Recent development of Geophysical Methods for Geothermal Exploration in Sedimentary Basins

IMAGE Project overview

Mathieu DARNET (BRGM), Chrystel Dezayes (BRGM), Cedric Schmelzbach (ETHZ), Stefan Carpentier (TNO), Fabienne Reiser (ETHZ), Philippe Steeghs (TNO), Hansruedi Maurer (ETHZ), Stewart Greenhalgh (ETHZ), J.F. Girard (BRGM), F. Bretaudeau (BRGM), L. Capar (BRGM), A. Bitri (BRGM)
Executive Summary

• High capital investments for geothermal exploration, drilling wells, and plant installation subject to significant geological risks
• Geophysical methods are therefore key to de-risk the exploration and development of geothermal resources (e.g. seismic, electromagnetics, gravity, satellite)
• As part of the FP7 IMAGE project, focus has been on developing Seismic and Electro-Magnetic techniques for geothermal exploration in sedimentary basin
• These geophysical methods are well suited for geothermal exploration as
  ❖ Strong density/resistivity contrasts are expected where favorable conditions for EGS development are met
  ❖ Such contrasts can be remotely sensed with seismic and EM methods provided that adequate acquisition, processing and imaging parameters are used
  ❖ Value of such information is potentially huge compared to their costs
ECONOMIC VALUE OF GEOPHYSICAL INFORMATION
Typical Geothermal Project Economics

- High capital investment for exploration, drilling wells, and plant installation, but low cost for operation and maintenance
- Break-even date late in the project life
- Highly sensitive to geological risks (e.g. reservoir presence and performance over project lifetime)
Value of Geophysical Information

- Value of geophysical information (VOI) = Risked Net Present Value (NPV) of a project with geophysical information – Risked NPV of a project without geophysical information
- As geophysical surveys aims at reducing geological risks, risked project NPV with geophysical information is usually greater than without (VOI > 0) i.e. more profitable investment
- However, a tradeoff exists between the cost and confidence in the geophysical survey and the prior project risk profile

\[
\text{Risked NPV} = \begin{cases} 
X \times (\text{Income1} - \text{CAPEX1} - \text{OPEX1}) & \text{Success} \\
(1-X) \times (\text{Income2} - \text{CAPEX2} - \text{OPEX2}) & \text{Failure}
\end{cases}
\]

\[
\text{Risked NPV} = \begin{cases} 
Y \times (\text{Income1} - \text{CAPEX1} - \text{OPEX1} - \text{Survey cost}) & \text{Success} \\
(1-Y) \times (\text{Income2} - \text{CAPEX2} - \text{OPEX2} - \text{Survey cost}) & \text{Failure}
\end{cases}
\]

\[
\text{VOI} = \text{NPV2} - \text{NPV1}
\]
Value of Geophysical Information

• As an example:
  
  NPV Success = \(10\text{mlnEUR} \) (Income – CAPEX)
  NPV Failure = \(-25\text{mlnEUR} \) (0 – CAPEX)
  Success rate without additional geophysics = \(3/4\)
  Success rate with additional geophysics = \(9/10\)

• Investing up to 5\text{mlnEUR} in an additional geophysical survey would result in an increase of the project value (e.g. a 1\text{mlnEUR} survey would bring 4\text{mlnEUR} additional)
WHY SEISMIC AND EM METHODS FOR GEOTHERMAL EXPLORATION IN SEDIMENTARY BASINS?
WHY SEISMIC METHODS?

- Strong acoustic impedance contrasts (density*velocity) are expected where a permeable zone of sufficient temperature and fluid movement is present for geothermal development (e.g. faults and fractures)
Structural Imaging from Seismic in Oil & Gas

• Provided that adequate acquisition, processing and imaging parameters are met, seismic data allows imaging in great details the present day and past structural history

⇒ Key information to understand geothermal reservoir behavior
Passive seismic for geothermal exploration

- Definition of the background seismicity, detection of active faults and their geometry
- Evaluation of the rough 3D velocity model with tomography methods
- First step to estimate the future induced seismicity

⇒ Key information to understand geothermal reservoir architecture
WHY EM METHODS?

- Strong electrical conductivity contrasts are expected where a permeable zone of sufficient temperature and fluid movement is present for geothermal development (e.g. faults and fractures)

Present day outcrop – core analysis

The more alteration…
The higher porosity…
The lower formation factor…
The higher the permeability…
The higher the surface conductivity…
The higher the rock conductivity

Soultz fracture

Basement >1000 Ω.m
Fracture 20/30 Ω.m

with:

$$\sigma_0 = \sigma_w + \sigma_z$$

$$\sigma_w = \text{rock conductivity}$$
$$\sigma_z = \text{surface conductivity}$$
$$\sigma_w = \text{fluid conductivity}$$
$$F = \text{rock formation factor}$$
EM Imaging over hydro-thermal system in a volcanic area

• A 3-D electrical resistivity model has been developed from MT data and used to construct a generalized geological model of the shallow hydrothermal system in Long Valley Caldera, California

   Key information to understand geothermal reservoir behavior
Geophysical Methods for Geothermal Exploration in Sedimentary Basins

- Passive/active and EM methods are well suited for geothermal exploration in sedimentary basins as rock acoustic impedance and electrical resistivity depends on:
  - Geology (e.g. fracturing, degree of alteration, lithology)
  - Nature of pore space (e.g. porosity, tortuosity, permeability)
  - Fluid chemistry (e.g. ionic concentration, multi-phase)
  - In situ Pressure and Temperature conditions

- Very valuable information for geothermal resource assessment!
SEISMIC AND EM METHODS FOR GEOTHERMAL EXPLORATION IN A NUTSHELL
Seismic and EM Methods for geothermal exploration in a nutshell

<table>
<thead>
<tr>
<th>Method</th>
<th>Equipment</th>
<th>Resolution</th>
<th>Depth of investigation</th>
<th>Typical Price Tag</th>
<th>Typical Survey Duration</th>
<th>Peri-Urban Areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active Seismic</td>
<td>Vibroseis + 3C geophones</td>
<td>~10’s meters</td>
<td>4/5 km ok</td>
<td>100’s k$/km²</td>
<td>Weeks</td>
<td>Challenging</td>
</tr>
<tr>
<td>Passive Seismic</td>
<td>Natural acoustic emissions + Seismometers</td>
<td>~100’s meters</td>
<td>4/5 km challenging</td>
<td>A few k$/km²</td>
<td>Months</td>
<td>Very challenging</td>
</tr>
<tr>
<td>Active EM (CSEM)</td>
<td>Electric dipole + MT stations</td>
<td>~100’s meters</td>
<td>4/5 km challenging</td>
<td>10’s k$/km²</td>
<td>Weeks</td>
<td>Challenging</td>
</tr>
<tr>
<td>Passive EM (MT)</td>
<td>Natural EM waves (solar winds, lightning) + MT stations</td>
<td>~100’s meters</td>
<td>4/5 km ok</td>
<td>A few k$/km²</td>
<td>Weeks</td>
<td>No-Go</td>
</tr>
</tbody>
</table>
RECENT DEVELOPMENTS IN SEISMIC METHODS FOR GEOTHERMAL EXPLORATION IN SEDIMENTARY BASINS
Active seismic methods in geothermal exploration

• Seismic imaging powerful tool for subsurface characterization
• Successful application in hydrocarbon exploration
• Various sophisticated seismic imaging tools developed
• It needs to be investigated how these techniques need to be adapted and applied to geothermal sites
New and advanced processing of existing reflection seismic data: surface data

- A next-generation reprocessing algorithm from video- and photo processing industry (Non Local Means multichannel filter) has been developed and tested on a ultra-deep geothermal exploration case in the Netherlands.
- The NLM filter outperforms several state-of-the-art multichannel filters such as the fx-decon and eigenvector filter in terms of reflection continuity enhancement and fault preservation. Seismic attributes perform substantially better on NLM reprocessed data and enable interpretation by autotracking of horizons up to 6 km depth.
- At a relatively low cost, large amounts of seismic data can be reprocessed in this way delivering interpretable signal up to 6 km depth.
New and advanced processing of existing reflection seismic data: VSP

- We have developed a novel strategy for optimizing VSP survey layouts suitable for mapping fracture zones over hardrock basement geothermal environments.
- The ideal survey layout strongly depends on the dip and location of the fracture zone. Therefore, a priori information on the expected subsurface structures is essential for survey design.
- For all scenarios considered in this study good results could be obtained with a relatively small number of source positions. Adding more data did not improve the quality of the images, but rather deteriorated the image quality.
RECENT DEVELOPMENTS IN EM METHODS FOR GEOTHERMAL EXPLORATION IN SEDIMENTARY BASINS
Variability of EM Noise Spectra

- EM noise varies significantly with the distance to anthropic activities.
- In peri-urban areas, quality of MT/CSEM soundings may be poor.
- This can be compensated by increasing the source dipolar moment and/or optimizing survey setup (layout, frequency band etc).

CSEM spectra in the vicinity of the Strasbourg city (France)
The “LEMAM” electromagnetic array

- LEMAM = “Long Electrode Mise à la Masse”
- Borehole-to-surface array with source and sensors of electric type. Possible measurements of the magnetic field as well.
- Injection of the source-current directly in the deep conductive layers via at least one metallic casing used as long electrode → optimally energizes reservoir layers

The current lines are “attracted” by the conductive stimulated EGS reservoir. The current distortion modifies the electric potentials measured at the surface.
High Quality CSEM data acquired in urban area (Litomerice, Czech republic)

- 29/31 good CSEM stations while MT only usable to image shallow resistivity variations (<500m)
- CSEM allows mapping main geological features in the area of interest (transition young/old sediments, basement fault)
Conclusions

• High capital investments for geothermal exploration, drilling wells, and plant installation subject to significant geological risks
• Geophysical methods are therefore key to de-risk the exploration and development of geothermal resources (e.g. seismic, electromagnetics, gravity, satellite)
• As part of the FP7 IMAGE project, focus has been on developing Seismic and Electro-Magnetic techniques for geothermal exploration in sedimentary basin
• These geophysical methods are well suited for geothermal exploration as
  ❖ **Strong density/resistivity contrasts are expected where favorable conditions for EGS development are met**
  ❖ **Such contrasts can be remotely sensed with seismic and EM methods provided that adequate acquisition, processing and imaging parameters are used**
  ❖ **Value of such information is potentially huge compared to their costs**
New active seismic processing techniques developed for geothermal exploration

- For EGS reservoirs in hardrock (basement), impedance contrasts and reflection coefficients between most igneous and metamorphic rocks are smaller than those of sedimentary rocks, the signal to noise ratio will be low, making it more difficult to image structures (e.g., fracture zones, fluids).
- 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 are mostly inadequate for imaging steep dips within basement. Moreover, there is a lack of adequate velocity information which can be extracted from the limited T-X moveout patterns to properly migrate basement structures.
- 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 receivers and to aid with the interpretation of the data.
- 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 3-component sensors, coupled with sophisticated processing, including attribute analysis, polarization filtering/migration and the separation of diffracted and specular reflected wavefields. Full waveform inversion and shear wave birefringence investigations can be profitably carried out provided that the data are of sufficient quality. Careful attention to receiver installation and sufficient source energy are required, along with detailed analysis of statics.
- There are grounds for optimism that the geothermal reservoir imaging problem can be meaningfully tackled!
Principle of Active Seismic Acquisition
A valuable tool for geothermal projects

• Useful for the exploration and exploitation phase, possibility to reuse parts of the network (economic gains)
• Exploration : first step for 3D velocity models that can be further refined with active seismic focused on most promising targets
• Exploitation : Main tool to monitor and control induced seismicity
• Small land usage
• Better public acceptance
Principle CSEM/MT methods
Passive Seismic – Exploration in Rhine Graben