Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Geothermal Exploration and Reservoir Assessment in Magmatic Systems
The IMAGE Project

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Keywords: IMAGE, geothermal exploration, reservoir assessment, magmatic systems, processes and properties, exploration techniques, field integration

ABSTRACT

IMAGE (Integrated Methods for Advanced Geothermal Exploration) was a four years EU funded research project that finished in late 2017. IMAGE involved 20 partners from 9 different countries. The main idea was to address the problems encountered in geothermal exploration and reservoir assessment through a three-step methodological approach. In IMAGE, these were 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 consisted of the following:

Firstly: 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. **Secondly:** 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. **Thirdly:** Integrate information and results obtained in IMAGE to develop solid methodology for exploration and assessment of high temperature geothermal fields in magmatic environment.

The research leading to these results has received funding from the EU 7th Framework Program, under grant agreement n. 608553 (Project IMAGE).

1. INTRODUCTION

IMAGE (Integrated Methods for Advanced Geothermal Exploration), the four years EU funded research project lasted from late 2013 to late 2017. The project developed a range of exploration and assessment methods for critical exploration parameters in geothermal reservoirs (e.g. temperature, flow rate, sustainability of flow) using an interdisciplinary and integrated approach based on three general pillars. The working concept of IMAGE is described in the Description of Work of the project (IMAGE, 2013) and demonstrated on Figure 1, with its basic subdivision into magmatic systems (subproject, SP2) and basement/sedimentary systems (subproject, SP3). In this paper the work within magmatic systems (subproject, SP2) will be discussed.

Each subproject was divided into three Work Packages (WPs) depending on the methodological approach. The **three** WPs included:

- Understanding the *processes and properties* that control the spatial distribution of critical exploration parameters at different scales. In particular focusing 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 of key *properties* to be used for predictive models, and exploration techniques

- Radically improving well established *exploration techniques* for imaging, detection and testing of novel geological, geophysical and geochemical methods to provide reliable information on critical subsurface exploration parameters. These methods included 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.

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

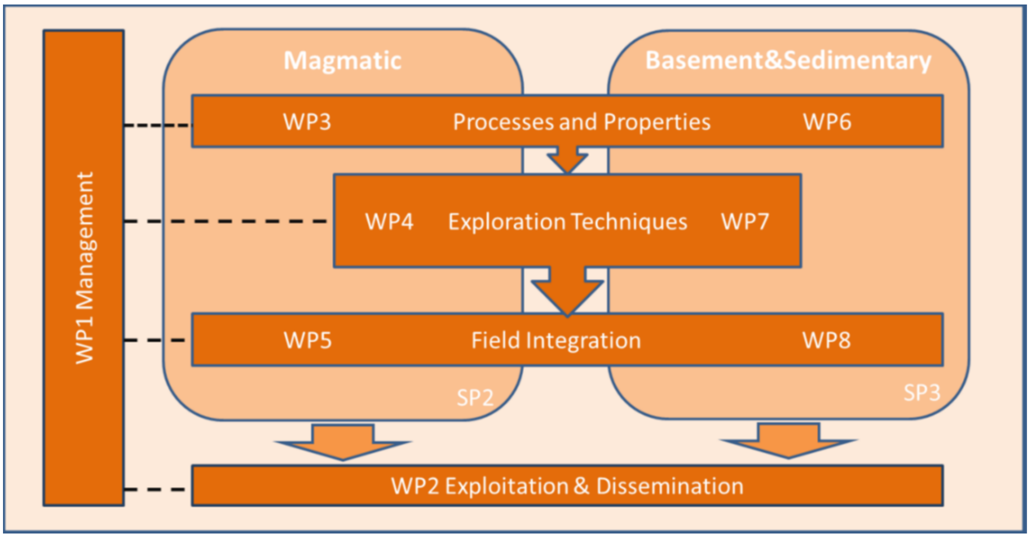

Figure 1. The working concept of IMAGE (IMAGE, 2013).

The methods were tested extensively and validated at new and existing geothermal sites in high temperature magmatic systems, including supercritical owned by the industry partners of the project. Application of the methods as part of exploration in newly developed fields provided means of direct transfer from the research to the demonstration stage.

A number of tests have been performed at existing sites (Brownfield) where the reservoir was already located, in Iceland and Italy in well-known subsurface structures, or targeted structures and parameters already known from other sources. This allowed to validate the novel techniques. Subsequently the methods have been applied to new sites (Greenfields) and used to complement ongoing exploration activity on the Azores. The 20 IMAGE partners from 9 countries and the test sites are shown on Figure 2.

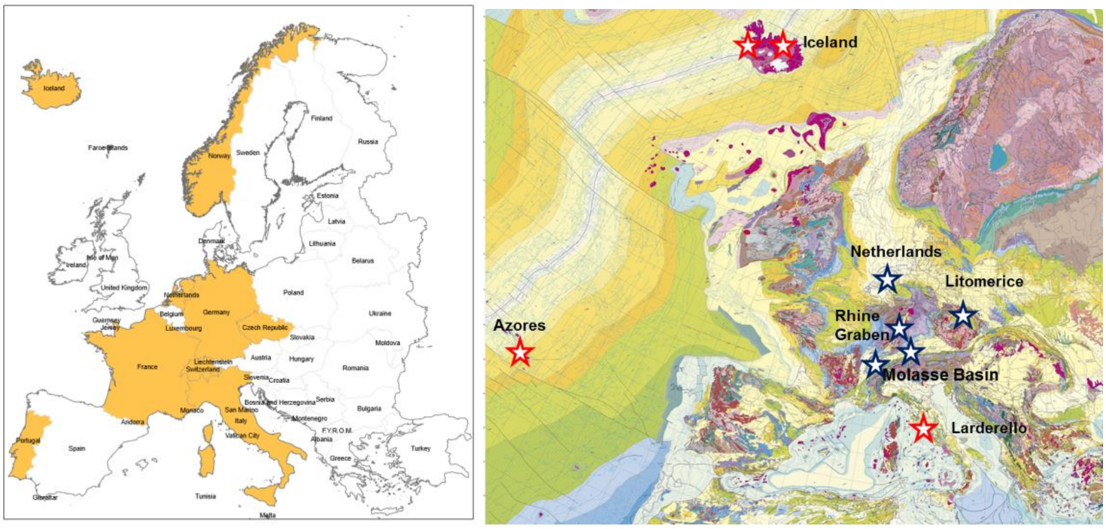

Figure 2. A map of the 9 IMAGE partner countries to the left and geothermal sites to the right where field tests and studies were performed. Red stars denote magmatic settings and the blue one's the basement/sedimentary settings (IMAGE, 2013).

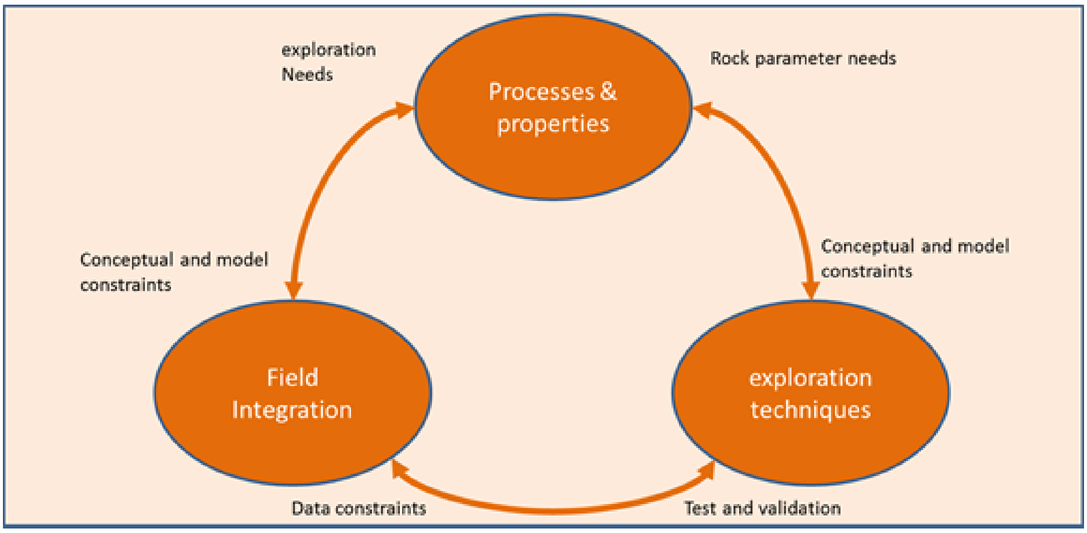

Figure 1. The concept of developing exploration methods in IMAGE: Advanced understanding of processes and properties of the system - development of exploration techniques - field integration and validation as a feedback loop (IMAGE, 2013).

Figure 3 shows the working concept of IMAGE and how the different Work Packages – the three general pillars - are intertwined and interconnected. Towards the end of the project a book was published summarizing the main findings of IMAGE, *Beyond a standarized workflow for geothermal exploration – Deliverable D2.05* (IMAGE, 2017).

2. PROCESSES AND PROPERTIES

In IMAGE one of the objectives was to gain 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. This was accomplished through field work and rock sampling in fossil and exhumed geothermal systems in key areas of eastern Elba Island, Italy and Geitafell, SE-Iceland (also through core drilling) where micaschist and magmatic rocks analogue to the deep reservoir of Larderello and Krafla, respectively, crop out. The structural study permitted to evaluate the distribution of fractures and their spacing, defining an average permeability of $5{\cdot}10^{-15}$ m^2 for the Elba Island and $5{\cdot}10^{-16}$ for Geitafell, respectively. Study of fluid inclusions indicates that high saline fluids were circulating in micaschist whereas very low saline fluids characterized the Icelandic example. In both cases P-T values compatible with fluids in supercritical conditions have been documented. The study of the exhumed geothermal systems permitted to demonstrate the key role of the transfer/transform fault zones as the most favorable structural conduits to channel deep geothermal fluids. Furthermore, the analysis of the deep structural levels of Elba Island and Geitafell as proxies of Larderello and Krafla shaded new light on the research of super-hot to supercritical fluids at technically reachable depth. By integration of laboratory and field data from exhumed geothermal systems proxies of active ones, reliable values of permeability, fluid properties and hydraulic conductivity can be defined. It implies that crucial data for predicting models can be obtained before drilling, with benefit for the exploration costs and economic outlook Liotta et al., 2015).

Figure 3. Inspecting core samples from Geitafell.

The exploitation of supercritical geothermal resources, i.e. subsurface fluids of extremely high temperature and pressure, may become a game changer in the power generation market. Supercritical conditions for pure water are reached at temperatures higher than 374 °C and about 221 bar pressure. In Reykjanes, SW- Iceland the reservoir fluids have the salinity of seawater which has a critical point at 406 °C at 298 bar.

IMAGE produced a database of parameters governing supercritical conditions and of places in Europe where they can be potentially encountered and exploited. Mapping of supercritical resources is mainly driven by thermal models derived from crustal and lithospheric constraints and data interpolation from available deep wells. Crustal thinning favors shallow magmatic emplacement. A combination of frequent seismicity and shallow brittle-ductile transition provides a good indication of geodynamic conditions favourable to shallow magmatic emplacement. The map of supercritical resources provides a clear overview of the distribution of potential resources in Europe, based on analytical data (see Figure 4). The map highlights areas where investment in knowledge has the highest probability of being productive, as in Iceland, where supercritical resources have been reached. Supercritical potential in Iceland is within a drillable depth of 4-5 km in the 32,000 km^2 volcanic rift zone where temperature above 400 °C and adequate pressure are expected (Manzella et al., 2017).

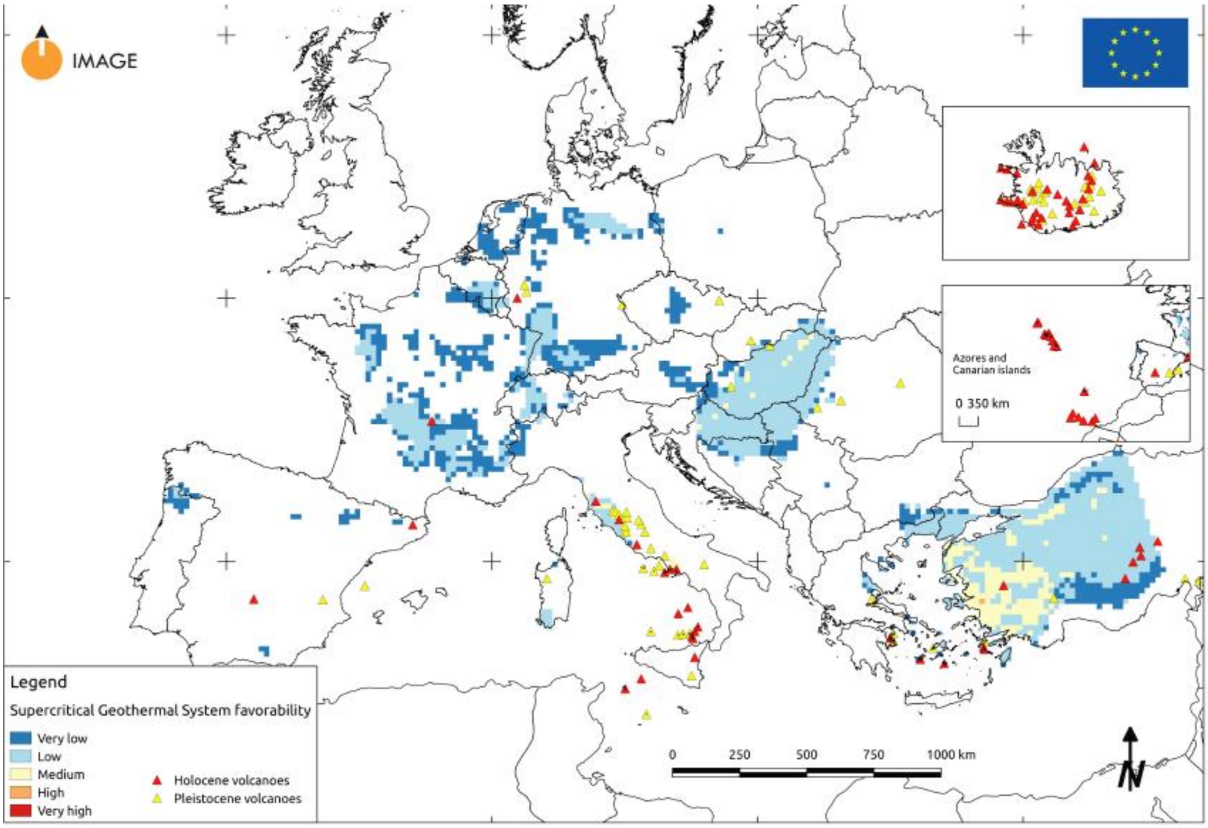

Figure 4. Supercritical geothermal system favorability (Manzella et al., 2017).

Growing economic interest in exploiting supercritical geothermal reservoirs calls for an improved understanding of fluid-driven processes in magma-related hydrothermal systems. The knowledge of the physical properties of the geothermal fluid and the formation interacting with the fluid above 374 °C and 221 bar is a prerequisite to develop valid reservoir models. Up to date, there has been a lack of calibration data for the models, as experimental set-ups capable of pore fluid flow are restricted to max. 250 °C due to the technical complexity of high temperature laboratory set-ups. In IMAGE experimental conditions were adapted to in-situ conditions in the deeper parts of the active Reykjanes (SW Iceland) and Krafla (NE Iceland) geothermal reservoirs. Borehole samples from both sites were studied as well as cores from an exhumed geothermal system in Geitafell (SE-Iceland), which is regarded as a proxy for the Krafla reservoir (Kummerow et al., 2017).

Exploitation of supercritical fluids is expected to increase the electricity generation of a single well substantially. Exploration of potential sites requires a good knowledge of the physical properties of rocks under these extreme conditions. However, there are no data available on physical properties of rocks on which geophysicists can rely on to localize these reservoirs. In particular, electrical conductivity (E.C.) data are lacking under these conditions. In IMAGE, experimental limitations were surpassed using a new E.C. cell allowing for laboratory measurements up to supercritical conditions on geothermal reservoir rocks. A first database was provided which highlights supercritical fluids signatures as a function of the rock-type (Nono et al., 2017).

A catalogue of rock physical properties, essential for geothermal exploration was developed within IMAGE. The PetroPhysical Property Database (P^3) contains laboratory-measured rock properties complemented by meta-information for further evaluation of the data. The database provides easily accessible information on physical rock properties for geothermal exploration and reservoir characterization in a single compilation and represents rock samples from all over the world. It is a publicly accessible web-based interface to facilitate specific queries on petrophysical properties with the aim of assisting new geothermal projects with the first assessment of geothermal rock properties (Bär et al., 2017; Mielke et al., 2017).

Smectite is a good electrical conductor compared to the surrounding minerals in hydrothermal systems. Therefore, resistivity methods are used to locate a shallow “clay cap”, usually present at the top of hydrothermal reservoirs and richer in smectite than the rock underneath. In IMAGE, Cation Exchange Capacity (CEC) was measured by the back titration of Copper–tri-ethylenetetramine adsorption in four wells within three different high temperature areas in Iceland and the results compared with resistivity logs in the wells (Weisenberger el al., 2019). Furthermore, electrical conductivity and porosity was measured on cores from Krafla, NE-Iceland. They proved to be consistent with borehole logs when the in-situ temperature is low (inactive section of the geothermal system), while a significant effect of temperature is observed in the active section (Lévy et al., 2018).

3. EXPLORATION TECHNIQUES

Another objective within IMAGE was to 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; processed and interpreted – the best approaches for exploration of magmatic geothermal fields were 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. VSP borehole experiment was carried out in Krafla, NE-Iceland; crustal stress and fracture permeability were estimated in Iceland; tracers for supercritical conditions have been investigated and tested, and deep structures imaged with electrical resistivity in Larderello, Italy. Finally, a method was developed to measure high temperature by the production of synthetic fluid inclusions in high temperature geothermal wells.

A dense seismic network was installed on and around the Reykjanes peninsula in SW Iceland consisting of 30 on-land stations and 24 Ocean Bottom Seismometers (OBSs – see Figure 6) in addition to 30 other stations from local networks on the peninsula (see Figure 5). During a period of about 17 months over 2000 earthquakes where recorded along the mid-ocean ridge on-land and off-shore and in the geothermal area at the tip of Reykjanes peninsula. The hypocenters line up along the spreading axis. Earthquake hypocentres associated with the geothermal area occur in the uppermost 2 km while events along the spreading axis occur at 4–6 km depth on-land and appear to deepen with increased distance from the shore, probably associated with the rifting processes. In the geothermal area itself earthquakes are located at shallow depths, underlain by an aseismic zone with no activity present. NNE of the geothermal area, a cluster of around 200 earthquakes was induced by the onset of injection in a newly drilled borehole. The Vp/Vs ratio was of 1.78 which is consistent with earlier studies. Focal mechanisms calculated for selected events reveal a regime dominated by strike-slip and normal faulting (Blanck et al., 2019).

Additionally, 3D S-wave tomographic image over the western Reykjanes Peninsula high-enthalpy geothermal fields was produced and the reliability of the tomographic results for different resolutions evaluated through simulated and real data. The 30 broadband stations were used, and ambient noise seismic interferometry applied for each station-pair (Martins et al., 2019).

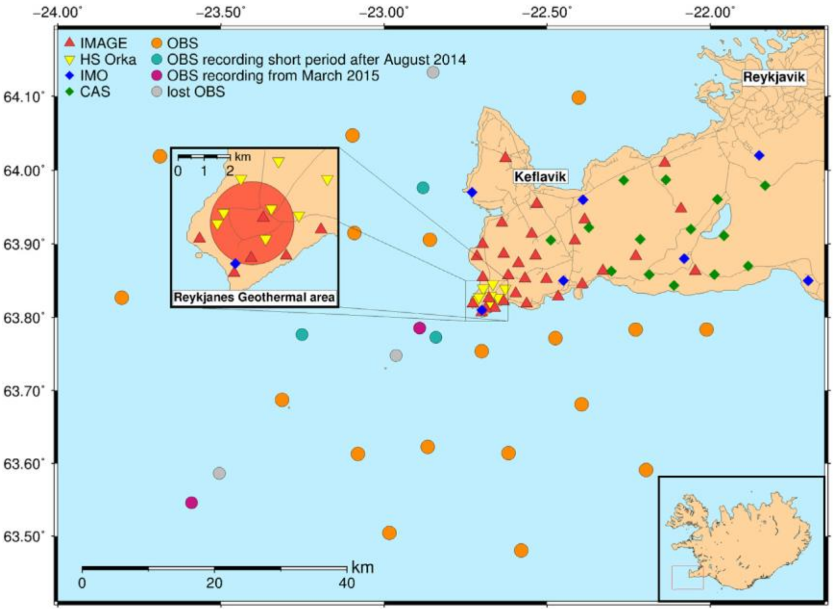

Figure 5. Seismic network on the Reykjanes peninsula operating from 2014 to 2015. The circles and the red triangles represent OBSs and on-land IMAGE stations, respectively. Other seismic stations in the area are the permanent network in Iceland operated by the IMO (blue diamonds), the local network in the geothermal area operated by ÍSOR on behalf of HS Orka (yellow triangles) and a long-term network monitoring activity in a non-exploited geothermal system in the east of the Reykjanes peninsula operated by CAS (green diamonds). Taken from Blanck et al., 2019.

The distribution of seismic velocities, Vp/Vs ratio, and attenuation properties of rock reflect underground geology, and fluid/rock distribution and conditions. The distribution of elastic properties is a good complement for integration of seismic observations in exploration and monitoring. The outcome of the tomographic images obtained by the seismic tomographic methods performed during the IMAGE project in Reykjanes indicates:

- Several mechanisms of seismic activity, both natural and injection induced.
- Low Vp velocity in the upper reservoir until few km depths.
- Low Vp/Vs ratio at depth, indicating the absence of large magma reservoir.

These results were confirmed by the drilling of IDDP-2 down to a depth of 3.6 km.

Figure 6. Retrieving an Ocean Bottom Seismometers (OBS with the assistance of the Icelandic Coast Guard.

Seismic methods are particularly suited for investigating the Earth's 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. IMAGE's approach was to apply the fibre optic distributed acoustic/vibration sensing (DAS/DVS) technology to acquire seismic data with a very dense resolution in time and space.

A fibre optic cable was installed behind an anchor casing of a newly drilled geothermal well within the Reykjanes geothermal field in SW-Iceland. Additionally, a 15.3 km fibre optic telecommunication cable at the surface was used for the IMAGE experiment (Jousset et al., 2018). A DAS read-out unit was connected to the downhole cable, a second unit to the surface cable. Seismic data were collected continuously for 9 days with a sampling rate of 1 kHz and a spatial resolution of 4 m at the surface and 1 m downhole. During this period 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. Two explosive sources were used on-land on both ends of the surface cable and seven shots were performed in the surrounding sea. Several natural seismic events could be recorded with magnitudes of up to ML 2.3.

For active seismic recording, seismic hammer shot recordings along the surface cable were performed and traced for up to 300 m from individual shot locations. During the recording period, several earthquakes occurred, and passive seismic data could be acquired along the surface cable as well as the downhole cable. The P- and S-wave arrivals could clearly be separated. DAS proved to be suitable for recording seismic data with a high spatial and temporal resolution in magmatic environments (Jousset et al., 2018).

Using fibre optic cables as seismic sensor is, therefore, a cutting-edge technology which allows recordings in wellbores with high spatial and temporal resolution at temperatures exceeding operating temperatures of conventional geophones.

Mapping of reservoir properties in magmatic provinces represents a major challenge for the geothermal industry. The challenges arise partly from the heterogeneous nature of the igneous rocks in the subsurface, but also due to the high cost or lack of appropriate technology. The development of new imaging technologies may help to identify new geothermal resources and assist in cost-efficient development of igneous reservoirs.

Vertical Seismic Profiling (VSP) had not been done in a high temperature area in Iceland before IMAGE. The Krafla geothermal field was chosen as a VSP test site since its subsurface structure is quite well known from surveying, drilling and geothermal production during the past four decades. Magma was also recently drilled into in this area. A successful VSP seismic data acquisition was completed during two weeks in June 2014, using a VSP string with 17 receivers (see Figure 7). The survey encompassed several different experiments including; zero-offset VSP, far-offset VSP, multi-offset VSP, source comparison, and passive seismic monitoring. In addition to the VSP experiments, sonic and televiewer logs were acquired in one of the VSP test-well (K18) and borehole cuttings were reanalyzed to correlate the geological structure to the VSP data (Millet et al., 2018). Prior to the VSP experiment the test-well (K18) had to be cooled down to allow downloading of the VSP seismic instruments. Afterwards resistivity was measured in the well while it was being heated up to monitor resistivity changes with temperature (Vilhjálmsson et al., 2016).

The study showed that VSP experiments have a clear potential for imaging igneous complexes in geothermal areas including:

- Upgoing P- and S-wave reflections can be recorded within the drilled sequence and from below the borehole.
- Zero-offset VSP data can be used to obtain velocity-depth functions, Vp/Vs ratios, and one-dimensional stacks.
- Multi-offset VSP can be used to image dipping and sub-well targets away from and below the borehole.

However, the VSP method needs refinements to be more cost-efficient and downhole instruments would benefit from a higher temperature rating for routinely use (Kästner et al., 2018; Reiser et al., 2018).

Figure 7. From the VSP experiment in Krafla, NE-Iceland.

A comprehensive understanding of the in-situ stress state is a fundamental component for a safe and sustainable subsurface utilization, e.g. for geothermal and hydrocarbon reservoirs. The orientation of the maximum horizontal stress S_{Hmax} and the stress regime provide valuable information on the stress state. In the framework of the IMAGE project the World Stress Map database for Iceland and Europe have been updated from the last release in 2008. The update of the Iceland stress map increased the amount of data records from 38 S_{Hmax} orientations in 2008 to 495 data records (Ziegler et al., 2016). This makes Iceland one of the countries with the highest data density per area. The European update more than doubled the amount of data records in the World Stress Map database (Heidbach et al., 2016). This massive increase in available data not only provides a comprehensive image of the stress state but also allows the statistical analysis of the stress pattern.

One of the objectives of the IMAGE project has been development and qualification of tracers for magmatic reservoirs which could be stable at supercritical conditions. Tracers chosen for these experiments was a family of perfluorinated cyclic hydrocarbons (PFC) used extensively by oil and gas industry. The results of these experiments have shown that PFCs are indeed stable around critical point of water (374 °C, 218 atm) for more than 2 months. Surprisingly the PFC did not pass through a column packed with crushed rock from Krafla field on Iceland. The same experiment was repeated, replacing the Krafla rock with silica sand. This time all the tracers were detected after they passed through the column (Viig et al., 2017).

In 2016 a reservoir tracer test was conducted as a part of IMAGE in the Krafla geothermal field, NE Iceland (Óskarsson et al., 2019). Three liquid-phase tracer compounds were injected into one of the wells; two naphthalene sulphonate molecules and potassium iodide. Tracer recovery was only observed in one out of five monitoring wells. The first tracer breakthrough was observed within 26 hours of injection and the recovery peak about 15 days after injection. One-dimensional convection-diffusion models were fitted to the measured concentration data, resulting in a good fit for all tracer types. The excellent correspondence of the calibrated parameters for all three tracers suggests that no thermal breakdown of two NDS compounds has occurred.

Recent deep drilling projects in magmatic areas suggest that super-hot geothermal systems can be a possible target for future geothermal exploration either for the direct exploitation of fluids or as potential reservoirs of Enhanced Geothermal Systems (EGS). Reservoir temperature measurements are crucial for the correct assessment of the geothermal resources. However, high-temperature determinations (>380 °C) in super-hot geothermal systems are often difficult or impossible by using either pressure gauges (Kuster device) and electronic devices. To overcome this challenge a new method for high-temperature borehole measurement was developed within IMAGE, based on the production of synthetic fluid inclusions.

Trapping temperatures of synthetic fluid inclusions formed in well KJ-35 in Krafla, NE-Iceland at 1750 m depth were close to the measured temperature, see Figure 8. A test carried out in a well in Larderello geothermal field in Italy indicates that trapping temperatures of synthetic fluid inclusions can also estimate temperature as low as 250°C. Such results indicate that the proposed method is highly valuable for estimating temperature in geothermal wells. Laboratory experiments also showed that such method produces synthetic fluid inclusions recording external temperature of up 400 °C in less than two days. Moreover, the method can be potentially applied for temperature measurements of geothermal wells with temperature up to 424 °C (i.e. the working temperature limit of the utilized commercial micro-reactor). This limit can be exceeded by using a different micro-reactor.

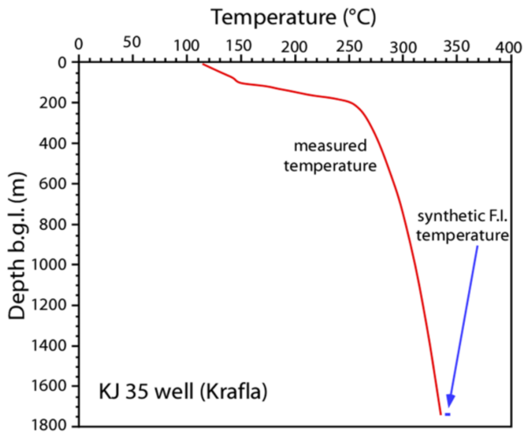

Figure 8. Temperature (measured by Kuster device) as a function of depth in well KJ-35 in Krafla, NE-Iceland compared with the temperature evaluated from synthetic fluid inclusion produced at a depth of 1750 m (Ruggieri et al., 2016).

4. FIELD INTEGRATION

The third and final objective was to integrate information and results obtained in IMAGE to develop solid methodology for exploration and assessment of high temperature geothermal fields in magmatic environment. This included the development of a workflow for a 3D model representation and visualization (bringing together results based on characterization, exploration results and modelling of known physical properties) of two existing Brownfields; in Krafla, NE-Iceland and Larderello, Italy and apply the workflow to the less known Greenfield magmatic system in Pico Alto, Azores. Furthermore, MT-inversion techniques with external constraints have been tested and developed, analogue modelling for fracturing has been performed and a strategy plan for targeting a deep well at supercritical fluid conditions has been made.

The drilling history of Krafla spans 43 years. The geothermal field is defined as a *Brownfield* due to its extensive exploration history and geothermal development. In IMAGE, a geological static field model was constructed based on geophysical and geological data in order to gain a better understanding of the system, whose structure has proven to be rather complex. Data compilation and comparison gave an overview of available interpretation that is essential for geoscientists to highlight gaps of understanding and to facilitate the next logical steps. Having a common platform where all results are brought together, saves time and results in a faster way of comparing multi-disciplinary dataset. The geological model is composed of a lithological and a structural model, including new and revised borehole data for lithological intra-well correlations, ranked surface and subsurface data, such as gravity, magnetics, resistivity, seismic data, and fault and fissure interpretation. Specifically, 1D and 3D resistivity inversion models were compared to analyse the structural trends in an interactive 3D work environment (Thorsteinsdóttir, 2017; Thorsteinsdóttir et al., 2019).

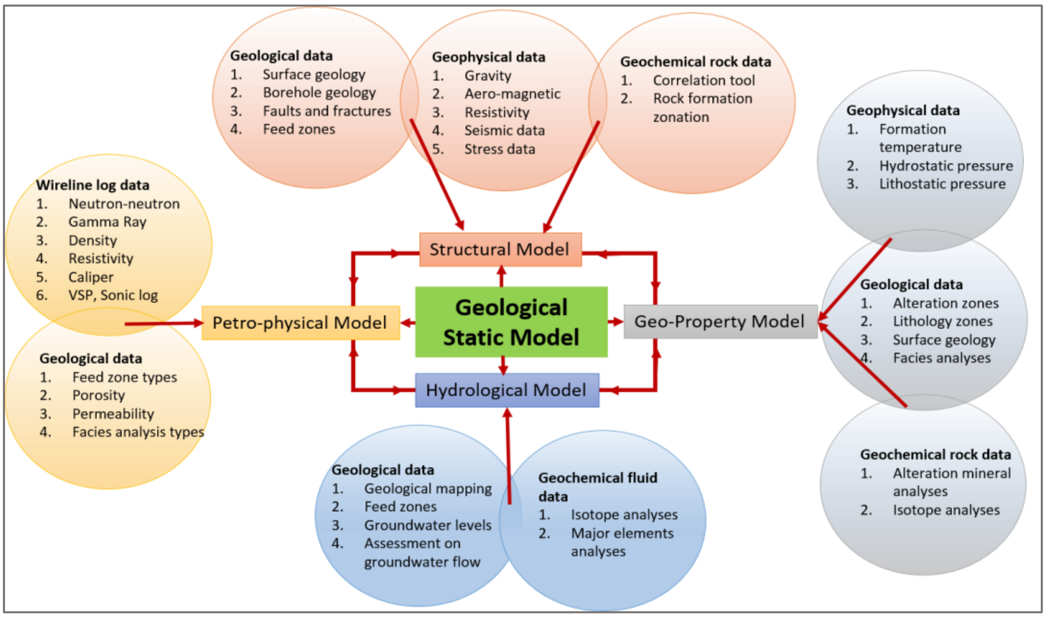

Figure 9. Subdivision of main datasets used for the construction of 3D geological static models (Thorsteinsdóttir, 2017).

Based on lessons learned during the construction of the 3D geological static model for the high temperature geothermal field of Krafla, NE-Iceland, as well as literature study from other areas, workflow for conceptual modelling has been proposed (see Figure 9). The workflow describes sub-division of available data and how steps are preformed throughout the modelling process. It has been tested in the less known and the less exploited Pico Alto, Greenfield high temperature geothermal area on Terceira Island, Azores (Thorsteinsdóttir, 2017).

The broader conceptual model of the Larderello geothermal system, including its deepest roots possibly in supercritical condition and its complex heat source evolution, has been defined with IMAGE. Very important information was retrieved about the fluid-rock interaction at supercritical conditions. This knowledge is of primary importance for the exploration in Larderello as well as other high temperature fields worldwide (Gola et al., 2017).

The intrinsic complexity of geothermal systems is a major challenge. The most efficient way to mitigate the related geological risk is the collaborative integration of multidisciplinary data and interpretations into a geo-model. An integrated, multi-disciplinary approach allowed a better understanding of the deep roots of the Larderello geothermal field. In the study area, temperature exceeding 400 °C is recorded at a depth of less than 3 km and the very high impedance of a seismic marker hints toward the presence of supercritical fluids above a shallow magma body (Calcagno, 2015).

3D inversion of MT data is a highly underdetermined and unstable problem. A variety of resistivity models can explain the same dataset. Joint interpretation using different data has been a major challenge within the MT community. Applying external constraints in the inversion from other geoscientific disciplines might be one of the solutions. Within IMAGE, three different datasets were proposed to be used to better constrain 3D inversion of MT-data.

- TEM data to correct for the static shift of MT data, and constrain the uppermost part of the model.
- Fictitious borehole data were used as starting and prior models in the inversion to better constrain the location of the low-resistivity (clay) cap.
- Information on the brittle-ductile boundary from seismic data were used to define the upper boundary of the deep lying low-resistivity layer, which underlies most of Iceland.

The results of the fictitious borehole case demonstrated how resistivity measurements from boreholes can be used to better constrain the location of the low-resistivity (clay) cap. The resistivity borehole data need to be of good quality if they are to be used as a-priori information. An aseismic region in the Námafjall area, NE-Iceland marks the location of the brittle-ductile boundary. At a similar location the deep lying low-resistivity layer of Iceland domes up. Assuming that the two observations have the same origin, an attempt was made to use this inferred connection, by making the deep low-resistivity coincide with the aseismic zone in the initial and prior models. The strategy was worthwhile and should be explored further. However, in this study it did not result in a better data fit than previously obtained probably due to limited resolution of MT data of anomalies at such depths (Benediktsdóttir et al., 2017).

Integrated (MT and DC) surface and in-hole resistivity survey has been developed within IMAGE, which provided new insights in the deep structure of the Larderello geothermal system in Italy (Santilano et al., 2015). A probabilistic and evolutionary algorithm was successfully tested for the simultaneous analysis of Magnetotelluric (MT) and Time Domain EM (TDEM) data while correcting for galvanic distortion (static shift) of MT data (Santilano et al., 2017).

In strategy for supercritical well design, possible scenarios of temperature, pressure and fluid chemistry play a big role. The learning curve of designing and drilling deep geothermal wells aiming for superheated/supercritical conditions has been steep and many challenges have been solved along the way over the past decades. However, some challenges remain unsolved and undoubtedly more will emerge in future deep drilling projects. Proper material selection for such harsh environment, fluid handling, well control, casing and wellhead design for stable structural integrity are the keys for utilizing future deep geothermal resources. The IMAGE project has been a part of the design phase by involving scientists, engineers and other technical personnel.

5. CONCLUSION

IMAGE was the framework for testing more than 20 novel geological, geochemical and geophysical exploration methods and techniques of direct relevance to industry workflows. More than 5 best practice documents, catalogues and databases were produced for guidance in exploration workflows and as constraints for models. More than 200 publications have been generated in peer reviewed journals and conference proceedings, more than 50 deliverables were reported. Furthermore, IMAGE has contributed to the geothermal knowledge network between universities, knowledge organizations, and geothermal industry.

A large number of methods and technologies of IMAGE have shown their practical value in industry workflows. However, many technologies need to be further developed, but have great potential.

IMAGE demonstrates rapid and radical advances, including borehole fibre-optic, passive seismic and resistivity imaging and modelling at high temperature conditions. These have been dedicated to the major challenges at hand in geothermal exploration, with major breakthroughs in a relative short time span of four years.

IMAGE allowed the implementation of a reliable workflow at different scales to help industries in their choices for deep geothermal exploration. The static model representing the geological structures is the skeleton of the physical and dynamic models, like thermal, mechanical and groundwater flow models, which help industries to determine the location of hidden deep reservoirs.

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