. The result is a new thermal model of the European lithosphere which allows to better explain the observed temperature variations within the upper crust (including the sedimentary basins) and assess the effect of differences in lithosphere structure, thermal properties and tectonic processes. The thermal model is also used together with compositional data and rheological laws to estimate the integrated strength of the lithosphere. The strength distribution is a first step in estimating the stress field which is important for optimizing the pressure applied to geothermal wells to enhance flow rates, while minimizing the risks of induced seismicity.

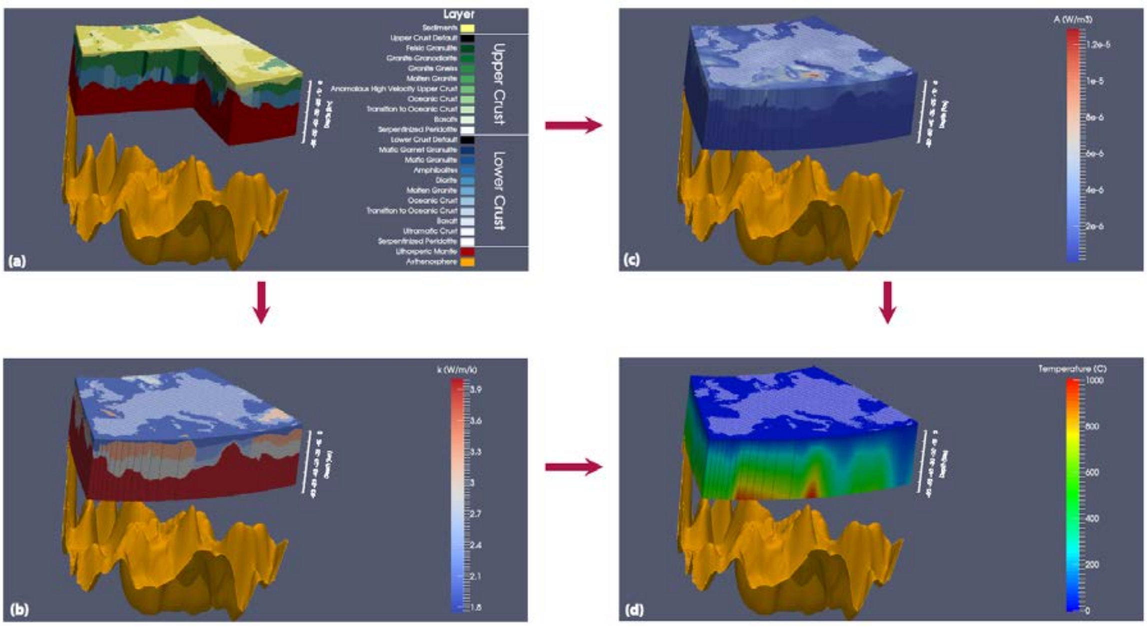

Fig 1: (a) Geometry and composition. (b) Thermal conductivity. (c) Radiogenic heat production. (d) Thermal model.

3D GeoModelling: an Integrated Method for Advanced Geothermal Exploration

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Geothermal exploration aims at locating favourable areas for exploitation. To reach this goal, various disciplines are implemented. Among the most common ones are geology, geophysics and geochemistry. Data are generally acquired in the field, such as geological observations, gravimetric surveys, or thermal sources sampling. These data are interpreted to characterize the geometry, and the properties of the explored zone. They provide separate but complementary information to understand the area. However, combining geological, geophysical and geochemical interpretations is not an easy task. In such a context, one of the main difficulties lies in how to mix all this information to infer a coherent geothermal conceptual model. Putting data in the same space can help their combination to lead to a consistent understanding. First of all, this methodology allows to check the location of separate figures and to ensure their coherence. Moreover, it makes possible to build an overall interpretation based on inputs from various disciplines. GeoModelling in 3 dimensions is an interesting candidate for this job because it allows to gather contributions from various backgrounds to achieve such an interpretation. GeoModelling provides an integration platform for interpretation during the exploration phase of a geothermal project. The final model can be completed through successive stages bringing new information at each step. For instance, a preliminary 3D model can be based on very rough data from bibliography, even before any fieldwork dedicated to the exploration. In a second time, geological data can be observed in the ground and incorporated in the model to refine the interpretation. The process can be continued using a gravimetric survey to improve the model at depth. Then, magnetotelluric resistivity can be injected in the model to infer possible fluid occurrence. Finally, location and properties of geothermal springs can be displayed in the 3D model to complete the interpretation. This kind of interdisciplinary workflow leads to a coherent conceptual model integrating geology, geophysics, geochemistry, and other relevant methods. Nevertheless, every sequence of the workflow is somewhat frozen and quite independent from the others. In addition, the later a discipline appears in the workflow, the more important is its influence on the final model.

A Lithospheric-scale 3D structural and thermal model of the Upper Rhine Graben and western Molasse Basin

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The Upper Rhine Graben and the western Molasse Basin have a large socioeconomic relevance as they provide a great potential for geothermal energy production in Germany, France and Switzerland. For the utilisation of this energy resource it is crucial to understand the structure in these areas. In the framework of *IMAGE*, we apply a data-driven numerical modelling approach to quantify the processes and properties controlling the spatial distribution of temperature variations in the subsurface. We use a multidisciplinary dataset (e.g. well data, seismic reflection data, existing structural models) to construct the geometries of the sediments, the crust and the lithospheric mantle that control the spatial distribution of thermal conductivity and radiogenic heat production and hence temperatures. In particular, we integrate 2D reflection and refraction seismic profiles (e.g. DEKORP lines) and the measured gravity anomaly of the area into a 3D gravity modelling approach to map out units with different reflectivity, velocity and density within the crystalline crust. The resulting 3D structural model includes 14 sedimentary units, 7 different zones in the upper crystalline crust (including the Variscan domains, the Alps and the Odenwald), the lower crust and the lithospheric mantle. By applying a data-based and lithology-dependent parameterisation of this lithospheric-scale 3D structural model and a 3D finite element method, we calculate the steady-state conductive thermal field for the entire region. Available measured temperatures (down to depths of up to 5 km) are considered to validate the 3D thermal model. Our model shows that the Variscan domains with their different thermal properties influence the regional thermal field, while a thermal blanketing effect due to thick thermally low conductive sediments locally causes higher temperatures in the Upper Rhine Graben. Producing a 3D model by associating complementary methods is an interesting perspective but giving these methods the opportunity to interact is even more powerful. Indeed, geological, geophysical, and geochemical interpretations are not disconnected. A preliminary work has to be carried out separately by each discipline to set up the data and prepare an interpretation intrinsic to the specific discipline, as it is done commonly. But afterwards, the interpretation coming from one discipline can be enhanced by the others instead of putting them one after the other in a sequential workflow. To do so, the methodology has to be object oriented instead of workflow oriented. In this advanced approach, the central object is the conceptual geothermal model. Finally, the 3D model benefits from a common interpretation implemented jointly by geologists, geophysicists and geochemists. In other words, they can compare, connect, discuss, adapt, and integrate their own approaches for a mutual result on a GeoModelling platform. At the end, the conceptual model is not a conglomerate of distinct interpretations but a consensus agreed by the contributors. The methodology described above will be illustrated with examples to demonstrate how 3D GeoModelling is helpful to integrate multi-sources information and infer a collaborative interpretation during the exploration phase. In addition, the model can be enhanced during the next phases, when new data are acquired, to provide an up-to-date image of the investigated region. Such a 3D model can also be used to mesh the modelled geometry of the zone and to compute dynamic simulations. In the exploitation phase, this is a valuable tool to monitor the sustainability of the geothermal field.

Development of a stress model of the Rhine Graben

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Any geological setting embedding a geothermal reservoir is cut by a more or less complex fault network resulting from a tectonic history. Even if the stress state associated with a given tectonic event can be assumed to be homogeneous at the regional scale, the local stress distribution is greatly affected by the preexisting faults. By developing zones of greater or lesser compression, the heterogeneous local stresses have an impact on the natural transmissivity of the faults, and on the possibility of stimulating them during the geothermal system operating phase. Studying the stress distribution in a geothermal reservoir can thus give information on favorably exposed faults from a mechanical point of view, and help siting the exploration well. Given the 3D complex interactions of the faults, the stress distribution must be studied using 3D mechanical-oriented softwares where the geometry is derived from *in situ* structural knowledge. The complete mechanical model consists of the geometry, physical laws, and boundary conditions (BC). Once the equilibrium of the mechanical model is achieved, the stress distribution is obtained throughout the whole geometry: this is the so-called "stress model". Several scales must be considered to get the stress model in the geothermal reservoir. First, the study must be performed at the regional scale where, as said above, the natural stresses resulting from a tectonic event can be considered as homogeneous. Then, the mechanical model corresponding to the geothermal system can be obtained by zooming in on the regional model (or, this procedure can be repeated recursively until the model dimensions reach those intended for the geothermal system). By doing so, the BC of the smaller scales can be extracted from the heterogeneous stress model of the larger scales. The work presented here is based on Soultz-sous-Forêts geothermal system, where the well triplet is located at approximately 5 km deep. This work focuses on the regional scale, which corresponds to the Rhine Graben in our test case. The methodology used in this study is detailed here, and relies on two key steps: first, the regional fault network is derived from seismic reflection results (~150x130 km^2). A structural review must give *a priori* the faults playing a greater role in the system mechanical response since we do not want to over-complexify the geometry but rather focus on the main structures (not to mention computer memory limitations). At the end of this first step, the network is given as a 2D map of fault traces at the top of the crystalline basement. The second step of this study aims at extrapolating the 3D network, where each fault is generated as a plane with a single dip and dip direction. This step is performed using computational geometry tools in order to make the process automatic, and requires structural models to derive fault priority rules in 3D (e.g., Riedel structures).

Session 1.2

Exploration techniques for sedimentary/basement settings

(Chair: Chrystel Dezayes, BRGM)

Active seismic methods in geothermal exploration – A review

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Introduction

The high temperatures needed for economical geothermal electricity production are generally found at depths of at least a few kilometres in the Earth's crust. Suitable subsurface imaging tools are required to identify and characterise geothermal reservoirs in detail at these depths. Seismic-reflection imaging has a greater depth penetration with reasonable resolution compared to other geophysical methods used to investigate geothermal reservoirs (e.g., gravity, magnetic, electrical-resistivity and electromagnetic surveys). Although it is used extensively in hydrocarbon exploration, seismic-reflection imaging has been only rarely used in geothermal exploration to date. Seismic surveying provides a powerful and essential pre-requisite to assess the feasibility of geothermal projects and to reduce the risk associated with an expensive drilling programme. Targets in geothermal exploration are permeable zones of sufficiently high temperature and fluid movement; such zones are mostly controlled by faults and fractures. Hence, the focus in seismic geothermal exploration is mapping deep sedimentary and basement structures such as faults and fracture zones. Various sophisticated seismic imaging techniques have been developed for the oil and gas industry, not only for exploration but also monitoring of reservoirs during production. It needs to be investigated how these techniques can be adapted and applied to geothermal sites to improve the planning and development of geothermal reservoirs. Here, we (1) summarize the challenges and current status of geothermal seismic exploration, (2) discuss how geothermal seismic exploration can benefit from experience with seismic methods in hydrocarbon and metaliferrous ore exploration, and (3) review advanced seismic processing techniques that could potentially be of value for the seismic imaging of geothermal reservoirs.

Challenges and status of geothermal seismic exploration

Most reservoirs in enhanced geothermal systems (EGS) will be located in hardrock basement rather than in the sedimentary section. Because the impedance contrasts and reflection coefficients between most crystalline rocks are smaller than those of sedimentary rocks, the signal-to-noise ratio (S/N) will be low, making it more difficult to image structures (e.g, fracture zones, fluids) in the basement. Moreover, the target reflectors are likely to be rough and of limited spatial extent, further reducing signal amplitudes and exacerbating their detection. A further problem is that long offsets are needed to get reliable velocity information and to image basement. Recently, Hlousek et al. (2015) reported on the 3D imaging of fault zones in the western Erzgebirge (Germany) using advanced imaging techniques; Abul Kahir et al. (2015) proposed a seismic work flow for EGS to characterize fracture zones within deep hot granites in the Cooper Basin (Australia).

Hydrothermal systems are naturally occurring, they are limited in geographic location and it is a key challenge to find them. Seismic exploration can be used to image the lateral extent of an aquifer and to characterize the associated fault and fracture systems. As an example, Lüschen et al. (2014) analysed a 3D seismic data set from Unteraching (Munich, Germany) to study the Malm sequence that is the target formation for a hydrothermal reservoir. Seismic attributes were used to distinguish different facies and azimuth-dependent reflectivity provided indications on preferred fracture orientations.

Lessons to be learned from hydrocarbon and hardrock seismic exploration

Geothermal exploration is an emerging technology and extracting energy from deep sedimentary basins (and/or the underlying basement) has become a desirable option. Oil companies have explored in great detail many sedimentary basins throughout the world, hence, a lot can be learned from the oil and gas industry in terms of advanced exploration techniques. For example, fracture zone imaging and characterization is of equal importance to hydrocarbon exploration as it is to geothermal exploration. Several studies have been published on fracture mapping using, for example, amplitude-versus-offset (AVO) variations. The development of 3D seismic technology allowing the accurate positing of reflectors in three dimensions had a major impact on hydrocarbon exploration. Furthermore, 3D seismic data cubes provide the possibility of extensive attribute analyses, which is widely used for fracture characterization. The repeated acquisition of 3D seismic data (4D or time-lapse seismic monitoring) enables the mapping of changes in reservoir properties such as saturation, temperature and pressure, provided that the changes in these properties lead to detectable changes in seismic signals at the surface and the repeatability of the surveys is high.

EGS systems have their maximum potential in crystalline rock. So far, extensive seismic-exploration studies over hardrock environments are mainly related to mineral exploration, finding suitable underground repositories for radioactive waste, and assorted geological studies, especially crustal investigations. There are several challenges one needs to face in hardrock seismic exploration: reflection amplitudes are generally weak and the resultant low S/N makes it challenging to image features within the basement; reflectors are often small, steeply dipping and laterally discontinuous due to more complex morphology, lithology and deformation; the high velocities in crystalline basement result in a loss of resolution due to the relatively longer wavelengths; anisotropy can be introduced through fractures and layering leading to complex wave propagation. Deep crustal studies helped to develop the requisite acquisition and processing techniques for crystalline environments. These large-scale images can also provide valuable information when looking for potential geothermal sites.

Advanced seismic processing techniques

Over the last few decades, numerous advanced seismic processing techniques have been developed by the oil and gas industry. It needs to be established through detailed testing which of these techniques can be best adapted and applied to geothermal seismic exploration.

<u>Seismic attributes</u> are quantities that can be derived from seismic data in order to extract structural and lithological information of the subsurface. Azimuth and dip attributes, coherency, curvature and spectral decomposition have been used to characterize fracture zones in detail. These as well as other attributes could be further tested to evaluate the potential for fracture mapping in crystalline basement. Applications of attribute analysis in geothermal exploration to enhance the visibility of fracture zones have been reported by, for example, Lüschen et al. (2014) and Abul Khair et al. (2015).

<u>Multicomponent seismic data</u> offer many advantages compared to standard vertical component seismic data in that additional and useful information can be extracted such as polarization properties. Polarization information can be used to determine the direction of different arriving wave types as well as to provide the possibility for application of polarization filters and wavefield separation techniques. For example, by implementing polarization information in migration algorithms, different P- and S-wave images can be obtained. Since P- and S-wavefields sample the subsurface in different ways, complementary information can be extracted. S-wave imaging has the advantage of being less affected by absorption in gas bearing fracture zones, enables studying anisotropy by shear wave splitting, provides more detailed lithological characterization, and improves fluid discrimination and reservoir monitoring. Characterizing fractures (orientation, density) as well as understanding the stress state of the subsurface is of great importance in geothermal exploration. Studying S-wave splitting on, for example, vertical seismic profiling (VSP) data, could therefore provide critical information on fracture orientation and intensity in the subsurface.

The seismic responses of the typically small and steeply dipping targets of importance in geothermal exploration (e.g., fracture planes, shear zones, fluid pathways, faults) in the hardrock basement are more characteristically diffractions (diffuse wavefield) rather than specular reflections. The detection and processing of such small diffraction signatures places severe demands on seismic data acquisition and requires specialized processing tools. Yet, diffraction imaging potentially provides high-resolution (sub- wavelength) information and makes it possible to detect small-scale discontinuities.

Full Waveform Inversion (FWI) is an imaging method that aims to exploit simultaneously the whole seismic data along each trace to reconstruct high-resolution quantitative images of the characteristic parameters (seismic velocities, density, attenuation) of large areas of the subsurface. Since the whole seismograms are used for FWI, the most complete representation of the subsurface is expected. Thus, FWI is expected to be able to provide quantitative images with the resolution of migration and diffraction imaging (half of the shortest wavelength expected for favourable illumination). To date, FWI has not been used for geothermal exploration. As the exploration depth and surface illumination configurations are similar to oil and gas exploration, application of FWI to geothermal targets can benefit from all the developments made for oil prospecting, but will still be subject to the same difficulties and limitations (cost of forward modelling; construction of an accurate initial model for velocity, density and attenuation; data pre-processing when the modelling relies on strong assumptions such as acoustic propagation only).

Conclusions and outlook

Most EGS reservoirs will be located in hardrock (basement) rather than the sedimentary section. Because the impedance contrasts and reflection coefficients between most crystalline rocks are smaller than those of sedimentary rocks, the S/N will be low, making it more difficult to image structures (e.g, fracture zones, fluids) in the basement. Moreover, the target reflectors are likely to be rough and of limited spatial extent, further reducing signal amplitudes and exacerbating their detection and delineation. Consequently, particular care must be taken in survey planning, acquisition and processing to maximize the signal-to-noise ratio. The structures of importance in geothermal exploration are expected to be complex in shape and steeply dipping, which means that the reflections will tend to arrive at the surface in unexpected locations. Therefore it will be necessary to model surveys beforehand in future seismic experiments to determine optimum locations for sources and receivers and to aid with the interpretation of the data. The targets (e.g. fracture zones) are small and will more likely appear as diffractions rather than as reflections on seismic profiles. Most existing reflection seismic data over potential geothermal fields data were acquired for hydrocarbon exploration purposes, where the survey layout was designed to image the sedimentary column. The recording apertures (maximum source-receiver distances) are mostly inadequate for imaging steep dips within the basement. Very few successful geothermal-specific seismic reflection surveys have been carried out in the past. Future surveys will require every degree of sophistication that can be brought to bear. The vast experience of oilfield seismic imaging has much to offer in illuminating the route towards a solution but the geothermal problem is unique. The major technical modifications need to be in the use of 3D arrays and multicomponent sensors, coupled with sophisticated processing, including attribute analysis, polarization filtering/migration and the separation of diffracted and specular reflected wavefields. Full waveform inversion and S-wave splitting investigations can be profitably carried out provided that the data are of sufficient quality. There are grounds for optimism that the geothermal reservoir-imaging problem can be meaningfully tackled.

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Getting an image of Vs variations at the basin interface level with surface waves

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Successful exploitation of a geothermal field is dependent on a correct circulation of fluid between the wells. This circulation is usually done by the stimulation of existing fracturation, and therefore a sizeable part of the exploration efforts is devoted to evaluate the orientation and the density of fracturation in the target level. Comparing tomographic images of Vp and Vs seismic waves speeds can give good insights into the fracturation level. Vp tomographies are usually done with active seismic imaging methods, while Vs tomographies are usually obtained using local/regional earthquakes as a source, or more recently surface waves obtained from correlations of ambient noise.

This last method obtained good results for volcano tomography, however using this method for geothermal exploration in sedimentary basins can be tricky :

- While Vs variations in an active volcano are very large due to the presence of molten rock, Vs speed variations due to different levels of fracturation are smaller and are likely not to be seen by the standard methods;
- Sedimentary basins are usually populated, and anthropic noise can hinder observations;
- Since surface waves are mostly trapped right under the surface, they are overly sensitive to surface variations (presence of water etc.) and less sensitive to variations in depth.

We have therefore to improve the processing of surface waves observations. We will show in the presentation that a smart combinaison of different surface waves measurements and perturbation calculations can allow us to downplay the bias introduced by surface variations and therefore get a better precision for Vs variation measurements at the desired depth. The algorithm stability has to be improved and is currently under work. This method can also be used beforehand, provided we have a correct estimate of the Vs speed profile : by using modelisations, we can examine the sensitivity kernels and decide if this method can be applied or not even before the network is deployed on the field. This gives more flexibility to the exploration team, so that they can prepare the field measurements and the best methods to choose.

Imaging changes at depth: coda wave depth sensitivity in 3D heterogeneous media

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In the context of seismic monitoring, recent studies successfully made use of the diffuse character of seismic coda waves to locate medium changes in the Earth on the horizontal plane. The depth location, however, remains a challenge. We use 3D wavefield simulations to investigate the lapse-time dependent depth sensitivity of seismic coda waves towards velocity perturbations in an elastic heterogeneous medium. We introduce a thin layer with a perturbed velocity at different depths. Then, we determine the apparent relative velocity changes due to this layer at different times in the coda and for different degrees of heterogeneity of the model. We show that in all cases, the depth sensitivity can be modeled as a combination of bulk and surface wave sensitivity. The partition ratio between bulk and surface waves shows a universal behavior and can be used to construct probabilistic 3-D sensitivity kernels for imaging purposes that combine surface and bulk wave propagation. We show numerical results where we use these 3D kernels to locate changes in different types of media.

Active and passive electromagnetic measurements for geothermal exploration close to urban areas

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A geophysical survey has been performed in the area of Litoměřice (Czech Republic) where a geothermal exploration drilling has been performed in the Bohemian massif in 2000. Measurements have been performed from 6 to 11th September by BRGM and Geomedia staff, with the logistic help of Litoměřice city. The survey aims at measuring electrical resistivity at depth to image the main geological features underground until few kilometers in urban areas with the challenging problem of cultural noise. Because the first method (MT) can be severely affected by electromagnetic (EM) noise induced by anthropogenic activities such as cities and industries and DC trains such as in Czech Republic (and many regions in Europe), CSEM (active controlled-source electromagnetics) and MT (passive method, natural sources) data were both collected to be able to provide a resistivity imaging of the area. 27 CSEM stations and 7 collocated MT stations have been recorded. The CSEM survey has been conducted using surface and borehole high power emissions and two pseudo-orthogonal polarizations. A set of frequencies ranging between 0.125 Hz to 128 Hz has been selected to investigate the medium. Results provide apparent resistivity maps at various frequencies and for both polarizations reflecting the geological variations from north to south. MT robust signal processing has been performed using synchronous recordings performed locally (30 km) and at far (> 500 km) remote stations. Data were processed using advanced robust techniques in each possible configurations (3 remote reference stations and single site processing). As the ambiant noise and MT sources are not stationnary, a time-lapse approach based on an error threshold was used to select the best MT estimates. MT soundings were obtained in the [7mHz-1kHz] frequency band (such as station 06 shown on Fig. 1). Their quality will be discussed in the presentation.

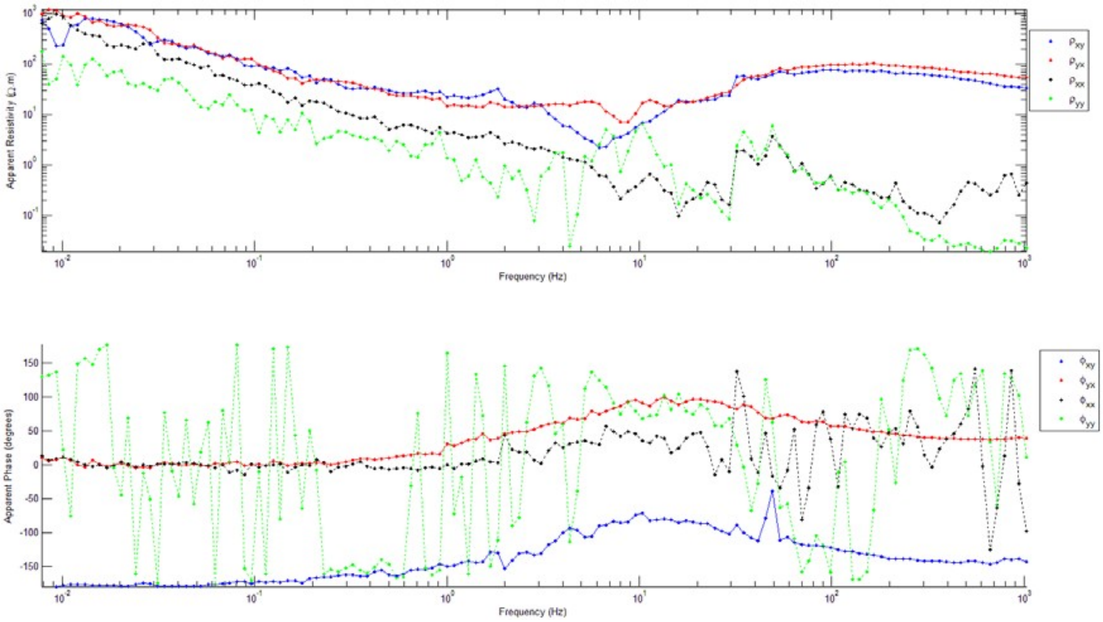

Fig 1: MT sounding associated with MT station 6. Upper pannel: 4 components of the apparent resitivity tensor, lower pannel: 4 components of the apparent phase tensor.

Poster Session 1

Sedimentary/Basement Systems

Relation between natural fracturing system and borehole breakouts in Basel geothermal system (BS-1 well)

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The characterisation of the natural fracture systems is central to the development of a geological model of Enhanced Geothermal System (EGS) reservoirs. In addition, the modeling of processes activated during the stimulation of such reservoirs requires an estimate of the current day stress field. In the case of the Basel EGS reservoir, previous studies of logs run in the BS-1 borehole have been performed independently on the natural fracturing system (Ziegler et al. 2015) and borehole breakouts (Valley and Evans 2009; Valley and Evans 2015). In this paper, we try to relate the distribution of natural fractures and their properties with borehole breakouts inferred from image logs. Two dominant fracture sets are present in the BS-1 borehole referred as set-1 and set-2. These fracture sets together encompass more than 50 percent of the total number of fractures. The dip direction of members of these sets is indicated on Fig. 1 together with the mean azimuth of breakouts. Although the azimuth of the breakouts are generally similar to the dip direction of the two dominant fracture sets, there is no clear correlation between the local variations of fracture dip direction and breakout orientation. When looking at breakout width variations, a decreasing trend of breakout width with depth is measured consistently for both diametrically opposite breakouts (referred below as breakout legs). A discrepancy in breakout width between the two legs is observed only for two intervals, both of which are affected by keyseats, i.e. mechanical wearing of the borehole wall by the drill string, that tends to enlarge one leg compared to the other. In addition, a weak reverse correlation between dynamic E-modulus derived by combining sonic and density logs and breakout width was identified when averaging data over 200 meter intervals, although such reverse correlation was not evident when using smaller averaging intervals. The relations between rock property variations and breakout width are at the moment poorly understood and will be further investigated. In addition, we analyzed the zones where no breakouts occur. Generally, breakout-free intervals relate to the presence of fracture zones. Only one interval that is free of breakouts is unaffected by fracture zones. Various processes could explain these observations, including stress relief associated with fracture zones and/or changes in rock mechanical properties due to hydrothermal alteration along the fracture zones. Further investigations are required to evaluate the relative importance of these potential explanations.

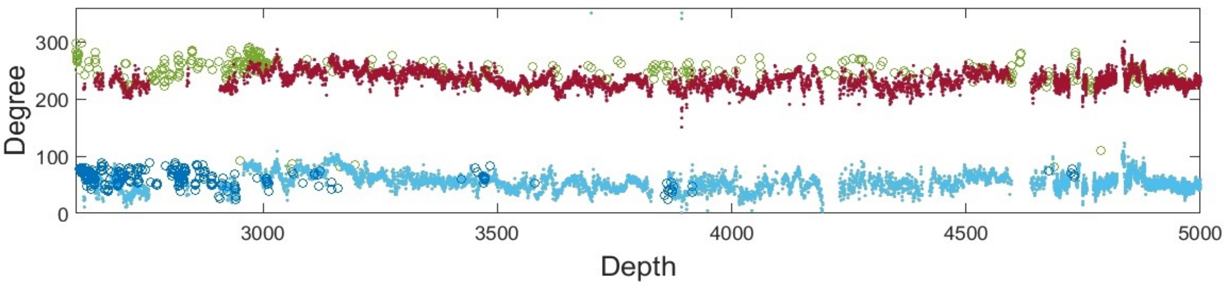

Fig.1: Orientation of diametrically opposite breakouts (referred as breakout legs, blue and red dots) along the BS-1 well compared to the dip direction of the two dominant fracture sets (set-1 as green and set-2 as dark blue circles). **Abstract References** **(1)** Valley B, Evans K (2009) Stress orientation to 5 km depth in the basement below Basel (Switzerland) from borehole failure analysis. Swiss J Geosci 102:467–480. doi: 10.1007/s00015-009-1335-z. **(2)** Valley B, Evans K (2015) Estimation of the stress magnitudes in Basel Enhanced Geothermal System. In: Proceedings of the world geothermal congress 2015. Melbourne, Australia. **(3)** Ziegler M, Valley B, Evans K (2015) Characterisation of Natural Fractures and Fracture Zones of the Basel EGS Reservoir Inferred from Geophysical Logging of the Basel-1 Well.

Permeability key situations in sedimentary basins

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The challenge in the IMAGE project WP6.4 is to identify key-parameters controlling permeability in geothermal reservoirs in the geological context of sedimentary basins, at a sufficient depth. Three fundamental parameters have been identified: the lithology of the reservoir, natural fractures and faults, and stress fields, considering multi-scale information (from field scale to fine scale). In sedimentary basins and considering the geothermal context, the resource is diffuse: the heat is stored both in the rock and in the fluid. Its spatial extension is not delimited by reservoir boundaries. The resource is recovered through the fluid circulations and all the heat close enough to the flow path will be recovered by diffusive processes independently of the connection of porosity network. Consequently, permeability, independently of porosity, is a key-factor to characterize the resource exploitability. The produced flow rates and associated permeability threshold are much higher than in the petroleum industry. The prototypes of such highly permeable paths are faults and fractures which are ubiquitous features of many geothermal reservoirs. At a crustal and lithospheric scale, geo-thermo-mechanical models of the upper 10 km help to understand and predict the present-day field stress state and the faults on basin and basement heat flow. At a geodynamic scale, tectonic structures may be a medium or on the contrary a barrier for the groundwater flow and as a consequence for the heat transport. Deep fractured areas in Europe have been identified around the peri-alpine front (European Cenozoic Rift System, peri-alpine forelands) and the Alpine front (complex back-arc basins, post-collisional grabens). At a reservoir-scale, permeability and the way it is distributed in a reservoir are one of the most important parameters governing fluid transport processes to build realistic 3D models which properly capture geological heterogeneities and petrophysical parameters. Fluid circulation pathways are indeed controlled both by conduction through the reservoir matrix (sedimentary facies and diagenesis knowledge) and by convection with large-scale permeability factors (faults and fractures characterization). At a well scale, the knowledge of diagenesis impact on rock properties, fluid characteristics and fracture network characterization are essential data. One of the most important challenges in reservoir simulation is to determine an equivalent permeability for the fracture network. All these parameters lead either to permeability enhancement or to permeability reduction or both as a function of time. Geothermal reservoirs do not necessary imply a high permeability. What is important is the flow and heat transport so that even a zone of small permeability can produce a major thermal feature. Convection is considered as a much important key-factor than conduction but the two heat transfers systems are both complementary. Having 3D geological model, realistic and conceptual, with integrated multi-scale processes simulated through thermo-hydro-chemical models (THMC) are important to evaluate and quantify preferential hydraulic flows paths and quantitative parameters involved in geothermal reservoirs exploration.

3D geological models in the Rhine Graben and the Molasse Basin

Chrystel Dezayes[1] and Laure Capar[1]

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One of the objectives of the IMAGE project is to apply the developed methods on field. In this framework, local 3D geological models have to be built or improved from existing ones. Since several years, BRGM has developed 3D geological modelling software in order to better image the subsurface geology. In several projects, 3D geological modelling was used to aid to better located favorable areas for geothermal energy development. Two geological local models were presented here: one located in the Rhine Graben between Strasbourg and Obernai (Dezayes *et al.*, 2010), one located in the Molasse Basin between Geneva and Chambéry (Capar *et al.*, 2015). The Strasbourg-Obernai geological model, in the Rhine Graben, has been developed in the framework of project co-funded by the French Energy Agency (ADEME). The goal of this project was the geothermal potential assessment of clastic reservoirs. In order to assess the geothermal potential in a limited area, Muffler and Cataldi (1978) computation method has been used with 3D geological model to estimate the volume of the reservoir formation (Dezayes *et al.*, 2008). Then, this methodology has been tested on a 30km x 35km area located between Strasbourg and Obernai in France. Based on a detailed geological study combining data derived from 13 previous oil boreholes and 143km length of seismic profiles, the main sedimentary interfaces including geological layers and faults have been interpreted between the outcropping Quaternary layers and the deeper parts made of Permo-Triassic formations. From that interpretation, 3D geological models have been yielded based on different hypotheses allowing calculating the volume of modelled silicoclastic formations. The Geneva-Savoy geological model, in the south-western end of the Molasse Basin, has been yielded in the framework of the Interreg Alpine Space Program with project namely GEOMOL (Diepolder *et al.*, 2015; www.geomol.eu). The aims of this project are to model the subsurface geology of the Molasse Basin and to assess its geopotentials. In the case of the Geneva-Savoy Pilot Area, the focus was done on the geothermal potentials for transnational use of geothermal energy at medium and great depths. This area extends from Geneva to Chambery forming a narrow (max. 40km in width) elongated (approx. 110kn in length) NNE-SSW depression between the subalpine frontal thrust and the eastern edge of Jura Mountain folds. The building of the model is based on the geological map and the DTM, seismic profiles (980km, French and Swiss) and boreholes (531 including 125 reaching Mesozoic). The main formation units have been modelled, also the main tectonic structures such as ramp faults. These both models available in the IMAGE project can be improved by incorporating novel explorations results deployed on the brown site (Rhine Graben) and the green site (Molasse Basin).

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Update of the European stress database

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The World Stress Map (WSM) Project that was initiated in 1986 under the auspices of the International Lithosphere Program compiles the orientation of maximum horizontal stress S_{Hmax} and information on the stress regime from a wide range of stress indicators such as borehole breakouts, drilling induced tensile fractures, hydraulic fracturing, earthquake focal mechanism solutions, overcoring and geological data. The WSM quality ranking scheme assigns each data record a quality from A to E and thereby ensures comparability [Heidbach et al., 2010]. The revised and updated European part of the stress database from Iceland in the North to the Mediterranean region in the South is part of the ongoing new global compilation for the 30th anniversary of the WSM project in 2016. We added 3663 new data records with 2423 of them having A-C quality. The new European database displayed in Fig. 1 has now 4529 A-C quality data records.

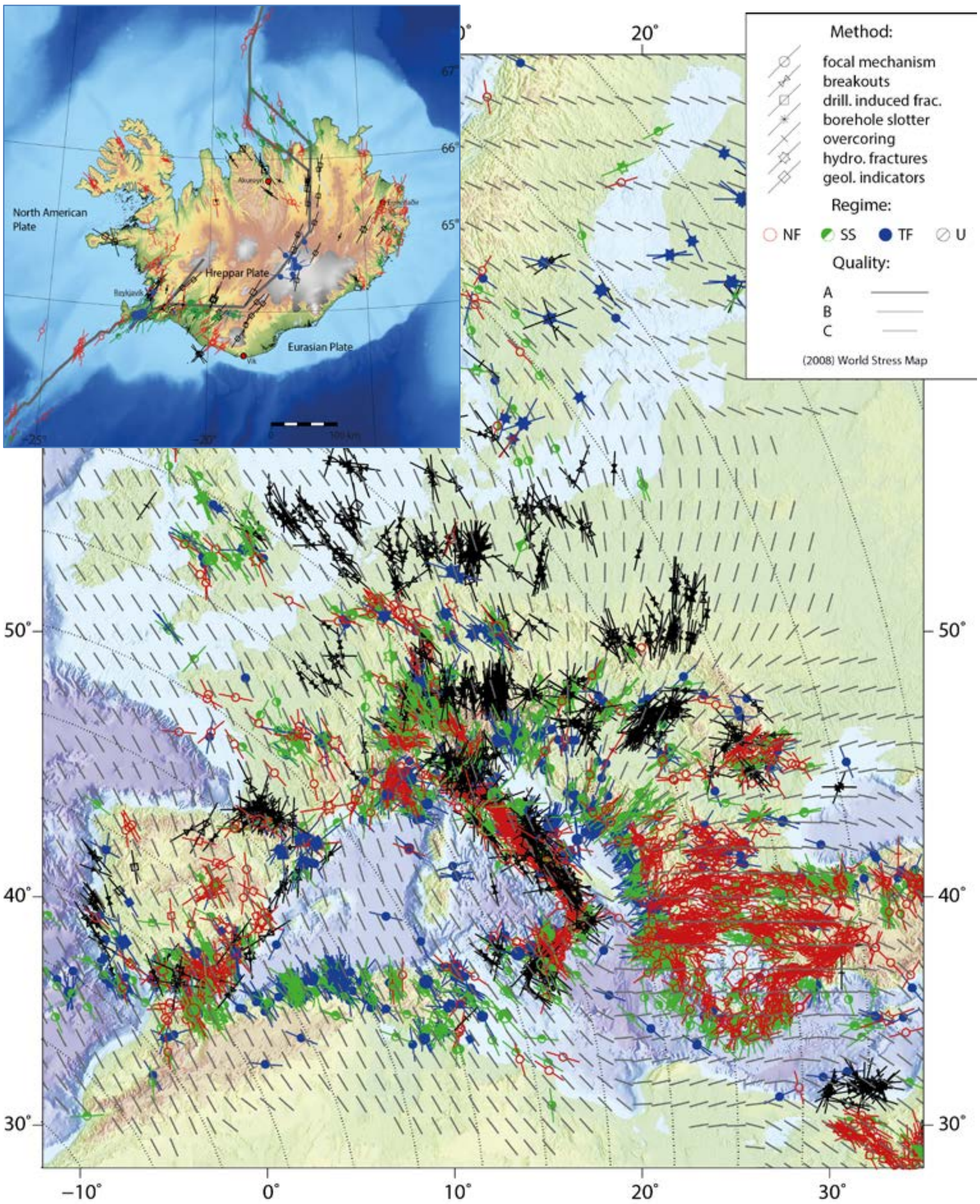

Fig. 1: European stress map and Iceland stress map from Ziegler et al. (subm.) based on the new data compilation with 4529 A-C quality data records. Lines represent the orientation of maximum horizontal stress S_{Hmax}; line length is proportional to data quality. Colours indicate stress regimes with red for normal faulting (NF), green for strike-slip faulting (SS), blue for thrust faulting (TF), and black for unknown stress regime (U). Dotted lines show relative plate motion trajectories of Africa vs. Europa; mean S_{Hmax} orientations on a 1° grid are estimated with 500 km search radius and with weighted by data quality and distance to the grid point.

Numerical modelling of thermal convection related to fracture permeability in Dinantian carbonate platform, Luttelgeest, the Netherlands

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The presence of convective fluid flow in permeable layers can create zones of anomalously high temperature which can be exploited for geothermal energy. Temperature measurements from the Luttelgeest-01 (LTG-01) well in the northern onshore region of the Netherlands indicate variations in the thermal regime that could be indicative of convection. This thermal anomaly coincides with a 600 m interval (4600 – 5200 m) of Dinantian carbonates showing signs of increased fracture permeability of ~60 mD. Three-dimensional numerical simulations provide insight on possible flow and thermal structures within the fractured carbonate interval, as well as illustrate the role of permeability on convection development and the resulting temperature patterns. The development and number of convection cells is very much a time dependent process. Many cells develop in the beginning of simulations, but they seem to gradually converge until steady state is reached. The shape of convective upwellings varies from circular or hexagonal to more elongated upwellings. Furthermore, geometric aspects of the carbonate platform itself likely control the shape and location of upwellings, as well as the fracture network geometry within the aquifer. In summary, convective upwellings can create significant temperature enhancements relative to the conductive profile and in agreement with the observations in the Luttelgeest carbonate platform. This enhancement is critically dependent on the aquifer thickness and geothermal gradient. Given a gradient of 39 °C/km and an aquifer thickness of 600 m, a temperature of 203 °C can be obtained at a depth of 4600 m directly above upwelling zones. Contrarily, downwelling zones result in a temperature of 185 °C at the same depth. This demonstrates the strong spatial variability of thermal anomalies in convective fractures aquifers at large depth and can have strong effects on exploration opportunity and prospective areas. Numerical models can facilitate in exploration workflows to assess thermal variation and location of upwelling zones.

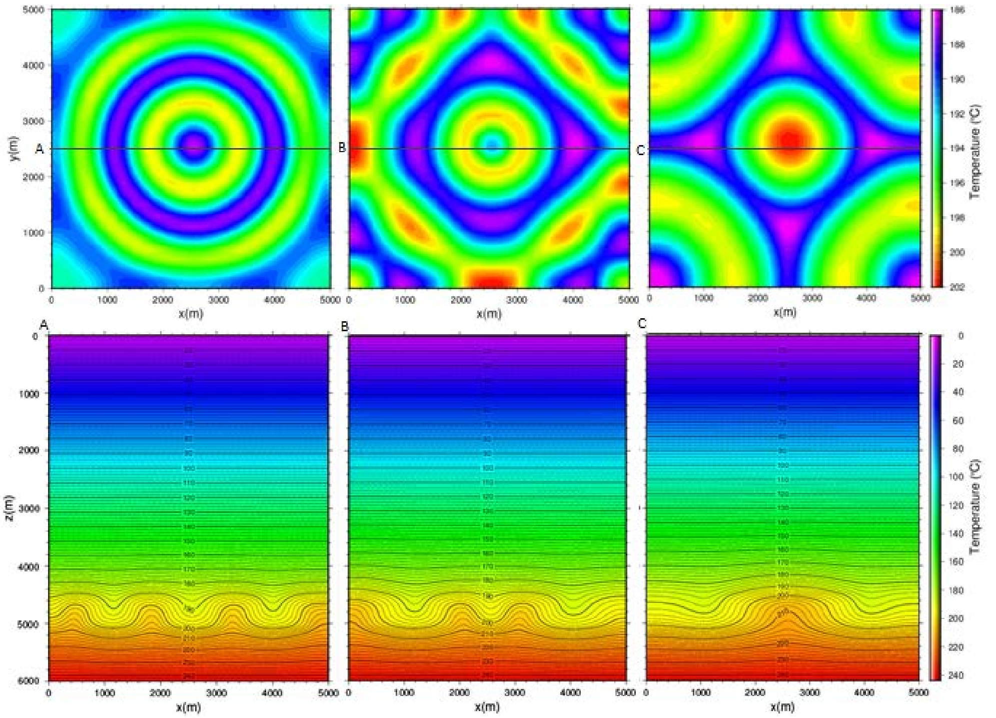

Fig. 1: Numerical results for a gradient of 39 °C/km, aquifer thickness of 600 m and permeability of 60 mD at 15k years (left), 50k years (middle) and 150k years (right). Top: Temperature difference at top of aquifer. Bottom: Cross section through middle of model.

Potential of ambient seismic noise techniques to monitor injection induced subsurface changes at the St. Gallen geothermal site.

Anne Obermann[1], Toni Kraft[1] and Stefan Wiemer[1]

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The failures of two recent deep geothermal energy projects in Switzerland (Basel, 2006; St. Gallen, 2013) have again highlighted that one of the key challenges for the successful development and operation of deep underground heat exchangers is to control the risk of inducing potentially hazardous seismic events. In St. Gallen, after an injection test and two acid injections that were accompanied by a small number of micro- earthquakes (ML < 0.2), operators were surprised by an uncontrolled gas release from the formation (gas kick). The “killing” procedures that had to be initiated following standard drilling procedures led to a ML3.5 earthquake. With ambient seismic noise cross correlations from nine stations, we observe a significant loss of waveform coherence that we can horizontally and vertically constrain to the injection location of the fluid. The loss of waveform coherence starts with the onset of the fluid injections 4 days prior to the gas kick. We interpret the loss of coherence as a local perturbation of the medium. We show how ambient seismic noise analysis can be used to assess the aseismic response of the subsurface to geomechanical well operations and how this method could have helped to recognize the unexpected reservoir dynamics at an earlier stage than the microseismic response alone, allowed.

3D-ambient noise group velocity tomography of Snaefellsjökull volcano, Iceland

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[1]ETH Zürich, CH; [2]MIT, Cambridge, USA.

From May to September 2013 21 seismic stations were deployed on Snaefellsjökull volcano, Iceland. We cross- correlate the 5 months of seismic noise and measure the Rayleigh wave group velocity dispersion curves. We use a 3D tomography procedure to compute velocity maps between 0.9 and 4.8 s. The results allow us to constrain the size and depth of the magmatic reservoir as well as the geological structures beneath Snaefellsjökull volcano. We provide accurate velocity models for the peninsula.

Optimizing the design of vertical seismic profiling (VSP) surveys for imaging of geothermal reservoirs

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Compared to oil and gas exploration seismic techniques have been applied only rarely to geothermal exploration. The primary focus of geothermal seismic imaging is to map dipping faults and fracture zones that control the permeability and the water flow. However, in hardrock environments the detailed seismic imaging of subsurface structures within basement (such as fracture zones) is challenging due to the large impedance contrast between the overlying sediments and the crystalline basement. Furthermore, weak impedance contrasts between lithological units in crystalline rocks, generally low signal-to-noise ratios and often steeply dipping structures complicate the problem. The goal of this study was to optimize vertical seismic profiling (VSP) survey layouts for imaging gently to steeply dipping fracture zones in the basement based on acoustic synthetic modelling with a 2D finite difference scheme. The geophysical model used for our survey design study was obtained from logging information from the geothermal site at Soultz-sous-Forêts. There, seismic velocities gradually increase with depth within the sediments in the upper part (depth < 1.4 km) and in the basement (Fig. 1b). To simulate a realistic degree of heterogeneity, stochastic fluctuations were added to the velocity model. The simulated borehole was inclined at 30° to the vertical, with a receiver array located between 3700-4900 m depth at an element spacing of 20 m. A 40 m thick fracture zone characterized by a reduced velocity and density of 15% was added to the model, starting at a depth at 4390 m. The dip of the fracture zone and its horizontal distance from the borehole was varied for the numerous tests. Acoustic synthetic data were modelled with a finite difference code (sofi2d) for sources placed every 100 m along the surface of the 9000 m wide model. After the application of a basic processing sequence (geometrical spreading correction, tau-p filtering, Kirchhoff depth migration), combinations of final migrated common-source gathers were analysed. Optimal source positions were determined by the maximum crosscorrelation value of a single or combination of migrated images compared with a reference image using the comprehensive data set (all shots). Starting with the optimum single image, the image that yielded the highest increase in correlation of the sum compared to the reference was added iteratively. Based on the resultant benefit-cost curves (number of images vs. correlation coefficient) and the quality of the migrated images, the optimal survey layout can be chosen. An example is shown in Fig. 1, where just 9 source positions were deemed to be sufficient for imaging a 70° dipping fracture zone 300m away from the borehole.

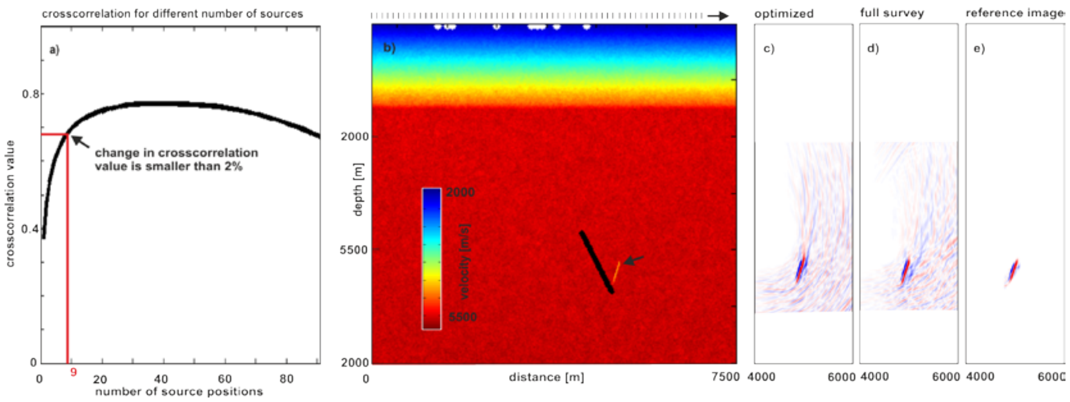

Fig.1 a) Crosscorrelation value for different numbers of stacked migrated images with the reference (best) image. Nine source positions lead to an optimal survey layout as indicated in red. **b)** Velocity model with a 70° dipping fracture zone marked by the black arrow, receivers in black and the optimal 9 source positions in white. **c)** Migrated image using the optimized survey layout of the 9 optimum source positions. **d)** Migrated image using all 91 source positions. **e)** Reference image that corresponds to the migrated image of the full survey, but tapered around the fracture zone.

Development and use of auxiliary chemical geothermometers applied to low-temperature fluids collected from the crystalline basement in the Litomerice area, Czech Republic

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One of the major applications of water geochemistry in the exploration of the potential geothermal reservoirs involves estimation of their temperature using chemical and isotopic geothermometers. Since 1965, several chemical and isotopic geothermometers are applied on fluid samples collected either from geothermal wells or thermal springs. Most of these geothermometers are based on empirical or semi-empirical laws derived from known or unknown chemical equilibrium reactions between water and minerals occurring in the geothermal reservoirs. Unfortunately, the estimations of temperatures given for the deep geothermal reservoirs using these classical tools are not always concordant (chemical equilibrium not reached, water mixing processes, mineral dissolution/precipitation reactions during the deep fluid rising, seawater influence, etc.). Given this discordance, auxiliary geothermometers such as Na-Li and Mg-Li were also developed and proposed in the literature, and sometimes gives more reliable deep temperature estimates than those using classical geothermometers, even if their working is badly known and seems to be dependent on the nature of the rocks and of the fluid salinity. In the framework of this study, after an exhaustive literature review about the use of potential auxiliary chemical geothermometers, the chemical compositions of deep fluids discharged from existing boreholes drilled up down the crystalline basement, in the Litomerice area, Northwest Bohemia, were collected and exploited. Only the chemical compositions of fluids from five deep boreholes were found and among these boreholes, only one could (and can) be sampled by Geomedia (PVGT-LT1 borehole). Globally, these fluids indicate different chemical compositions (Na-HCO_3, Na-Ca-HCO_3 and Na-Cl types) with TDS values ranging from 346 to 957 mg/L. Their concentrations of dissolved silica are very low, which suggest low deep temperatures for these fluids. For three of them (TH-20, TH-10 and HV-3C), the chalcedony geothermometer gives estimations of temperature (21, 28 and 7°C, respectively) close to those measured into the boreholes (27.1, 31.0 and 12.0°C, respectively). For the TH-31 fluid, the temperature using this geothermometer is over-estimated (59°C) relative to that measured in the borehole (13.0°C). The Na-Cl fluid collected from the PVGT-LT1 borehole indicates an anomalously low SiO_2 content, given its temperature measured at the bottom-hole, close to 56.5°C, at a depth of 1800 m. Consequently, when applied to this fluid, the silica geothermometer gives bad estimated temperatures (< 0°C) whereas the Na-K or Na-K-Ca geothermometers yield overestimated temperatures (> 150°C). Only the Na-Li, K-Mg, K-F, K-Fe and K-Mn geothermometers give estimations of deep temperatures (43-58°C) close to that measured at the bottom-hole. For the other fluids, apart TH-20, only the temperatures estimated using the K-Fe geothermometer (33, 3 and 16°C, respectively) are close to those measured in the boreholes (31.0, 12.0 and 13.0°C). For the HV-3C fluid, the temperature estimated using the K-Mn geothermometer (18°C) is also in agreement with the measured temperature (12.0°C). The relatively poor concordance between the temperatures estimated using chemical geothermometers and the measured values in the boreholes is probably due to the low values of temperature of these fluids, which do not allow them to reach chemical equilibrium with the surroundings rocks at these temperatures. At these low values, only the chalcedony and K-Fe geothermometers seem to be able to give relatively good estimations of temperatures. At temperatures > 50°C (only for the PVGT-LT1 fluid), more chemical geothermometers seem to be available (Na-Li, K-Mg, K-F, K-Fe and K-Mn). However, additional chemical analyses of this fluid are necessary to confirm and complete the representativeness of its deep chemical composition and test other auxiliary geothermometers such as Na-Rb and Na-Cs. We will also try to find and collect other thermal fluids discharged from the crystalline basement, in the Litomerice area, in order to confirm the use of such auxiliary chemical geothermometers. In addition to the development of these geothermometers, it is also envisaged to develop isotopic tools (δ^7Li, $\delta^{11}B$ and $\delta^{18}O_{H2O-SO4}$) to estimate the temperature of geothermal fluids discharged from the crystalline basement at low temperature.

A 3D stress field model for Munich/Germany

Moritz Ziegler[1,2], Oliver Heidbach[1] and John Reinecker[3]

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In the Northern Alpine Foreland Molasse large geothermal resources are available. Water from the Malm formation is already used for district heating, balneologic purposes, and for electric power generation. In the share of geothermal energy within the next years shall be increased significantly as a part of a 9bn € investment to entirely supply the city by renewable energies. In addition to a detailed knowledge of the subsurface structure this project requires a comprehensive understanding of the stress state. However, only few stress data are available in this area. For a continuous description of the 3D stress state geomechanical-numerical modelling is inevitable. We present an integrated approach for a calibrated 3D-geomechanical-numerical model of the stress state in the Bavarian Molasse basin in the Munich area (70x70x10 km^3). We follow the procedure proposed by Reiter & Heidbach (2014) which uses a regional and a local model. The regional model is calibrated with stress orientations and magnitude mainly from borehole data and provides the boundary conditions for a local model. The local model contains a significantly higher resolution representation of the subsurface geometry around boreholes of a projected power plant. This approach using two models is an alternative to the required trade-off between resolution, computational cost and calibration data which is inevitable for a single model. The incorporated regional 3D geological model contains the topography from a digital elevation model and 6 stratigraphic units with different elasto-plastic rock properties. To constrain the initial and boundary conditions for this base model we use the orientations of maximum horizontal stress (SHmax), the stress regime information, and the magnitudes of the minimum horizontal stress (Shmin) derived from leak-off tests. The local model contains high resolution topography and four different stratigraphic units constrained by a high resolution 3D seismic survey. In addition the anticipated borehole paths to a planned geothermal site in Bernried and the areas around the planned open-hole sections are discretised with a significantly higher resolution compared to the regional model. We successfully calibrated the regional model with stress data available in the model area. The validity of the prevailing stress state in the vicinity of Munich is controlled by several additional stress data which were not used for calibration. The 3D stress state from the regional model is successfully implemented in the local model. It provides stress paths along the planned boreholes and the stress state on fault surfaces within the reservoir.

Day 2

Session 2.1

Process and Properties in Magmatic Systems

(Chair: Gudmundur Ómar Fridleifsson, HS Orka hf)

Introduction to the programme of the day and its implication for IMAGE and SP2

Gylfi Páll Hersir[1]

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IMAGE (Integrated Methods for Advanced Geothermal Exploration) is a four years research project which began in November 2013 and is funded by the European Community's Seventh Framework Programme. The main idea is to address the problems encountered in geothermal exploration and reservoir assessment through a three-step methodological approach. In IMAGE, these are adapted to specific geological environments with the basic subdivision into magmatic systems (subproject, SP2) and basement/sedimentary systems (subproject, SP3). The three-step methodological approach within subproject, SP2 consists of the following: **(1)** Provide basic information and understanding of the physical and geological properties of high temperature geothermal systems and the processes that control these in order to design and develop proper exploration methods and interpret the results in geothermal terms with interdisciplinary approach. In IMAGE this has been accomplished through field work and rock sampling in the fossil and exhumed geothermal systems in Elba Island, Italy and Geitafell, SE-Iceland (through core drilling). Their geological units and tectonic setting analogous to the active geothermal system to be exploited has been exposed, and the result compared with the study of active geothermal systems. In the opening session, a talk explaining some of the results was given by Liotta (UniBari): *Understanding of magmatic geothermal systems from studies of exhumed systems in continental and oceanic settings.* Rock/fluid interaction at supercritical conditions and the physical properties of rock at reservoir conditions have been studied as well. The interaction will be discussed by Ruggieri (CNR): *Fluid-rock interaction experiments to investigate super-hot geothermal reservoirs,* while there are three talks on the properties of rocks: *Permeability and electrical conductivity of Icelandic deep geothermal reservoirs: HT-HP experiments,* given by Nono (UMontpellier 2), *Physical properties of fluids and rocks at simulated near- and supercritical conditions*, given by Kummerow (GFZ) and finally, *Assessing the sensitivity of exploration techniques by a quantitative link between chemical properties of fluid/rock and electrical resistivity,* given by Weisenberger (ÍSOR) .**(2)** Develop novel geophysical exploration methods for magmatic environments to detect, prior to drilling, zones of high permeability, steam and magma and to estimate reservoir temperature. In IMAGE, this was accomplished through the deployment of a dense network of seismic stations on- and off-shore the Reykjanes high temperature geothermal field, SW-Iceland. Data were collected for one and a half year and are being processed and interpreted – the best approaches for exploration of magmatic geothermal fields will be defined. A fibre optic cable was set-up to obtain high resolution seismic image of the geothermal reservoir and compared with the more conventional seismic technology. This part of SP2 is discussed in three talks: *Passive seismic data acquisition on and around the Reykjanes peninsula, Iceland,* given by Blanck (ÍSOR); *Seismic velocity models in Reykjanes, SW Iceland: preliminary results from on-land stations,* given by Jousset (GFZ) and finally, *Distributed Acoustic Sensing Technology in Magmatic Geothermal Areas – First Results*, given by Reinsch (GFZ). Tracers for supercritical conditions have been investigated and will be tested. VSP borehole experiment was carried out in Krafla, NE-Iceland (*Seismic Imaging of High-Temperature Geothermal Reservoirs in Basaltic Rocks in the Krafla Area, Iceland,* a talk given by Planke (VBPR)) ; crustal stress and fracture permeability was estimated (*The stress pattern of Iceland*, a talk given by *Ziegler* (GFZ)) and deep structures will be imaged with electrical resistivity (*Imaging deep structures of the Larderello geothermal field (Italy) by electrical resistivity measurements: The IMAGE experiment*, a talk given by *Rizzo (CNR))*. **(3)** Integrate information and results obtained in IMAGE to develop solid methodology for exploration and assessment for high temperature geothermal fields in magmatic environment. Test the workflow for a 3D model representation and visualization of two existing brownfields; in Krafla, NE-Iceland and Larderello, Italy and apply the workflow in two greenfields; in Pico Alto, Azores (magmatic system) and Reykjanes, SW-Iceland (where supercritical fluids are to be expected). This part of SP2 will be covered by two talks: *3D Geothermal favorability: An analytical approach to data integration,* given by Manzella (CNR) and *Conceptual model of the Krafla high temperature area in N-Iceland - A learning experience,* a talk given by Helgadóttir (ISOR).

Fluid-rock interaction experiments to investigate super-hot geothermal reservoirs

Giovanni Ruggieri[1], Andrea Orlando[1], Laura Chiarantini[1], Giordano Montegrossi[1], Valentina Rimondi[1], Daniele Borrini[2] and Tobias B. Weisenberger[3]

[1]CNR-IGG, Firenze, I; [2]Università di Firenze, I; [3]ÍSOR, Iceland GeoSurvey, Reykjavík, IS.

Understanding super-hot (>370°C) geothermal reservoirs is a major challenge in the future exploitation of geothermal energy. This is also one of the main targets of the Integrated Methods for Advanced Geothermal Exploration (IMAGE) project. The approach of the IMAGE project to this task is to obtain information on super-hot geothermal systems from the study of two exhumed geothermal systems considered to represent proxies of two different active geothermal areas: 1) Eastern Elba Island (Italy) hydrothermal system, characterized by quartz-tourmaline veins and masses within Mt. Calamita micaschists and 2) Geitafell (Iceland) basaltic hydrothermal system, characterized by a contact-metamorphic event overprinted by a lower-temperature hydrothermal stage. The first is assumed to represent a proxy of a super-hot reservoir present below the exploited Larderello-Travale geothermal reservoir, whereas the second is considered to resemble the supercritical reservoir that might be present within contact-metamorphic aureolas below exploited Icelandic geothermal reservoirs. Fluid-rock interaction experiments have been carried out to get information about the physical-chemical processes within the high-temperature geothermal systems; this information may help to design and develop proper exploration and exploitation methods in these extreme environments. Experiments were performed using sealed gold capsules in an externally heated pressure vessel for ~1 week duration. Besides, some experiments were planned in order to extract and analyse the liquid phase at the end of the experiments. The aim of the experiments on Mt. Calamita micaschist from Elba Island was to reproduce the reactions that produced the observed tourmaline-rich hydrothermal rocks. To this purpose, the experiments have been carried out by reacting Mt. Calamita micaschist with H_3BO_3-rich (up to 3 mol/kg) fluids of variable salinities (0-20 wt.% NaCl), temperature (500-600 °C) and pressure (100-130 MPa). Experimental results indicate that tourmaline can easily precipitate and that biotite is the major supplier of the elements. In addition, the dissolution of plagioclase provides Na for tourmaline crystallization. Chamosite in the micaschists disappears after the experimental runs but its role in tourmaline formation is probably marginal. The interaction process is associated with fluid enrichment in K and Fe when saline fluids were used as fluid reactant. Our results prove that interaction between a micaschist with a B-rich fluid, exsolved from acidic intrusion (similar to that presumably present below the Larderello-Travale exploited geothermal reservoir) caused extensive tourmalinization. This conclusion is supported by tourmaline-rich fragments erupted from San Pompeo 2 geothermal well, which encountered a deep high-temperature pressurized fluid. Thus, the finding of tourmaline-rich rocks during drilling could suggest the approaching of the drilling to the super-hot reservoir. Such a reservoir may contain B-rich, saline fluids with a high content of metals (in particular Fe). To model the Geitafell hydrothermal system, experiments have been carried out between 400 and 600 °C, at50 MPa by reacting a representative fresh basalt from Eyjafjallajökull volcano with: 1) water or 2) an aqueous solution of HCl (pH=3) or 3) the same aqueous solution of HCl plus $Ag_2C_2O_4$ so that its decomposition assure a CO_2 molality of about 0.2 in the fluid. Experiment conducted at 400 °C produced a palagonitization, whereas precipitation of scapolite, Na-rich plagioclase, and actinolite was detected mainly at higher temperatures (500-600 °C). The formation of the latter two phases is in agreement with their occurrence in natural samples from Geitafell contact-metamorphic aureole. However, other minerals occurring in this aureole (i.e. augite, hedenbergite, garnet etc.) were not found after the experiments. This may relate to kinetic reasons and/or to the experimental temperature that may have not reached the stability fields of these phases. The liquid after the experiments disclose significant S content likely derived from the alteration of S-bearing basaltic glass suggesting that sulphur in geothermal reservoir within Icelandic basalts may not be only produced from magma degassing.

Permeability and electrical conductivity of Icelandic deep geothermal reservoirs: HT-HP experiments

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Although the Icelandic geothermal system has been intensively investigated over the years, targeting increasingly deeper reservoirs (i.e. under supercritical conditions) requires a good knowledge of the behaviour of physical properties of the host rock types at high temperatures and pressures. Up to this date, there is only very limited data available on this topic, especially for magmatic rocks, which is attributed to difficulty to access these extreme conditions at laboratory scales. In this study, we investigate permeability and electrical conductivity behaviours at elevated T and P conditions (100°C < T < 800°C and P up to 120 MPa) of drilled samples from the Reykjanes Peninsula (holes RN17B_hyaloclastites, RN19-RN30_dolerites), the Nesjavellir (holes NJ17_Basalts, NJ17B_hyaloclastites) and the Ölkelduháls (holes ÖJ-1_hyaloclastites) geothermal fields. We performed permeability and electrical conductivity measurements at deep conditions with a good accuracy using a Paterson press. We have observed a significant decrease of permeability with effective pressure for the micro-fissural samples (dolerites) when compared to the generally inter-granular hyaloclastites. The decrease is about 1 to 2 order of magnitudes for the dolerites, ranging from about 10µD to 0.01 µD for RN-19 and from 0.1µD to 0.01 µD for RN-30 while the effective pressure increases from 10 MPa to 120 MPa, respectively. We related this behaviour of rapid decrease of permeability to the closure of micro-cracks at low effective pressures. This effect is not reversible when the effective pressure is re-decreased. On the other hand, effective pressure seems to sparsely affect the permeability of hyaloclastites, having permeabilities close to 1µD, 0.1mD, and 1mD for NJ-17B, ÖJ-1 and RN-17B, respectively. Log (k) varies linearly with the effective pressure with very low hysteresis. At high temperature, permeability decreases with increasing temperature. However, some samples (dolerite RN19) displayed a reproductive increase by about two order of magnitude from 10^{-2}µD to 1µD between 200°C and 300°C. At 500°C, we are also observing a time dependent behaviour for NJ-17B (hyaloclastite), showing a decrease of permeability from 10µD to 1µD over a time span of one hour. Important changes in microstructures, such a pore collapse, fracture sealing, or thermal cracking, can be invoked to explain such behaviours. Electrical conductivity of these samples have been measured in dry conditions and as a function of temperature. The logarithm of electrical conductivity increases linearly with temperature up to 400-500°C, then an increase in the slope is observed at higher temperatures. Temperature cycles have been performed systematically. They show for most of the samples irreversible changes when temperatures exceed 500°C. These changes are interpreted as destabilization/dehydration of alteration minerals that could lead to the presence of a conductive fluid phase in the samples.

Physical properties of fluids and rocks at simulated near- and supercritical conditions

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The growing interest in exploiting supercritical geothermal reservoirs calls for a thorough identification and understanding of physico-chemical processes occuring in geological settings with a high heat flow. In reservoir engineering, electrical resistivity tomography (ERT) is a common geophysical exploration and monitoring strategy. However, a realistic interpretation of field measurements is based on the knowledge of both, the physical properties of the rock and those of the interacting fluid at defined temperature and pressure conditions. Thus, laboratory studies at simulated in-situ conditions provide a link between the field data and the material properties in the depth. The physico-chemical properties of fluids change dramatically above the critical point, which is for pure water 374.21°C and 221.2 bar. In supercritical fluids mass transfer and diffusion-controlled chemical reactions are enhanced and cause mineral alterations. Also, ion mobility and ion concentration are affected by the change of physical state. All this cause changes in the electrical resistivity of supercritical fluids and may have considerable effects on the porosity and hydraulic properties of the rocks they are in contact with. While there are some datasets available for physical and chemical properties of water and single component salt solutions above their critical points, there exist nearly no data for electrical properties of mixed brines, representing the composition of natural geothermal fluids. Also, the impact of fluid-rock interactions on the electrical properties of multicomponent fluids in a supercritical region is scarcely investigated. For a better understanding of fluid-driven processes in geological settings with a high heat flow, in the framework of IMAGE we have constructed and tested two experimental set-ups to measure the temperature dependence of (1) the electrical resistivity of geothermal fluids and (2) physical properties of potential reservoir rock samples saturated with the fluid. The permeability and electrical resistivity of a quartz-gabbro from a fossil hydrothermal system on Iceland were determined between 25 – 350°C at a controlled pore pressure of 22.2 MPa. The measured resistivities are correlated with resistivity data obtained in the fluid measuring cell for a synthetic brine that mimics the composition of Icelandic Krafla geothermal fluid. Additionally, fluid samples were taken at every temperature step for chemical analyses. Both physical and chemical data indicate only slight fluid-rock interactions, which is due to the low permeability of the studied rock sample and the limited contact area between fluid and rock.

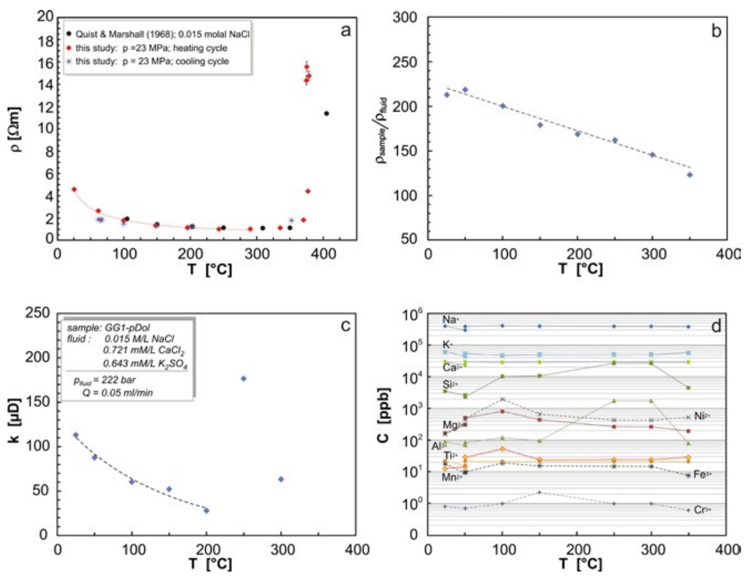

Fig. (a) Electrical resistivity of a synthetic Krafla fluid in dependence of temperature. For comparison, resistivity data of Quist and Marshall (1968) for a 0.015 molal NaCl solution along the 222 bar isobar are plotted. **(b)** The ratio of sample (quartz-gabbro) and fluid resistivities vs. temperature. **(c)** Permeability of the quartz-gabbro sample from Geitafell/ Iceland measured as function of temperature. **(d)** cation concentration analysed in percolated fluid sample.

Assessing the sensitivity of exploration techniques by a quantitative link between chemical properties of fluid/rock and electrical resistivity

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Resistivity models based on TEM (Transient Electro Magnetic) and MT (Magneto Telluric) soundings are widely used in geothermal exploration to select sites for exploration drilling. Árnason et al. (1987a, b) showed that the structure of the resistivity model within the Nesjavellir high-temperature field in SW Iceland mimic the dominant alteration mineralogy conditions in the subsurface. Thereby the typical observed boundary between the low resistivity cap and the underlying resistive core in high temperature systems could be related to change in secondary minerals having different cation exchange capacity (CEC), i.e. from smectite dominated cap rock to chlorite dominated core (Árnason and Flóvenz 1992). Alteration minerals with a high CEC favour the conduction of an electrical current between the pore fluid and the pore walls in the rock. This interface or surface conduction is caused by the highly mobile ions that form a conductive layer on the surface of the pore walls. The mobility of ions is thereby related to the CEC of the mineral phase. The higher the CEC the higher is the interface conduction. Nevertheless electrical conductivity can also be affected by other parameters: (i) degree of fluid saturation, (ii) conductivity of the rock matrix, (iii) salinity of the pore fluid, (iv) water–rock interaction and alteration mineral assemblage, (v) temperature, (vi) porosity and pore structure of the rock, and (vii) type of pore fluid like the content of water, steam, gas, and oil (Flóvenz et al. 2012). The aim of this task within the Integrated Methods for Advanced Geothermal Exploration (IMAGE) project is to assess the sensitivity of exploration techniques by a quantitative link between chemical properties of fluid/rock and electrical resistivity. The 2215 m deep well KJ-18 from the Krafla high-temperature geothermal field in NE-Iceland was selected. Several resistivity logs have been carried out in well KJ-18, including resistivity time series during the heating of the well. The CEC is measured on drill cuttings. Thereby the CEC is a direct proxy of the degree and type of alteration of the volcanic rocks. Rock sampled within the smectite alteration zone yields the highest CEC, whereas rocks within the chlorite zone or even epidote-actinolite zone result in a significant lower CEC and corresponding lower conductivity. The CEC, resistivity logs and temperature profile are compared to quantify the degree of physical and chemical parameters that control the electrical conductivity. This allows to quantify the direct influence of each of those parameters on the electric resistivity The recent CEC measurements from well KJ-18 and their correlation to other physical parameters will be presented at the mid-term conference in Pisa.

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Session 2.2

Passive and Active Seismic in Magmatic Systems

(Chair: Adele Manzella, CNR-IGG)

Imaging and monitoring of subsurface structures using reflections retrieved from seismic interferometry

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The seismic-reflection method with body waves is the most frequently used exploration method for imaging and monitoring subsurface structures with high resolution. It has proven its qualities from the scale of regional seismology to the scale of near-surface applications that look just a few meters below the surface. The seismic-reflection method makes use of controlled active sources at known positions to generate propagating body waves that are recorded at known receiver positions. The two-wave travel information of the recorded reflections is used to extract desired subsurface information about a structure, for example a geothermal reservoir.

When obtaining information of a subsurface structure is required on a frequent basis, like for example in monitoring of geothermal reservoirs, utilization of controlled active sources might be costly. Because of that, optimal use of the data they generate is required to effectively reduce their cost. The active sources would provide desired information, but they cannot be used continuously for monitoring purposes. Furthermore, when used again after some time, the seismic conditions of the near surface might have changed, which might lead to lower resolution of the seismic results. All this issues could be addressed by different applications of seismic interferometry.

Seismic interferometry is a method that retrieves new seismic responses from the correlation, coherence, convolution, or deconvolution of existing responses (Schuster, 2001; Wapenaar et al., 2002; Campillo & Paul, 2003; Schuster et al. 2004; Snieder, 2004; Wapenaar, 2004). For this, one can make use of recordings from controlled active sources, passive sources – microseismicity, earthquakes, ambient seismic noise.

A very promising application of seismic interferometry for geothermal applications is for retrieval of the reflection response between receivers at the surface from passive recordings (Fig. 1) from subsurface sources. The passive sources might be connected to the activity of a subsurface reservoir or unrelated to it.

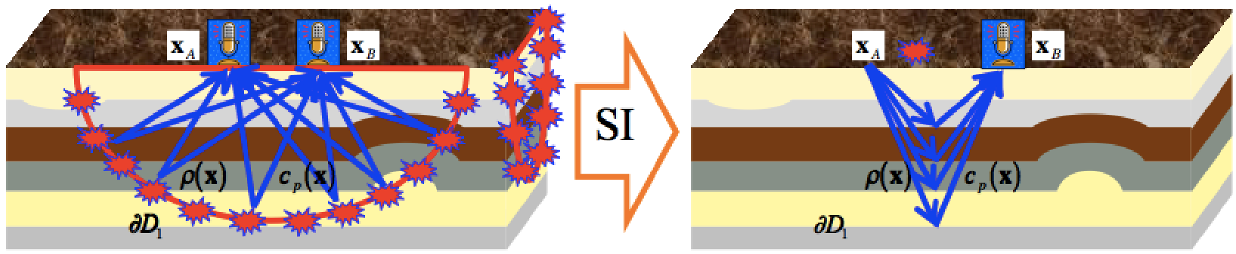

Fig. 1: (left) Recordings at two receiver positions from subsurface sources, acting separately in time or overlapping in time. Using seismic interferometry (SI) these recordings can be used to retrieve the reflection response at one of the receivers as if the other receivers were a source **(right).** The retrieved source is also labeled as virtual sources.

Fig. 2: (left) shows the pseudo-3D image of the subsurface obtained below a 2D patch of surface seismic recorders along eight parallel lines. The survey was carried out in Libya and recorded ambient seismic noise for about 11 hours along (Draganov et al., 2009; 2013). The ambient noise was preprocessed to enhance retrieval of body-wave reflections. After that, seismic interferometry by cross-correlation was applied to retrieve the reflection response between virtual sources and receivers along each of the lines. The retrieved recordings were processed per line to obtain an image of the subsurface below each line. The images from the separate lines were interpolated to obtain the pseudo-3D image. The purpose of this field application was to test the applicability of seismic interferometry with ambient noise for exploration imaging.

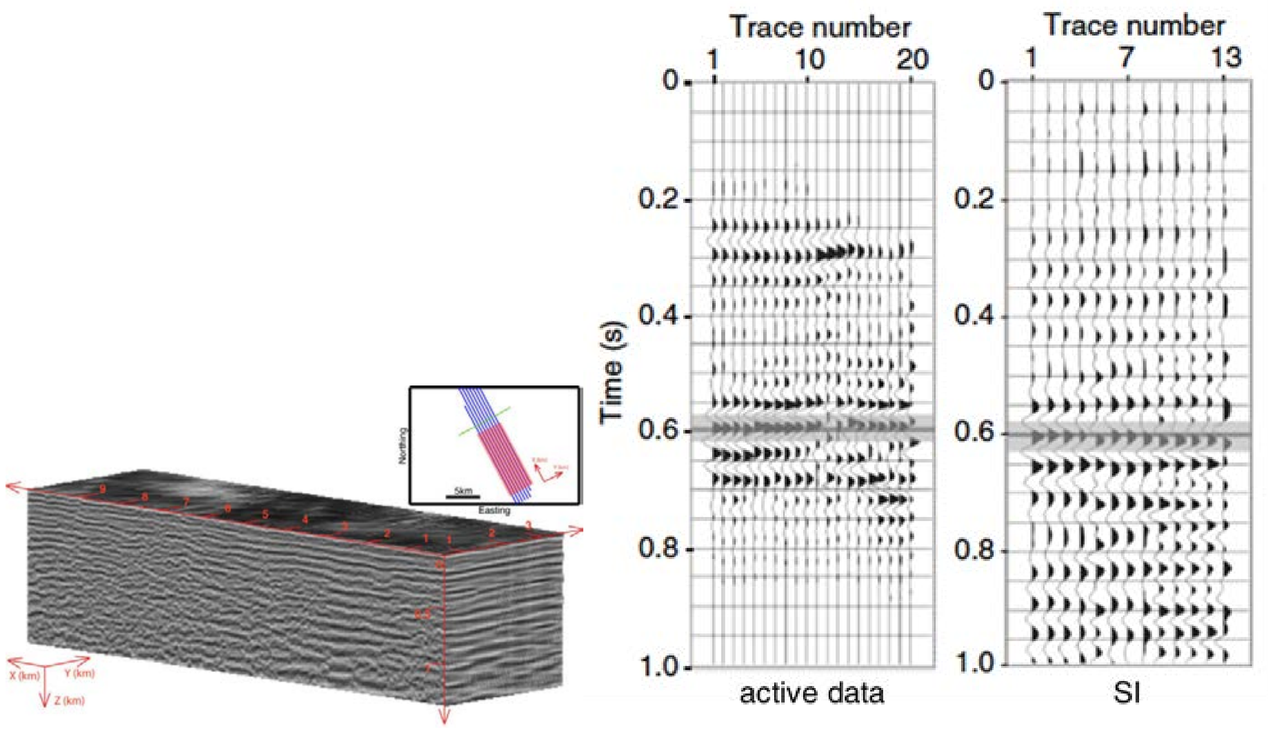

Fig. 2: (left) Image of the subsurface down to about 1.5 km below the red part of eight survey lines (see the inset) that recorded about 11 hours of ambient noise. The image was obtained from reflections retrieved from seismic interferometry. (right) Ketzin stacked section obtained from active source at the surface compared with the result retrieve from seismic interferometry by autocorrelation applied to ambient noise (modified from Boullenger et al., 2015). The gray line indicated the expected arrival from the K2 marker reflector.

Fig. 2: (right) shows the result of application of seismic interferometry with ambient noise for monitoring of CO_2 sequestration (Boullenger et al., 2015). The ambient-noise data was recorded at the Ketzin test site, Germany. The continuous recording at the site started after the CO_2 front passed the passive array. The array was composed of 13 four-component recorders buried at a depth of 50 m and forming a line. Because the total length of the array is 120 m and because the target is at about 800 m depth, here seismic interferometry was applied using autocorrelation with the goal to retrieve the zero-offset reflection response at each receiver from a coinciding with it virtual source. In total, one day of noise was used. The retrieved result clearly shows the tuned reflections from the marker K2 reflector (gray), which forms the top of the reservoir formation (on average 80 m thick). For comparison, also a stacked section is shown, which was obtained using recordings from active sources at the surface.

Because the passive recordings started only after the CO_2 front passed the array, a real monitoring experiment could not be conduced. Instead, Boullenger et al. (2015) carried out numerical-modelling feasibility study for detecting changes due to CO_2 injection at Ketzin. The response to ambient-noise sources, confined below the reservoir, was modelled before injection and after injection. Seismic interferometry by autocorrelation was applied to both modelled datasets for retrieval of the zero-offset reflection response. Taking the difference of the two retrieved results showed clear amplitude changes of the reflection signals at the reservoir level.

The above two examples show the feasibility of using ambient noise for imaging and monitoring subsurface reservoirs. But also active-source recordings from surface sources could be used with seismic interferometry for monitoring purposes. Such application is very useful for describing layer-specific changes of velocity at the reservoir and cap-rock layer, for example (Draganov et al., 2012).

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Triggered earthquakes suppressed by an evolving stress shadow from a propagating dyke; Bárðarbunga volcano, Iceland

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Large earthquakes can generate small changes in static stress: increases that trigger aftershock swarms, or reductions that create a region of reduced seismicity—a stress shadow. However, seismic waves from large earthquakes also cause transient dynamic stresses that may trigger seismicity. This makes it difficult to separate the relative influence of static and dynamic stress changes on aftershocks. Dyke intrusions do not generate dynamic stresses, so provide an unambiguous test of the stress shadow hypothesis. Here we use GPS and seismic data to reconstruct the intrusion of an igneous dyke that is 46 km long and 5m wide beneath Bárðarbunga Volcano, central Iceland, in August 2014. Locations of earthquakes focussed at the leading edge of the dyke map out its northward segmented propagation in short rapid bursts. Combining this with daily GPS solutions we construct a time-dependant model of dyke opening. We find (Green et al. NatGeosci 2015) that during dyke emplacement, bursts of seismicity in volcanic geothermal fields at a distance of 5 to 15 km were first triggered and then abruptly switched off as the dyke tip propagated away from the volcano. We calculate the evolving static stress changes during dyke propagation and show that the stressing rate controls both the triggering and then suppression of earthquake rates in three separate areas adjacent to the dyke. Our results imply that static stress changes help control earthquake clustering. Similar small static stress changes may be important for triggering seismicity near geothermal areas, regions being hydrofractured and deflating oil and gas fields.

Passive seismic data acquisition on and around the Reykjanes peninsula, Iceland

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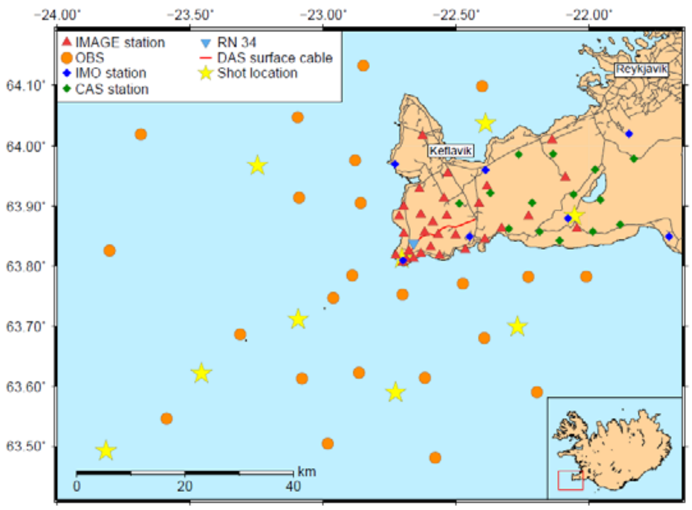
From April 2014 until August 2015 a dense network of seismic stations was deployed on Reykjanes peninsula, SW-Iceland, and off-shore in the Atlantic Ocean surrounding it. The setup of the network was designed to monitor the seismic activity along the Mid-Ocean Ridge to image the Reykjanes geothermal system located at the tip of the peninsula. The processing and interpretation of the data has started and preliminary results obtained. The deployment and the subsequent processing and interpretation of the data are a part of IMAGE, carried out by GFZ, ISOR, TNO and HS Orka, the industrial partner that runs a couple of power plants on the Reykjanes peninsula. The IMAGE on-land network consisted of 20 Broadband and 10 Short Period seismometers which were set up on-shore Reykjanes in March and April 2014 by GFZ and ISOR in cooperation with HS Orka. They were placed at the open end at the bottom of a barrel, buried at the depth of some 60 to 80 cm on solid rock. This was done to protect the seismometers from wind and bad weather and at the same time assuring a good coupling to the ground. During the data acquisition these stations were visited every two months. The batteries were replaced and the data downloaded. The exact location of the seismometers was determined with a differential GPS and their orientation was measured with a gyrocompass which uses the rotation of the earth. In August 2014, 24 Ocean Bottom Seismometers (OBSs) were deployed in the Atlantic Ocean around the peninsula by the Alfred Wegener Institute (AWI) together with ISOR and GFZ. The OBSs completed the layout of the network which was designed as concentric circles around the Reykjanes geothermal system at the tip of the peninsula. Additionally, IMAGE has access to other seismic networks in the area. The Iceland Meteorological Office (IMO) runs 7 seismic stations on the peninsula, the Institute of Geophysics of the Czech Academy of Sciences (CAS) 15 stations and another 8 stations are operated by ÍSOR on behalf of HS Orka. In early 2015 the network was temporary enlarged by 150 3-component geophones which were made available by GFZ. In this period the DAS (Digital Acoustic Sensing) cable experiment was carried out. One cable was installed in the casing of the new RN-34 well. It reaches down to a depth of about 175 m. A second cable that connects the two geothermal areas Reykjanes and Svartsengi was also used for recordings. It is about 15 km long, is used for telecommunication and was made available by the Míla company. With those two cables seismic waves were recorded for nine days, the data acquisition was executed by the Silixa company. To locate the channels of the surface fiber precisely, 34 of the 150 geophones were placed along the cable. Hammer seismic shots were carried out at the geophone locations to compare the distance along the cable given from the acquisition tool with the real distances. Explosions were performed both on- and off-shore to calibrate the network and to obtain information on the orientation of the OBSs. Two on-land shots of different size were placed in Lake Grænavatn in the east of the peninsula, another shot was executed in a borehole at the tip of Reykjanes peninsula at the west end of the surface cable. While the cables were recording four off-shore shots were carried out around the peninsula, another three shots were executed later to increase the angle coverage for the orientation of the OBS. In August 2015 both the on-land stations and the OBSs were retrieved. After finishing the acquisition phase, the focus lies now on the more advanced processing techniques and interpretation.



Seismic velocity models in Reykjanes, SW Iceland: preliminary results from on-land stations

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Analogue outcrops of hydrothermal fossil systems, simulating pressure/temperature conditions in the laboratory are classical methods for assessing supercritical conditions in magmatic environments. Prior to scientific drilling, our understanding of structural and dynamic characteristics of geothermal systems can be improved through application of advanced and/or innovative exploration technologies. Unlike resistivity imaging, active and passive seismic techniques have rarely been used in volcanic geothermal areas, because processing techniques were not adapted to geothermal conditions. Recent advances in volcano-seismology have introduced new processing techniques for assessing subsurface structures and controls on fluid flow in geothermal systems. We present here preliminary analyses of seismic records around a geothermal reservoir located both on-land and offshore along the Medio-Oceanic Ridge and Reykjanes, SW-Iceland. We deployed a network of 234 seismic stations (including 24 Ocean Bottom Seismometers), between April 2014 and August. We analyse about a year of part of those records. For example, OBS data is under process: in order to properly orientate the OBS stations, we used Rayleigh wave's planar particle motions from large magnitude earthquakes. We checked this method with a gyro-compass at seismometers on-land. We obtained first 3D velocity images from local earthquakes travel time tomography, using on-land stations. The processing includes first arrival picking of P- and S- phases using an automatic detection and picking technique based on Akaike Information Criteria. We locate earthquakes by using a non-linear localization technique, as *a priori* information for deriving a 1D velocity model. Our model is similar to previous models obtained in the area. We then inverted 3D velocity model by joint inversion of earthquakes location and velocity anomalies with respect to the 1D model. We discuss the results after selecting carefully earthquakes, with respect to the network. We also performed ambient noise cross-correlation techniques in order to derive a velocity model, especially when earthquakes did not occur. We present first images. Preliminary results reveal a high velocity anomaly under the tip of the Reykjanes, where the geothermal field is exploited. OBS data will allow us to image the extension of this anomaly at sea.

Distributed Acoustic Sensing Technology in Magmatic Geothermal Areas – First Results

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Seismic methods are particularly suited for investigating Earth subsurface. Compared to measurements from the surface, wellbore measurements can be used to acquire more detailed information about rock properties and possible fluid pathways within a geothermal reservoir. For high temperature geothermal wells, however, ambient temperatures are often far above the operating temperature range of conventional geophones. One way to overcome this limitation is the application of fiber optic sensor systems, where only the passive optical fiber is subjected to downhole conditions. Their applicability is thus determined by the operating temperature range of the optical fiber. Choosing appropriate fibers, such sensor systems can be operated at temperatures far above 200°C. Along an optical fiber, the distributed acoustic sensing technology (DAS) can be used to acquire acoustic signals with a high spatial and temporal resolution. Previous experiments have shown that the DAS technology is well suited for active seismic measurements (e.g. Daley et al. 2013). Within the framework of the IMAGE project, a fiber optic cable was set up within a newly drilled geothermal well (RN-34) within the Reykjanes geothermal field, Iceland. Additionally, a 15.3 km fiber optic cable already available at the surface was connected to a DAS read-out unit. Acoustic data was acquired continuously for 9 days. Hammer shots were performed at the wellhead as well as along the surface cable in order to locate individual acoustic traces and calibrate the spatial distribution of the acoustic information. During the monitoring period both signals from on- and offshore explosive sources and natural seismic events could be recorded. We compare the fiber optic data to conventional seismic records from a dense seismic network deployed on the Reykjanes in the course of the IMAGE project (Fig. 1). First results will be presented.

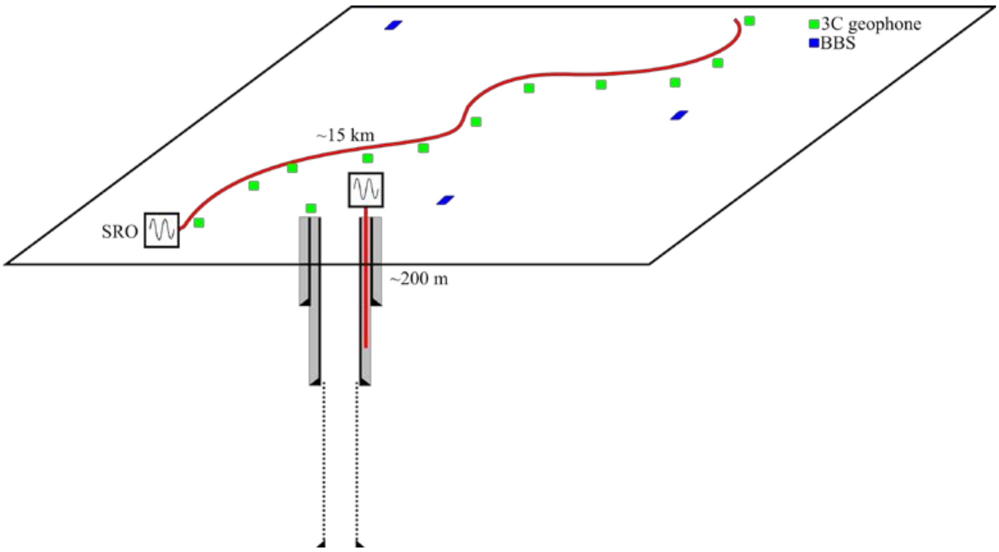

Fig.1: Experimental set-up for the DAS acquisition on the Reykjanes peninsula.

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Seismic Imaging of High-Temperature Geothermal Reservoirs in Basaltic Rocks in the Krafla Area, Iceland

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The Krafla geothermal region in northern Iceland comprises one of the best studied examples of a high-temperature geothermal field within an active volcanic rift zone. Vertical seismic profiling (VSP) data were acquired in borehole K-18 in the Krafla geothermal field in 2014 as a part of the IMAGE project. The primary objective of this sub-project was to assess the applicability of VSP surveying as a method for sub-surface mapping in volcanic geothermal fields including zones of magma, supercritical fluid, superheated steam and high permeability. A secondary objective was to test the complementary use of micro-earthquakes and noise recorded by surface network and well bore recording to image the subsurface. We have completed an integrated study of the downhole volcanic stratigraphy from well K-18 based on both new and existing data. The initial processing of the zero-offset VSP data show that the data quality is generally good, with a useful frequency bandwidth of about 5-40 Hz. Additional newly acquired sonic and televiewer log data were analyzed in conjunction with existing wireline data (gamma, resistivity, neutron porosity and caliper) and new ditch cuttings analysis. The quality of ditch cuttings from the K-18 well was in general very good, and allowed the identification of a wide range of primary volcanic textures. These include systematically differing proportions of vesicular, fresh to altered glass and crystalline basalt along with distinct intervals of aggregated pumice shards and volcaniclastic units. Alteration increases significantly, but non-uniformly, with depth. Due to casing down to 663 m, no sonic log data were available for the upper part of the well. The quality of the sonic and VSP logs for the rest of the well is generally very good, in contrast to the televiewer log, which gave generally poor results for the majority of the borehole. Interval velocity histograms, wireline log traces, cross plots and average interval VSP velocities have been used in conjunction with the old log data to define six main log units. The new velocity data provide important statistics on the petrophysical properties of the volcanic facies encountered within the well. The velocity data demonstrate clearly that the high gamma intervals near the base of the well are unlikely to be intrusions but confirm the dominantly intruded nature of much of the lower three quarters of the well.

Session 2.3

Exploration and Integration of Magmatic Systems

(Chair: Ásgrímur Gudmundsson, Landsvirkjun)

3-D Full-tensor Magnetotelluric Analysis of Coso Geothermal Field

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Previous analysis of 100+ magnetotelluric (MT) soundings from the Coso Geothermal Field, CA revealed important correlations with known fault locations, injection and production well intervals, and zones of drilling losses (Newman et al., 2008). However, this three dimensional inverse modeling effort considered only the off-diagonal elements of the impedance tensor, and initialized from interpolated two-dimensional TM results. Phase data in the Zyx component of the impedance tensor exhibited unique out-of-quadrant behavior that could not be reproduced with this inversion workflow. Recent experience modeling resistivity in complex three dimensional environments using MT shows that it is necessary to analyze the full impedance tensor, because analysis using only the principal component tensor data (i.e., the off-diagonal components) can produce artifacts in the imaging process. Here we show how full-tensor three-dimensional inversion, initializing from a homogeneous 30 Ohm m half-space, retrieves a better-fitting model than previous work, and in particular is able to explain the anomalous Zyx phase trend. Furthermore, this result does not make simplifying assumptions about dimensionality and directionality of the Earth. In complex three-dimensional (3-D) geologies, where many geothermal resources remain undiscovered or obfuscated, electrical resistivity mapping requires large-scale modeling and imaging capabilities, as well as the ability to treat significant data volumes, which can easily overwhelm single-core and modest multicore computing hardware. To treat such problems requires large-scale parallel computational resources, necessary for reducing the time to solution to a time frame acceptable to the exploration process. For over a decade the magnetotellurics (MT) community relied on the existence of constant geologic structure (i.e., a 2-D Earth model) within the area of interest. This assumption reduces the computational burden by eliminating secondary portions of the dataset (i.e., on-diagonal impedance tensor elements). However, in truly complex 3-D settings this assumption is invalid. Recent MT research has explored the trade-offs involved in analyzing full MT impedance tensor data in 3-D inversion, compared with inverting subsets of the data (Patro and Egbert, 2011; Kiyan et al., 2013; Tietze & Ritter, 2013; Newman et al., 2008). One observation of these works is that on-diagonal variances naturally collapse to real errors as on-diagonal element amplitudes approach off-diagonal element amplitudes, rendering full tensor analysis critical. Newman et al. (2008) analyzed MT data from Coso geothermal field. They first inverted Zyx data in 2-D easting profiles, and then interpolated the 2-D results into a 3-D starting model for inversion of the off-diagonal elements. The on-diagonal elements were not included because they significantly slowed the inversion. The present paper analyzes this Coso MT dataset, using the same 3-D inversion code, but considers implications of inverting the full tensor data.

Imaging the deep structures of the Larderello geothermal field (Italy) by electrical resistivity measurements: the IMAGE experiment.

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In this research we are developing an integrated method for exploring deep geothermal systems based on electrical resistivity surveys at surface and at depth and integrated modelling in the Larderello test site. In this area, the oldest field in the world under exploitation for power production, a vapour-dominated system with temperatures exceeding 350°C is exploited from two different reservoirs. Many geological and geophysical data have been acquired in the frame of previous exploration projects but nowadays several critical issues on deep features of the field are still matter of debate, e.g., permeability distribution in the hydrothermal reservoir and the presence of fluids at supercritical condition at depth. Electrical resistivity distribution provides an important contribution to the characterization, however previous survey results left unsolved questions, mainly related to the difficulty to interpret low resistivity anomalies in dry-steam reservoirs. A new detailed MT survey suitable for 3D modelling is planned in the frame of IMAGE Project, to be acquired in the western sector of the Larderello field, covering an area only partially covered by previous MT surveys. In this area heat flow shows the highest values and partial melting condition is supposed to be very shallow. In order to support acquisition of a MT survey in the Larderello field, previous MT data were re- analysed and two-dimensional inversions were performed along E-W profiles crossing the area of interest. Furthermore, the integration of geological, geophysical and well data was performed in Petrel environment (Schlumberger) in order to improve the 2D inversion of MT data by setting a well-constrained a-priori model and to check inversion results supporting the interpretation. The analysis of the data integration confirmed the effects of strong resistivity inhomogeneity at the depth of the crystalline basement, where a resistive behaviour is expected. Similar results have been achieved for the Travale field (eastern part of the Larderello area) in the frame of a previous scientific project I-GET. In order to constrain the resistivity response at the depth of the deep reservoir hosted in the crystalline units, we designed an experimental, high resolution Surface-boreHole Deep Electrical Resistivity Tomography (SHDERT) to be carried out in the area surrounding a borehole accessible thanks to the support of Enel GP. In short, the characteristics of the well are: i) 2.1 km deep, accessible down to 1.6 km; ii) temperature up to 250°C; iii) casing down to 1 km. The proposed experiment represents a challenge for the applied geophysics. The deep electrical resistivity tomography will be obtained by using a dipole-dipole array configuration, with a transmitting station that injects the direct current (5-7 A) into the ground and a multichannel receiver that records the generated voltage signals. Transmitting and receiving electrodes will be aligned using multi-receiver cables, one in-hole and two along profiles as shown in Fig. 1. Several voltage recording from 5 to 20 minutes will be acquired simultaneously for each current injection, using in-hole and surface sensors as transmitter and receiver, and viceversa. The in-hole electrical cable has been designed in order to stand high temperature and is equipped with flexible, metallic electrodes to be located along the openhole portion (1050m-1600m) (Fig. 1). The integration of 3D MT model and experimental DC resistivity measurements will improve the knowledge on the deep structures of the Larderello field.

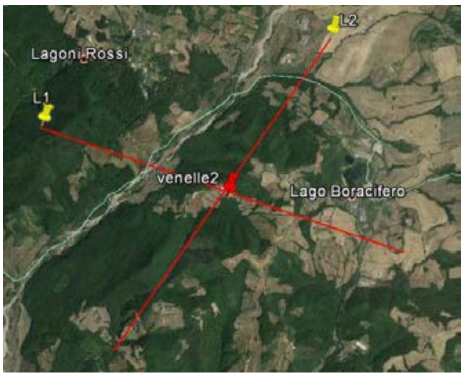

Fig. 1:

(left) Location of L1 and L2 profiles close to the well.

(right) A prototype of the in- hole cable.

The Stress Pattern of Iceland

Moritz Ziegler[1,2], Oliver Heidbach[1], Mojtaba Rajabi[3], Gylfi Páll Hersir[4], Kristján Ágústsson[4], Sigurveig Árnadóttir[4] and Arno Zang[1,2]

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In the framework of the IMAGE project we compiled the first comprehensive stress map of Iceland from different stress indicators and new analyis of data from 51 Icelandic geothermal boreholes. In total we interpreted ~34 km of acoustic image logs for stress indicators, i.e. borehole breakouts and drilling induced tensile fractures. Furthermore we revised the existing 38 data records for Iceland in the World Stress Map and conducted an extensive literature research to compile all available focal mechanism solutions and geological stress indicators. The new stress compilation consists of 444 data records for the orientation of the maximum horizontal stress (S_{Hmax}) in and around Iceland with 307 data records of A-D qualities according to the World Stress Map ranking scheme (Fig. 1). Most of the A-D quality data records are from geological fault inversions (38%) and focal mechanism solutions (27%). Borehole related indicators (breakouts, drilling induced fractures, hydro-fractures) have a share of 14% while data from the alignments of volcanic vents, fissures and craters contribute with 12%. The inversion of several focal mechanism solutions make up 9% of the dataset. The mean orientation of S_{Hmax} is 16° +/- 39° for all A-D quality data. A closer look at subregions reveals four different provinces with fairly consistent S_{Hmax} orientation. They are in the Capital area and Southern Lowlands (mean S_{Hmax} = 38° +/- 29°), the eastern Highlands and Eastfjords (mean S_{Hmax} = 9° +/- 25°), the Tjörnes Fracture Zone and Akureyri (mean S_{Hmax} = 152° +/- 21°), and the Westfjords (mean S_{Hmax} = 137° +/- 17°). This distribution of S_{Hmax} orientations is in agreement with the prevailing structural geology. At the spreading ridges Reykjanes and Kolbeinsey in the South and North respectively an orientation of S_{Hmax} parallel to the plate boundary is observed. The same is observed in the Northern and Eastern Volcanic Zones and it is also indicated by the few indicators associated with the Western Volcanic Zone. In the transform South Iceland Seismic Zone and Tjörnes Fracture Zone which produce Icelands largest earthquakes, S_{Hmax} is at an angle of approximately 20° to 60° to the transform faults which define the plate boundary. A rotation from ridge parallel to the general intraplate ridge normal S_{Hmax} is expected at some distance from the plate boundary. Such a rotation is observed in the Westfjords, NW-Iceland.

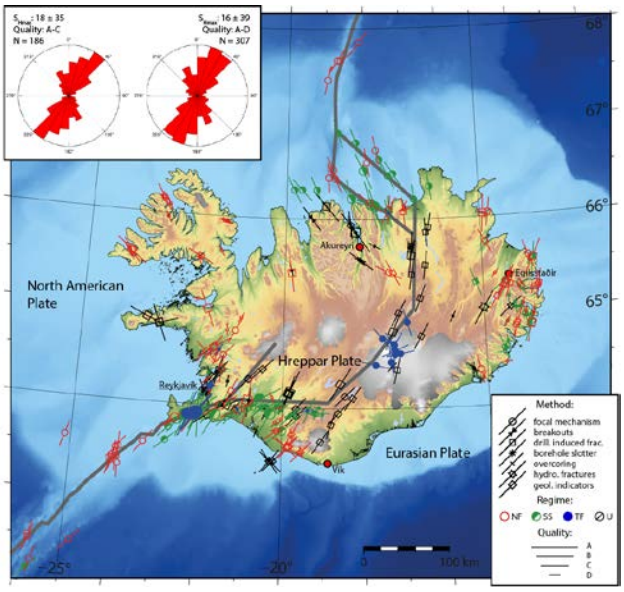

Fig. 2: Stress indicator of quality A-D in Iceland. The lines represent the orientation of S_{Hmax}. Major tectonic features are shown.

3D geothermal favourability: an analytical approach to data integration

Adele Manzella[1] and IMAGE and Geothermal Atlas Team

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The most ambitious target of the IMAGE project is to define and develop integrated approaches for geothermal exploration and assessment. Mapping of geothermal favourability is a way to integrate different data and provides a practical analytical framework for the systematic capture of information relevant to the assessment of geothermal resources. The approach used in the Geothermal Atlas of Southern Italy (GASI), a national project conducted by the Italian National Research Council, is aimed at organizing and integrating subsurface data, and at providing a methodology to establish a hierarchy of geothermal areas based on their potential for conventional and unconventional power production, where conventional refers to exploitation of hydrothermal geothermal resources with natural permeability and unconventional refers to: enhanced geothermal systems (EGS) requiring enhancement of permeability; magmatic systems by exploiting the heat of magmatic intrusions; supercritical systems with reservoir fluids at supercritical conditions. In GASI Geographical Information System (GIS) software provides tools for the spatial analysis of multiple parameters to assist selection of prospective sites, based on pre-defined criteria (Trumpy et al., 2015). The factors facilitating the recovery of exploitable geothermal energy are defined, and their spatial correlation established by GIS models. By prioritizing favourable conditions using an Index Overly method, "favourability" maps are obtained. The maps consider both geological and economic aspects, and energy recovery is considered for current technologies. The approach and maps of GASI are useful for developing and planning regional or national energy policies including geothermal energy. At a concession scale, the same approach may be used in a more refined way, taking advantage of 3D integrated as well as reservoir modelling and producing 3D favourability volumes. To this aim, we are working in IMAGE in order to establish a link among the various "worlds" (geological, geophysical, geochemical, reservoir modelling), attempting an overall resource modelling. See the example shown in Fig. 1.

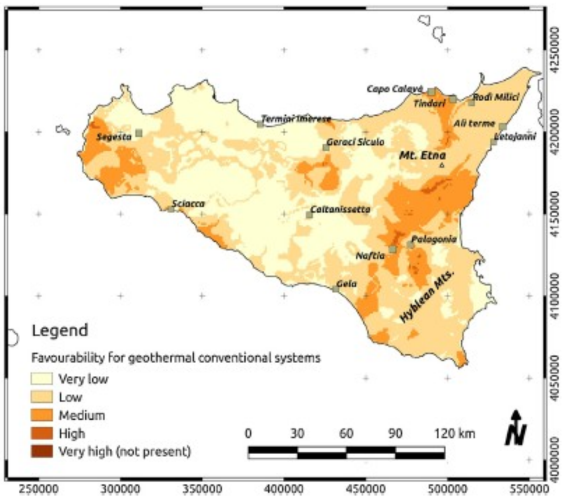

Fig. 1: An example of favourability map produced in GASI.

Reference

Trumpy E., Donato A., Gianelli G., Gola G., Minissale A., Montanari D., Santilano A., Manzella A., 2015. Data integration and favourability maps for exploring geothermal systems in Sicily, southern Italy. Geothermics 56 (2015) 1–16

Conceptual model of the Krafla high temperature area in N-Iceland - A learning experience

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Modelling of the brownfield Krafla high temperature area in NE-Iceland has gone through a few phases since geothermal research began in the field in 1969. The most recent conceptual model was published in 2009. Since then the work has continued and is ongoing. This extensive experience provides the base for a workflow for a 3D model representation and visualization. A workflow which will be applied to the greenfield Pico Alto geothermal field in Terceira in the Azors. ISOR applies the Petrel 3D software to incorporate into the Krafla conceptual model surface data, faults, lithology from a number of wells, alteration zones, formation temperature (from borehole data), aquifers interpreted from temperature logs and circulation losses, resistivity data, gravity and seismic data, pressure changes etc. This has resulted in various 3D models; a geological facies model, a temperature model based on well data, an alteration zones model and a resistivity model. The present conceptual model will be updated as more data will become available. The 3D petrophysical model will be updated with seismic models based on the IMAGE's Vertical Seismic Profile borehole experiments (VSP) done in mid-2014 to test if zones of magma, supercritical fluid, superheated steam and high permeability can be revealed. Past experience has shown that one of the important aspects of the making of conceptual models is the work on the data used. The data needs careful handling and classification. As an example the lithology data comes from various sources, some of the well cuttings may have been analysed more thoroughly than others and the borehole data may have gone through different procedures through the years. One of the first steps of a geothermal conceptual model is to incorporate data from the exploration phase. These data include surface data such as geological mapping (surface geology, faults and fractures, geothermal surface manifestations), aerial images and topography and geophysical data such as resistivity, magnetic and gravity studies and location of micro-earthquakes. Well paths and eventually data from boreholes (cuttings analysis, lithological logs, pressure and temperature logs) need to be incorporated into the conceptual model. These data include lithology (stratigraphy) from each of the well resulting in a geological model; alteration (alteration zones, appearance of temperature dependent alteration minerals) resulting in an alteration model; aquifers in relation to the structural mapping, intrusions and lithological contacts; temperature logs which with time result in a formation temperature model and geophysical logs such as resistivity, neutron-neutron, gamma ray, televiewer etc. Drilling data such as circulation losses should also be added. Petrel has proven to be somewhat problematic when faced with the lithology of an active volcanic zone where rock formations pile up instead of spreading. The software assumes that there are layers with approximately constant thickness. This is not very practical for hyaloclastite units as they form mountains and ridges instead of spreading laterally. At the mid-term conference in Pisa, a conceptual model of the Krafla high temperature area, NE-Iceland will be presented and a workflow that has been constructed and developed and is to be applied in a greenfield area will be demonstrated.

Poster Session II

Magmatic Systems

Analogue modeling set-up and materials: First results and applications to the transversal structures controlling magma upwelling, geothermal fluid flow and recent deformation in the Larderello area

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Previous studies on magma emplacement and the evolution of caldera/resurgent domes in different tectonic contests were mainly addressed to the analysis of the system evolution, magma depth, intrusion shape, etc., and rarely on the analysis of the brittle deformation of the overburden (i.e., fractures/faults quantification, spacing, orientation, relationships with the existing tectonic stresses and the preexisting brittle structures). This is even more true for analogue models of magma emplacement, in which the brittle deformation in the overburden is often neglected or only qualitatively showed. In the frame of the task 5.2 activities, we developed and tested a brittle material able to guarantee certain results in term of number of developed structures and structural details, and capabilities of detecting a wide range of features. The selected material is a mixture of quartz sand (Fontainebleau quartz sand, widely used in analogue modelling) and K-feldspar fine sand (Kaolinwerke-AKW feldspar SF 900 SF sand). We analyzed the behavior of five different sand mixtures and its response to deformation. The analysis was performed running models in extensional setting for each mixture. The adopted set-up was the one used as analogue benchmark for the GeoMod 2004 (Schreurs et al., 2006). The 70% Qz sand + 30% K-feld sand mixture seems to be the one which gives the better results and the best compromise in terms of number and details of developed structures and frictional properties. Frictional parameters (internal friction angle and cohesion) were measured by means of empirical methods (faults dips in model sections, critical angle of repose, highest vertical wall stable with no failure). We also designed and developed a new modeling device with the aim of overcoming some of the limitations inherent in previous analogue models of magma emplacement. The new device consists in a Plexiglas box (33x38x15 cm) to be combined with the deformation machines already existing at the CNR Tectonic Modelling Laboratory. These deformation devices will be used to study the parameters able to control the patterns of magma emplacement, such as: the possibility of multiple (and even diachronous) intrusions during deformation, the presence of complex rheological layering in the upper crust, and particularly the fault/fracture development within the country rocks as a consequence of magma migration and emplacement. Finally, we present the preliminary results of the field survey conducted in the Larderello area to map and characterize the transverse structures that according to Finetti et al. (2005) would be intimately related to magma emplacement in the area. In particular, starting from the study of historical data, actual distribution of geothermal manifestations as well as past testimonies of such manifestations - well developed prior to the intensive industrial exploitation of geothermal resources - we identified the deformation features supposed to be responsible for geothermal fluid flow on top of the upwelling magma bodies. These features and their relationships with magma migration and emplacement will be one of the main investigation targets for the next year of analogue modeling activities.

IMAGE rock property database – fast access to a comprehensive catalogue

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Petrophysical rock properties are key to populate local and/or regional numerical models, and for the interpretation of many geophysical investigation methods. To date, large numbers of datasets are available in numerous sources (e.g. Landolt-Börnstein, PetroMod, Clauser and Huenges 1995, Schön 2004, Hantschel and Kauerauf 2009). This diversification often causes time-consuming literature research with often limited success due to a lack of detailed information on the sample location and measuring method. An open-access database is currently in development within the scope of the EU funded project IMAGE (Integrated Methods for Advanced Geothermal Exploration). Similar to the World Stress Map (Heidbach et al. 2010), the IMAGE database aims at providing information on published petrophysical properties in one single compilation. The database is designed to allow for an easy access to data relevant for geothermal exploration and reservoir characterization. Collected data include raw and bulk density, total and effective porosity, matrix and rock permeability, thermal conductivity, thermal diffusivity, specific heat capacity, radiogenic heat production, P- and S waves speed, Young's Modulus, Shear Modulus, Lamé-Modulus, cohesion, friction coefficient, Poisson's ratio, uniaxial compressive strength, tensile strength, electrical resistivity and magnetic susceptibility. Additionally, the petrographic description for each sample, the sample location (geographic coordinates, altitude and sampling depth) and information on the experimental set-up (methodology, pressure, temperature, degree of saturation) as well as the literature reference are given for additional quality control. So far more than 20,000 data points from all over the world, but mainly located in Europe, were collected. It is planned to make the database publicly accessible through a web-based interface and to update the provided data continuously. The collected data will help researchers and users in the early stages of new geothermal projects to make a first assessment of the geothermal rock properties and can be used for the planning of future exploration projects. Additionally, the database helps improving local and regional prediction models.

If you want to support and enhance this project with your data please contact us.

Petrophysical characterization of the Larderello deep geothermal reservoir based on field (Elba Island) and laboratory studies.

Gildas Beauchamps[1], Benoit Gibert[1], Domenico Liotta[2] and Andrea Brogi[2]

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The deepest geothermal reservoir of Larderello, Italy, is located in the metamorphic unit of the Tuscan metamorphic complex (Paleozoic micaschist). Seismic reflection profiles have put in light a reflector located in this level, characterized by a high reflectivity, the K-horizon. The nature of this signal is still misunderstood. Some authors make the hypothesis of presence of fluids at supercritical conditions (Hamilton, 1987; Deemer and Hurich, 1994; Blundell, 1990; Mooney and Meissner, 1992; Gianelli et al., 1997; Liotta and Ranalli, 1999). In order to better characterize fluid circulation at this depth, an analogy with the deepest geological unit of Elba Island has been made. Indeed, on Elba Island, the Monte Calamita is made of paleozoic micaschist, very similar to those present at depth in Larderello (Bortolotti et al., 2001 and Garfagnoli et al., 2005). Moreover, the presence of Iron mineralization in the Monte Calamita micaschists indicates a paleo-hydrothermal fluid circulation in similar conditions to those located in the deepest reservoir of Larderello (450-600°C, 1Kbar). By analysing the distribution of these mineralizations and by characterizing the petrophysical properties of the host-rock (permeability, mechanical behaviour and conductivity), this study aims to better understand the present deep fluid circulation of Larderello area. The main results of this study are as follow. The fieldwork, performed on the Ginevro mine area (Monte Calamita), has brought to light that mineralization (implicitly fluids circulation) was controlled by both faults and schistosity. The petrophysical study of the Monte Calamita micaschists, in P-T conditions similar to those of the deep reservoir of Larderello (T>400°C, P_C>100MPa), has shown that this host-rock presents very low permeability ($k<10^{-21}$ m^2), but displays a brittle and dilatant behaviour up to 600°C when it is submitted to a deviatoric stress. Conductivity measurements performed on dry samples reveal a high electrical conductivity, that is thermally active at high temperature and might be mainly driven by biotite. These measurements represent preliminary results and more petrophysical data have to be acquired to better characterize this micaschist host rock, for favoring a better understanding of the geophysical data.

Tracers for supercritical conditions, results of recent laboratory tests

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The use of tracers is a well-established technique for monitoring dynamic behaviour of water and gas through a reservoir. In geothermal reservoirs special challenges are encountered due to high temperatures and pressures. In this work, tracer candidates for monitoring water at supercritical conditions (temperature > 374°C, pressure ca 218 bar), are tested in laboratory experiments. Testing of tracers at supercritical water conditions requires experimental set-ups which tolerate harsh conditions with respect to high temperature and pressure. In addition stringent HES (health, environment and safety) factors have to be taken into consideration when designing and performing the experiments. The setup constructed in this project consists of a pressure vessel, high pressure pump, instrumentation for pressure and temperature control and instrumentation required for accurate sampling of tracers. In order to achieve accurate results, a special focus has been paid to the development of the tracer sampling technique. Perfluorinated cyclic hydrocarbons (PFCs) have been selected as tracer candidates. This group of compounds is today commonly used as gas tracers in oil reservoirs. According to the literature they are stable at temperatures up to 400°C. To start with, five PFCs have been tested for thermal stability in static experiments at 375°C and 108 bar in the experimental setup described above. The tracer candidates will be further tested for several months at the relevant conditions. Preliminary results indicate that some of the PFC compounds show stability after three months. However, in order to arrive at conclusive results, the experiments have to be repeated over a longer period and paying special attention to more accurate sampling procedures.

Geological and structural setting of the Eastern Elba Island exhumed geothermal system (Italy)

Caterina Bianco[1], Marco Meccheri[2], Andrea Brogi[1] and Domenico Liotta[1]

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Eastern Elba Island is characterized by Fe-oxides and sulphides ore deposits deriving from the hydrothermal activity developed during cooling of the Porto Azzurro pluton (5.9Ma). We present the results deriving from a new geological and structural map (scale 1:10000) carried out in the last two years. Tectonic units belonging both to the Tuscan continental and Ligurian oceanic environments were recognized in eastern Elba Island and their relationships have been defined. Their stacking occurred during late Oligocene-early Miocene. The deeper outcropping continental unit (continental unit 1) is made up of early Carboniferous micaschist and its Triassic-Jurassic siliciclastic and carbonatic cover (Porto Azzurro Unit). The 2nd continental unit is made up of a complete succession of metamorphic rocks consisting of middle Ordovician porphyroids (Ortano porphyroids) with its Mesozoic continental to marine metasediments cover. The latter are late Triassic to Jurassic metacarbonates calcschist and metaradiolarite passing to a Cretaceous succession made up of calcschist and phyllite with levels of metasiltstone and metasandstone. Calcschist represents the base of the succession and contains discontinuous lenses of metabasite with relics of HP-mineralogic phase. The third continental unit consists of low-grade metamorphic rocks including late Carboniferous phyllite, overlain by Triassic continental quartzite and phyllite, lateTriassic-Jurassic marble and by the Cretaceous-Oligocene carbonatic and terrigenous metasedimentary succession. The 4th continental unit is related to the sedimentary Tuscan Nappe, composed of late Triassic, locally vacuolar and fragmented calcareous dolostone, overlain by Jurassic marine carbonate and Cretaceous-Oligocene calcareous and marly pelagic sediments. The oceanic unit 1 is interposed between the second and the third continental units by means of out-of-sequence thrust referred to Early Burdigalian. This unit is a tectonic slice made up of Jurassic ophiolite. Finally, the oceanic units 2 and 3 consist of remnants of the Jurassic ophiolite, Jurassic radiolarite and Cretaceous-Eocene calcareous and terrigenous sediments, with levels of ophiolitic breccias. Since early-middle Miocene, the area has been affected by extensional tectonics, developed through normal and oblique-slip faults, the latter mainly SW-NE oriented and several example are here presented. Mineralization is mostly concentrated along these structures and mineralized shear veins have been extensively recognized in the fault-slip surfaces and related damage zones. Metasomatic processes accompanied the fluid flow affecting the cataclasite. Significantly, the permeable geological bodies, hydraulically connected with these shear zones, are affected by metasomatism, too. Consequently, the main mining activities were located along the SW-NE shear zones or in the surrounding geological bodies.

HP-LT metamorphism in Elba island: implications for the geodynamic evolution of the inner Northern Apennines (Italy)

Caterina Bianco[1], Andrea Brogi[1], Alfredo Caggianelli[1], Giovanna Giorgetti[2], Domenico Liotta[1] and Marco Meccheri[2]

[1]Università di Bari, I; [2]Università di Siena, I.

The inner Northern Apennines belt (i.e., northern Tyrrhenian Sea and Tuscany) is an Alpine chain affected by high-P metamorphic conditions during its evolution. Although Elba Island is structurally located close to the Adria-Europe suture zone, for several authors it represents a sector of the orogen affected by low-P metamorphism. The involvement of Elba Island tectonic units in high-P metamorphism was only suspected for the sparse presence of phengitic white mica in the metasedimentary rocks. Here we present the first clear evidence of high-P and low-T metamorphism found in metabasite rocks embedded in the Cretaceous calcschist of eastern Elba Island. Mineral composition of metabasite includes Gln+Cpx+Ep+Ab+Act+Qtz+Ilm±Ti-oxide±Spn and is indicative of a former equilibration in the epidote blueschist subfacies and subsequent retrogression in the greenschist facies. Recorded metamorphic conditions are P= 0.9-1.0 GPa and T=330-350°C. Tectonic discrimination using immobile elements in the metabasite does not point to an oceanic setting. As a consequence, the metasedimentary succession containing metabasite is explained as belonging to the Tuscan continental domain and not to the Ligurian-Piedmont Ocean, as previously interpreted. The results have two significant implications: (i) it is confirmed and strengthened that the tectonic stacking of the Elba Island units did not occur in a low-pressure context; (ii) Elba Island is now completely reconciled in the tectonic and metamorphic evolution of the inner Northern Apennines.

Synthetic seismic reflection modelling of the deep portion of the Larderello geothermal system from field data collected in the exhumed eastern Elba analogue

Andrea Brogi[1], Grazia Caielli[2], Roberto De Franco[2], Gianluca Groppelli[2], Domenico Liotta[1], Gianluca Norini[2], Giordano Montegrossi[3], Lorenzo Petracchini[4] and Davide Scrocca[4]

[1]Università di Bari, I; [2]CNR-IDPA, Milano, I; [3]CNR-IGG, Pisa, I; [4]CNR-IGAG, Roma, I.

Exploration strategies of geothermal reservoirs may significantly benefit from the development of synthetic seismic reflection profiles by confirming the possibility to detect prospective features on acquired seismic reflection data and to calibrate geological-geophysical interpretation and model reconstructions. To be elaborated a synthetic seismic reflection profile requires a conceptual geological model of the subsurface structure and physical properties. In this study, well data available for the Larderello geothermal field will be integrated with detailed information on reservoir rocks, fracture systems and fault zones properties gathered from the analysis of an exhumed geothermal systems (Elba Island, Capoliveri-Porto Azzurro area), which could be considered an outcropping analogue of the deeper (and poorly known) portion of the Larderello geothermal system. A conceptual model of the Larderello geothermal system will be produced by integrating densities and seismic velocities obtained by available well data, or from measures on rock samples, with properties of the deeper portion of the reservoir derived by upscaling the fine-scale 3D geological model of the outcropping analogue of the Elba Island. Finally, based on this conceptual model, a synthetic seismic reflection modelling will be carried out. The results of this modelling exercise will be compared with already acquired seismic reflection data made up by crustal seismic profiles (CROP-18A and CROP-18B) and existing commercial seismic data.

NE-trending shear zone across the Larderello geothermal area (southern Tuscany, Italy) and its possible impact on the fluids path

Andrea Brogi[1] and Domenico Liotta[1]

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We have refined the structural setting of a key-area passing through the Larderello geothermal field. Such an area mainly follows the trend of regional, NE-striking fault zone that was mapped in the geological maps during the 60's. Surprisingly such a fault disappeared in the most recent geological maps, (Geological Map of Italy at 1:50.000 scale). We present a new structural and geological map integrated with public boreholes and geophysical data (by ENEL GreenPower) where the previously mentioned NE-striking structure has been (re-) documented. Our results describe its geometry, architecture and kinematics. Such a structure consists of up to 3km wide shear zone formed by sub-parallel and anastomosed faults segments with composite kinematics: strike-slip (mainly left-lateral) movements were superimposed by oblique-slip and normal ones, as indicated by kinematic indicators mainly consisting of old calcite slikenfibers overprinted by mechanical striations. Such a shear zone interrupts the continuity of NW-trending normal faults delimiting the Pliocene-Pleistocene structural depressions (Tuscan basins), filled by marine to continental sediments. In other cases the NW-trending faults dissect the NE-trending segments, thus suggesting a coeval activity between the two systems of faults. The structural and kinematics data allow us to interpret the NE-trending shear zone as a transfer zone active during the Neogene-Quaternary extensional tectonics that gave rise to the development of the Tuscan basins. Borehole data attest a widespread geothermal fluid circulation in correspondence of fractured levels nearest the fault zones forming the shear zone, as well as in those segments of NW-trending faults intersecting the transfer zone. This reveals the role of the shear zone in feeding geothermal fluids that are laterally channeled through the NW-trending faults nearby their intersection and therefore stored in the reservoirs. Furthermore, the occurrence of a cooling magmatic body, located at 6-7km below the surface, along such a shear zone (as indicated by geophysical data), accounts for the possible control exerted by the NE-trending shear zone on the emplacement of the magmatic body. Such a picture underlines strict analogies, in terms of fluids paths and faults pattern, with the setting of the Elba Island (Capoliveri-Porto Azzurro area) where the interplay between normal faults and transfer faults has been documented in a analogue deeper level.

Evidence of paleoseismicity during fault activity in the Elba Island fossil geothermal system (Italy)

Andrea Brogi[1], Domenico Liotta[1], Cecilia Viti[2], Andrea Dini[3], Martina Zucchi[1], Enrico Mugnaioli[2] and Richard Spiess[4]

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Present geothermal systems are characterized by active seismicity, a necessary feature for maintaining an efficient permeability in the system. Although recognition of paleoseismic features is always rare in any tectonic context we report, for the first time, the evidence of co-seismic activity of a tourmaline-quartz bearing fault, as it is highlighted through micro to nano-scale structures of the slip zone. Our data are from a Messinian-Pliocene fault affecting the Paleozoic micaschist, the structurally deepest rocks of the inner Northern Apennines, cropping out in the southern Elba Island and constituting the host- rock of the deep reservoir of the present Larderello geothermal system. The shear fracture under study is a part of a NW-striking system of faults with tourmaline+quartz+goethite shear veins that can be thick up to 15 cm. Superimposed mechanical striations characterize faults surface, with movements from oblique-slip to normal. The last movement gave rise to mirror-like surface on the study tourmaline shear veins, mainly composed by tourmaline crystals with interstitial goethite. The mirror surface, a few μm thick, is formed by naturally polished tourmaline crystals, and is characterized by: 1) disappearance of interstitial goethite; 2) highly variable grain size, from 200 μm to 200 nm; 3) compact impinged microstructure and 4) tourmaline random crystallographic orientation. The deformation mechanisms active in the fault zone have been investigated from the outcrop to the nanoscale. The investigation revealed the superposition of brittle processes, giving rise to a clastic/ultracataclastic principal slipping zone, a few mm thick, and localized decomposition/recrystallization processes, responsible for the formation of the polished mirror surface itself. In particular, we suggest that frictional heating during seismic slip induced goethite decomposition and produced a poorly-crystalline viscous-like material, able to flow away from the ultracataclasite, leaving a thin monomineralic film of polished and sintered tourmaline crystals. Tourmaline mirror faults represent therefore the traces of ancient earthquakes and, similarly to other mirror faults, they can be considered as the micrometer-sized products of a “seismic metamorphism”, with mineralogy and micro/nanostructures variable as a function of protolith (i.e., the fault rock) and “metamorphic” conditions (e.g., slipping rate and T rise by frictional heating).

Relationships between geological structures and hematite-pyrite-quartz mineralization in the Valle Giove mining area (Elba Island)

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We present a detailed structural and geological map of one of the most exploited mining area of Elba Island, named as Valle Giove locality (Rio Marina) as an example where, given the continuity of exposure, the relationships between mineralization (mainly consisting of hematite+pyrite+quartz) and geometry of geological bodies can be described. The main results indicate that the pre-existing geometry of the geological bodies (belonging to the Triassic Verrucano Group, mainly) influenced the hydrothermal fluid paths. We have in fact recognized re-folded folds developed during the orogenesis of the Northern Apennines (late Oligocene-early Miocene) that are only partially or totally metasomatised depending on their orientation with respect to the main structural channel controlling the fluid flow. Particularly, the main conduits that fed the hydrothermal fluids developed mainly where the pre-existing foliation (main schistosity) was favourably oriented with respect to the new deformational field during the magma cooling (Messinian- Pliocene) of the Porto Azzurro monzogranite . The rock mass corresponding to the main structural conduits are characterised by a sub-vertical NNW-trending thick volume (up to 20 meter wide) of metasomatised rocks, whose boundaries are often marked by mineralized shear planes with normal to oblique-slip movement. Hydraulic breccias are often associated to the shear zones, indicating the fluid pressure played a significant role in enhancing fractures. Lateral migration of fluids is primarily controlled by lithology, being the quartz-conglomerate bearing levels the most suitable for metasomatism and, secondly, by the geometry of the pre-existing folds.

Geochemistry of Volatile Organic Compounds (VOCs) in fluids from the Krafla and Reykjanes geothermal systems, Iceland

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In the framework of the IMAGE (Integrated Methods for Advanced Geothermal Exploration) European project, a sampling campaign for fluids from boreholes and fumaroles was carried at two different geothermal fields: Krafla and Reykjanes in North-East and South-West Iceland, respectively. The Krafla high-temperature geothermal system lies in the northern part of the neo-volcanic zone, within the caldera of the Krafla central volcano formed about 105 years ago. The Reykjanes geothermal field, located at the southwest tip of the Reykjanes peninsula, 55 km southwest of Reykjavík, is characterized by extensive Postglacial lava fields. Sampling was carried out between 19 and 23 May 2014. Three boreholes (depth from 800 to 2248m) and three fumaroles were sampled from each system in order to constrain the relationship between the composition of the Volatile Organic Compounds (VOC's) and the chemical physical conditions at their source. In particular, we focused our attention on the use of VOCs as geochemical tracers for the study of chemical-physical processes that characterize volcanic and hydrothermal environments, e.g. formation, mixing and transport processes, with the aim to contribute to the study of indicators that can reveal the presence of fluids at supercritical conditions. The inorganic main gas composition of the two areas is typical of hydrothermal emissions, being dominated by steam (H_2O >96%) and showing a dry gas phase mainly consisting of CO_2, H_2S, H_2, N_2, with minor concentrations of CH_4, Ar, O_2, and He. The $\delta^{13}C$-CO_2 values ranged from -4.15 to -0.57permil vs. V-PDB. Up to 16 different VOCs, pertaining to the alkane (7 compounds), alkene (2 compounds), aromatic (4 compounds), sulfonated (3 compounds) groups, were identified and quantified. The composition of aromatics was largely dominated by Benzene (up to 1,800 ppb), whereas Thiophene (up to 1,600 ppb) was the most abundant among S-bearing compounds. These two gases typically become enriched at hydrothermal conditions, whereas they tend to be degraded in presence of hot, highly oxidizing fluids, such as those released from a magma source. On the contrary, furans (O-substituted) are typical products of gases deeply influenced by magmatic fluid contributions (Tassi et al., 2010). Thus, their absence in the analyzed samples, coupled with that of acidic gases (i.e. SO_2, HCl and HF), suggests that the possible inflow of magmatic fluids is efficiently buffered by the two hydrothermal reservoirs. The study of S and O-substituted compounds and their relationships (i.e. thiophenes and furans) could be an interesting application for geochemical monitoring during future deep drilling, in order to detect any changes in the conditions related to the arrival of deep magmatic fluids.

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Hydrothermal fluid paths during cooling of the Geitafell gabbro (Iceland)

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The study Tertiary gabbro represents the inner part of the Geitafell Central volcano. The Miocene-Pliocene gabbro emplaced at shallow depth (2-4 km) and intruded in Late Miocene flood-basalts beds. The Geitafell volcano, believed to be located in the rift valley during Miocene and in the framework of the crustal accretionary process affecting the divergent margins, have been migrating south-eastwards up to the present location, about 20km far from the Icelandic cost. Thermometamorphism of host-rocks is reduced to few meters in the surroundings of the gabbro, and it is clearly marked by the occurrence of mm-size hornblende and augite in the rock-fabrics. The gabbro and its hosting rocks are affected by two significant sets of fractures, SW-NE and NW-SE oriented.The first system is mainly typified by a dominant normal component, whereas oblique-slip movements chiefly define the second system of faults. The fault surfaces and the damage zones (up to 50 m thick) of both systems are characterized by shear veins, filled with hydrothermal minerals, such andradite, epidote, quartz and calcite (+zeolith). These minerals are also recognizable as amigdales, up to 10cm in size, in the more porous tholeitic levels. Usually, andradite is present in the structures and geological bodies closer to the gabbro, whereas epidote, quartz, calcite and zeolite are found far from it. Existing Information from fluid inclusions and isotope studies indicate that the hydrothermal fluid was of meteoric origin and temperature of hydrothermal fluids was T<350°C, thus indicating that cooling of magma was occurring in an open system, while shear fractures were active. Mineralized (epidote) hydraulic breccias are often associated with the main faults, suggesting that the hydrothermal fluid pressure was locally exceeding the lithostatic pressure during faulting. We therefore describe the hydrothermal fluid path during cooling and we argue that the meteoric fluids were channeled to depth through the main faults and their related damage zones. Porous geological bodies, when hydraulically connected with the main permeable structures, were infiltrated by the hydrothermal fluids through their primary and secondary permeability.

Seismic imaging of volcanic systems of the Northern Volcanic Zone, Iceland

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The Northern Volcanic Zone in Iceland consists of five volcanic systems each containing a central volcano from which the fissure swarms emanate. The two most active and well studied are the Askja and Krafla volcanic systems. These central volcanoes are mature volcanic systems with developed caldera structures and associated magma chambers in the upper crust. The Askja and Krafla central volcanoes also contain high temperature geothermal fields. The Krafla-Leirhnjukur field within the Krafla caldera has been operated as a power plant since 1975. Over the past 8 years a dense array of three-component broadband seismometers has been collecting continuous data across the Askja and Krafla volcanic systems, and more recently surrounding the volcanic systems beneath the Vatnajokull ice cap. Analysis of the microseismic activity at Askja reveals persistently seismogenic regions particularly beneath the surface geothermal field on the east side of Oskjuvatn lake, and on a series of strike-slip faults in the Herdubreid area (Green et al. 2014). Smaller clusters of events are also observed below the brittle-ductile transition at 10-15 km, to the east of the central volcano. These are interpreted to be generated by melt migration at depth (Greenfield & White. In review JGR, 2015). At Krafla microseismic sources are concentrated in the upper 4 km within the Leirhnjukur and Namafjall geothermal fields. Moment tensor inversion of these earthquakes reveals a highly complicated stress field around Krafla as stresses have not built up since the last rifting episode (1974-85). In addition, non-double-couple volumetric decreases are observed in some earthquakes reflecting cavity collapse due to the movement of fluids in the shallow crust (Watson et al. Submitted GRL, 2015). We have used both local body wave tomography from the persistent seismicity, and ambient noise surface wave tomography (taking advantage of the long deployment periods) to image the crustal structure of these volcanic systems. Here we present results from this ambient noise and body wave tomography at both Askja and Krafla central volcanoes. A large low Vp, low Vs and high Vp/Vs anomaly is centred at 6 km depth beneath the Askja central volcano reflecting the presence of a large magma storage region which has heated the surrounding crust. Using the reduction in the seismic velocity melt fractions of ~10% have been calculated, similar to that observed at other volcanoes around the world. Within the lower crust diffuse regions of high Vp/Vs associated with clusters of earthquakes reveal a complex plumbing system beneath the Askja volcanic system. Melt is currently being injected at discrete locations throughout the volcanic system although only melt injected beneath the central volcano reaches shallow magma storage regions where it can be intruded into the crust or erupted on the surface. Beneath Krafla two low Vp anomalies have been imaged beneath the Leirhnjukur geothermal field, matching two attenuating bodies discerned during the Krafla rifting episode of 1974-85. Using the calculated Vp/Vs ratio a shallow low Vp/Vs region and a deeper high Vp/Vs region reveal complexity within the high temperature geothermal fields as a result of changes in the crack porosity. The low Vp/Vs in the shallow chamber is due to a greater crack porosity while the higher Vp/Vs of the deeper reservoir may be linked with the low porosity properties of intrusive rocks. A deep low Vp/Vs region underlies both these geothermal reservoirs as a result of a super-heated steam zone within felsic rock overlying rhyolitic melt.

Fluid inclusion and isotopic studies in the eastern Elba Island (Italy) exhumed geothermal system. Part 2: The Terra Nera and Rio Marina areas.

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In eastern Elba Island, the mid-upper crustal Porto Azzurro granitoid (5.9 Ma) gave rise to a widespread boron-rich contact metamorphic aureole, intense hydrothermal circulation, and Fe-ore deposits. Two main hydrothermal subsystems may be distinguished: 1) the tourmaline-bearing metasomatic bodies and quartz- tourmaline hydrothermal veins system, located in the Calamita Peninsula; 2) the hydrothermal Fe-ore deposits of Terra Nera and Rio Marina areas. Samples collected from these two areas correspond to different stratigraphic and structural levels. The Fe-ore deposits (hematite-pyrite) of the Terra Nera and Rio Marina areas can be indeed considered as representative of paleo-fluids circulation within paleo-geothermal reservoirs interpreted as possible analogue of the shallower reservoirs presently exploited in the Larderello- Travale geothermal fields. In this presentation the results on fluid inclusion studies and isotopic analyses of samples from the Fe-ore deposits are presented. The fluid inclusions (FIs) were studied in hydrothermal quartz, calcite, and adularia from Rio Marina (Valle Giove, Bacino, Topinetti) and Terra Nera mineralization, to derive: i) the chemical characteristics and P-T conditions of fluids circulating in this paleo-geothermal system and ii) the origin and evolution of the fluids. FIs were studied by optical microscopy and microthermometry. SEM–EDS, Raman spectroscopy, and LA-ICPMS were employed as complementary techniques to characterize fluid composition. Samples were collected from stratigraphic levels belonging to the Monticiano-Roccastrada Unit. FIs are mainly of the L-type (liquid+vapor), S-type (liquid+vapor+halite) inclusions were sporadically found only in adularia and calcite from Valle Giove, registering hypersaline fluids (31-33 wt.% NaCl eq.). In L- inclusions, we found: 1) at Bacino, cooling of fluids with moderate salinity (13-17 wt.% NaCl eq.) and Th (200-300°C); 2) at Topinetti, mixing and cooling of fluids with low to moderate salinity (1-21 wt.% NaCl eq.) and Th (170-330°C); 3) at Valle Giove, mixing of several cooling fluids, with highly variable salinity (1-33 wt.% NaCl eq.) and Th (170-340°C); 4) at Terra Nera, not-coeval fluids with moderately higher ranges of Th (270-350°C) and salinity (19-27 wt.% NaCl eq.), and locally with a peculiar composition in terms of the ice- against salt-hydrates- melting temperatures. Semi-quantitative analysis by LA-ICPMS showed that NaCl, $MgCl_2$, KCl, and $FeCl_2$ are dominant in these areas, with some differences in their relative amounts among different areas, especially for Terra Nera and Valle Giove. None or very low contents of $CaCl_2$ were observed in almost all areas. Significant amounts of Li and, subordinately, B were observed in all areas, especially Terra Nera and Topinetti. $\delta^{18}O$ was determined in quartz and hematite from Valle Giove: 10.49/12.51‰ and -1.14/-2.67‰, respectively; and from Terra Nera: 13.39/15.90‰ and 0.2‰, respectively. From the $\delta^{18}O$ fractionation of the quartz-hematite pair it was calculated a temperature of about 350° for Valle Giove and 365°C for Terra Nera. Calculated isotopic compositions of the fluid ($\delta^{18}O_{H2O}$) in equilibrium with quartz range from 5.4 to 10.6‰.with the highest value at Terra Nera. In general, FIs in hydrothermal Fe-deposits of Rio Marina and Terra Nera areas record circulation and mixing of several fluids, from low-salinity fluids of probable meteoric origin (at Topinetti and Valle Giove), to saline (all areas) and hypersaline (at Valle Giove) fluids. The chemical features of FIs (i.e. high-salinity and significant presence of Li, B, Fe, K etc.) and the isotopic data (rather high $\delta^{18}O_{H2O}$) suggest that the saline and hypersaline fluids can be similar to the fluids of magmatic derivation found in the FIs in quartz-tourmaline veins of Calamita Peninsula that undergone cooling and dilution before entering the hydrothermal systems of Fe-mineralization.

Seismic velocity structure of a fossilized Icelandic geothermal system: A combined laboratory and field study

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Magmatic geothermal systems, as they exist in Iceland, are complex geological structures. Key features, such as hydrothermal upwelling zones and intrusive heat sources, are embedded in a highly heterogeneous host rock, comprising quasi-horizontally layered basaltic lava flows of variable texture and morphology, repeatedly intruded magma chambers, and numerous intersecting sub-vertical dykes and sub-horizontal sheets. In order to estimate whether seismic techniques can detect these geothermal key features, we examined the seismic velocity structure of the fossil geothermal system of Geitafell, in southeast Iceland. We combined seismic tomography field experiments with ultrasonic measurements in the laboratory to obtain a comprehensive picture of the velocity systematics and to investigate the scale-dependence of experimental velocity determination. We recorded six shallow seismic profiles over outcrops of different parts of the exposed magmatic system and we investigated 10 specimens of basalt, dolerite, and gabbro in the laboratory. Our results demonstrate that in the fossilized geothermal system of Geitafell, seismic velocities can vary over a wide range of around 1500 m/s (see Fig. 1). Considering this large spread of wavespeeds, velocity anomalies induced by geothermal activity are likely to be masked by the heterogeneity of the host rock, why high quality data and an optimal survey design is required to successfully explore them with seismic methods. Moreover, we discovered ultrasonic velocities measured in the laboratory under comparable depth-pressure conditions to be up to 15 % higher than seismic velocities inverted from the field data. This is of great importance and has to be considered when interpreting exploration-scale field tomograms with the help of laboratory investigations.

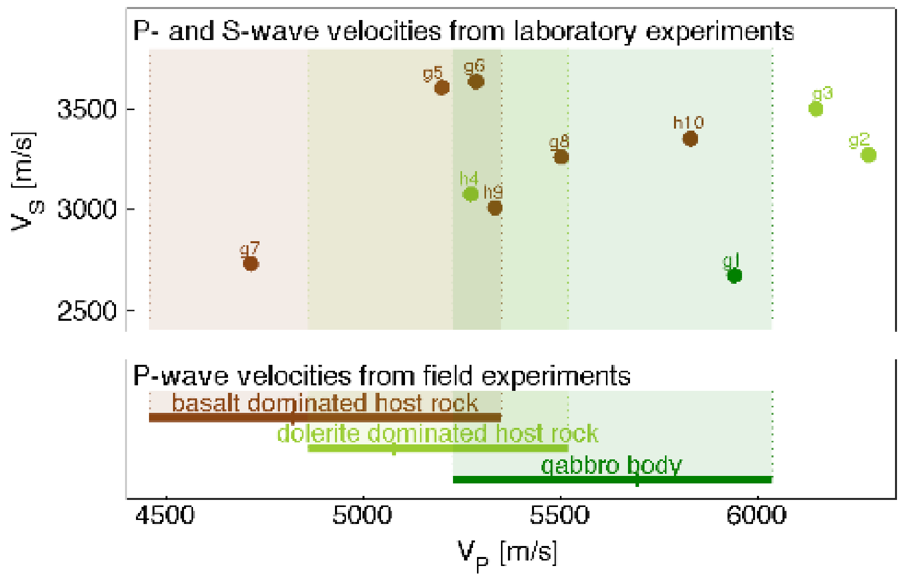

Fig. 1: Comparison of P-wave velocities (together with S-wave velocities) determined in the laboratory for a confining pressure of 0.5 MPa (top), with P-wave velocities measured in the field at depths of 15-20 m below surface (bottom). In brown are the velocities of the dry basalt samples and the basalt dominated host rock, in light green the velocities of the dry dolerite samples and the dolerite-dominated host rock and in dark green the velocities of the dry gabbro sample and the gabbro body, respectively.

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Vertical Seismic Profiling in the Krafla Geothermal Field, NE-Iceland

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A VSP test experiment at the high temperature geothermal field Krafla in NE-Iceland has been carried out. In two boreholes a zero-, far- and multi-offset VSP has been applied to assess the applicability of VSP as a method for delineating subsurface structures like magmatic bodies, zones of supercritical fluids, superheated steam and zones of high permeability in volcanic geothermal fields. Because of high well temperatures (~150 °C) and high attenuating surface layers a careful field preparation and evaluation was needed. Three-component data were recorded with a high signal-to-noise ratio and provide a good basis for several processing and imaging techniques. As part of a Master's thesis novel processing techniques of a subset of the data (zero and far-offset from one well) has been tested and shows promising results in accordance with the lithology from well data. Besides determining velocity profiles for both P- and S-waves a 3D migration has been deployed and tested. First results show structures in the vicinity and below the well and it can be assumed that further interpretations and integration will provide a great alternative and addition to hitherto only applied surface seismic, teleseismic and potential methods. Especially, for geothermal sites, VSP methods may provide more detailed information of geometries where dipping faults and fracture zones are expected.

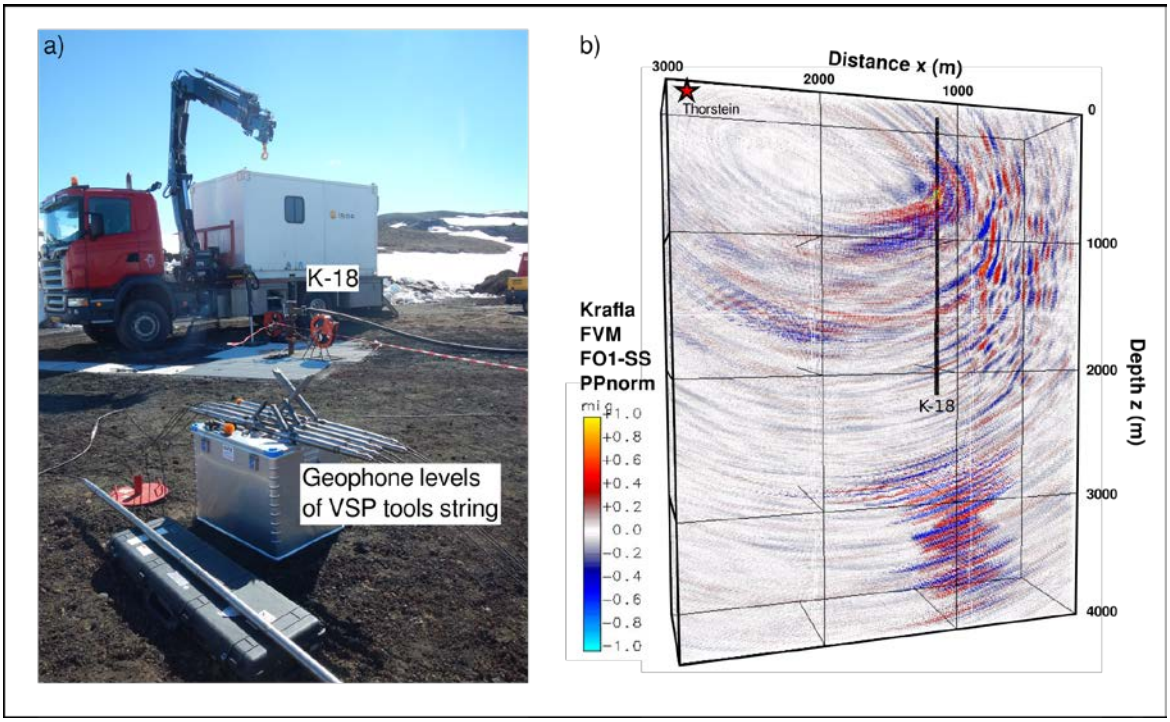

Fig.1: a) Geophone chain in front of K-18 well head and installation crane within the Krafla Geothermal Field. **b)** Three-component Fresnel volume migration (FVM) of the single far-offset (Thorstein) VSP shot using S-S reflections at a constant velocity model (vP=4600m/s, vS=2700m/s). Reflections below the well can be detected which may also give a hint of the inferred magma chamber at 2.5 - 3 km depth.

Coexistence between low-angle normal faults and transfer zones during hydrothermal fluid flow in continental crust (Elba Island)

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We deal with the kinematic and chronological relationships among low angle normal faults and high angle strike- to oblique-slip faults in an exhumed mineralized area, where shear veins and minor associated structures with the same mineral assemblage has been interpreted as indicators of coeval fault activities. The study area is located in the eastern Elba Island, where a mineralized late Miocene-early Pliocene low- angle normal fault (Zuccale fault) and high-angle strike- to oblique-slip faults extensively crop out, the latter giving rise to the Capoliveri-Porto Azzurro shear zone. The field study highlighted that: (a) the damage zones of both fault sets are mineralized by syn-kinematic tourmaline, graphite, Fe-oxides and/or Fe-oxyhydroxides shear veins, thus indicating their coeval activity during the hydrothermal event (5.9-5.4 Ma); (b) the Capoliveri-Porto Azzurro shear zone is constituted by a network of fractures, whose geometry and kinematics display the evolution of a NE-trending left-lateral oblique-slip transtensional shear zone; (c) its internal architecture is defined by tourmaline and Fe-oxides and/or Fe-oxyhydroxides mineralized veins, framed in the same kinematic field characterizing the Zuccale fault evolution; for this reason, the Capoliveri- Porto Azzurro shear zone is interpreted as a transfer zone active during the low-angle fault activity; (d) the Capoliveri-Porto Azzurro shear zone played the role of a significant normal fault during the Late Pliocene- Pleistocene, therefore favouring the deepening of the Tyrrhenian Basin with respect to the uplift and exhumation of the mid-crustal rocks of the Elba Island. It is finally argued that the interaction between the low-angle normal fault and the almost vertical shear zone determined an increase of permeability, favouring the mineralizing fluid flow during the hydrothermal stage and, reasonably, the previous emplacement of the Porto Azzurro magmatic body.

Integrating static and dynamic modeling into the geothermal exploration workflow

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Building interactive conceptual models of geothermal reservoirs integrating static and dynamic modeling in the same exploration workflow is mandatory to validate flow circulation hypothesis and therefore reduce uncertainties. As high energy magmatic reservoirs are always located in complex geological settings and involve the circulation of hot brines over a wide range of thermodynamical parameters, we must be able:

1. to quickly build structural models involving geological bodies of any shape and with the occurrence of discontinuities,

2. to produce conformable meshes of such models,

3. to perform multiphase thermo-hydraulic simulations with phase change on these meshes without numerical artefacts.

Over the years, iso-potential surface mapping has proved an efficient framework to achieve goal 1 and it is now implemented in several commercial softwares (e.g. GeoModeller). Yet, when it comes to goal 2 the implicit nature of surfaces make volumic meshing a non-trivial task. We recently used the Computational Geometry Algorithms Library (CGAL) to build conformal simplicial (tetrahedral) meshes that exactly match any geological 3D object and its boundaries or internal 2D features such as fault surfaces. Finally, to reach goal 3 we used the Vertex Approximate Gradient finite volume scheme which has been adapted to model mass and energy over any polyhedral meshes with the possibility to take into account objects of codimension 1 such as fault surfaces which may act as corridors for fluid flows.

Validation of orientation of IMAGE Seismometers with seismic Rayleigh Waves on Reykjanes, SW Iceland

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Within the project IMAGE, we deployed 30 seismometers (10 short-period and 20 broadband seismometers and 24 Ocean-bottom seismometers on and around Reykjanes. They recorded the seismicity from April 2014 until August 2015. The aim is to create a velocity model of the region, study source mechanisms and anisotropy. The orientation of the seismometers is fundamental for source mechanisms and anisotropy studies. We oriented all stations of IMAGE network with a gyro-compass. When deployed, OBS are not oriented with respect to the North. Rayleigh Wave polarization can be used for determining the earthquake back azimuth and the angle Θ between seismometer direction and real north. Rayleigh waves cause a retrograde elliptical particle motion in direction of the wave propagation. The optimal motion can be seen on the radial component of the seismometer for one angle α, when it's in line with the wave propagation ray from the earthquake to the seismometer. The difference out of α with the great circle station-to-event azimuth gives then Θ. We validated this method for the IMAGE stations deployed on land. We used 167 earthquakes with M>6.0 between April 2014 and May 2015, recorded on the 3 components of the network, to derive orientation of each seismometer. The comparison of the Rayleigh Wave Method and results from gyro compass measurements shows small differences between both methods. It is in the range of 1°-3° for the broadband sensors and up to 10° for the short period seismometers. This outcome proves, that the Rayleigh wave polarization can also be used for the proper orientation of the Ocean Bottom Seismometers.

Geochemical numerical modeling of super-hot geothermal systems

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Geochemical numerical models require a comprehensive and coherent thermodynamic database. Although today's geochemical database are quite complete, including the most common reaction and reaction constants, some reactions typical of specific environments are not included yet. As part of the EU FP7-funded Integrated Methods for Advanced Geothermal Exploration (IMAGE) project, a building up of a thermodynamic database with Pitzer formalism, focused on minerals that likely occur in super-hot geothermal systems, was carried out. The thermodynamic properties of several minerals have been added to the Thoughreact Pitzer default database (data0.ypf). Input data, in a modified format were also added to the provided Toughreact (Thermok.dat) and Phreeqc (llnl.dat) databases, to be used both in Debye-Hückel [1] and in the Pitzer [2] aqueous model. The data were taken from available literature on thermodynamic properties of minerals, and in particular from the thermodynamic data collection of Holland and Powell [3] and Holland et al. [4] among many others. The new data collection allow to carry out two simple models of interest in fossil super-hot geothermal systems in Elba Island (Italy) and Geitafell (Iceland). The first is considered the exposed proxy of the deepest part of the Larderello-Travale geothermal field (Italy), whereas the second is believed to be a possible analogue of the Krafla geothermal system (Iceland) for which the existence of supercritical fluid stored in deep reservoirs is hypothesized. These models were computed with Phreeqc. The first involves the formation of tourmaline from biotite which could be also related to tourmaline formation in the Larderello-Travale geothermal field. The second model shows the hydrothermal alteration at high temperature (>400°C) of an Icelandic basalts due to heated meteoric with or without the addition of magmatic gasses (i.e. HCl and/or SO2).

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Porosity, seismic velocities and electrical conductivity of Icelandic deep geothermal reservoirs

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Exploration and exploitation of deep high temperature geothermal ressources in Iceland require a better knowledge of the physical properties of their reservoir rocks. In particular, the possibility of targeting supercritical reservoirs is currently under investigation within the frame of the IMAGE project. Under these conditions (>225 bars, 374°C for pure water), rock properties are poorly investigated. In this study, we focus on the experimental determination of petrophysical properties of samples drilled at great depth from different boreholes located on the Reykjanes Peninsula (holes RN17B, RN19, RN30) and in the Nesjavellir geothermal field (holes NJ17, NJ17B) in Iceland. Three types of rocks, representative of the lithology variability, are investigated: intrusive rocks (dolerite), basalts and hyaloclastites. These rocks experienced a high degree of alteration correlating to the amphibole facies and representing high temperature conditions (>350°C). Petrophysical properties are first determined at ambient conditions in order to establish relationships between lithology, microstructures and physical properties. This preliminary approach has been used prior to the high pressure and high temperature measurements, giving a first physical evaluation of the reservoir in respect to seismic, hydraulic, or electrical events. Porosity of the mini-cored samples ranges between 1% and 30%, whereas the dolerite porosity lies between 1 and 3%. A narrow interval has been found for basalt porosities, varying between 18 and 21%. Because the hyaloclastites are more heterogeneous, we have found a higher variability of their porosities, ranging between 3% and 30%. Seismic velocities of P and S waves (under dry or saturated conditions) all show a linear correlation with porosity. All these results display a linear decreasing trend of wave speed propagation with increasing porosity. However, the P wave velocities in “dry” dolerites are much smaller than the overall linear trend, while “saturated” dolerite samples follow the above-mentioned general trend of seismic velocities. This different behaviour can be explained by the presence of micro-fissure porosity in dolerites, which stands in contrast to the inter-granular porosity microstructure of hyaloclastites (controlling the wave velocity decrease). These results have been confirmed quantitatively by pore size Mercury porosimetry measurements. The electrical conductivity properties of the saturated rocks have been investigated at high fluid conductivity through the electrical formation factor F, studying the F-porosity relationship (Archie’s law). This power law provides an estimation of the cementation factor for the dolerites (1.5), the basalts (2.83), and the hyaloclastites (2.25). This increase of the cementation factor describes the change in the shape of conductivity channels, which is in good agreement with our previous seismic results. At very low fluid conductivity, surface processes control the electrical currents. The surface conductivity, resulting from the electrical double layer, increases with the porosity. Cation exchange capacity measurements (CEC) confirm that the most altered and oxide-rich samples are indeed the hyaloclastites, while our dolerite samples are fresher and have a lower surface conductivity. Finally, sample permeabilities have been measured at low confining pressure (20 MPa) and ambient temperature, showing a good correlation with the electrical properties of our rock samples. Furthermore, their permeability increases by 3 orders of magnitude with increasing porosity.

Geothermal exploration in very active volcanic areas - The example of deep geothermal drilling on the Island of Montserrat (Caribbean Lesser Antilles)

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Montserrat is an active volcanic island in the Caribbean Lesser Antilles arc. Two geochemical surveys carried out in March 1991 and September 1992 revealed the existence of a hydrothermal system in the southern portion of Montserrat Island, below Soufrière Hills Volcano, resulting in a conceptual geochemical model of the hydrothermal-volcanic system of southern Montserrat island (Chiodini et al, 1996). Unfortunately, renewed eruptive activity from the Soufriere Hills volcano in 1995 and following years destroyed the main town of Plymouth and left approximately a third of the island uninhabitable. Due to the strong urgency for the people of Montserrat to reinvigorate the depressed island economy, after the volcanic crisis, and the persistence of the volcanological alarm on the island, which severely limits the use of its territory for tourism and other activities, in 2008 Montserrat Government promoted new Geothermal exploration on the Island with the aim to drill 1-2 deep geothermal wells for the alimentation of a 3-5MW plant. In this framework IGG-CNR was charged by United Nation Economic Commission for Latin America and the Caribbean (UN ECLAC) to perform a Scoping Survey aimed at *(i)* defining the persistence of a geothermal potential on Montserrat after the 1995 volcanic crisis; *(ii)* individuate the area which major indications of heat flow persistence; and *(iii)* define the investigations to be carried out for the siting of the two geothermal wells (Principe, 2008). Following the indication of the Scoping Survey a second phase of geothermal exploration on the Island was conducted in 2009 (EGS, 2010). Preferred sites were identified in a zone protected from potential hazards, mostly pyroclastic flows and lahars, within a faulted area between St George's and Garibaldi Hills. Two successful wells were drilled in this area during 2013 (Brophy et al, 2014).

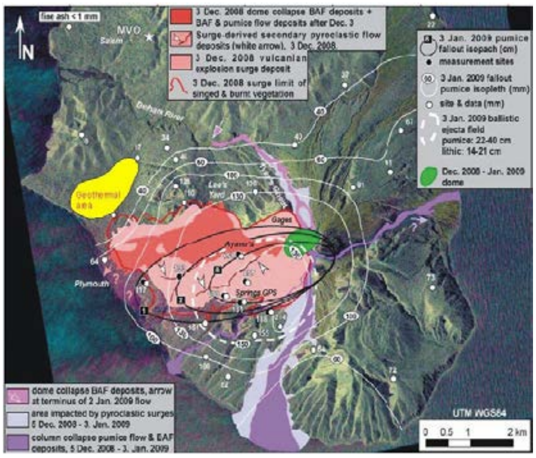

Fig.1: Location of the area of geothermal interest in respect of the deposits of the recent volcanic crisis

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Fluid inclusion and isotopic studies in the eastern Elba Island (Italy) exhumed geothermal system. Part 1: The Calamita Peninsula

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In the Calamita Peninsula, tourmaline-bearing metasomatic bodies, and a complex quartz-tourmaline hydrothermal system ascribed to hydrofracturing events, are now exposed at surface, and evaluated as a possible exposed analogue of the deepest part of the present-day Larderello-Travale geothermal fields. Here, we present the results of a fluid inclusions (FIs) study conducted in the quartz-tourmaline veins occurring at Cala Stagnone, Ripalte and Morcone to derive: i) the characteristics of fluids circulating in a paleo-geothermal system similar to the super-hot system presents below the exploited reservoir of the Larderello-Travale ones, ii) the P-T conditions of the system, and iii) the reactions occurred between the host rocks and fluids. FIs were studied by optical microscopy and microthermometry. SEM–EDS, Raman spectroscopy, and LA-ICPMS were employed as complementary techniques to characterize fluid composition. Moreover, H, B, and O isotope analysis were conducted on tourmaline and quartz to derive the possible source of the fluid. At Stagnone and Ripalte we found 1) S-type, or multiphase FIs, with 1-5 daughter minerals; 2) L-type FIs, homogenizing to the liquid phase; 3) V-type FIs, homogenizing to the vapor phase. S-type inclusions are hypersaline (29-49 wt.% NaCl eq.) with moderate total Th (<400°C); L- and V-type FIs are saline (16-29 wt.% NaCl eq.) with moderate to high Th (up to 600°C). At Morcone, FIs are rarely of the S-type, whereas they occur as L- and V-type, displaying Th around 370°C and mean salinity of 7.5 wt.% NaCl eq. Quantitative analysis by LA-ICPMS indicated that NaCl, $FeCl_2$ and KCl dominate the composition of the fluid in these areas, and only minor $CaCl_2$ is present. Particularly, Fe concentrations in the fluid were comparable to or greater than the contents of other major cations. The presence of B was also significant. Isochores were calculated using the data for the H_2O-NaCl system to derive trapping P-T conditions of the fluid. At Stagnone and Ripalte, FIs observations and microthermometric data suggest that high temperature L inclusions have exsolved directly from a crystallizing magma at moderate pressure. At Stagnone, mild fluctuations in pressure resulted in conditions which shifted fluid density below and above critical conditions, producing the typical assemblage of V- and L-type FIs. Estimated trapping pressure and temperature are: 800 bar<Pmax<1600 bars and 550°C<Tmax<650°C. Similar pressures but lower temperature was associated to the system of Ripalte, being comprised in a temperature range of 420-540°C. Progressively sealing of the system resulted in increasing pressure (>2000 bars) and salinity of the fluid, corresponding to the stage when S-type FIs were formed, and that predates hydrofracturing events. Similarly to Stagnone, the association of L- and V-type at Morcone indicates pressure fluctuation above critical temperature, although they occur at lower temperature than at Stagnone. Considering the critical temperature of 443°C for a 7.5 wt.% NaCl eq. fluid, trapping temperature was near that value, corresponding to a trapping pressure of ~760 bars. Then, based on FIs data, Ripalte and Morcone represent cooler (and depressurized?) parts of the deepest reservoir localized at Stagnone. δD in tourmaline range -75‰ to -60‰ at Stagnone, while a lower value of -49‰ was found at Morcone. The near-constant boron isotopic composition (from -7.7 to 8.3 ‰) of tourmaline from magmatic (monzogranite and leucogranite) and hydrothermal (veins, breccias) rocks suggest a dominant contribution from crustal magmatic fluids and negligible isotopic fractionation. Recalculated isotopic composition of the fluid (δD_{H2O}) at 550°C indicated δD_{H2O} of -48.9‰ to -64.2‰ at Stagnone, while at Morcone δD_{H2O} (recalculated at 440°C) was -24.9‰. On the contrary, recalculated $\delta^{18}O_{H2O}$ from O isotopes in quartz are similar between the two areas, corresponding to values of +11.3‰ (Stagnone) and +11.2‰ (Morcone). Ranges observed at Stagnone are compatible with a fluid derived from a peraluminous granite. Boron and oxygen isotope data are consistent with a magmatic origin of fluids; the variable δD values need to be investigated in more detail but it could suggest a complex fluid separation dynamics at the magmatic-hydrothermal transition.

Fluid inclusions and isotope study of the Geitafell exhumed geothermal system (Iceland)

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The Geitafell Central Volcano (5-6 Ma), located in SE Iceland, was formed within a rift zone in central Iceland, and it was active for about 1 Ma. Thanks to glacial erosion of ~2km, the fossil hydrothermal system is now partially exposed at surface. It consists of a main magmatic body (gabbro) and its associated contact-metamorphic aureole within the host rocks (mainly tholeiitic lavas), later affected by hydrothermal circulation. This system is considered the possible analogue of the Krafla geothermal system for which the existence of supercritical fluid stored in deep reservoirs is believed possible. In May 2014, seven boreholes were drilled in the Geitafell metamorphic aureole to reconstruct P-T conditions of the high temperature stage of the hydrothermal system. In this study, we present the results of the fluid inclusion (FIs) study and isotopic data of eight core-samples and two lava samples collected at the surface, consisting of hydrothermally altered basalts. FIs were studied in hydrothermal quartz, calcite, and rarely in garnet by optical microscopy and microthermometry. No fluid inclusions were observed in other hydrothermal mineral. Sr, O and C isotope analysis were conducted on different hydrothermal minerals (epidote, garnet, zeolite, calcite) to derive the possible source of the fluid. In quartz and calcite, FIs were divided in four types on the base of the phase assemblage observed at room temperature: i) liquid-rich fluid inclusions (L+V), denoted as L1, with L/V ratio very variable from 70% to 30%; ii) liquid-only inclusions (L), denoted as L2, presenting no vapour bubble at room temperature; iii) vapour-rich inclusions (V+L), denoted as V1, where the liquid is confined to few percent of FIs volume ; iv) vapour only inclusions (V), denoted as V2, where the liquid phase is absent at the resolution of the optical microscope. In garnet, FIs were extremely rare and isolated inside the crystals. FIs are generally of L1 type with relatively constant L/V ratio (~70%); some dark inclusions were found in association with L inclusions. Microthermometric data indicates that L1 inclusions in quartz formed in a Th ranging between 260 and 300 °C, while calcite between 150°C and 250°C. Tm_{ice} ranged -1.1° to 0.0°C for both L and V inclusions, corresponding to salinity of 0 to 1.9 wt.% NaCl eq., although in some sporadic FIs salinity reached values of 5.5 wt.% NaCl eq.; in calcite Tm_{ice} is mostly in the range of the associated quartz, although it may locally present Tm_{ice} values as low as -6.9°C, corresponding to a salinity of 10.3 wt.% NaCl eq. In garnet, data are inhomogeneous, and Th spread in the 213-357°C range; Tm_{ice} is similar to that reported for quartz (-1.4°C to -0.4°C). The genetic coexistence of L1, L2, V1 and V2 in hydrothermal quartz and calcite of Geitafell system likely suggests that these phases precipitated during fluid immiscibility processes, such as boiling. Under this assumption, there is no need to apply a pressure correction to this system, and the temperature range of 260-300°C represents the trapping temperature for fluid in quartz at Geitafell. Moreover, FIs show evidences that the Geitafell hydrothermal system was mainly fed by low-salinity meteoric water, with local increase in fluid salinity due to boiling preocesses. Assuming garnet was not formed during boiling, an isochore starting from 357°C and 1.1 wt.% NaCl eq. was calculated. If a paleodepth of 2km is assumed in hydrostatic conditions, an ice cover of ~1000 m is necessary to obtain a trapping temperature above the supercritical temperature of pure water (374°C). $^{87}Sr/^{86}Sr$ isotope ratios in garnet, calcite and epidote are consistently comprised between 0.703214 and 0.703889, indicating the source fluid has requilibrated with the host basalt rocks. $\delta^{18}O$ and $\delta^{13}C$ of calcite range from -1.21‰ to +11.96‰, -6.06‰ to -4.62‰, respectively. Recalculated $\delta^{18}O$ of the fluid ($\delta^{18}O_{H2O}$) based on FIs data are very different between superficial and boreholes samples. The first one are typical meteoric ($\delta^{18}O_{H2O}$ ~ -8‰), while the others are more positive ($\delta^{18}O_{H2O}$ up to +5‰), suggesting strong interaction of the fluid with the host basalt rock or low fluid/rock ratios. Recalculated $\delta^{13}C$ of CO_2 is in the range of -4.8‰ to -0.3‰, suggesting a mixed source of CO_2, i.e. atmospheric and magmatic.

3D geological, thermo-physical and rheological modelling for geothermal exploration: the case study of Ischia Island, Southern Italy

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In the frame of the “Geothermal Atlas for Southern Italy” Project, a detailed 3D geological, thermal and rheological model of Ischia Island was built by integrating geological, geophysical and geochemical data. A critical review of publicly available data allowed us to organize a complete dataset in Petrel (Schlumberger) environment for the 3D geological modelling. The geological maps, well data and several geophysical data were used to constrain the shallow part of the model. Seismic data were used to constrain the deeper level of the Ischia Island up to the Meso-Cenozoic Carbonate rocks. Moreover, in order to implement the thermal and rheological analysis, we modeled the deeper surfaces of crystalline basement and Mohorovičić discontinuity based on previous studies in literature. In the second step, we performed a 3D numerical modelling of thermal field by using the a priori geological and geophysical information and by consideration of thermo-hydraulic properties including internal heat production. We solved the heat and fluid transport equation in a conductive/convective steady-state regime. We simulated the effects on the thermal field of a laccolith intrusion at shallow level in the crust. Subsequently, a parameters optimization procedure was applied to minimize the difference between the computed and measured temperature data. Finally, the thermal model was used as a priori information to image the 3D rheological stratification beneath the volcanic Island of Ischia in order to understand the mechanical behavior of the crust in this area. As result of our study, we proposed the 3D geometry of the Brittle/Ductile transition, calculated numerically, for the active volcano of Ischia Island. The thermal field in the geothermal reservoir has also been Fig.d out.

Geothermal potential mapping: the VIGOR example

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The ratified Kyoto Protocol in 2005 establishes the target of greenhouse gases cap emissions for different countries in the future, with respect to 1990 levels, resulting in an emission reduction by 20% in 2020 and 50% in 2050 respectively. To gather these challenging targets, many efforts have been done, and are being done, to increase the use of renewable energy by private and public sectors. Geothermal energy can play an important role in the abatement of greenhouse gases, in particular spreading the exploiting areas in locations that have so far been considered less favourable. Carbonate reservoir usually present an excellent natural permeability and important geothermal gradient at depth for geothermal development of heat and power. Furthermore, permeable reservoirs have been investigated largely by the hydrocarbon industry up to now producing a large quantity of data. Harnessing subsurface data acquired by the hydrocarbon surveys into a geothermal prospector's perspective and to deploy numerical modelling and simulation to be able to assess techno-economic potential and underlying uncertainty at any point in the reservoir is a key to success for the assessment of undiscovered geothermal resources. In this study, a new approach for geothermal potential assessment was set up and applied in four regions of southern Italy. Our procedure, so called VIGORThermoGIS, relies on the volume method of assessment and uses a 3D model of the subsurface to integrate thermal, geological and petro-physical data producing as output, 2D geothermal potential maps for three different uses: district heating, district heating and cooling and electrical power production. In the studied regions the overall heat stored in the carbonate units within a maximum depth of 5 km results in the order of $4{\cdot}10^7$ PJ for a total area of 6 10^4 km^2. The total technical potential in the four regions is evaluated to be 2.1 10^3 GW_{th} for the district heating, 2.2 10^3 GW_{th} for the district heating and cooling and 77 GW_e for the electrical power production. Policy makers as well as investors can take advance from our resulting maps to establish new policies and to locate the main promising place for geothermal development, in agreement with low carbon international strategy.

Validation of laboratory results with in situ down-hole measurements of physical properties at virgin temperatures up to 340°C.

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Resistivity soundings are one of the most powerful prospecting tools in geothermal exploration as resistivity is highly dependent on many physical properties of interest, such as temperature, porosity, salinity and hydrothermal alteration. In essence, water-saturated rocks conduct electrical currents more readily than dry rocks and conductivity increases with increasing temperature. In high temperature areas where the host rocks are volcanic, alteration becomes the dominating conductivity factor at temperatures above 100°C, producing the characteristic resistivity image, i.e. a conductive cap underlain by a resistive core. Comparison of borehole lithology and resistivity has confirmed the correlation between resistivity and alteration (see e.g. Árnason et al., 1987). Furthermore, experiments have been performed in sophisticated laboratories to find the relation between resistivity and specific physical properties, such as salinity and temperature (see e.g. Flóvenz et al., 2005; Kulenkampff et al., 2005). The actual change in resistivity as a function of temperature in natural conditions has not been investigated thoroughly. This was done as a part of IMAGE. Well KJ-18 in Krafla high-temperature geothermal field, NE-Iceland was used for this purpose. The well is 2215 m deep and was drilled in the early 1980s. Although, rock temperature in the well exceeds 300°C, it is not usable for power production and was thus considered suitable for this study as well as for several other studies carried out within IMAGE. Cold groundwater was injected into the well for several months to cool it down prior to the experiment. After the injection was stopped, resistivity and temperature logs were carried out repeatedly to monitor the resistivity change with time and temperature as the well was heating up. During the first 48 hours, 11 resistivity logs and 8 temperature logs were performed. The following 12 days, a total of 6 resistivity and 3 temperature logs were added. After statistical analysis of the borehole logs in order to correct for drifts in the depth determination, obvious drop in resistivity is seen with rising temperature. The measured resistivity is though not directly linked to the conditions in the host rock. The effects of the well fluid must be removed and intrusion of well fluids into the host rock considered. Concurrently to this study, Cation Exchange Capacity (CEC) experiment of cuttings from well KJ-18 was performed. The aim of this task within the IMAGE project is to use the resistivity and temperature time-series together with results of the CEC study as well as various other geophysical logs and results from the subsurface geology and alteration to understand the relationship between borehole resistivity logs and the actual rock resistivity and temperature. The ultimate goal is then to put those results in context with resistivity data obtained from electromagnetic methods on the surface. At the upcoming IMAGE meeting in Pisa the first results of this study will be presented.

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Estimating fracture permeability from field data (Elba Island)

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Geothermal fluids circulation is strongly influenced by the geometry and permeability of geological body. The most effective permeability is produced by network of fractures. In exhumed geothermal systems it is possible to quantify permeability since the passage of fluids through fractures is marked by deposition of hydrothermal minerals. We present a simple field-based methodology to derive permeability from mineralized fractures. The areas under study are exposed in the eastern part of Elba Island (Tuscan Archipelago, Italy), an exhumed geothermal system triggered by the emplacement of a granitoid at mid-crustal levels (the Porto Azzurro monzogranite, 5.9 Ma). This Late Miocene geothermal system can be considered as a fossil analogue of the presently exploited Larderello geothermal field. In order to estimate the permeability at different structural levels, some key-areas have been selected; in particular, Cala dello Stagnone and Topinetti areas were chosen as representative of a deep and shallow structural levels, respectively. In each area, field data were collected by means of detailed structural maps (1:100), scan lines (about 13 m long) and scan boxes (40x40 cm^2, located along the scan lines); within each box, length, width and frequency of each generation of mineralized fracture was recorded and analysed, adapting existing algorithms to the study case. Cala dello Stagnone area is located in the south-eastern part of Elba Island and it is characterized by Paleozoic micaschist dissected by different generations of normal fault and fractures, mineralized by fine- grained tourmaline (schorl-dravite and/or uvite) and quartz. This area represents the deepest level of a geothermal system, and it is believed to be an analogue of the structural level where the seismic K-horizon have been highlighted in the Larderello geothermal area. The second study area, named Topinetti, is located in the north-eastern part of Elba Island and it is characterized by Triassic quartzite, affected by hematite+pyrite+quartz fault and mineralized extensional and shear veins. The estimated permeability values of both areas are in the range between 10^{-9} and 10^{-18} m^2. The variability is influenced by the width of the fractures rather than their length. The resulted values are comparable with the permeability data measured in the boreholes of the present active Larderello geothermal system.

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