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IMAGE
Integrated Methods for Advanced Geothermal Exploration

IMAGE-D2.7:
Potential environmental impacts of the Project

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1 Introduction

The project Integrated Methods for Advanced Geothermal Exploration (IMAGE) is developing a reliable science based exploration and assessment method to geothermal reservoirs using an interdisciplinary approach based on three general pillars:

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

2. Improving well-established exploration techniques for imaging and detection beyond the current state of the art and testing of novel geological, geophysical and geochemical methods to provide reliable information on critical subsurface exploration parameters. Methods include a) geophysical techniques such as ambient seismic noise correlation and magnetotellurics with improved noise filtering, b) fibre-optic down-hole logging tools to assess subsurface structure, temperature and physical rock properties, and c) the development of new tracers and geothermometers.

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

The IMAGE project consists of eight work packages (WP) in total, each of them covering several tasks and activities. As defined in WP2 Task 2.7., the IMAGE project has been subject to identification of potential environmental impacts.

2 Evaluation method of environmental impact significance

The list of project activities is given in Tab. 1. Although most of the IMAGE project activities do not reveal any impact on the environment (e.g. management activities, laboratory work, data processing, dissemination activities etc.), some of them including primarily field work were subject of rigorous assessment and evaluation. Project activities in Tab. 1 have been marked if they are or are not relevant for the environmental assessment considering following aspects: vegetation, wildlife, water, soil, air, noise and vibrations.

Tab. 1 Overview of all IMAGE activities. Activities marked + in the PEI column (potential environmental impact) are subject for the description of the environmental impact in further chapters.

WP	Task	Particular activities	PEI
3	3.1	Field work and rock sampling in fossil and exhumed geothermal systems	+
3	3.1	Laboratory analysis of the samples	-
3	3.1	Reconstruction of the kinematic and geometric features of the active deformation in presently active fields	-

WP	Task	Particular activities	PEI
3	3.1	Integration of the geochemical and isotope characteristics of the fossil fluids	-
3	3.1	Analysis of fracture geometry and its distribution in boreholes	-
3	3.1	Usage of information on the geometry of the main structures by correlating field data	-
3	3.2	Assessment of chemical water - rock interactions by hydrothermal autoclave apparatus at variable supercritical pressure-temperature	-
3	3.2	Establishment of the chemical evolution of fluids	+
3	3.3	Build a database of existing measurements of physical properties at reservoir temperature	-
3	3.3	Measurement of geomechanical, electrical and hydraulic properties on rock samples from exhumed and active systems by laboratory investigations	-
3	3.3	Validation of laboratory results with in situ down-hole measurements of physical properties at virgin temperatures	-
3	3.3	Assessment of the sensitivity of exploration techniques by a quantitative link between chemical properties of fluid/rock and electrical resistivity	-
4	4.1	Deployment of a dense network of seismic broadband stations	+
4	4.1	Reviewing of tomography seismic imaging with advanced techniques and conventional passive techniques and conventional active seismics	-
4	4.1	Processing of seismic data obtained in Reykjanes using the best defined techniques to image Reykjanes geothermal field prior to drilling	-
4	4.1	Validation of images of velocity models obtained by different techniques	-
4	4.1	Setting-up of a fibre-optic cable in a deep well to test and apply the cutting edge Distributed Acoustic Seismics technology	-
4	4.1	Identification of structural time dependence characteristics by natural seismicity due to exploitation and/or other dynamic excitation	-
4	4.2	Active seismic profiling VSP	+
4	4.3	High temperature measurement	+
4	4.4	Well-bore breakouts data analyses in geothermal systems	-
4	4.4	Analysis of fracture network and kinematics in the field	-
4	4.4	Comparison of fracture network in borehole and the structural geologic study at the surface	-
4	4.4	Analysis of focal mechanisms from local micro-seismicity	-
4	4.4	Integration with the regional tectonic data and geophysical models	-
4	4.5	Construction of experimental set-up for supercritical conditions, static batch autoclave experiments	-
4	4.5	Fluid flow experiments under supercritical conditions in a flow cell	-
4	4.5	Field tracer tests	+
4	4.6	Imaging deep structure with electrical resistivity	+
5	5.1	Development of workflow for a 3D model representation and visualization to bring together multidisciplinary results based on characterization, exploration results and modelling of known physical properties	-
5	5.1	Building of a-priori 3D model for 2 selected brownfields	-
5	5.1	Updating of conceptual model with exploration results	-
5	5.2	Definition of new analogue modelling procedures and requirements to predict the 3D complexity of fracture network development	-
5	5.2	Test and validation of these methods in reproducing mechanical features related to the emplacement process in fossil sites	-
5	5.3	Development of software that regularizes the inversion, by imposing a-priori constraints on the model.	-
5	5.3	Optimisation of image resolution by connecting a-priori information on geometrical distribution of the main geological and physical units with their contrasting resistivity	-

WP	Task	Particular activities	PEI
5	5.3	Application in two greenfield sites.	-
5	5.3	Development of recommendations for optimised MT site spacing for different a-priori constraints	-
5	5.4	Making of a strategy plan for targeting a deep well at supercritical fluid conditions.	-
5	5.4	Development of a strategy for the well design of IDDP-2 based on an Expert group technical meeting and finalization of the selection of the drill site.	-
5	5.5	Evaluation of the potential of magmatic supercritical systems and creating of a European database of possible geothermal sites with potential supercritical conditions.	-
6	6.1	Inventory of key factors controlling the permeability in prospective sedimentary and basement rocks at great depth and different geological contexts	-
6	6.1	European reference catalogues for thermal and mechanical properties of different rock types	-
6	6.1	European deep structural and generalized compositional input for physics based models capable of bridging European to regional scales	-
6	6.1	Physics based reference models for temperature, stress and seismogenic characterization at European scale	-
6	6.2	Building of 3D regional model framework for "static" geological models for the Molasse Basin and Upper Rhine Graben and capability to interface with dynamic models and exploration methodological processing and results	-
6	6.2	Populating of 3D regional model with predictive method results of Task 6.3	-
6	6.2	Diagnostic analysis of region specific key parameters and processes	-
6	6.2	Identification of well layouts for maximum natural hydraulic efficiency based on synthetic conceptual models derived from key situations	-
6	6.3	Application of geomechanics based techniques to evaluate the regional stress field from well data, natural earthquakes and neo-tectonics	-
6	6.3	Investigation of the physical linkage between power-law scaling relations inferred for observed stress heterogeneity, b-value of induced seismicity and fracture scaling using data-constrained models	-
6	6.3	Relation of seismic catalogues to spatially differentiated seismogenic characterization for fracture and faults	-
6	6.3	Predictive integration: integrate above into predictive models approaches for temperature, stress and fracture permeability at regional scale	-
7	7.1	Evaluation of the feasibility of detection of fluid circulations along faults with deep roots, and deep bed rock	-
7	7.1	Optimisation of dedicated VSP acquisition layouts testing dedicated VSP performance	-
7	7.1	Testing and refinement of seismic processing of existing seismic datasets for selected sites	-
7	7.1	Development of best practice guidelines for processing and analysis of VSP data	-
7	7.2	Definition of criteria for the use of ambient noise and interferometry techniques	-
7	7.2	Evaluation of the applicability of interferometry for broadband receivers to analyse regional variations in cover-basement velocity anomalies indicative for fluid content	-
7	7.2	Prognosis imaging resolution for specific regional and local settings offset against seismic receiver/monitoring density	-
7	7.3	Scoping of potential auxiliary chemical geothermometers and tracers for the origin and deep circulation of fluids for medium-high temperature geothermal reservoirs	-
7	7.3	Theoretical development of dedicated geothermometers and tracers	-
7	7.3	Geothermometers and tracers - field validation	+
7	7.4	Resistivity techniques - testing CSEM/MT	+
7	7.5	Development of practical methods to transfer these field data through quantifiable values to local models.	-
7	7.5	Collect field data on sedimentary heterogeneities, and fracture and fault heterogeneities	-

WP	Task	Particular activities	PEI
7	7.6	Organisation of Technical Meetings	-
8	8.1	Selection of exploration techniques	-
8	8.2	Application of exploration techniques	+
8	8.3	Construction of site geological models honouring high resolution 3D structural and compositional information	-
8	8.3	Application of thermal and gravity backstripping of regional to local models	-
8	8.3	Building of a stress heterogeneity and seismogenic model	-
8	8.3	Building of a stress model for the considered sites	-
8	8.3	Building of a hydrothermal model on the basis of process based concepts for opening and healing of fractures for the considered sites	-
8	8.4	Combination of results on predicted parameters from the previous task in an integrated 3D framework and application of multi-criteria performance assessment on these parameters	-
8	8.4	Partially couple models based on physical integration of previous local models	-
8	8.4	Evaluation of the merits of the new workflow through comparison of performance by adopting standard and improved prediction performance	-
8	8.5	Proposition for integrated exploration method	-

For the purpose of the assessment of potential environmental impacts a three-step classification has been applied (A, B, C, see Tab. 2). A significance of potential impacts has been determined according different factors such as extent of the affected area, duration of evaluated activities, interactions with the surrounding environment, etc.

Tab. 2 Applied classification of potential environmental impact

Impact classification	Description
A	High significance
B	Medium significance
C	Small significance

3 Description of potential environmental impact for particular IMAGE activities

The potential environmental impact of the pertinent activities and its significance is described here below. Tab. 3 provides an overall overview of environmental impact classification.

- *Task 3.1 Field work and rock sampling in fossil and exhumed geothermal systems*
  This Task includes collection of core samples in 50 m deep core holes. Environmental impacts depend on the way of rock sampling in exhumed geothermal systems in Elba island in Italy and in Geitafell in Iceland. Local surface degradations might be foreseen, however the overall impact is expected to be negligible due to small sample size. Collection of core samples is carried out from already existing boreholes.

  Impact classification: C - vegetation, wildlife and soil

- *Task 3.2 Establishment of the chemical evolution of fluids*
  Chemical evolution of fluids is to be established as a function of temperature (50-1100°C), pressure (0-500bar) and mass flow (10-100kg/s) from heat source to geothermal reservoir. The focus will be on fluid concentrations and isotope ratios of volatile species that are released from

magma during cooling. Steam and liquid samples will be collected from 3-4 geothermal systems in Italy and Iceland and their fluid compositions used to validate the chemical evolution outlined above. The samples are to be handled carefully to avoid interaction with the surrounding environment.

Impact classification: C - vegetation, wildlife, water and soil

- *Task 4.1 Deployment of a dense network of seismic broadband stations*
  Passive and active seismic is to be carried out at the Reykjanes high temperature field during this activity.
  - Passive seismic measurements are to be recorded during 1,5 year when the stations are removed. The stations shall be placed very shallow to less that 1 m depth.
  - Active seismic shall last a few days. The shots shall be generated at a few meters depth, one shot in 0,5 km depth.

  Seismic stations are to be deployed inland (30 over area 50x30 km) and off-shore (24 over area 100x100 km). Inland locations are characterised by no or very little vegetation cover, therefore the potential impact on vegetation is negligible. However, the off-shore locations are rich in fish occurrence. These activities can effect fish during off-shore experiments. Fish might be disturbed during the installation, shots, recording and removing of the equipment. The installation of equipment on the surface requires the site preparation (making holes for stations, etc.).

  Impact classification: C – vegetation, B – wildlife (fish), C - soil

- *Task 4.2 Active seismic profiling (VSP)*
  Application of VSP borehole experiment will be carried out inland in the Krafla high temperature field, NE Iceland 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. The expected affected area is 4 x 4 m km by applying 2 air-gun pits. Two boreholes 2,2 km deep shall be used for the experiment. Additionally 10 new holes are to be drilled to the depth of 9 m and shall be used for shots (1 shot/well) using repeated explosions (Viti lake). The vegetation is absent as there is a bare soil with snow fields. These activities shall be finished within two weeks.
  Most significant impacts are expected to occur near explosion sites, including noise and dust.

  Impact classification: C – vegetation, wildlife, B - soil, air, noise

- *Task 4.3 High temperature measurement*
  A method to measure high reservoir temperature by the production of synthetic fluid inclusions will be developed using an apparatus placed in high-temperature geothermal wells. Synthetic fluid within the apparatus might contain some chemicals that - in case of accident - might have negative impact in contact with water, fauna and flora. These potential negative impacts are minimized to zero by proper apparatus handling, which is expected.

  Impact classification: C – vegetation, wildlife, water

- *Task 4.5 Field tracer tests*
  Both high temperature tolerant organic isomer and mineral salt will be injected with re-injection waters into a borehole that is in direct contact with magma. Their return will be monitored from production wells. In this field test, a family of tracers based on sulphonic acids and alcohols is used. The tracer tests using organic compounds (naphthalene sulfonate type) shall be applied in geothermal boreholes in the Krafla geothermal field in Iceland (36 km^2). The most significant environmental impact is for groundwater bodies, however the naphthalene sulfonates are environmentally safe (see paper of Greim et al., 1994) and toxicity and ecotoxicity of sulfonic acids is low (very low adsorption on the soils, no significant bioaccumulation expected, > 60%

degradability, no carcinogenic potential). Moreover, tracers will be considerably diluted by the formation water.
Occurrence of vegetation is limited to scarce boreal shrubs, mosses and wild grass.
The duration of tracer injection into the injection well shall be less than half a day. Subsequent tracer monitoring shall be carried out during the following 1-2 months.

Impact classification: B – water

- *Task 4.6 Imaging deep structure with electrical resistivity*
These activities shall lead to acquire and analyse resistivity, induced polarization and self-potential data from an experimental cross-hole set-up in Larderello (Italy) marked by temperature close to supercritical conditions in order to constrain resistivity zonation and interpretation of magnetotelluric (MT) data at great depths and high temperature. Resistivity methods pertain to the traditional geophysical methods. An electric current is conducted into the ground using AB current electrodes and the measuring electrodes assess the ingress voltage while the rock resistivity is calculated.
The methods of MT sounding and profiling belong amongst the electromagnetic inductive methods of geophysical surveying, that specifically utilise the natural variations of the earth's magnetic field as a source field for induction into conductive earth. The utilisation of the Earth's natural electromagnetic fields facilitates the simplification of experimental technology by not requiring any form of artificial signal generator.
Such geophysical measurements are minimally invasive. It requires only to ensure appropriate acces to the measurement sites, which might sometimes require to clear teh vegetation at the measurment spot.

Impact classification: C – vegetation, wildlife, soil

- *Task 7.3 Geothermometers and tracers – field validation*
Field validation of auxiliary geothermometers and tracers constrained by fluid collection from thermal springs and existing boreholes shall take place in the area of Litomerice (Eger Graben). Few boreholes shall be selected for groundwater sampling and tracer testing.
In this field test family of tracers based sulphonic acids and alcohols is used (naphthalene sulfonate type). The most significant environmental impact is for groundwater bodies, however the naphthalene sulfonates are environmentally safe (see paper of Greim et al., 1994) and toxicity and ecotoxicity of sulfonic acids is low (very low adsorption on the soils, no significant bioaccumulation expected, > 60% degradability, no carcinogenic potential). The expected concentration is 200g/L and shall be further diluted by the formation water.
Occurrence of vegetation is grass and forest type.
The duration of tracer injection into the injection well shall be less than 5 hours. The production duration shall be higher than 1 week. Several short production periods (< 1 day) at different time slots during some months (1 year maximum) are also envisaged.

Impact classification: B – water

- *Task 7.4 Resistivity techniques – testing CSEM/MT*
MT / CSEM surveys are minimally invasive geophysical surveys. The fuel consumption for the transmitter (CSEM) and accessing the measurement sites are the only direct impacts, but very marginal. MT surveys have minimal impact on the environment. Joint MT - CSEM field survey will be performed in Litomerice using the PVGT- LT1 borehole as a source and recording local and far remote station for MT filtering.

Impact classification: C – vegetation, wildlife, soil, air, noise

- *Task 8.2 Application of exploration techniques*

Exploration techniques improved and/or tested in WP7 are applied at the sites considered in the Upper Rhine Graben and in the Molasse Basin. The following potential applications are envisaged:

- Field study to complement geological information if needed
- Passive seismic
- MT method to be tested in the Northern Alsace in the Upper Rhine Graben with the new scheme developed in WP7 and compared with a standard MT survey that was done in the past
- Seismic reprocessing to image deep sediment and basement reflectivity and faults and fracture, on a site to be chosen during the project in the Upper Rhine Graben and in the Molasse Basin.

Environmental impacts of these activities are generally low and were described within previous Tasks.

Impact classification: B – vegetation, soil, C - wildlife, water

Tab. 3 Overview of potential environmental impact significance for pertinent activities

WP	Task	Activity	Test site	Participant	Vegetation	Wildlife	Water	Soil	Air	Noise
3	3.1	Field work and rock sampling in fossil and exhumed geothermal systems	Elba, Geitafell	UniBari, ISOR, HS-Orka	C	C		C		
3	3.2	Establishment of the chemical evolution of fluids	Italy, Iceland	CNR, ISOR	C	C	C			
4	4.1	Deployment of a dense network of seismic broadband stations	Reykjanes	GFZ, HS Orka, ISOR	C	B		C		
4	4.2	Active seismic profiling VSP	Krafla	ISOR, GFZ, VBPR, Landsvirkjun	C	C		B	B	B
4	4.3	High temperature measurement		CNR, BRGM, ISOR	C	C	C			
4	4.5	Field tracer tests	Krafla	BRGM, ISOR, Landsvirkjun			B			
4	4.6	Imaging deep structure with electrical resistivity		CNR	C	C		C		
7	7.3	Geothermometers and tracers - field validation	Litomerice	BRGM, Geomedia, CNR	C	C	C			
7	7.4	Resistivity techniques - testing CSEM/MT	Litomerice	BRGM, CNR, ISOR, Geomedia	C	C		C	C	C
8	8.2	Application of exploration techniques	Upper Rhine Graben, Molasse Basin	BRGM, Fonroche, TNO, GFZ, AXPO, Sol-E-Suisse	B	C	C	B		

4 Conclusion

This Assessment of the potential environmental impacts was subject of Task 2.7 (D2.7). The IMAGE activities were rigorously evaluated in a two-step assessment:

- 1. step: Identification of activities relevant for environmental impact assessment (classified as PEI + in Tab. 1)
- 2. step: Classification of relevant activities based on detailed plan and available information on planned measurements, commonly used methods, intended approaches etc.

In total, ten project tasks include activities with potential risk to the surrounding environment. Its significance was rated according the impact on vegetation, wildlife, water, soil, air and noise (vibrations). Three rating levels were applied – A,B,C, where A corresponds to the risk with the highest significance, C stands for the risk with the smallest significance.

The results of the environmental impact assessment were summarized in Tab. 3. None of the evaluated activities belong to the A level rating. Few of them represent medium potential impacts related primarily to increased disturbance of fish during the deployment of a seismic network off-shore, during active seismic campaigns and during tracer tests in the field.

However, all above mentioned risks are to be mitigated during the realization of these activities by proper handling of equipment and chemical substances, following standardized methods, consistent monitoring, minimizing negative environmental impacts in general.