



Book of Abstracts

IMAGE Final Conference

Novel Approaches for Geothermal Exploration

4-6 Oct. 2017

ÍSOR, Akureyri, Iceland



This project has received funding from the European Union's Seventh Programme for research, technological development and demonstration under grant agreement No 608553.

IMAGE Integrated Methods for Advanced Geothermal Exploration
www.image-fp7.eu

Editors:

Brynja Jónsdóttir and **Gylfi Páll Hersir** - ÍSOR- Iceland GeoSurvey, Grensásvegur 9, 108 Reykjavík, Iceland

Contact person: brj@isor.is

Published by ÍSOR- Iceland GeoSurvey, Iceland, 2017

Printed by Pixel ehf. Iceland

Photos on cover page by Philippe Jousset and Ásgeir Eggertsson

This Book of Abstracts can be found on the IMAGE website after the conference as IMAGE-D2.08

ISBN 978-9935-9323-3-4



Book of Abstracts

IMAGE Final Conference

Novel Approaches for Geothermal Exploration

4-6 Oct. 2017

ÍSOR, Akureyri, Iceland

IMAGE

Integrated Methods for Advanced Geothermal Exploration

www.image-fp7.eu

Project Coordinator

Jan Hopman, TNO, the Netherlands

The IMAGE Consortium

TNO the Netherlands (Project coordinator)

Axpo Power AG, Switzerland

BKW Energie AG, Switzerland

BRGM Bureau de Recherches Géologiques et Minières, France

CNR Consiglio Nazionale delle Ricerche, Italy

EDA Electricidade dos Açores, Portugal

ENEL Green Power SpA, Italy

ETH Zurich, Switzerland

Fonroche Géothermie, France

GEOMEDIA s.r.o, Czech Republic

GFZ Helmholtz Centre Potsdam German Research Centre for Geosciences, Germany

HS Orka, Iceland

IFE Institute for Energy Technology, Norway

ÍSOR Iceland GeoSurvey, Iceland

Landsvirkjun National Power Company, Iceland

Technische Universität DARMSTADT, Germany

UNIBARI University of Bari Aldo Moro, Italy

UM Université de Montpellier, France

UU Utrecht University, the Netherlands

VBPR Volcanic Basin Petroleum Research AS, Norway

Contents

Welcome Address	6
General and Conference Information	7
Programme	8
List of Abstracts - Poster Session	10
Abstracts of Speakers	13
Abstracts of Posters	47
List of Participants	124

Welcome Address

Dear participants of the IMAGE final conference on Novel Approaches for Geothermal Exploration. We planned this conference as a platform to share results of our 4-year collaboration within the IMAGE project, but also to get feedback from you and to hear about your own research on geothermal exploration.

IMAGE - Integrated Methods for Advanced Geothermal Exploration: is the name of the project. It was designed to bring together expertise from different fields, from 20 partners both academic and industry, and from several EC countries. The different ideas and approaches were part of a whole concept, complementing methods to improve our overall knowledge and our imaging capacities of the subsurface for the exploitation of geothermal resources. EU framework programmes for research and development provide opportunities to bring these different areas of expertise from different countries together. That way colleagues have visualized the subsurface below Krafla and Reykjanes peninsula, tested new techniques and approaches and combined them with proven methods; approaches developed in Iceland and Italy were tested on the Azores; the regional subsurface below the Upper Rhine Valley in terms of temperature, stress and mechanical properties has been further improved, as a prerequisite for further developments at the local scale. Some of the approaches are now tested at other sites both with our European industry partners and elsewhere. The GEMex project, a large cooperation between Europe and Mexico that started one year ago, is in large part a spin-off of IMAGE. Numerous papers were presented and published, and this is still an ongoing process.

We are therefore proud and happy that so many of you made your way to Iceland to join us for this final conference, coming from all over the world. The conference programme reflects this variety of participation with a broad spectrum of contributions: Two days packed full of talks and presentations, posters will be all around us for the entire two days including an extended poster session, and a final field trip will round up the event, including a visit to Iceland's newest geothermal power plant at Þeistareykir.

We hope you will enjoy it and thank you for coming.

The organizing committee:

Jan Hopman (IMAGE coordinator)

David Bruhn

Gylfi Páll Hersir

General and Conference Information

Registration

Registration desk is located in the opening hall in Hof, Akureyri.

Opening hours:

Tuesday 4 pm - 7 pm

Wednesday 8 am - 9 am

Badges

Participants will receive a name badge upon registration. Everyone is kindly requested to wear his name badge when attending the meeting.

Emergency Telephone Numbers

The emergency phone number is 112.

Insurance

The organizers of the conference do not accept liability for any injury, loss or damage, arising from accidents or other situations during the conference or field trips. Participants are therefore advised to arrange insurance for health and accident prior to travelling to the conference.

Internet Facilities

Wi-Fi connection available and free of charge in Hof: **Wi-Fi: GEMEX-Image**
Password: ISOR.2017

Official Language

The official language of the conference is English.

Poster Session

Poster participants will receive instructions were to hang up their poster upon registration. Poster participant is responsible that the poster is in requested size, A0. It has to be on the display board the whole conference and the poster presenter is responsible to remove it at the end of the conference.

Social Event

Wednesday, Oct 4: Conference dinner in Hof, Akureyri at 7 pm

Field trips (optional):

Sunday, Oct 1: Reykjanes: Departure from ÍSOR, Grensásvegur 9, Reykjavík at 8.30 am - 1.30 pm

Friday, Oct 6: Krafla and Þeistareykir: Departure from Hof, Akureyri at 8 am - 5 pm

Programme

Tuesday, October 3

18:00-19:00 Welcome and registration, Hof, Akureyri

Wednesday, October 4

08:00 Registration

Opening Session - Chair : Jan Hopman, IMAGE coordinator, TNO

- 09:05 Welcome - **Ólafur G. Flóvenz**, ÍSOR-Iceland GeoSurvey
- 09:15 Welcome - **Helgi Jóhannesson**, CEO Norðurorka Ltd. - Utility Company
- 09:30 EC geothermal policy & funding - **Filippo Gagliardi**, European Commission officer
- 09:50 Introduction to IMAGE Final Conference - **Jan Hopman**, IMAGE coordinator, TNO
- 10:00 IMAGE in magmatic settings - **Gylfi Páll Hersir**, ÍSOR-Iceland GeoSurvey
- 10:20 IMAGE in sedimentary/basement settings - **Chrystel Dezayes**, BRGM
- 10:40 COFFEE BREAK

Session I - Structures and Fluid Flow - Chair David Bruhn, GFZ Potsdam

- 11:00 Multi-Faceted Approach for Harnessing the Vast Geothermal Potential of Nevada
- **James Faulds**, University of Nevada
- 11:20 Permeability and hydraulic conductivity - **Domenico Liotta**, University of Bari
- 11:35 A Fracturing Point of View in Geothermal Fields. Case Study: The Trans-Mexican Volcanic Belt
- **Victor Hugo Garduño Monroy**, Universidad Mochoacana de San Nicolas de Hidalgo
- 11:55 The 3D in-situ stress field and its induced changes in a geothermal reservoir - **Moritz Ziegler**, GFZ Potsdam
- 12:10 Geomechanical Play-Fairway Analysis - **Nicholas Davatzes**, Temple University
- 12:30 LUNCH

Session II - Geophysical methods 1 - Chair Adele Manzella, CNR

- 13:30 Innovative Geophysical Tools for Monitoring Geothermal Production and ReInjection Adapted to Exploration Objectives - **Chris Bromley**, GNS Science
- 13:50 Ambient seismic noise monitoring during the injection phases at the deep geothermal projects in Basel and St. Gallen, Switzerland - **Anne Obermann**, ETH Zurich
- 14:05 Seismic imaging in the Krafla high-temperature, volcanic geothermal field, NE-Iceland: Results from the VSP experiment in well K-18 - **Felix Kästner**
- 14:20 Surface-Wave Tomography by Ambient Noise Seismic Interferometry to image volcanic and geothermal systems in South Iceland - **Joana Martins**, TNO
- 14:35 Analysis of seismological data on Reykjanes peninsula, Iceland - **Hanna Blanck**, ÍSOR-Iceland GeoSurvey
- 14:50 Controlled-Source Electromagnetic Surveying for geothermal exploration in deep sedimentary and basement areas - **Mathieu Darnet**, BRGM
- 15:10 COFFEE BREAK

Session III - Geophysical methods 2 - Chair **Gylfi Páll Hersir**, ÍSOR-Iceland GeoSurvey

- 15:40 Enhanced Characterization of Induced Seismicity - **Gregory A. Newmann**, Lawrence Berkeley National Laboratory
- 16:00 High resolution gravity models for sedimentary basins and underlying basement - **Jan-Diederik van Wees**, TNO
- 16:15 Hybrid gravity monitoring of Soultz-sous-Forêts and Rittershoffen - **Nolwenn Portier**, IPGS EOST
- 16:30 Active and passive electromagnetic measurements in a deep fractured sedimentary basin in peri-urban context in NE Belgium - **Virginie Harcouet-Menou**, VITO
- 16:45 MT-inversion techniques with external constraints - **Ásdís Benediktsdóttir**, ÍSOR-Iceland GeoSurvey
- 17:00 A surface-hole deep electrical resistivity acquisition in the Larderello geothermal field (Italy) - **Enzo Rizzo**, CNR-IMAA
- 17:15 **Keynote:** Drilling toward Supercritical Fluid: The DESCRAMBLE experience at Larderello
- Ruggero Bertani, Enel Green Power. Presenter: **Adele Manzella**, CNR.

Thursday, October 5

Session IV - Processes and Properties - Chair **Chrystel Dezayes**, BRGM

- 09:00 Heat flow measurements in the Acozcalco Caldera, Mexico
- **Rosa Maria Prol-Ledesma**, Universidad Nacional Autonoma de Mexico
- 09:20 Use and development of auxiliary chemical geothermometers for geothermal fluids from crystalline and sedimentary reservoirs - **Bernard Sanjuan**, BRGM
- 09:35 The electrical structure of Icelandic deep geothermal - **Franck Laurel Nono Nguendjio**, Pau University - DMEX
- 09:50 Physical rock properties and their relation to fluid-rock interactions at supercritical conditions
- **Juliane Kummerow**, German Research Centre for Geosciences
- 10:05 New (Zealand) perspectives on continental arc geothermal systems - Greg Bignall, GNS Science
- Presenter: **Chris Bromley**, GNS Science
- 10:20 COFFEE BREAK

Session V - Posters - Chair **Brynja Jónsdóttir**, ÍSOR-Iceland GeoSurvey

- 10:30 Poster Session - (List of Abstracts on page 10-12)
- 12:30 LUNCH - Poster Session continues
- 14:10 COFFEE BREAK

Session VI - Integration and Advanced Modelling - Chair **Jan-Diederik van Wees**, TNO

- 14:30 Regional 3D structural and (hydro)thermal modelling of the Upper Rhine Graben - **Jessica Freyemark**, GFZ Potsdam
- 14:45 Optimum geothermal doublet placement in fractured reservoirs - **Jan ter Heege**, TNO
- 15:00 Integrated coupled modelling and microseismic mapping: identifying and targeting volumes with higher potential for transmissivity enhancement in unconventional geothermal applications - **Stefano Benato**, Cranfield University
- 15:15 A 3D Geological Static Field Model of the Krafla Geothermal Area, NE-Iceland – constructing a workflow applied to the Pico Alto Geothermal Area, Azores - **Unnur Þorsteinsdóttir**, ÍSOR-Iceland GeoSurvey
- 15:30 Conceptual model of the supercritical geothermal system in the Larderello area (Italy) using multidisciplinary exploration data - **Adele Manzella**, CNR
- 15:45 Thoughts on integrated application in magmatic settings geothermal field models - **Simon Lopez**, BRGM

16:00 Panel - What next for geothermal energy?- Chair **Mike Sandiford**, University of Melbourne

Egill Júlíusson, Landsvirkjun
Adele Manzella, CNR

Ómar Sigurðsson, HS-Orka
Anne Obermann, ETH
Jan-Diederik van Wees, TNO

- 17:00 Closing remarks - **Jan Hopman**, IMAGE coordinator, TNO

List of Abstracts - Poster Session - Display no, alphabetical order of presenter, (abstract page no)

1. How to establish a very precise chrono-lithostratigraphic log based on cuttings, core samples, gamma ray logs and analogues: application on the Soultz-sous-Forêts and the Rittershoffen geothermal wells (Rhine Graben, France) - **Aichholzer, Coralie**. EOST (page 48)
2. 3D Groundwater flow model at the Upper Rhine Graben scale to help locating the deep geothermal resource - **Armandine les Landes, Antoine**. BRGM (page 49)
3. A methodology for delineating preferential target areas for geothermal projects based on 3D mechanical and 3D groundwater flow model - **Armandine les Landes, Antoine**. BRGM (page 50)
4. A 3D mechanical model to help locating the deep geothermal resource - **T. Guillon**, BRGM – DGR/DES, presenter: **Armandine les Landes, Antoine**. (page 75)
5. Micro-seismicity in Námafjall high temperature area, NE-Iceland - **Ágústsson, Kristján**. ÍSOR (page 51)
6. P³ - PetroPhysical Property Database – comprehensive dataset enhancing the determination of empirical correlations between thermal and other petrophysical properties - **Bär, Kristian**. TU Darmstadt (page 52)
7. 3-D lithospheric-scale temperature modeling: application for the Hungarian part of the Pannonian Basin - **Békési, Eszter**, Department of Earth Sciences, Utrecht University (page 53)
8. Geological and structural setting of the Eastern Elba Island exhumed geothermal system (Italy) - **Bianco, Caterina**. University of Bari (page 54)
9. Vertical seismic profiling survey at the Thonex Well (Geneva) - **Bitri, Adnand**. BRGM (page 55)
10. Seismotectonics of the Geysir area in South Iceland during the years 1995 to 2001, revealed with relative earthquake locations - **Bjarnason, Ingi P.** University of Iceland (page 56)
11. Temperature in the subsurface of the Netherlands from new data and novel modelling methodology - **Bonté, Damien**. Utrecht University (page 57)
12. Characterizing permeable structures in geothermal fields – A case study in Lahendong - **Brehme, Maren**. GFZ Potsdam (page 58)
13. 3D reconstruction of the electric resistivity with land CSEM Numerical developments and application to geothermal prospection - **Bretauudeau, François**. BRGM (page 59)
14. Stress field from fault data inversion in North-East Iceland, **Brogi, Andrea**. University of Bari (page 60)
15. Kinematic data of the NE-trending shear zone affecting the Larderello geothermal area (southern Tuscany, Italy) and comparison with local focal mechanisms - **Brogi, Andrea**. University of Bari (page 61)
16. Imaging the resistivity structure of the Reykjanes high-enthalpy geothermal field with the Controlled-Source Electro-Magnetic method - **Darnet, Mathieu**. BRGM (page 63)
17. Advances in geophysical methods for geothermal exploration in deep sedimentary and basement areas - **Darnet, Mathieu**. BRGM (page 64)
18. Improving the depth penetration of seismic surface wave based methods with H/V methods for sedimentary basins - **Delatre, Mickael**. BRGM (page 66)
19. 3D Geological and temperature models in the Strasbourg area (Upper Rhine Graben, France) - **Dezayes, Chrystel**. BRGM (page 67)
20. Impact of thermal stressing on the strength and permeability in reservoir rocks at Krafla volcano - **Eggertsson, Guðjón Helgi**. University of Liverpool (page 68)
21. New tracers: Krafla field test - **Gadalia, Alain**. BRGM (page 70)
22. A new research project on interaction of geothermal, tectonic, and magmatic processes in the Hengill area - **Geirsson, Halldór**. Institute of Earth Sciences (page 71)
23. Petrophysical and mineralogical characterization of IDDP-2 mini-core samples from depths of 3650 to 4650 m - **Escobedo, David**. Laboratoire Géosciences Montpellier, presenter: **Benoit, Gibert**. (page 69)
24. Electrical conductivity of basaltic and rhyolitic melts from Krafla central volcano, Iceland - **Benoit, Gibert**, . Géosciences Montpellier (page 72)

25. Exploring the geothermal heat: Seismic properties as a function of reservoir conditions - **Grab, Melchior**. (page 73)
26. Wave-length of the crustal stress pattern in Western Europe and the Mediterranean - **Heidbach, Oliver**. VITO NV (page 75)
27. Alteration Minerals and Fluid Inclusions in Garnet from Geitafell, SE-Iceland
- **Helgadóttir, Helga Margrét**. ÍSOR (page 76)
28. Low-temperature geothermal exploration in Hoffell, southeastern Iceland. Hot water for the municipality of Hornafjörður
- **Ingimarsson, Heimir**. ÍSOR (page 77)
29. Exploring the potential of imaging a peri-urban geothermal site by using teleseismic receiver functions
- **Imtiaz, Afifa**. BRGM (page 78)
30. Validation of the Influence of Cation-exchange Capacity on Resistivity Logs within Hydrothermal Systems
- **Weisenberger, Tobias Björn**. ÍSOR, presenter: **Ingimarsson, Heimir**. (page 122)
31. Structural-geological impact on soil gas composition at Los Humeros Volcanic Complex
- **Jentsch, Anna**. Helmholtz-Zentrum Potsdam Deutsches GeoForschungsZentrum GFZ (page 79)
32. Integrated geophysical imaging of Reykjanes, SW Iceland - **Jousset, Philippe**. GFZ (page 80)
33. Injection-induced surface deformation and seismicity at the Hellisheidi geothermal field, Iceland
- **Juncu, Daniel**. Institute of Earth Sciences (page 81)
34. The role of smectites in the electrical conductivity of active hydrothermal systems: electrical properties of core samples from Krafla volcano, Iceland - **Lévy, Léa**. ÍSOR (page 83)
35. Thermo-mechanical characterization of the European lithosphere for geothermal exploration
- **Limberger, Jon**. Utrecht University (page 84)
36. Normal faults and transfer zones during Late Miocene mineralization in eastern Elba Island (Italy)
- **Liotta, Domenico**. University of Bari (page 85)
37. Fractures analysis and hydrothermal mineralization in the Neogene Geitafell central volcano (Iceland): insights for fluid pathways in the fossil geothermal system - **Liotta, Domenico**. University of Bari (page 86)
38. NW-Trending tectonic structures in Krafla geothermal area - **Liotta, Domenico**. University of Bari (page 87)
39. Supercritical geothermal resources in Europe: how to IMAGE them? - **Manzella, Adele**. CNR (page 88)
40. Surface-Wave Tomography by Ambient Noise Seismic Interferometry to image volcanic and geothermal systems in South Iceland - **Martins, Joana**. TNO (page 89)
41. The importance of borehole imaging logs in revealing volcanic facies and structure: Examples from Hawai'i and Iceland
- **Millett, John**. VBPR (page 90)
42. Supercritical fluid flow close to shallow magma intrusions: suggestions from analogue modelling
- **Montanari, Domenico**. Institute of Geosciences and Earth Resources, National Research Council of Italy (CNR) (page 91)
43. Geochemical model of high temperature gas-water-rock interaction - **Montegrossi, Giordano**. CNR-IGG (page 93)
44. 3D Numerical Model of Larderello Area - **Montegrossi, Giordano**. CNR-IGG (page 94)
45. What can we learn from laboratory experiments on tracer behavior?
- **Muller, Jiri**. Institute for Energy Technology (IFE) (page 95)
46. Ambient seismic noise monitoring during the injection phases at the deep geothermal projects in Basel and St. Gallen, Switzerland - **Obermann, Anne**. ETH Zurich (page 96)
47. 3D-ambient noise Rayleigh wave tomography of Snaefellsjökull volcano, Iceland
- **Obermann, Anne**. ETH Zurich (page 97)
48. Probabilistic sensitivity kernels to image lapse time changes - **Obermann, Anne**. ETH Zurich (page 98)
49. What seismic studies reveal about LUSI, a clastic dominated geysiring system in Java, Indonesia
- **Obermann, Anne**. ETH Zurich (page 99)
50. Synthesis of tourmaline under upper crustal conditions: a clue to understand processes occurring in both fossil and active geothermal areas - **Orlando, Andrea**. CNR- Istituto di Geoscienze e Georisorse, Firenze (page 100)
51. Practical methods to transfer rock mass fracturing field data to quantifiable values for modelling
- **Peter-Borie, Mariane**. BRGM (page 101)

52. Key situations to lead an optimized and adapted exploration - **Peter-Borie, Mariane**. BRGM (page 102)
53. 3-D geological-geophysical model and synthetic seismic reflection modelling along CROP-18A line in the Larderello area - **R. de Franco**, CNR-IDPA, presenter: **Petracchini, Lorenzo**. (page 67)
54. Seismic imaging and interpretation of basaltic complexes - **Planke, Sverre**. VBPR (page 103)
55. General stratigraphy, volcanic evolution and geomechanical characterization of Pleistocene hydrothermal-altered rhyolitic lavas of the Acoculco Caldera Complex, central Mexico
- **Pola, Antonio**. Escuela Nacional de Estudios Superiores - Unidad Morelia. UNAM (page 104)
56. Geological expression on Flores Island in Indonesia: the transition from oceanic to continental plateau subduction
- **Purwandono, Ahmad Fauzi**. Utrecht University (page 105)
57. Testing vertical seismic profiling (VSP) as a subsurface mapping method at the Krafla volcanic geothermal field in Iceland - **Reiser, Fabienne**. ETH Zurich (page 106)
58. Temperature measurement tests in geothermal wells by using synthetic fluid inclusions
- **Ruggieri, Giovanni**. CNR-IGG (page 107)
59. Deep exploration of the Larderello geothermal field (Italy) by means of electromagnetic methods: integrated models and inversion - **Santilano, Alessandro**. CNR-IGG (page 108)
60. Surface and body waves ambient noise tomography near Soultz-sous-forêts (France) using the dense EstOF seismic array - **Lehuteur, Maximilien**. EOST-IPGS, Université de Strasbourg/CNRS, presenter: **Schmittbuhl, Jean**. (page 82)
61. Influence of the geothermal fluid rheology in the large scale hydro-thermal circulation in Soultz-sous-Forêts reservoir, France - **B. Vallier**, EOST, Université de Strasbourg, presenter: **Schmittbuhl, Jean**. (page 115)
62. Real-time seismic monitoring of operational changes at the Hellisheiði geothermal power plant
- **Sigfússon, Bergur**. Reykjavik Energy (page 109)
63. Geodetic imaging of changes in geothermal reservoirs and magma transfer: Towards improved modeling of volcanic and geothermal processes
- **Sigmundsson, Freysteinn**. Nordvulk, Institute of Earth Sciences, University of Iceland (page 110)
64. Brief over view of the Icelandic deep drilling RN-15/IDDP-2 at Reykjanes, Iceland - **Sigurðsson, Ómar**. HS Orka (page 111)
65. The Characteristic of Sumatran Geothermal Systems from Geological Perspective
- **Sutrisno, Lukman**. Utrecht University (page 112)
66. Topography, faults, and lithology control the non-magmatic hydrothermal system of the Têt Valley, Eastern Pyrénées (France) - **Taillefer, Audrey**. Géosciences Montpellier (page 113)
67. Seismic network survey design and performance - **Toledo Zambrano, Tania**. GFZ-Potsdam (page 114)
68. Characterization of deep geothermal reservoir using fractal models and linking observed fractures, stress heterogeneities and micro-seismic observations - **Moein, Mohammad**. Geological Institute, presenter: **Valley, Benoît**. (page 92)
69. Novel noise based seismic acquisition and processing techniques, de-risking geothermal exploration and monitoring
- **Vandeweyer, Vincent**. TNO (page 116)
70. Low-cost geothermal exploration through reprocessing of vintage seismic data with a new edge-preserving de-noising algorithm - **Carpentier, Stefan**. TNO, presenter: **Vandeweyer, Vincent**. (page 62)
71. Passive seismic reflection interferometry at Reykjanes peninsula, SW Iceland - **Verdel, Arie**. TNO (page 117)
72. Imaging and structural analysis of the Geysir field, Iceland, from underwater and drone based photogrammetry
- **Walter, Thomas R**. GFZ (page 118)
73. Continuous MT monitoring: Resistivity variations related to the large March 9, 1998 eruption at La Fournaise Volcano - **Wawrzyniak, Pierre**. BRGM (page 119)
74. MT and CSEM data robust processing techniques. New developments - **Wawrzyniak, Pierre**. BRGM (page 119)
75. Crustal Stress Pattern of Iceland - **Ziegler, Moritz**. GFZ Potsdam (page 122)
76. Fractures and mineralizing fluid paths in the eastern Elba Island exhumed geothermal system (Italy)
- **Zucchi, Martina** (page 123)

Abstracts of Speakers

Geothermal exploration and reservoir assessment in magmatic systems

The IMAGE Project

Gylfi Páll Hersir¹, Ólafur G. Flóvenz¹, David Bruhn², Domenico Liotta³, Sæunn Halldórsdóttir¹ and Adele Manzella⁴

¹ÍSOR (Iceland), ²GFZ (Germany), ³UniBari (Italy), ⁴CNR-IGG (Italy)

E-mail: gph@isor.is

IMAGE (Integrated Methods for Advanced Geothermal Exploration) is an EU funded research project which began in November 2013 and ends here in Akureyri four years later. 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 consists 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. 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 (also through core drilling). Their geological units and tectonic setting analogous to the active geothermal system to be exploited has been exposed, and the results compared with the study of active geothermal systems. Rock/fluid interaction at supercritical conditions and the physical properties of rock at reservoir conditions have been studied as well.

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. 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 have been 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.

Thirdly: 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 has been tested and developed, analogue modelling for fracturing has been performed, a strategy plan for targeting a deep well at supercritical fluid conditions has been made and a database for potential supercritical conditions.

The research leading to these results has received funding from the EU 7th Framework Program, under grant agreement no. 608553 (Project IMAGE).

Main results of exploration method development for basement and sedimentary basins

Chrystel Dezayes¹ and IMAGE-SP3 team^{1, 2, 3, 4, 5, 6, 7, 8, 9}

¹BRGM, 3 av. Cl. Guillemin, 45060 Orléans, France, ²GFZ, Telegrafenberg, 14473 Potsdam, Germany, ³Technische Universität Darmstadt, Schnittspahnstrasse 9, 64297 Darmstadt, ⁴TNO, Princetonlaan, Utrecht, Netherland, ⁵Institute of Geophysics, ETH Zurich, Switzerland, ⁶GEOMEDIA Ltd., Hornokrcska 707/7, 140 00 Prague 4, Czech Republic, ⁷SIG, Chemin Château-Bloch 2 - 1219 Le Lignon, Switzerland, ⁸Department of Earth Sciences, University of Geneva, Rue des Maraichers 13, CH-1205 Geneva - Switzerland, ⁹CHYN, University of Neuchâtel, Switzerland

In order to expand the geothermal energy exploitation, the non-magmatic areas have to be explored. These less favourable regions are the major part of the European territory with large population and where geothermal power production is a valuable local source of energy, produced near the consumers. Nowadays, with the improvement of the binary power plant productivities, the exploitation temperature could be available between 120°C and 200°C. In a normal geothermal gradient (30°C/km) context, this temperature range is reached between 4 and 6km depth and corresponds to the 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 economical production and the re-injection of the fluid.

In the framework of the IMAGE project (Integrated Methods Advanced for Geothermal Exploration), one of the both sub-projects is dedicated to the exploration of this sedimentary basin and basement context, a major issue for Europe. The overall objective of this IMAGE sub-project is to set up and validate an integrated methodology that consists in building, step by step, models based on larger scale models and key situations identifiable by innovative and validated exploration methods. Therefore three questions arise:

- What are we looking for? What are the key parameters and the key situations that allow withdrawing the geothermal fluid?

Database and large scale models for different parameters (temperature, stress, geology and hydrogeology) have been yielded for Europe, Upper Rhine Graben and Lower Rhine Greben. Even if these database and 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.

- Which methods are able to identify these key situations at the different scales?

Classical exploration methods, such as active and passive seismic, electromagnetism, geothermometry and geology have been developed in the specific basement and sedimentary context (deep targets, urban noises...) and validated to be relevant to identify the key situations. Whereas, these types of investigations can be expensive, the benefits in term of derisking project could be important. In the framework of the IMAGE project, we have improved the methodology to acquire and process these types of data.

- How used these methods to find the best drilling place and reduce the financial risk of drilling?

The exploration methods have been used in the targeted local area (based on the Regional models) in order to give help to the building of the local models. Three sites have been selected to applied exploration methods and building local models: the western part of Strasbourg (France), Luttelgeest areas (Netherland) and Bad Waldsee (Germany). Other places have also been chosen to applied different types of methods Litomerice town (Czech Republic) for CESM and geothermometry, the Thonex well near Geneva (Switzerland) for VSP and geothermometry, Eclepens (Switzerland) for geology, Soultz (France) and Basel (Switzerland) wells for stress analysis.

Based on these results, we propose an integrated geothermal exploration workflow for exploring deep sedimentary basins and the underlying basement. A basis geological and structural model has been done from public data and improves from geophysical and geological analysis. Thermal, Hydraulic and Mechanical models, independent, coupled or partially coupled, are built based on this geological model and from other data like temperature, fluid geochemical analysis, stress data. Three scales have been considered in this pre-drill exploration workflow: European scale (around 1000kmx1000km) considers temperature, heat flow and stress field that constrain regional scale; the Regional scale (50 to 100km) covers a geological region considered as relevant; the Local scale (10 to 25km) corresponds to the focus which is made at the last step. The way between the different scales is made by the analysis of the key situations defining the geothermal location. Finally, at the smaller scale, the best geothermal location is refined in terms of risk and cost for the first exploration well.

Multi-Faceted Approach for Harnessing the Vast Geothermal Potential of Nevada and the Great Basin Region, Western USA: A Summary of Recent Studies and Advances

James E. Faulds¹, Nicholas H. Hinz¹, Mark F. Coolbaugh^{1,2}, Drew L. Siler³, and Lisa A. Shevenell²

¹Nevada Bureau of Mines and Geology, University of Nevada, Reno, NV 89557

²ATLAS Geosciences Inc., Reno, NV 89509

³U.S. Geological Survey, Menlo Park, CA

As a result of its transtensional to extensional tectonic setting, Nevada and the surrounding Great Basin region are richly endowed in geothermal resources. Estimates suggest that the Great Basin region is capable of producing much greater amounts of geothermal energy than the current ~670 MW from ~25 power plants. Similar to most hydrocarbon deposits, studies also suggest that most of the geothermal resources in the region are blind (i.e. lack surface hot springs and steam vents). Thus, it is imperative that the favorable conditions for geothermal activity be synthesized and exploration methodologies developed to discover new robust systems. For areas lacking sufficient permeability, development of unconventional resources in hot, relatively impermeable rocks in enhanced geothermal systems (EGS) holds significant promise.

We have therefore been proceeding on multiple fronts to 1) characterize the favorable settings for conventional geothermal activity, 2) improve methodologies for evaluating geothermal potential of conventional systems, and 3) select a site suitable for EGS research and development. Because most geothermal systems are fault controlled in this active tectonic region, characterization of conventional systems has focused on evaluating the favorable structural settings for geothermal activity. Nearly 90% of the systems reside in step-overs in normal faults, normal fault terminations, fault intersections, and accommodation zones. High fault and fracture density in these settings facilitate high permeability and fluid flow. These findings were incorporated into a regional geothermal play fairway analysis, whereby nine geologic, geochemical, and geophysical parameters were synthesized to produce a detailed geothermal potential map of 96,000 km² from W-central to eastern Nevada. These parameters were grouped into subsets and individually weighted to delineate rankings for heat and local, intermediate, and regional scale permeability, which collectively defined the play fairways (i.e. most likely areas for geothermal fluid flow). ~25 highly prospective areas, including known undeveloped systems and previously undiscovered potential blind systems, were initially identified for further analysis. Five particularly promising sites were then selected for detailed studies. Multiple techniques, including geologic mapping, Quaternary fault analysis, 2-m temp surveys, gravity surveys, LiDAR, geochemical studies, seismic reflection analysis, and 3D modeling, were employed in these areas to define likely sites for high permeability and prospective drilling targets. The detailed studies have revealed several potential newly discovered, high temperature systems.

In addition, work is proceeding on the EGS front with the Fallon FORGE project (Frontier Observatory for Research in Geothermal Energy). FORGE is a U.S. Department of Energy (DOE) program designed to establish a dedicated field laboratory for developing technologies, techniques, and knowledge needed to make EGS a commercially viable electricity generation option. The Fallon site lies ~10 km southeast of Fallon, Nevada, in the Carson Sink, an extensional Neogene basin in W-central Nevada. Fallon was selected for a potential FORGE site due to abundant available well (45 wells) and geophysical data, existing infrastructure, and documented temperatures, permeability, and lithologic composition of potential EGS reservoirs. Fallon meets all FORGE criteria, and thus was one of two sites chosen by the DOE to advance to Phase II, which involves acquisition of new data to better characterize the site and allow for selection of a final FORGE site. Four wells penetrate the entire Neogene section of sedimentary and volcanic rocks and bottom in Mesozoic metamorphic and granitic basement. The structural framework is dominated by a gently W-tilted half graben cut by widely spaced, moderately to steeply dipping N- to NNE-striking normal faults. Well data indicate relatively high temperatures (>175°C) in crystalline basement but insufficient permeability for conventional geothermal development. Two possible, competent target formations for EGS stimulation include: 1) Jurassic felsic metavolcanic rocks/and or metaquartzite; and 2) Cretaceous granitic intrusions. The abundant well and geophysical data permitted development of a detailed 3D model.

Permeability and hydraulic conductivity from field and fluid inclusions data in exhumed geothermal systems

C. Bianco¹, A. Brogi¹, A. Caggianelli¹, M.Ciacci¹, A.Dini², R.A. Fregola¹, G.Ó. Friðleifsson³, H.M.Helgadóttir⁴, D. Liotta¹, G. Montegrossi⁵, G. Ruggieri⁴, V. Rimondi⁶, M. Zucchi¹

¹Dipartimento di Scienze della Terra e Geoambientali, Università di Bari (Italy), ²CNR-Istituto di Geoscienze e Georisorse, Pisa (Italy),

³HS Orka, Reykjanesbær (Iceland), ⁴ÍSOR-Iceland GeoSurvey, Reykjavík, (Iceland), ⁵CNR-Istituto di Geoscienze e Georisorse, Firenze (Italy),

⁶Dipartimento di Scienze della Terra, Università di Firenze (Italy)

The understanding of the relationships between geothermal fluid flow and geological structures represents one of the main tasks 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 occurring during the cooling history of the upper-crustal Porto Azzurro monzogranite (5.9 Ma). 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 a fluid with salinities of 11-30 wt.% NaCl eq. and T up to 650°C and a late stage fluid with salinity encompassed between 29% and 49% wt. NaCl eq. and T up to 420°C; these fluids also circulated at shallow structural levels (hematite+quartz veins in Triassic quartzite), but their T tends to decrease (T<470°C) whereas isotope analyses and salinity values (in some cases around 0wt. % NaCl eq.) indicate a progressive contribute of meteoric water that mixed with the saline fluids of magmatic derivations. Estimated fracture permeability from field data resulted in the range $1*10^{-13}$ - $1*10^{-17}$ m². Fluid inclusions provided also fluid density values, representing the other parameter to estimate hydraulic conductivity that is encompassed between $1*10^{-8}$ and $1*10^{-13}$ m/s. 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 former magma chamber is represented by a shallow gabbro pluton emplaced in Miocene flood-basalts host-rocks. The field activity was based on collection of: (a) field-samples for laboratory analyses; (b) structural and kinematic data from the surroundings 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^{-13} - 10^{-18} m². Fluid inclusions studies, carried out in samples from boreholes, clearly indicate that the hydrothermal fluids were characterized by boiling, T mostly between 150 and 360°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. Concluding, the whole collected data indicate that meteoric fluids were channeled 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.

The research leading to these results has received funding from the EC 7th Framework Program, under grant agreement no. 608553 (Project IMAGE).

A FRACTURING POINT OF VIEW IN GEOTHERMAL FIELDS. CASE STUDY: THE TRANS-MEXICAN VOLCANIC BELT

Víctor Hugo Garduño-Monroy

UMSNH-INICIT-CEMIE-GeO, Morelia, Mexico

E-mail: vgmonroy@umich.mx

The geothermal exploitation of any field in the world located in tectonic volcanic scenarios features uncertainties in the exploration studies when we do not have a clear idea of the fault geometry and of the petrophysical properties of the lithological units affected by the faults. A fault or a fracture may be suitable channels for fluids circulation, but they may also be boundaries.

In igneous rocks, the circulation of fluids will depend on the following factors:

1. A primary permeability in the rock matrix (Primary).
2. The structure of the rock, in autobrecciated material at the time of its formation (Primary).
3. The fracturing by magma cooling or emplacement of igneous bodies (Primary).
4. The fracturing by tectonic processes (Secondary)

In the areas with hydrothermal activity, the primary and secondary permeability can be reduced by the rapid precipitation (months) of hydrothermal materials. However, fractures can be reopened by seismicity, especially when seismicity is due to optimally oriented cracks in the crust stress field.

All the geothermal fields of the Trans-Mexican Volcanic Belt are subject to two important tectonic contexts: a) The first is linked to the active process between oceanic plates (Rivera and Cocos), continental plates (North America) and mixed plates (Caribbean), with subduction or transforming faults boundaries; b) The second is linked to the southern part of the North American plate tectonic fragmentation, which controls the spacial distribution of magmatism and faulting, and also plays a prominent role in the opening of planar elements, where geothermal fluids can circulate. Likewise, they are responsible for the recent seismic activity of the faults and possibly for the recent volcanic activity (Jorullo volcano was born in 1758 on NE-SO structures and Parícutín volcano was born in 1943 on NE-SW structures). This context of fragmentation could also explain the non-parallelism between the TMVB and the Cocos trench.

With the scenario proposed above, it would be almost impossible for some of the TMVB's geothermal fields not to have circulation of fluids. Possibly, for now, we have failed to understand and characterize the planar or lithological elements essential for the circulation of fluids. Or simply, the drilling methods in geothermal fields are masking the favorable fractures for the fluids' circulation.

The 3D in-situ stress field and its induced changes in a geothermal reservoir

Moritz Ziegler^{1,2}, Oliver Heidbach¹, Arno Zang^{1,2}

¹Helmholtz Centre Potsdam, German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany

²University of Potsdam, Institute of Earth and Environmental Science, Karl-Liebknecht-Str. 24-25, 14476 Potsdam-Golm, Germany

The exploitation of geothermal energy requires the extraction and often also the injection of fluids into a reservoir. A frequently observed phenomenon inherent to such operations is the occurrence of induced seismic events. The rock fails due to the induced pore pressure changes that alter the stress state up to the point where the stress exceeds the strength of the rock. In zones of weakness – pre-existing faults – the potential for the occurrence of induced seismic events is larger than in the intact rock mass since the friction is lower. In particular the potential is higher if the stress field is favourably oriented with respect to such pre-existing fractures.

In order to assess the potential for induced seismicity two sets of information are required. (1) The initial in-situ stress state in the reservoir indicates the absolute initial criticality of the rock and faults in the reservoir. The in-situ stress state is estimated by a calibrated 3D geomechanical-numerical model. (2) The stress changes that are imposed on the reservoir by the exploitation operations are used to estimate the relative changes in criticality. The relative stress changes are estimated by a 3D thermo-hydro-mechanical process modelling. In combination the absolute initial stress state and the relative changes allow to estimate the absolute changes in criticality of the reservoir rock and faults before, during, and after exploitation. Such an approach indicates the absolute potential for the occurrence of induced seismic events and the relative changes in potential due to exploitation operations.

We present an integrated approach to 3D geothermal reservoir criticality modelling. In a multi-stage modelling approach we derive a calibrated high resolution 3D stress state in a reservoir model from a calibrated larger scaled regional 3D geomechanical-numerical model. This approach is beneficiary in that it includes both high detail reservoir geometry (in the reservoir model) and a sufficient number of data records for calibration (within the larger regional model). In addition, we investigate the physical response of the reservoir to the injection of fluid. In particular we focus on the phenomenon of injection induced stress tensor rotations and their implications for induced seismicity on pre-existing faults. The rotation angle of the stress tensor is controlled by the permeability of the reservoir rock, the injection rate, and the initial differential stress. We demonstrate that the rotation of the stress tensor renders faults optimally oriented that were previously unfavourably oriented in the initial stress state. We propose that in order to mitigate the occurrence of induced seismic events and to indicate criticality of the intact rock mass and pre-existing faults (1) the absolute in-situ stress state and (2) the relative stress changes and rotations of the stress tensor are required.

Geomechanical Play-Fairway Analysis of Geothermal Prospects in the Cascades Range of Washington State, USA

Nicholas C. Davatzes¹, Michael W. Swyer², Trenton T. Cladouhos², Alex Steely³, Corina Forson³

Affiliations: ¹EES, Temple University; ²AltaRock Energy, Inc; ³Washington Geological Survey, USA

The objective of this project is to develop robust models of heat, permeability, and fluid favorability which together characterize geothermal resource potential. We integrate multiple types of temperature data, geophysical measurements of subsurface characteristics, and mechanical analysis of active faulting resulting in elastic stress/strain fields. In addition, constraints on commercial development due to supporting infrastructure, terrain, available and in-place leases, or societal limitations are compiled into an infrastructure favorability model. These models and their uncertainties are weighted and integrated through an analytical hierarchy process (AHP) to map the potential for geothermal systems, the attendant risk of development, and the potential commerciality reflecting the size of the resource in terms of reservoir temperature, contiguous reservoir volume, permeability potential and development limitations.

The integrated map of development potential is rooted in the conceptual models of geothermal systems characteristic of the play-fairway defined by the Cascadia magmatic arc in Washington state, USA. Common to each conceptual model is the definition of a geothermal system as a source of heat, a pathway for heat movement typically aided by channeled fluid flow along portions of active faults, and a shallow, accessible heat reservoir mechanically maintained within an active fracture network. This whole-system approach allows for (1) analysis to be tailored to specific plays as well as (2) appropriate transfer of knowledge gained from analysis of one play to analysis of another within the fairway.

The analysis benefits from using multiple lines of evidence, such as geophysical measurements, surface mapping, and geomechanical modeling of active faults to reduce uncertainty and cross-validate predictions. A key result of this analysis is not only the characterization and relative ranking of individual plays, but the definition of specific validation targets. The favorability models reveal the relative importance of measurements used in their construction and thus the location and type of additional data that will reduce uncertainty and development risk. These maps are further characterized by corresponding maps of uncertainty in each model input as well as the integrated model uncertainty. Together, the map of resource favorability and its uncertainty form the basis for evaluating the risk of successful development.

No geothermal resource is discovered until the first well encounters high temperature and fluids. Given the complexity of crustal permeability and cost of wells, this is the single highest risk and impediment to resource discovery and development. By developing a clear map of drilling favorability addressing all elements of the geothermal system within a play, in conjunction with a map of risk, relatively few targeted discovery wells are necessary to test the favorability model. Critically, results from each well or new data set can be used to iteratively improve the favorability model and reduce local risk. This approach explicitly minimizes risk and maximizes development potential by providing with a sound basis to target wells.

Three promising plays along the central axis of the magmatic arc have been characterized including: the Wind River valley, sites north and south of Mount St. Helens along the St Helens seismic zone, and southeast of flank of Mount Baker. The analysis of these areas has identified geothermal potential at depth and the necessary steps toward validation including acquisition of additional surface and geophysical data as well as specific targets for geothermal-gradient boreholes.

Innovative Geophysical Tools for Monitoring Geothermal Production and Reinjection Adapted to Exploration Objectives

Chris Bromley¹

¹GNS Science, Wairakei Research Centre, Private Bag 2000, Taupo,

E-mail: c.bromley@gns.cri.nz

Geophysical monitoring tools such as micro-gravity and seismicity provide geothermal reservoir modellers and resource managers with improved information on reservoir behaviour especially when fields are under development. As a consequence, different production and reinjection operating strategies can be trialled, and future scenarios can be fine-tuned to improve operational sustainability. Advanced and novel monitoring methods also help improve forecasts of near-surface environmental effects and monitor the results of mitigation efforts undertaken through adaptive reservoir management. This paper discusses the potential for using the knowledge gained from such methods to help develop better exploration tools.

Recent advances in research into geophysical continuous monitoring techniques include the use of: micro-gravity, seismic tomography, ground deformation, resistivity and various forms of remote sensing. Knowledge has also been gained from reviewing decades of experience from monitoring of physical changes occurring in conventional geothermal projects around the world. To make full use of this information, and to accurately simulate geophysical property changes resulting from reservoir fluid and heat transport, requires inter-coupled thermal, hydraulic, mechanical, and chemical modelling. Some of the rock properties used in reservoir simulation, such as permeability and porosity, will need to be treated as variables rather than constants over the lifetime of a reservoir.

The benefits of this improved understanding of reservoir processes will be improved conceptual models of geothermal resources and therefore better projections of their sustainable energy extraction capacity. This knowledge can also be applied to future exploration strategies.

Ambient seismic noise monitoring during the injection phases at the deep geothermal projects in Basel and St. Gallen, Switzerland

Anne Obermann¹, Gregor Hillers², Toni Kraft¹, Stefan Wiemer¹

¹Schweizerischer Erdbebendienst (SED), ETH Zürich, Switzerland

²ISTerre, Université Joseph Fourier, Grenoble, France

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.

The first visionary Swiss EGS project was within the city limits of Basel. In December 2006, a hydraulic stimulation of the crystalline basement at a depth of 5 km took place. The stimulation was accompanied by more than 10,500 earthquakes in the vicinity of the injection point in the first 6 days. These high rates of induced seismicity led operators to stop the stimulation after 6 of 21 originally planned days. A ML3.4 earthquake occurred 5 h after shut-in, causing slight structural damages that lead to insurance claims exceeding U.S. \$7 million. In the following 56 days three "aftershocks" of ML>3 followed and resulted in the final closure of the project.

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.

We report our results from monitoring the injection phases of these two very different projects with ambient noise cross-correlations. In the case of Basel, we observe a pronounced lapse time change that we interpret as an aseismic transient deformation related to the stimulation. In the case of St. Gallen, we observe a significant loss of waveform coherence that starts with the onset of the fluid injections 4 days prior to the gas kick. We interpret the loss of coherence as an infiltration of the gas in the formation.

Both case studies show that ambient noise correlations can be used to assess the aseismic response of the subsurface to geomechanical well operations, yielding additional important information on the reservoir dynamics.

References:

- Hillers, G., Husen, S., Obermann, A., Planès, T., Campillo, M., Larose, E., (2015) Noise based monitoring and imaging of aseismic transient deformations induced by the 2006 Basel reservoir stimulations, *Geophysics*, 80, 4, doi: 10.1190/GEO2014-0455.1
- Obermann, A., Kraft, T., Larose, E., Wiemer, S., (2015) Potential of ambient seismic noise techniques to monitor reservoir dynamics at the St. Gallen geothermal site (Switzerland), *JGR*, 120 (6), 4301-4316, doi: 10.1002/2014JB011817

SEISMIC IMAGING IN THE KRAFLA HIGH-TEMPERATURE, VOLCANIC GEOTHERMAL FIELD, NE-ICELAND: RESULTS FROM THE VSP EXPERIMENT IN WELL K-18

F. Kästner^{*1}, S. Planke^{2,3}, R. Giese⁴, J. Millett⁵, S. Halldórsdóttir¹, G. P. Hersir¹, K. Gunnarsson¹, A. Gudmundsson⁶, E. Juliusson⁶
and Ó.G. Flóvenz¹

¹Iceland GeoSurvey (ÍSOR), Iceland

²Volcanic Basin Petroleum Research (VBPR), Norway

³Centre for Earth Evolution and Dynamics (CEED), Oslo University, Norway

⁴Helmoltz Centre Potsdam, German Research Centre for Geosciences (GFZ), Germany

⁵Department of Geology and Petroleum Geology, University of Aberdeen, U.K.

⁶Landsvirkjun, Iceland

*formerly Iceland GeoSurvey (ÍSOR)

Among geothermal exploration methods, active surface seismic methods have played only a minor role to date. Especially in high-temperature volcanic systems, reflection seismic data often reveal poor delineation of volcanic sequences, due to the internal heterogeneity of volcanic sequences. To enhance the vertical resolution, one possibility is the application of downhole seismic methods like vertical seismic profiling (VSP). A test experiment was carried out in the Krafla high-temperature geothermal field, NE-Iceland, to assess the ability of VSP to image subsurface structures, such as fractures, zones of high permeability, magmatic bodies, and zones of supercritical fluids and steam. We present results of zero- and far-offset VSP data from the K-18 borehole from within the Krafla caldera, which reveal good correlation with the surrounding lithology. The three-component seismic data display good signal-to-noise ratios and dominant signal frequencies around 20 and 40 Hz, down to about 2200 m depth, for air gun and explosive sources, respectively. Moreover, to assess the use of different impulsive sources, a source comparison was carried out providing additional information for future survey designs. We identified stratigraphic boundaries such as lavas, hyaloclastites, and intrusions, which are in good agreement with existing well data. A P- and S-wave velocity model was calculated from first arrival times and a depth-converted corridor stack of the zero-offset shot was determined. In addition, multicomponent Kirchhoff depth migration and Fresnel volume migration were tested around the borehole. The 3D results are promising, but the specific shape and lateral extent of the reflectors could not be determined due to limitations of the shot geometry. Our study demonstrates that vertical seismic profiles are able to detect changes in the subsurface volcanic stratigraphy in a high-temperature geothermal field. A more detailed reservoir characterization can be achieved by further data integration, enhanced survey design including more source positions, and improved processing and imaging techniques, such as full-waveform inversion.

Surface-Wave Tomography by Ambient Noise Seismic Interferometry to image volcanic and geothermal systems in South Iceland

Joana E. Martins^{1,2}, Elmer Ruigrok³, Cornelis Weemstra², Arie Verdeli¹, Philippe Jousset⁴, Gylfi P. Hersir⁵, Deyan Draganov², Andrew Hooper⁶, Ramon Hansen², Robert White⁷, Heidi Soosalu⁸

¹TNO, Utrecht, The Netherlands

²Delft University of Technology, Delft, The Netherlands

³KNMI, Utrecht, The Netherlands

⁴GFZ, Potsdam, Germany

⁵ÍSOR, Reykjavik, Iceland

⁶University of Leeds, Leeds, United Kingdom

⁷Cambridge University, Cambridge, United Kingdom

⁸Tallinn University of Technology, Estonia

Tomographic studies based on passive seismic measurements have proven to be a powerful tool to image the subsurface. This especially holds in areas like Iceland, where the microseism coverage arriving from the Ocean is excellent.

In this study, we apply Ambient Noise Seismic Interferometry (ANSI) to generate a tomographic image of Rayleigh waves velocity anomalies and further inversion to S-wave anomalies at two Icelandic locations. We derive a tomographic image over Reykjanes Peninsula geothermal system using 30 Broad-Band (BB) stations deployed under IMAGE project framework and operating for approximately one year and a half. In the other case study, we derive a tomographic image of Torfajökull volcano using 23 BB seismometers recording ambient noise for ~100 days acquired in 2005 by Cambridge University.

We retrieve the surface-wave part of the Green's functions by cross-correlation between station pairs and consecutive stacking of the cross-correlations to obtain coherent ballistic surface waves (BSW). We pick the arrival times of the BSW, which are the input for the tomographic analysis. Both datasets show remarkably high signal-to-noise-ratio of surface-wave arrivals between 0.1 and 0.5 Hz, even with only ~100 days of recorded ambient noise. A beamforming analysis indicates a broad azimuthal coverage with persistent ambient noise arrives within three azimuthal quadrants, between 90 and 360 degrees. The highly coherent surface waves retrieval and the wide azimuthal coverage of the microseismicity arrival explain the success of ANSI techniques in Iceland.

For the tomographic inversion, we use a Tikhonov and a statistical regularisation to invert the ballistic surface-wave time arrivals to a 3D frequency dependent velocity variations. We detect low and high-velocity anomalies with changes between -15% and 15% from an estimated average velocity, which we interpret as possible old dyke intrusions and heat sources.

The research leading to these results has received funding from the European Community's Seventh Framework Programme under grant agreement No. 608553 (Project IMAGE)

Analysis of seismological data on Reykjanes peninsula, Iceland

Hanna Blanck¹, Philippe Jousset², Gylfi Páll Hersir¹, Kristján Ágústsson¹, Ólafur G. Flóvenz¹

¹ISOR, Iceland Geosurvey, Grensásvegur 9, 108 Reykjavík, Iceland

²GFZ Potsdam, Telegrafenberg, 14473 Potsdam, Germany

E-mail: hanna.blanck@isor.is

Seismological methods have not been applied much in geothermal exploration in volcanic environments in the past. New approaches show them to be a valuable pre-drilling exploration tool that can help to improve the understanding of the structure, stress and dynamics present in geothermal systems. Both classical analysis of seismological data as well as newer techniques have been applied to an extensive seismic dataset recorded in Reykjanes peninsula, Iceland.

From March 2014 until August 2015 a dense network consisting of 20 Broadband and 10 Short Period seismometers together with 24 Ocean Bottom seismometers (OBS) which were deployed in the Atlantic Ocean around the peninsula in August 2014 by the Alfred Wegener Institute (AWI) was recording earthquakes in Reykjanes. Data from another 29 stations of other (semi-) permanent seismic networks in the area was available. This adds up to a total of 83 seismometers in an area that is about 90 km in diameter.

From this unique data set an earthquake catalogue was created which contains more than 2000 events, the majority of them inside the geothermal field and along the Mid-Ocean Ridge. The earthquakes were automatically picked and located with the Seiscomp3 software and later manually revised. Based on the pick times a 1D velocity model was calculated using the SIMULPS software which was then used as a starting model for a 3D tomography conducted with both SIMULPS and tomoDD. All earthquakes were relatively relocated based on the new 1D model and focal mechanisms for 35 chosen events were calculated using the HASH software.

Those events came from two different regimes. The shallower events (< 4 km) are part of a cluster of induced earthquakes that occurred following the start of operation of a new injection borehole in Reykjanes. The faulting mechanisms of these earthquakes are mostly strike-slip dominated. The other group of events for which faulting mechanisms could be calculated lies deeper (ca. 6 km) and has been located along the Mid-ocean ridge. Here most earthquakes either occur on normal or oblique faults with strike-slip and thrust faults being an exception.

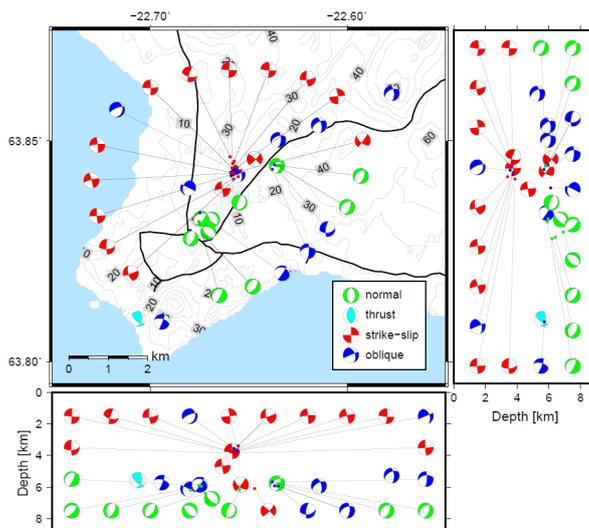


Figure 1: Focal mechanisms calculated for 35 chosen events in Reykjanes geothermal area, southwest Iceland. The distribution of fault types reveals different stress regimes in which the shallow induced, locally very limited cluster occurred in comparison to the deeper, mid-ocean ridge associated earthquakes.

Controlled-Source Electromagnetic surveying for geothermal exploration in deep sedimentary and basement areas

Mathieu Darnet, Nicolas Coppo, Pierre Wawrzyniak, François Breteau and Sebastien Penz

BRGM, France

Sedimentary basins have significant potential for low to medium enthalpy, deep geothermal energy resources. These resources are generally assessed using standard seismic exploration techniques to resolve geological structures. However, the electrical resistivity parameter, which can be directly impacted by the presence of a geothermal reservoir, is rarely investigated in such context. Therefore, the development of alternative and complementary exploration techniques such as Electromagnetic (EM) techniques may have an important role in reducing the cost and uncertainty associated with geothermal resource assessment.

While EM techniques have proven to be useful in geothermal exploration in high enthalpy areas in the last decades only a handful of studies assessed their applicability in low enthalpy sedimentary basins. There, challenges include identifying which sub-surface features can cause changes in electrical resistivity as low enthalpy reservoirs are unlikely to exhibit the hydrothermally altered clay layer above the geothermal aquifer that is typical for high enthalpy reservoirs. Yet a principal challenge is likely to be the high level of industrialization in the areas of interest. Infrastructure such as train tracks and power cables can create a high level of background noise that can obfuscate the relevant signal.

As part of the IMAGE project, we have undertaken to tackle these challenges by developing a comprehensive toolbox of EM techniques, with a special focus on active techniques like the Controlled-Source Electromagnetic technique (CSEM). In this paper, we will present the results from our research and development of this technique for geothermal exploration in sedimentary basins. We will show that in areas with high level of industrialization, it is the most cost-effective technique to image deep resistivity variations. We will however also touch upon the remaining resolution and interpretation challenges that we face when using resistivity measurements for geothermal de-risking in sedimentary basins. We will illustrate these aspects with two 3D CSEM surveys acquired in the Upper Rhine Graben and in the Bohemian Cretaceous Basin.

Enhanced Characterization of Induced Seismicity

Gregory A. Newman and Petr V. Petrov

Lawrence Berkeley National Laboratory, Earth Sciences Division, CA, USA

E-mail: gnewman@lbl.gov

At the most geothermal fields the activities associated with geothermal energy production and or enhanced geothermal system (EGS) development will cause increase seismicity, where the physical mechanisms are still not fully understood. For the definition of the nature of induced seismicity, a second-order dynamic moment tensor analysis may be used to ascertain if seismicity is arising from stress release along preexisting faults or from fracture permeability creation associated with EGS activities. With dynamic moment tensor analysis an accurate estimation of the source parameters, including location, in the presence of complex geological media with highly variable seismic velocity properties is a non-trivial task. Here, we employ the full elastic waveform inversion (FWI) in Laplace-Fourier domain to estimate the location and seismic moment tensor parameters of sources embedded in 3D isotropic heterogeneous media. Forward modeling is carried out with a 3D finite-difference code that generates P- and S-waves from the point sources defined by second-order moment tensors. The inversion algorithm is based on nonlinear gradient calculations for the minimization of the objective function for event location and source moment updating based upon the linear least-squares normal equations for the micro-seismic event at an assumed location, embedded in complex heterogeneous geological media. The FWI algorithm is shown to be stable in the presence of complex geometry including faults and random Gaussian noise. We present results of testing the FWI methodology on the synthetic dataset for the Raft River geothermal field, Idaho. The detectors were placed on the earth surface and seismic events were simulated at the depth about 2000 meters. Matching the waveforms from seismic events provides improved source location along with estimates of the pertinent components of the moment tensor. Investigation of the influence of velocity model and an initial position of an event are performed.

Keywords: Seismic moment tensor; 3-D inversion; Raft River Geothermal Field

High resolution gravity models for sedimentary basins and underlying basement

Jan-Diederik van Wees^{1,2}, Mark Vrijlandt¹, Gijs den Hollander², Fred Beekman², Jon Limberger², Eszter Bekesi²

¹TNO, Netherlands

²Utrecht University, Netherlands

Forward models on gravity can assist in obtaining constraints on deep subsurface structure in sedimentary basins. This is of particular relevance in view of Ultra deep Geothermal exploration (> 4km) for mid to high enthalpy resources (>> 100C). In order to effectively identify deeper gravity anomalies and to disentangle the effects of sediment and basement effects, and thermal and lithology related effects on gravity, we developed a model approach which :

- Calculates gravity using a high resolution density representation of the subsurface with up 100s of millions of cells, using FFT techniques
- Builds density models from detailed mapping of sedimentary basin structures, litho-stratigraphic interpretation and porosity-permeability relationships as a function of burial depth and burial anomalies.
- Integrates results from 3D thermal forward models of which the parametrization is consistent with the gravity models, and which are constrained by temperature observations
- Constrains deep model interpretation by gravity observations through Ensemble-smoother with multiple data assimilation.

The workflows has been used in interpretation of the deep subsurface of the Netherlands.

Hybrid gravity monitoring of Soultz-sous-Forêts and Rittershoffen (Alsace, France) geothermal reservoirs

Portier, N.^{1*}, Hinderer, J.¹, Riccardi, U.², Fehrat, G.¹, Bernard J.-D.¹

¹Institut de Physique du Globe de Strasbourg UMR 7516 Université de Strasbourg, 5 rue Descartes 67084 Strasbourg, France

²Università degli Studi di Napoli Federico II, Dipartimento di Scienze della Terra, dell'Ambiente e delle Risorse DiSTAR, Largo San Marcellino, 10 – 80138 Napoli, Italy

E-mail: nolwenn.portier2@etu.unistra.fr

The exploitation of Rittershoffen and Soultz-sous-Forêts geothermal energy in the northern Alsace (France) began in May and June 2016. Soultz-sous-Forêts site is the first enhanced geothermal system demonstration site producing electricity in France (4 wells, ~5km deep, 1.5MW, 165°C), while Rittershoffen site is dedicated to an industrial use for heat application (2 wells, ~2.5km deep, 24 MWth, 160°C). In order to study underground mass redistributions and hence to follow a geothermal reservoir both in its natural state or undergoing man-made stimulations, time-lapse gravity measurements have been made since 2014. Each summer, weekly repetitions with a Scintrex CG5 gravimeter of a network of 13 stations at the two sites allow us to calculate the gravity double differences. These differences show the gravity variation at each measuring point compared to a reference time and station. The stability of the reference station is investigated both by using repeated measurements of absolute gravity and by doing regular links with the Strasbourg gravimetric observatory J9, where several superconducting gravimeters operate continuously. Thus, we approach the concept of hybrid gravimetry. Furthermore, to perform a rigorous vertical control which can impact our measurements, all gravimetric sites are leveled: the height changes are less than 1 cm. So, we can consider that our gravity variations are only due to Newtonian attraction. We notice that the gravity values are lower next to the production area than next to the injection area after the beginning in summer 2016 of the exploitation in Soultz-sous-Forêts site. Rittershoffen site emphasizes another trend that we don't yet explain. We hope to improve our geothermal site understanding thanks to the future measurements on the sites in Alsace but also to our new time-lapse gravity project in Iceland (Krafla and Theistareykir geothermal sites) that begins this summer.

Keywords: time-lapse gravity, geothermal reservoir

Active and passive electromagnetic measurements in a deep fractured sedimentary basin in peri-urban context in NE Belgium

Virginie Harcouët-Menou¹, David Lagrou¹, Baptiste Rondeleux², Sebastien Gallo², Guillaume Trancart²

¹VITO, Boeretang 200, 2400 Mol, Belgium

²CGG, Massy, France

Within the frame of the SALK Research Project, our research efforts have been focusing on checking the feasibility of using electromagnetic methods for resistivity mapping in faulted deep sedimentary environments with a high level of electromagnetic noise. A previous study conducted in northern Belgium in the Campine basin (Coppo et al., 2016) showed that passive electromagnetics (MT) exploration was very challenging if not unfeasible in peri-urban contexts. To overcome these difficulties, controlled source EM techniques (CSEM) had been deployed in addition to the MT measurements. For the CSEM measurements, surface and borehole high power emissions have been used to improve the EM signal to noise ratios to allow mapping resistivity variations at the depth reaching 4 km. This first project demonstrated the benefits and limitations of electromagnetics methods for geothermal exploration in sedimentary basins in Belgium. There, the possibility of using electromagnetics techniques to aid identification of geothermal resources was the objective.

Based on the promising results obtained in the Campine basin, we set up a new campaign in the Limburg region. The purpose of this second survey was to study the potential of passive and active electromagnetic methods to map in 3D the deep boundary faults of the Roer Valley Graben (up to 4 km in depth), and to get insight into their hydrological behaviour. The geophysical survey was performed in the area between the cities of Bree and Maaseik where a seismic campaign had been conducted in 2007 by VITO.

Measurements have been performed from 22nd May to 9th of June 2017 by CGG and VITO staff. In an area of 5.5 by 7.5 km, 60 CSEM stations and 20 collocated MT stations have been recorded in two swaths (7.5 km x 2.7 km). In addition, 2 remote stations were set up at the Geophysical Center at Dourbes (Belgium) for further robust data processing. The CSEM survey has been conducted using surface and a combination of surface and borehole casing power emissions. Based on the results of a pre-design study and according to local constraints we installed a double orthogonal dipole surface-surface (L-shape) of 2x1 km south-east of the area providing two first polarizations (POL1 and POL2). A second double orthogonal dipole surface-surface and surface-500 m deep borehole (L-shape) of 2x1 km was deployed north-west of the target region. Injection in the north-west was more difficult due to the presence of a surficial resistive sandy/gravel layer. The intention was to use the casing of the deep well as a source electrode to improve even more the CSEM signal to noise ratio. The current injection was limited to 9 for 2 polarizations and to 11-14 for the 2 others polarizations. To reach the ambitious objective of providing apparent resistivity maps at various frequencies and for the different polarizations reflecting the geological variations in 3D over an area of ~40 km², a set of frequencies ranging between 0.125 Hz to 128 Hz was selected to investigate the medium.

The data of the MT and CSEM field survey are currently processed and will be presented during the final conference of the IMAGE project in Iceland in October 2017.

References:

COPPO N., DARNET, M., HARCOUET-MENOU V., WAWRZYNIAK P., MANZELLA A., BRETAUDEAU F., ROMANO G., LAGROU D., & GIRARD, J.-F., 2016. Characterization of Deep Geothermal Energy Resources in low enthalpy sedimentary basins in Belgium using Electro-Magnetic Methods – CSEM and MT results, European Geothermal Congress 2016, Strasbourg, 19-24 September 2016.

¹with the support of the EU, ERDF, Flanders Innovation & Entrepreneurship and the Province of Limburg

MT-inversion techniques with external constraints

Ásdís Benediktsdóttir, Gylfi Páll Hersir, Knútur Árnason and Ragna Karlsdóttir

ÍSOR-Iceland GeoSurvey, Iceland

E-mail: asdis.benediktsdottir@isor.is

Inverting MT data is a non-unique and a highly unstable problem. Joint inversion or interpretation using different datasets has been a common challenge for many scientists within the MT world. Applying external constraints in the MT inversion from other geoscientific disciplines is one of the solutions. MT-inversion techniques with external constraints was one of the tasks within the IMAGE project - a vital one - since having a reliable resistivity model is a key thing in conceptual modeling of geothermal areas.

Here, the origin and nature of static shifts and some tested methods for static shift correction are discussed, i.e. joint 1D inversion of co-located TEM and MT soundings, and spatial filtering and statistical assumptions about the shifts. A software is introduced which inverts the two datasets for both the resistivity model and the shift of the MT data. Besides determining the static shift, joint inversion is an important quality check of the TEM and MT data sets, i.e. whether they are compatible. In EM surveying, a preliminary joint inversion of TEM and MT data should be performed at base camp as a quality control to ensure that the field mission is not terminated until good quality data have been collected. Finally, the claim that 3D inversion of MT can deal with the static shifts, i.e. introduce shallow resistivity structures (not resolved by the data) to account for the shifts is tested.

Two examples of using external constraints in MT-inversion are demonstrated. On one hand the depth-location of a low-resistivity anomaly (the conductive smectite alteration zone), as observed from borehole data, is built into the starting model, giving the program a headstart into gaining information on the resistivity in the survey area and on the other hand information on the ductile-brittle boundary location is used to infer the location of a deep low-resistivity anomaly, which is put into the starting model of the inversion.

Borehole data provide important information about rock properties in the subsurface. Unlike the knowledge of the Earth gathered from surface exploration, where information is obtained through various modeling techniques, borehole data provide direct measurements and analysis of numerous properties of the subsurface. One set of measurements often included in borehole logging is resistivity and another data set is analyses of hydrothermal alteration. These information can be used as a-priori information for the resistivity models. It is, however, not obvious how one can implement information such as these into the model. In order to explore different options, a synthetic model was created imitating the resistivity structure of a high-temperature geothermal system, basing the depth-location and resistivity of the conductive cap on the two different datasets discussed above.

A deep-lying low resistivity layer is present underneath most of Iceland and domes up at the locus of rifting, underneath high-temperature geothermal systems. Recently, a seismic study of the Námafjall area, NE-Iceland revealed an a-seismic zone underneath the local high-temperature geothermal system in the form of a dome. In the same area, a resistivity model revealed up-doming of the deep low-resistivity layer. As the a-seismic layer in the seismic dataset marks the boundary of the ductile-brittle boundary, it may be concluded that the up-doming of the deep low-resistivity layer has the same origin. Here, the seismic data are used as a-priori information in the resistivity modeling, assuming that the up-doming of the a-seismic area delineates the up-doming low-resistivity.

The research leading to these results has received funding from the EU 7th Framework Program, under grant agreement no. 608553 (Project IMAGE).

A surface-hole deep electrical resistivity acquisition in the Larderello geothermal field (Italy)

E. Rizzo¹, V. Giampaolo¹, L. Capozzoli¹, G. De Martino¹, M. Tricarico¹, F. Perciante¹, A. Manzella², A. Santilano²

¹CNR-IMAA, Italy

²CNR-IGG, Italy

A new experimental deep electrical resistivity acquisition was carried out in Larderello geothermal area (Tuscania Region, Italy) by 3D Deep Electrical Resistivity Tomography (3D-DERT) acquisition. The electrical resistivity method (DC) along the earth's surface is a well-known geophysical exploration technique. Due to its conceptual simplicity, low equipment cost and ease of use, the method is widely applied in mining exploration, archaeological detection, civil and hydrological engineering, and environmental investigations. The DC method is based on the injection of a current into the ground, to measure the generated electrical field as a potential difference. Usually, the ERT method is used for near surface applications and the improvement in technology is well defined (i.e. multichannel system), but the deep ERT combined with new approach is highlighting several successes for geological and hydrogeological studies (Rizzo et al., 2004; Tamburiello et al., 2008; Santilano et al., 2015 and reference therein).

The investigated area is located close the Venelle2 well in the southern part of Larderello site, where there is the oldest field in the world under exploitation for power production (actual installed capacity is about 795 MWe). A vapour-dominated system is exploited to depth over 3500 m, with temperatures exceeding 350°C, from two different reservoirs. The Larderello area has been investigated by many geological and geophysical data 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.

The 3D-DERT system was designed in the area around Venelle2 well by two main steps: an only surface electrode distribution was involved in the first step; during the second one, surface and hole electrode distributions were implemented covering an area around 16km². The well (kindly provided by Enel GP) was accessible down to 1.6 km with a temperature up to 250°C and a metallic casing down to 1 km. In order to make this experiment, ad hoc special cable was built in the CNR-IMAA laboratory and a prototype georesistivity instrumentation were used to carry out the electrical resistivity data. The in-hole thermal electrical cable is characterized by n.12 flexible metallic electrodes with an electrodes space of 50m covering the open-hole portion (1050m-1600m). The surface electrodes are located around the Venelle2 hole on n.41 different positions connected to automatic datalogger to acquire the drop of potential and to transmitter device to inject the current (5-10A). The crucial task was the data processing, considering the large distance between the Tx and Rx systems that strongly reduces the signal to-noise ratio. To overcome this drawback, for each quadripole position the corresponding voltage signal was filtered, stored and processed.

The experimental DC resistivity measurements were used with the MT model and improved the knowledge on the deep structures of the Larderello field. The interpretation took advantage also of a detailed and integrated 3D modelling of many geological and geophysical data available in the area.

We thank the colleagues that supported the fieldwork during the MT and DC surveys. We thank Enel Green Power for the precious technical and logistical support on carrying out the borehole experiment. This study is part of the EU FP7-funded Integrated Methods for Advanced Geothermal Exploration (IMAGE) Project under grant agreement n° 608553.

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

R. Bertani

Enel Green Power

The DESCRAMBLE project will develop novel drilling technologies for a proof-of-concept test of reaching deep geothermal resources and contributing to a low-carbon European society. In the project we will drill and test the continental-crust condition for demonstrating novel drilling techniques, the control of gas emissions, and of the high temperature expected from the deep fluids. The project will also improve knowledge of deep chemical-physical conditions for predicting and controlling any drilling conditions.

To achieve this target we will drill this first-in-the-world intra-continental, mid-crustal borehole in high temperature condition. 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 deepened to 3 to 3.5 kilometer depth. The site is perfect for such an experiment, as it is representative of most deep crustal levels in Europe, cost effective (since drilling for reaching the target is reduced to a minimum), and practical due to the high probability of encountering high temperature conditions. 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 use.

Specific Objectives are:

- Demonstrating safe drilling of a deep geothermal well.
- Reducing 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.
- Reducing pre-drilling uncertainty in the exploration of deep geothermal wells.
- improve in-situ characterization by developing a special tool for super-high temperature and pressure measurements and by analysing fluid and rocks samples of deep, supercritical conditions
- Investigating the economic potential of exploiting chemicals and minerals by analysing fluid samples for valuable raw materials.

DESCRAMBLE is a 3-year project involving the following main activities:

1. Year 1: General preparation activities for drilling, data review and acquisition of new data, design and execution of seismic surveys, development of new instruments and tools, and modeling software; Activity completed
2. Year 2: Drilling and testing the borehole; On going drilling phase. Present depth 2,6 km
3. Year 3: Testing, validating and assessing of results.

Exchange of information with the EU-projects IMAGE, DEEPEGS and GEOWELL will be ensured via the partners common to both projects. This will make possible to provide access to relevant information and a fruitful scientific cooperation.

Update on recent achievement

A specific test on cement has been commissioned to Halliburton. The scope of work for this study was to advise on the potential for a cementing material suitable for high temperature (400-450°C) and to identify associated challenges and provide recommendations to mitigate risk. The cement has been chosen and utilized.

A casing performance evaluation has been carried out by Tenaris. The main purpose of the work was to select the pipe weight, grade and connections for last two casing sections of the well (9 5/8" and 7") in order to withstand the anticipated well conditions. The study also contains some considerations regarding material selection against environmental cracking and sweet corrosion of steels. In order to satisfy the constraints posed by the sour and thermal nature of the well and, at

the same time, in order to mitigate the risk of Annular Pressure Build Up (APB) phenomena, 7" TN125SS (high collapse and sour service grade) has been recommended for the tie-back. This casing is now safely in the well.

All the BHA components (rock bits, stabilizers, well head equipment and drill pipes/drill collars) have been selected and now they are in place. A specific test has been carried out with the Stinger rock bit from Smith, which has been selected for drilling into the high temperature section of the well. It will be used in the 6" drilling phase which is starting now.

In addition to the standard drilling services, some specific activities has been identified for the Venelle well: Managed Pressure Drilling, Mud Logging and Mud Cooling System; these services will be provided by Weatherford, Geolog and Drillcool System. All of them are now up and running.

A first set of logs has been carried out in the accessible section of the well before the drilling: HDIL (High Definition Induction log), WGI (Wellbore Geometry Instrument), TTRM (Temperature, Tension and Mud Resistivity sub), UXPL (Ultrasonic Explorer for CBIL Image log), XMAC (X-Multipole Array Acoustic log), FLEX (Formation Lithology eXplorer) and DSL (Digital Spectralog).

A set of about 20 rock samples from several wells in the metamorphic basement have been collected, as well as chemical fluid sampling from nearby wells. The chemical and mineralogical analyses are providing information related to deep seated chemical and thermodynamic condition.

A special high pressure and temperature tool has been designed, realized and tested in lab, on another EGP well at intermediate temperature and on Venelle well at 2,6 km depth. Its performances are good. Maximum well temperature (extrapolated) is 400°C.

A VSP survey was carried out at the Venelle 2 well by Western Atlas International. The survey included the acquisition of one zero-offset VSP and three offset VSPs. More over, a piggy back data acquisition has been carried out. The processing steps for the piggy back data focused mainly on migration velocity model building, the influence of the velocity model on the seismic image as well as on the structural interpretation of a reflection package from the geothermal reservoir.

The comparison between the different obtained results led to the depth estimation of the K horizon in correspondence of the Venelle 2 well. The well design has been targeted to the expected location of the K horizon.

The high resolution microseismic monitoring of the drilling site area has been increased by integrating the Larderello Travale Microseismic Network (LTMN) with 4 additional Temporary Seismic Stations (TSS) placed at 1.5 to 2 km distance from the Venelle 2 well.

Geochemical activity on geothermal fluids was carried out in selected geothermal wells from Venelle surrounding as a preparatory work of the Venelle drilling.

A regional structural and numerical model was created which covers an area around the borehole Venelle 2 of 15 km × 15 km. A local model around the Venelle 2 drilling was extracted and modelled by RWTH and discussed with CNR and EGP. This model will iteratively be updated alongside improvement of the regional model. The local model comprises a volume of 40 km³ (3 km × 3 km × 4.5 km) discretised in a rectilinear grid consisting of about 650 000 cells. Boundary conditions of the local model are taken from the regional model.

It is expected to reach the K horizon drilling target in October 2017.

Heat transfer in the Acozulco Caldera, Mexico

Rosa María Prol-Ledesma (P.I. Working package 5.3 Gemex)

Instituto de Geofísica, Universidad Nacional Autónoma de México. Cd Universitaria
Mexico City. 04510. Mexico

Determination of the heat transfer mechanisms is relevant to the planning of exploitation of this field. Two exploration wells show that within the upper 3000 m permeability is extremely low; however, shallow features indicate the occurrence of hydrothermal eruptions that would require the presence of hydrothermal fluids. Presently, the hydrothermal prospect in Acozulco is considered an EGS field by the company leading exploration (CFE) in the area.

This working package (5.3) is aiming to evaluate the main mechanisms of heat transport within the caldera by measuring the geothermal gradient in approximately 20 shallow wells that will be drilled with that purpose.

Drilling of the first 8 wells is scheduled to start at the end of this year and the wells are distributed in the caldera targeting the main structures that may serve as channels for hydrothermal flow to find evidence of heat transport by convection. One well will be sited outside the caldera for reference, and the geologists suggested a young pyroclastic flow as target.

Field work will be decisive to confirm the location and depth of the wells, and the results of the first 8 wells will be analyzed before the decision of the second batch is taken.

Use and development of auxiliary chemical geothermometers for geothermal fluids from crystalline and sedimentary reservoirs

B. SANJUAN¹, F. GAL²

¹BRGM, Department of Geothermal Energy, 45061, Orléans, France

²BRGM, Laboratory Division, 45061, Orléans, France

E-mail: b.sanjuan@brgm.fr, f.gal@brgm.fr

One of the major applications of water geochemistry in the exploration of geothermal reservoirs involves estimation of their temperature using chemical and isotopic geothermometers on fluid samples collected either from thermal springs or geothermal wells. Since the 1960s, several classical geothermometers such as Na-K, Na-K-Ca, K-Mg, SiO₂, and $\delta^{18}\text{O}_{\text{H}_2\text{O}-\text{SO}_4}$ are commonly available in geothermal exploration. Unfortunately, the estimates of reservoir temperatures using these tools are not always concordant, especially at low and medium temperatures. The absence of chemical or isotopic equilibrium reactions between water and minerals involving major species in the geothermal reservoirs, the mixing of the deep fluids with surface waters or their cooling and the associated precipitation/ dissolution processes during their rising to the surface, can be responsible of these discrepancies. Since the early 1980s, numerical multicomponent geochemical models are being developed for direct application to chemical geothermometry for geothermal exploration. These models allow numerical calculations of equilibration temperature of the geothermal water with respect to a suite of reservoir minerals, and thus the estimation of the reservoir temperature. However, the accurate determination of some key parameters that are necessary to these models, such as Al concentration or pH value representative of the reservoir water, is often difficult and hypothetical. Moreover, at low-moderate temperatures, the conditions of chemical equilibrium of the water-rock interaction processes involving major species are not always reached.

So, after an extensive literature review about the use of potential auxiliary chemical geothermometers, associating a major element with a trace element, we have identified several thermometric relationships proposed for dilute geothermal waters from European granite reservoirs [1], within the framework of the FP7-IMAGE project. We tested, developed and validated these thermometric relationships on two European low-temperature geothermal areas [2,3]: (1) the Litomerice and Teplice areas, in Czech Republic, in which the PVGT-LT1 deep geothermal borehole was drilled down to a crystalline basement (about 56°C at 2 000 m) and where some thermal springs are observed; (2) the Thônex (THX-1) and Lavey-les-Bains areas, in Switzerland, where two deep boreholes were drilled down to sedimentary formations (about 70°C at 2 100 m, and 105°C at bottom-hole, respectively). As the PVGT-LT1 and THX-1 boreholes have very low natural flow-rates, the collection of representative fluid samples was quite difficult. We have also developed three new Na-Rb, Na-Cs and K-Sr thermometric relationships using literature data, referring to 20 hot natural brines discharged from granites and sedimentary reservoirs [2], mainly located in the Rhine Graben (France and Germany, 70-200°C) with the exception of two from the Salton Sea, in the Imperial Valley (USA), which are the hottest reservoirs (300-320°C).

For an efficient application, these auxiliary geothermometers must be always combined with a global geochemical data interpretation, being ideally tools complementary to the classical geothermometry approach and to the integrated multi-component solute geothermometry approach. The existence of different thermometric relationships for a given geothermometer suggests that the latter not only depends on temperature, but also on other influential factors such as the nature of the rock, its degree of alteration, the water-rock ratio or the fluid composition and salinity. This allows concluding that it is essential to well define the environment in which these geothermometers will be applied before their use, and that additional investigations are mandatory for each specific environment.

[1] Michard G. (1990) Chem. Geol. 89, 117-134.

[2] Sanjuan et al. (2016) - FP7-IMAGE final report D7.03.

[3] Dezayes et al. (2017) - FP7-IMAGE final report D8.02.

The electrical structure of Icelandic deep geothermal reservoirs: insight from laboratory experiments

Franck Nono^{1,2}, Benoit Gibert¹, Fleurice Parat¹, Didier Loggia¹, Sarah B. Cichy^{3,4} and Marie Violay⁵

¹Laboratoire Géosciences Montpellier, University of Montpellier, France

²University of Pau UMS-DMEX, Pau, France

³University of Potsdam, Germany

⁴GFZ German Research Centre for Geosciences, Potsdam, Germany

⁵Ecole Polytechnique Fédérale de Lausanne, Lausanne, Suisse

Exploration and exploitation of deep high-temperature geothermal resources in Iceland require a good knowledge of the physical properties of their reservoir rocks. In particular, determination of the processes affecting electrical transport at in-situ conditions is a pre-requisite to interpret electrical resistivity soundings that are commonly used to characterize the reservoirs at depth. Until now, technical challenges related to pore fluid confinement, impeded to measure, at the laboratory scale, electrical conductivity of rock sample at temperature and pressure representative of very deep geothermal reservoirs. In this study, we overcome these limitations thanks to a new electrical resistivity cell installed on a Paterson apparatus. This allows us to perform resistivity measurement at temperature up to 700°C and effective pressure up to 70 MPa (a confining pressure of 100 MPa and an equilibrium pore pressure of 30 MPa). Rock samples come from five boreholes located in the Icelandic geothermal fields of Reykjanes (RN-17B/Hyaloclastite, RN-19/RN-30/dolerites) and Hengill (NJ-17/basalt and NJ-17B/Hyaloclastite). These samples were selected for their high degree of hydrothermal alteration in the epidote and amphibole facies (i.e. temperature of 250°C and 400°C respectively) and their various range of porosity (from 3% to 20%). The intra-mineral, electrolytic and surface contributions to the bulk rock electrical conductivity were determined by achieving conductivity measurements under dry conditions and under saturated conditions on 3 different fluid salinities while temperature varied from 25°C to 700°C.

From ambient temperature till 250-300°C, bulk conductivity increases mostly due to electrolyte and surface conductivity increase. The surface contribution is found to be very temperature dependent, and becomes the dominant conduction mechanism at the early stages (by 200°C). Under supercritical conditions, i.e. temperature from 375 to 500°C, electrical conductivity strongly decreases due to the change in fluid behavior. In these conditions, surface conduction is still the major contributor to bulk conductivity. At higher temperatures (500°C – 700°C), the rocks conductivity lie on the dry electrical conductivity values, suggesting that intra-mineral is the dominant conduction mechanism, with ferro-magnesian minerals as principal contributors. Amphibole rich samples show an irreversible increase in conductivity at temperature above 500-600°C, which can be attributed to amphibole dehydration.

These results provide a general trend for interpreting electrical conductivity soundings in the Icelandic crust. Reservoirs saturated with supercritical fluids should display a negative anomaly of electrical conductivity compared to conventional high temperature reservoirs (250-300°) exploited in Iceland.

Physical rock properties and their relation to fluid-rock interactions at supercritical conditions

Juliane Kummerow, Siegfried Raab, Jan Schüssler, and Romain Meyer

GFZ German Research Centre for Geosciences, Potsdam, Germany

E-mail: jule@gfz-potsdam.de

In recent years, the investigation of unconventional high-enthalpy hydrothermal systems linked to magmatic intrusions in active volcanic environments became a key target of scientific interest as the exploitation of reservoirs with fluid temperatures above 350°C is expected to increase the energy output by the tenfold. Electrolytes, which are commonly dissolved in hydrothermal solutions, have the tendency to associate at high temperature, which cause a removal of free charge carriers from the solution. This behaviour is intensified at supercritical conditions ($> 374.21^\circ\text{C}$ and 22.12 MPa), when density and dielectric constant are low. Moreover, at high temperature the chemical reactivity of aqueous fluids is enhanced, causing mineral dissolution and/ or precipitation and hence, changes in fluid salinity. Thus, electrical sounding methods are regarded to provide a convenient means for detecting supercritical roots of geothermal high-enthalpy reservoirs. However, up to date there is a lack of calibration data, because due to the extremely technical complexity of high-temperature set-ups, only very few petrophysical studies were performed at temperatures higher than 250°C, and none of them with the possibility of fluid flow.

In order to study the impact of fluid-rock interactions on the physical properties of fluids and rocks in near- and supercritical geological settings in more detail, hydraulic and electrical properties of rock cores from different active and exhumed geothermal areas on Iceland were measured up to supercritical conditions ($T_{\text{max}} = 380^\circ\text{C}$, $p_{\text{fluid}} = 25\text{ MPa}$) during long-term (2-3 weeks) flow-through experiments in an internally heated gas pressure vessel at a maximum confining pressure of 42 MPa. In a second flow-through facility both the intrinsic T-dependent electrical fluid properties as well as the effect of mineral dissolution/ precipitation on the fluid conductivity was measured for increasing temperatures in a range of 24 – 422°C at a constant fluid pressure of 31 MPa. Petro- and fluid physical measurements were supplemented by a number of additional tests, comprising microstructural investigations as well as the chemical analysis of fluid samples, which were taken at every temperature level.

Both physical and chemical data indicate only slight fluid-rock interactions below the critical point. Especially, for Si a continuous increase of ion concentration in the fluid samples is revealed for increasing temperatures, indicating a beginning mineral dissolution above 150°C, which however does not affect the physical properties. At near-critical conditions Si dissolution is going to accelerate and also Al is more intensively mobilized. The release of charge carriers to the formation fluid is accompanied by an increase in electrical fluid conductivity by factor 7 within seconds. This points to an extensive and spontaneous increase in rock solubility. However, above the critical temperature only temporary conductivity equilibria were reached in the order of several hours. Rather a continuous increase and decrease of conductivity was observed in fluid conductivities, which may indicate a dynamic interplay of the input of new charge carriers by to mineral dissolution and ion depletion by mineral precipitation due to the drop in supercritical water polarity. Regarding the measurements on rock samples we can resolve the influence of mineral precipitation only, which is indicated by a decrease in bulk conductivity by about 40% and in rock permeability by about 5% after the sample was exposed to supercritical conditions for 4 hours.

New (Zealand) perspectives on continental arc geothermal systems

Chambefort, I., Wilson, C.J.N., Bignall, G., Rowland, J.V.

GNS Science, New Zealand

A multidisciplinary project, involving researchers from several New Zealand institutions is underway to address a number of enduring geoscience questions, including what controls the longevity and position of geothermal systems in areas of active volcanism and rifting? Do deep-seated crustal discontinuities focus the upward transport of subduction volatiles and influence the compositional variability in magmatic and geothermal fluids? How can we link disparate deep seismic anisotropy and tomography, 3D magnetotelluric inversions, location and evolution of geothermal systems, magmatic and aqueous fluid compositions, locations of caldera formation and the North Island tectonic environment to better elucidate rifting-arc models of the Taupō Volcanic Zone (TVZ). Building on the results of recent geophysical, geological, geochemical and structural studies, we have initiated an integrated programme of research that test our hypothesis that the deep feed zones for TVZ geothermal systems occur at the crest of ridges on top of the ductile crust.

The TVZ is an extensional arc, representing the on-land continuation of the Tonga-Kermadec arc/back-arc system, and is marked in its central part by intense magmatism and geothermal activity. To accommodate the slightly oblique extension, the brittle crust is segmented, controlled by accommodation zones orientated perpendicular to the arc. These accommodation zones may be the expression of cross-arc magmatic migration as evident north of the TVZ in the Havre Trough, and commonly in arc/back-arc settings elsewhere, e.g. Japan.

Published 3D inversion magnetotelluric (MT) models of TVZ geothermal systems reveal deep feeder zones, with a NW-SE orientation (perpendicular to the overall arc alignment) below 5 km depth. These MT anomalies have been interpreted as resulting from magma or aqueous fluids in the crust. We hypothesise deep, long-lasting, crustal cross-arc discontinuities (accommodating the oblique extension) favour permeability in the ductile crust. These permeable zones are oriented roughly NW-SE, perpendicular to the NE-SW rift elongation and may represent buried caldera ring faults and / or basement shear zones.

The discontinuities are inferred to enable vertical mass transport from the mantle wedge, enhancing crustal melting and creating a ridge on the surface representing the brittle–ductile transition. This ridge creates a locus for groundwater convective cells, and explains the persistence of many of the geothermal systems (despite interruption in some cases by caldera collapse), and the variability of geothermal fluid chemistry and magma compositions.

Regional 3D structural and (hydro)thermal modelling of the Upper Rhine Graben

Jessica Freyremark^{1,2}, Judith Sippel¹, Mauro Cacace¹, Magdalena Scheck-Wenderoth^{1,2}, Kristian Bär³, Moritz Ziegler¹, Manfred Stiller¹, Johann-Gerhard Fritsche⁴ & Matthias Kracht⁴

¹GFZ German Research Centre for Geosciences Helmholtz-Centre Potsdam, Potsdam, Germany

²Faculty of Georesources and Material Engineering, RWTH Aachen, Aachen, Germany

³Institute of Applied Geosciences, TU Darmstadt, Darmstadt, Germany

⁴Hessian Agency for Nature Conservation, Environment and Geology (HLNUG), Wiesbaden, Germany

Numerical models that predict and help to understand subsurface hydrothermal conditions are key to reduce the risk of drilling non-productive geothermal wells. Such numerical simulations of coupled fluid and heat transport should be based on an extensive knowledge of the geological structure and the subsurface distribution of physical rock properties. Therefore, we used an integrated approach of data-based 3D structural, gravity, conductive thermal and thermo-hydraulic coupled modelling.

The Upper Rhine Graben (URG) is known for its large potential for deep geothermal energy that is already used in e.g. Soultz-sous-Forêts. In the frame of IMAGE, we assessed the dominant processes and effective physical properties that control the deep thermal field of the URG. Therefore, we have built a regional lithospheric-scale 3D structural model of the URG by integrating e.g. existing data-based 3D structural models and deep seismic reflection and refraction profiles. In addition, 3D gravity modelling was used to further assess the internal configuration of the crystalline crust. Based on the resulting gravity-constrained 3D structural model we calculated the present-day 3D conductive thermal field.

By comparing the calculated with measured temperatures we identified and differentiated areas of dominant conductive heat transport were differentiated from areas that are probably influenced by fluid flow. Largest deviations were found in the sedimentary infill of the URG, which is known for its pronounced fluid flow. Thus, smaller-scale models for coupled fluid and heat transport were simulated for the central URG. With these models we tested the hypothesis of a deep E to W fluid flow, which cannot be confirmed by the model results.

We present the workflow of building regional 3D structural and thermal models to better understand the heat transport processes on a basin-scale, as well as our results for the case study of the URG.

Optimum geothermal doublet placement in fractured reservoirs

Jan ter Heege, Sander Osinga and Stefan Carpentier

TNO Applied Geosciences, Utrecht, the Netherlands

The occurrence and properties of natural faults in geothermal reservoirs are key in determining reservoir flow properties, and thereby the success of many geothermal projects. Accordingly, exploration for new geothermal sites will benefit from site-specific data on fault-related factors like damage zone fracture density, connectivity and permeability. In most cases, such data is lacking during geothermal exploration, but existing knowledge can be used to constrain typical fault zone architectures, spatial distribution of permeability and characteristics of damage zone fracture populations. Site-specific characteristics of fault and fracture populations can be determined using seismic surveys, outcrop analogues, core material, and laboratory experiments.

In this study, permeability predictions and fluid flow in fractured reservoirs were based on three modelling approaches. First, analytical models for fault zone and fractured reservoir permeability were developed to describe bulk permeability on the basis of fault and fracture populations derived from outcrops and seismic surveys. Permeability is modelled using 3D permeability tensors that describe non-isotropic permeability in the fault core, damage zone and surrounding intact reservoir matrix. The bulk permeability of faulted or fractured reservoirs is described by volume averaging the contribution of fault zones or fractures based on the frequency distribution of fault dimensions (e.g., a power law distribution of fault lengths). The sensitivity of bulk permeability to the orientations of layers, fractures and faults as well as damage zone fracture density is analyzed using the fault zone permeability model. In addition, a graphical method is outlined that aid in choosing the orientation of injector-producer for optimum permeability and geothermal performance. Second, a semi-analytical model for performance assessment of geothermal doublets for direct heat applications has been used to analyze the evolution of temperature and pressure for a doublet in a fractured reservoir and explore the relation between permeability anisotropy and cold water breakthrough. Third, semi-analytical models of fractured reservoirs with anisotropic permeability caused by a power law distribution of fault sizes have been developed to explore theoretical relationships between micro-seismicity, pore pressure increase and permeability. The models are used to simulate fluid flow, fault reactivation and the distribution and characteristics of micro-seismicity during fluid injection.

The permeability models can be used to analyze the geothermal power for a doublet system consisting of a surface heat exchanger, an injection well ("injector") and a production well ("producer") that is placed in the vicinity of a fault zone or in a fractured reservoir. In these cases, factors such as preferred orientations and permeability of faults and fractures, local stress field, and injection/production rates interact to determine the geothermal power of a doublet system. With the permeability models and data on fault and fracture populations, optimum placement of geothermal doublet systems can be determined. Optimization of geothermal doublet designs in fractured geothermal reservoirs can be performed on the basis of data on fault and fracture populations from interpretation of seismic surveys. Such optimization helps de-risking geothermal exploration and exploitation as it outlines preferred placement of doublets in terms of optimum flow conditions.

Acknowledgements

The research leading to these results has received funding from the EC Seventh Framework Programme under grant agreement No. 608553 (Project IMAGE).

Integrated coupled modelling and microseismic mapping: identifying and targeting volumes with higher potential for transmissivity enhancement in unconventional geothermal applications

Stefano Benato

Cranfield University, Cranfield, UK

Fluid injection can generate poromechanical stress perturbations up to hundreds of meters away from the wells, especially when applied to tight formations. These perturbations can reactivate well-oriented and critically-stressed fracture sets and fault zones, typically with associated microseismicity and considerable fracture transmissivity enhancements.

The cause-effect relation may be particularly helpful in the initial stages of stimulation treatments, prior to deepening/deviating wells and carrying out higher-pressure phases. It may be used to identify targets with greater transmissivity enhancement potential (desirable), or structures that can potentially release larger events (undesirable, especially if in densely populated areas). Shallow minifrac/pressurizations induce relatively safe microseismic responses, as reduced differential stresses normally characterize shallower depths. Yet, a generated stress perturbation can extend beyond the overpressured volume and far afield, thus revealing suitable target structures.

Integrated coupled THMC models and microseismic mapping/event filtering may be used to test shear tendency and expected transmissivity enhancement of structural features highlighted by shallow minifrac operations, with different sets of fluid parameters. This integrated approach reduces uncertainty and costs of trial-&-error stimulation treatments in geothermal environments, supporting the design and decision-making of adopted strategies and optimizing injection and completion choices. As part of the Desert Peak EGS shallow interval stimulation, induced microseismicity laid emphasis on a geological structure prone to shear deformation, defined as Shearing Target Fault (STF). Integrated seismic mapping and coupled modelling suggested the feature was an attractive stimulation target, which could provide considerable transmissivity enhancements. Subsequent extended well completion and deeper stimulation improved access to the STF and delivered the required commercial injectivity.

A 3D Geological Static Field Model of the Krafla Geothermal Area, NE-Iceland – constructing a workflow applied to the Pico Alto Geothermal Area, Azores

Unnur Þorsteinsdóttir, Anett Blischke and Gylfi Páll Hersir

ÍSOR - Iceland GeoSurvey, Iceland

E-mail: unnur.thorsteinsdottir@isor.is

3D geological static field modelling is a useful tool to compile and summarize surface and subsurface data and their interpretations. The modelling purpose is to gain a better understanding of the nature and characteristics of the geothermal system, and minimize risks for future drilling targets. Our aim is to not just graphically illustrate data and allow the interpreter to view them from different perspectives, but to be able to map and query available datasets in a 3D environment. Geothermal systems behave differently and priorities of data vary in every case. The workflow approach allows documentation of each step during the modelling process that can be revised if parameters change with new data acquired.

The objectives here are threefold: (1) Develop a workflow for constructing a 3D geological static field model, which could be the basis for dynamic reservoir field modelling, applicable for brownfield and greenfield geothermal areas, which is based on the lesson learned through making the Krafla model; (2) Implement the workflow and update the Krafla brownfield model using additional data that have not been presented before, by comparing primarily sub-surface structural interpretation results from different datasets and their relationships; (3) Apply the developed workflow to the Pico Alto greenfield, located on Terceira Island, Azores, an area with a known high temperature geothermal system that has promising geothermal potential, and an area in its early stages of geothermal development.

The Krafla geothermal field in NE-Iceland has been explored since 1969. A large variety of datasets have been collected from 47 boreholes. Six comprehensive conceptual models have been put forward throughout the field's history. The various datasets provide the basis for a geological static model, primarily sub-divided into two groups: (1) geophysical surface data, and (2) subsurface borehole data. By recording the work already performed and the evolution of existing knowledge, the resulting workflow describes how to bring together multidisciplinary interpretation results, which in turn highlights areas of uncertainty and the future work required. Resulting primary questions concern general risk assessment, a better understanding of the structural mechanisms of the Krafla geothermal area and their link to production patterns across the field, which require future field work that has not been considered in depth, yet.

A geological static field model has been developed for the Pico Alto geothermal field that is based on the workflow constructed for the Krafla geothermal brownfield area. Five geothermal wells have been drilled in the Pico Alto field and some exploration study results have been made and presented. The existing database and static model provide a crucial tool to gain a better understanding of the geothermal field and provide a useful base to pinpoint and decide the further research needed.

The research leading to these results has received funding from the EU Seventh Framework Programme under grant agreement No. 608553 (Project IMAGE).

Conceptual model of the supercritical geothermal system in the Larderello area (Italy) using multidisciplinary exploration data

A. Manzella¹, G. Bertini¹, M. Bonini¹, S. Botteghi¹, A. Brogi², G. Caielli³, R. De Franco³, A. Dini¹, A. Donato¹, G. Gianelli¹, G. Gola¹, D. Liotta^{1,2}, D. Montanari¹, G. Montegrossi¹, L. Petracchini⁴, G. Ruggieri¹, A. Santilano¹, D. Scrocca⁴, E. Trumphy¹

¹CNR-IGG (Italy), ²University of Bari, Dept. Earth and Geoenvironmental Sciences (Italy), ³CNR-IDPA (Italy), ⁴CNR-IGAG (Italy)

An integrated, multi-disciplinary approach was implemented in order to achieve a better understanding of the deepest part of the Larderello geothermal field, nearby an important seismic reflector (the K-horizon) showing bright spot and dome-shaped features. Our study focused on the Lago Boracifero area where this deep seismic marker reaches its minimum depth and a temperature exceeding 400°C is estimated down to 3000 m b.s.l.

Since the essential components of a geothermal system include the heat source, the permeable reservoir, the cap rock, the recharge regime and the geothermal fluids origin, we systematized the available information coming from multiple geoscientific disciplines (e.g. structural geology, geochemistry, geochronology, petrology and geophysics) in order to define the aforementioned components. As the granitic intrusions are supposed to be the primary heat source of the deep-seated geothermal system, several studies have been performed in the Elba Island, as a proxy of the actual geothermal system of Larderello. In this context, fieldwork and laboratory analyses provided data for the fossil magmatic system, e.g. fracture networks and the physical conditions and the composition of the fluids that circulated in the proximity of the Elba granites during the early magmatic stage. These data represented essential constraints to perform a geothermal characterization of the actual, deep-seated, magmatic and hydrothermal systems existing below the Lago Boracifero area.

A comprehensive conceptual model of magma emplacement has been refined and corroborated through the review and updating of the velocity and resistivity models integrated with other geophysical evidences (e.g. seismological data, heat flow and gravity anomalies). This multidisciplinary approach allowed supporting our working hypothesis that a recent, still partially melted magmatic intrusion occurs at shallow levels beneath the Larderello area. In addition, based on the results of numerical thermal models, fluid inclusions and geothermometers data, the possible occurrence of super-hot fluids, likely of magmatic and/or thermo-metamorphic origin, in supercritical conditions nearby the K-horizon is envisaged.

Acknowledgements

The research leading to these results has received funding from the EC Seventh Framework Programme under grant agreement No. 608553 (Project IMAGE). Some authors acknowledge also the EU project DESCRAMBLE (funded by Horizon2020 Research and Innovation Program under grant agreement No 640573) for fruitful discussion and further research on this topic.

Thoughts on integrated modeling of magmatic geothermal fields

Simon Lopez¹, Philippe Calcagno¹, Unnur Þorsteinsdóttir², Gylfi Páll Hersir², Adele Manzella³

¹BRGM, (France)

²ÍSOR, (Iceland)

³CNR, (Italy)

The main objective of geothermal exploration is to locate the most favorable (hot and permeable) target for well drilling to exploit the heat resource. 3D conceptual models often provide a consistent framework to reach this goal and data integration is a crucial step towards such conceptual models. Integration of all available information into one model or a set of possible models, which are updated along with the development of the resource, is indeed a crucial key in providing a basis for a quantitative analysis of a geothermal operation. It is now common ground that it is a factor of consistency. The main challenge is to bring together multidisciplinary results based on direct or indirect measurements, with varying degrees of uncertainties and physical properties varying abruptly over a large range of scales.

This work reviews some feedback and methodological thoughts on the subject inspired from the work performed by IMAGE partners on the two geothermal brownfields of Krafla (NE-Iceland) and Larderello (Italy) and the Pico Alto geothermal greenfield (Azores) and some other experiences. There is no single definitive path from a greenfield conceptual model to a brownfield conceptual model as the data are site specific (quality of geological outcrops, varying performance of geophysical methods, type and number of wells...). In the first geological exploration phase, data are often archived in a 2D database such as a GIS. Then 3D geomodeling and integration tools are used. Putting data in the same space can help their combination to lead to a consistent understanding though efficient communication using such tools is sometimes considered as a specialist's job. First, this methodology allows to check the location of separate features and to ensure their (3D) spatial consistency. But another benefit is that it makes possible to build an overall interpretation based on inputs from various disciplines.

Nevertheless, if the workflow of contributions from various backgrounds is too sequential and inputs are independent from one another, the later a discipline appears in the workflow, the more important is its influence on the final model. Consequently, it seems promising to switch from a sequential way of working to a more interactive approach and multidisciplinary review of the model. This requires collaborative tools and special attention to the versioning of the different contributions. It may also be more demanding in terms of manpower, each evolution of the model being reviewed by all specialists.

Finally, the geological model gives a static view of the geothermal field but a true conceptual model involves a picture for the mass and energy transfers that explains the observed temperature distribution. The next logical step would then be to integrate static and dynamic modeling in the same exploration workflow to validate flow circulation hypothesis and their consistency with the geological architecture and therefore reduce even more uncertainties. Yet, due to computing power limitations, and especially because of the transient nature and the complexity of natural state of geothermal resource in magmatic settings, such an interactive integration of static and dynamic models, with improvement loops between the two approaches, is far from being fully operational. As a conclusion, we propose a tentative outline of what could be the principles and main components of such a framework.

The research leading to these results has received funding from the EC Seventh Framework Programme under grant agreement No. 608553 (Project IMAGE).

Brief over view of the Icelandic deep drilling RN-15/IDDP-2 at Reykjanes, Iceland

Omar Sigurdsson, Gudmundur O. Fridleifsson, Ari Stefansson, Þor Gislason

HS Orka, Iceland

Drilling operations for deepening well RN-15 at the Reykjanes field began 11th August 2016. The 2.5 km deep production well RN-15 was quenched and cooled down in the preparation for deepening to 5 km as Phase 2 of the Iceland Deep Drilling Project (IDDP). The IDDP aim is to attempt to sample and produce high temperature geothermal fluids from supercritical pressure-temperature conditions with the goal of using it for energy production. Furthermore, the aim was to investigate the deep roots of the overlying geothermal system. Deep injection of fluid may be necessary to create a permeable EGS system for that purpose. The Reykjanes Geothermal Field is recharged by seawater and is a geochemical analogue to seafloor "black smoker" that are found on the World's Ocean Ridges.

Well RN-15 was drilled vertically in 2004 to 2507m depth with 13 3/8" production casing set to 794 m and a 12 1/4" open hole below. The main feed zone was at approximately 2400m with formation temperature of ~290°C. The well supplied some 2-3 MWe to the Reykjanes power plant. The hole is located north of the main upflow zone of Reykjanes field so a slightly deviated drill hole should intersect the zone at target depth of 5000m. The Bentec Euro Rig 350, Þór, operated by Iceland Drilling Company (IDC) was on site in July. The well was cooled and logged in preparation for deepening to 3000m before casing with 9 7/8" and 9 5/8" casings. Total circulation loss in the hole during drilling prevented return of drill cuttings to the surface. The well was deviated in the direction 210° at a kick off depth at 2750m with the intention of building inclination to 16° from vertical. Depth of 3000m was reached on August 22nd. Casing was run to 2941.4m along with thermocouple cables and a fiberoptic cable attached to the outside of the casing to measure temperatures at various depths. Use of such cables outside casing is quite new in Iceland. The casing was cemented to surface with reverse cementing method completed on Sept. 6th.

Drilling continued with downhole motor, MWD tool and an 8 1/2" bit. Circulation losses quickly increased to total losses in the first 200 m interval below the casing. About 12 cement plugs were set in an attempt to cure the losses with limited results. At 3185 m a decision was taken to continue drilling in total circulation losses as deep as possible. The well was drilled to 4626 m and a 7" perforated liner was set to 4600 m as well as a sacrificial 7" casing to 1304 m and cemented to surface. A T/P log measured after setting the liner on Jan. 3rd gave 426°C and 340 bar at 4560 m depth which is above the critical point for seawater. A total of 13 coring runs were made that gave in average about 51% return. For the last cores the well was drilled with 6" bits to 4659 m. Geophysical logs were obtained by special tripping with LWD tools to 4623 m.

At end of drilling short stimulation with thermal cycling and pressurization was carried out that increased the indicated injectivity to about 3 L/s per bar. The drilling operation was completed on January 25th, 2017 by installing a 3 1/2" pipe to about 4590 m depth for further stimulation. Since then the well has been cooled and short thermal cycles carried out where the well temperature has been oscillated by 200-250°C. Fluid blocking material has also been used to divert the cool injection to the lesser permeable zones.

Currently, preparation for hydraulic fracturing in the interval below 4630 m is being carried out. Then plans are to cool the deep formation further by fresh water injection till autumn 2017.

Abstracts of Posters

How to establish a very precise chrono-lithostratigraphic log based on cuttings, core samples, gamma ray logs and analogues: application on the Soultz-sous-Forêts and the Rittershoffen geothermal wells (Rhine Graben, France)

Coralie AICHHOLZER¹, Philippe DURINGER¹, Sergio ORCIANI², Albert GENTER³

¹EOST-Université de Strasbourg, 1 rue Blessig 67084 Strasbourg, France

²GeoloG France SAS, 9/11 allée de l'Arche 92671 Courbevoie Cedex La Défense, France

³ES-Géothermie, Bâtiment Le Belem, 5 rue de Lisbonne, 67300 Schiltigheim, France

E-mail: caichholzer@unistra.fr

The Upper Rhine Graben (URG) is characterized by abnormal high geothermal gradient especially in Northern Alsace (France) and by the presence of natural brines circulating in the deep fault system. These high temperatures (50°C at 400 meters deep) and brines (on the order of 100g/L) triggered different geothermal projects in Alsace region (Housse 1984; Schellschmidt and Schultz 1991; Carlier et al. 1992; Vernoux et al. 1995; Sanjuan et al. 2010). The URG is therefore one of the most studied region in Europe, mainly for petroleum exploitation and recently for geothermal applications like on the French side with the Soultz-sous-Forêts geothermal site and the Rittershoffen industrial geothermal one. Between 2012 and 2014, at Rittershoffen, two new geothermal boreholes GRT-1 and GRT-2 were successfully drilled up to the granitic basement, final depth at 2562 m and 2707 m vertical depth respectively. The achievement of the Rittershoffen's geothermal doublet which was the subject of a particular attention in the acquisition of a very precise stratigraphic profile, enabled the establishment of a 3 km-thick complete geological section from the Quaternary formations, through the Cenozoic and Mesozoic sediments down into the granitic Paleozoic basement (Aichholzer et al. 2015). It is the first complete well documented geological log of the entire sedimentary cover of the URG combining the succession of the formations including thickness with precise limits of top and base, age and sedimentary facies. It is the result of a close combination between cuttings and gamma ray log (GR), field campaign and the study of core samples. The first step was to establish the lithostratigraphic log of the borehole with the cuttings and well data (especially the GR log, and some others like calcite and gaz logs). To be able to accurately define the precise geological limits, a field campaign based on relevant analogues has constituted the second step of this work. The last step was to carry out fine resolution analysis of outcrops to refine the precision of the limits especially in the lower Triassic. To do this the 400m length of Buntsandstein core samples were studied to find the objective limits in the sandstones formations, very difficult to differentiate with only the help of cuttings. From these data, we clearly defined each formation with facies descriptions, precise top and base limits (giving thickness) and also the gamma ray signature associated. Indeed, GR signal is intrinsically linked to the nature of the formations (clays have a high value, salt on the contrary have low value). Therefore, each formation being different has a particular GR signal. This precise geological log associated to the GR one, has allowed the complete stratigraphic reinterpretation of ancient geothermal wells (GPK-1, GPK-2). In addition, it will serve as a basis for future geothermal drilling operations scheduled beginning of 2018 in the Strasbourg area.

Aichholzer C, Duringer Ph, Orciani S, Genter A. New stratigraphic interpretation of the 28 year old GPK-1 geothermal well of Soultz-sous-Forêts (Upper Rhine Graben, France). In: 4th European geothermal workshop, 19–20 Oct 2015, Strasbourg; 2015.

Carlier C, Royer JJ, Flores EL. Convective heat transfer around the Soultz-sous-Forêts geothermal site (Rhine Graben). In: BRGM Eds doc. 223 V1th Int. Symposium continental scientific drilling programs, Paris; 1992.

Housse BA. Reconnaissance du potentiel géothermique du Buntsandstein à Strasbourg—Cronenbourg. *Géothermie Actualités*. 1984;1:36–41.

Sanjuan B, Millot R, Dezayes C, Brach M. Main characteristics of the deep geothermal brine (5 km) at Soultz-sous-Forêts (France) determined using geochemical and tracer test data. *CR Geosci*. 2010;342:546–59.

Schellschmidt R, Schultz R. Hydrogeothermic studies in the Hot Dry Rock project at Soultz-sous-Forêts. *Geotherm Sci Technol*. 1991;1:217–38.

Vernoux JF, Genter A, Razin P, Vinchon C. Geological and petrophysical parameters of a deep fractured sandstone formation as applied to the geothermal applications. EPS-1 borehole, Soultz-sous-Forêts, France. *Rapport BRGM/ RR-38622-FR*. 1995.

3D Groundwater flow model at the Upper Rhine Graben scale to help locating the deep geothermal resource

A. Armandine Les Landes, T. Guillon, M. Peter-Borie and X. Rachez

BRGM – DGR/DES, 3 Avenue C. Guillemin, BP 36009, 45060 Orléans Cedex 2, France

E-mail: a.armandineleslandes@brgm.fr

Among other objectives, the FP7-IMAGE project aims to understand “the processes and properties that control the spatial distribution of critical exploration parameters”. Such an understanding would help reducing the uncertainty on the localization of the geothermal resource, and hence, mitigating the pre-drill risk. The information leading to delineation of preferential target areas (i.e., areas where the resource has best chances to be located) should be collected from various disciplines such as, e.g., geology or geophysics, in order to improve the confidence in the predicted locations by cross-checking. This information can originate from in situ data and/or predictions of analytical/numerical models.

Geothermal anomalies are strongly influenced by fluid circulations within permeable structures such as fault zones. In order to better predict the location of the geothermal resource, it is necessary to understand how it is influenced by heat transport mechanisms such as groundwater flow. The understanding of fluid circulation in hot fractured media at large scale can help in the identification of preferential zones at a finer scale where additional exploration can be carried out. Numerical simulations is a useful tool to deal with the issue of fluid circulations through large fault networks that enable the uplift of deep and hot fluids. Then, the Upper Rhine Graben (URG) is a tectonically active rift system where the large fault network inherited from a complex tectonic history and settled under the sedimentary deposits hosts fluid circulation patterns.

Therefore, in this study, we propose an approach based on groundwater flow paths study at the URG scale (150 x 130km) to help locating preferential zones (deep geothermal resource). The numerical model is based on a hybrid method using a Discrete Fracture Network (DFN) and 3D elements to simulate groundwater flow in the 3D regional fault network and in sedimentary deposits, respectively. Firstly, the geometry of the 3D fracture network and its hydraulic connections with 3D elements (sedimentary cover) is built in accordance with the tectonic history and based on geological and geophysical evidences. Additional processing on the 3D regional fault network has been done using structural tools (e.g., Riedel systems for assessing fault priority rules). Then, from the simulated 3D groundwater flow model and based on a particle tracking methodology, groundwater flow paths are simulated.

Ensembles of regional groundwater flow paths results are extracted and processed. This analysis is based on criteria such as properties of groundwater flow paths which are used to delineate preferential zones to explore at lower scale.

A methodology for delineating preferential target areas for geothermal projects based on 3D mechanical and 3D groundwater flow model

A. Armandine Les Landes¹, T. Guillon¹, M. Peter-Borie¹, A. Blaisonneau¹, S. Gentier² and X. Rachez¹

¹BRGM – DGR/DES, 3 Avenue C. Guillemin, BP 36009, 45060 Orleans Cedex 2, France

²BRGM – DSR/DIR, 3 Avenue C. Guillemin, BP 36009, 45060 Orleans Cedex 2, France

E-mail: a.armandineleslandes@brgm.fr

Among other objectives, the FP7-IMAGE project aims to understand “the processes and properties that control the spatial distribution of critical exploration parameters”. Such an understanding would help reducing the uncertainty on the localization of the geothermal resource, and hence, mitigating the pre-drill risk. The information leading to delineation of preferential target areas (i.e., areas where the resource has best chances to be located) should be collected from various disciplines such as, e.g., geology or geophysics, in order to improve the confidence in the predicted locations by cross-checking. This information can originate from in situ data and/or predictions of analytical/numerical models.

In this work, we propose to highlight how results from a 3D mechanical model and a 3D groundwater flow model can be used to predict the location of preferential areas. Specific focus on mechanics and groundwater flows was chosen because both these physics strongly impact how the geothermal resource is setting up:

- Mechanics is responsible for the stress distribution within the medium and affects the creation of flow paths within the rock matrix (pore and fracture networks) or through the regional fault zone network,
- Fluid circulations within permeable structures such as fault zones have a significant impact on the distribution of geothermal anomalies.

Firstly, these two models are built at the regional scale based on the same geometry. Each one of them is then independently interpreted using specific criteria correlated to the presence of the deep geothermal resource. The cross-analysis of these results delineates preferential target areas where additional mechanical and groundwater flow simulations can be performed in order to eventually improve the precision of the predicted preferential target areas. In this second phase, at the lower scale, a dual-approach combining the cross-analysis of results from independent models (mechanical and groundwater flow) and the results from a one-way coupled mechanical-hydraulic model are used to highlight and delineate preferential target areas for geothermal projects.

The mechanical model is built using the Distinct Element Method-based software 3DECTM to study the stress distributions at the regional scale in the first place in order to a- understand the regional tendency, and b- infer the boundary conditions for lower scale models. The groundwater flow model is based on a hybrid method using a Discrete Fracture Network (DFN) and 3D elements to simulate groundwater flow in the 3D regional fault network and in sedimentary deposits, respectively. Then, a particle tracking methodology is introduced to study groundwater flow paths.

The overall methodology from regional to local scale will be illustrated using a case study located in the Upper Rhine Graben.

Micro-seismicity in Námafjall high temperature area, NE-Iceland

Kristján Ágústsson¹, Egill Árni Guðnason¹ and Ásgrímur Guðmundsson²

¹ÍSOR-Iceland GeoSurvey (Iceland)

²Landsvirkjun, Iceland

Námafjall is a high temperature geothermal area about 10 km south of Krafla, NE-Iceland. A 45 MWe power plant is planned in the area with a possible extension up to 90 MWe. The area is known for longest utilization history of high temperature in Iceland. Since 1969 a 3 MWe power plant has been operated in Bjarnarflag which within the Námafjall area. The National Power Company of Iceland (Landsvirkjun/LV) and Iceland GeoSurvey (Íslenskar orkurannsóknir/ÍSOR) operate an extensive seismic network from Námafjall in the south to Peistareykir in the north with additional data streams from the regional seismic network of the Icelandic Meteorological Office. Altogether, there are 26 stations and four of them cover the Námafjall area quite well. The sensitivity of the network in the Námafjall area is about 0,3 ML.

Námafjall is located in the southern part of the Krafla fissure swarm, which is natural progression of a seismically active lineament SSW of Krafla central volcano. During the period from 2014 to 2016 the located earthquakes have been smaller than 2,2 ML. The earthquakes have been used to improve the velocity model that is considerably different from the present Krafla velocity model. The depth of the earthquakes increases towards the south from 2-2,5 km in Krafla to about 7 km in Námafjall. The location of the earthquakes shows a kind of layering where "the layers" are slightly inclined to SSW. There is a significant difference in the magnitude distribution with depth.

During the 2014 to 2016 period, 430 earthquakes have been located in the Námafjall area or roughly an earthquake every other day. In the rifting episode associated with the Krafla Fires 1975 to 1984 much more activity was observed. Re-injection of 100-200 L/s is planned during the operation period of the power plant. It is not expected that the injection will cause significant seismic activity.

P³ - PetroPhysical Property Database – comprehensive dataset enhancing the determination of empirical correlations between thermal and other petrophysical properties

Kristian Bär¹, Thomas Reinsch³, Judith Sippel³, Ingo Sass^{1,2}

¹Department of Geothermal Science and Technology, Institute for Applied Geosciences, Technische Universität Darmstadt

²Darmstadt Graduate School of Excellence Energy Science and Engineering, Jovanka-Bontschits-Str. 2, Darmstadt, 64287

³Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Potsdam, 14473, Germany

E-mail: baer@geo.tu-darmstadt.de

Thermohydraulic numerical models for the simulation of the subsurface heat transport need reliable petrophysical properties for the parametrization. Petrophysical properties are also key helping with the interpretation of many geophysical exploration methods. A bibliographic search for rock property values that have been measured for a specific rock unit at a specific site might become very time-consuming since such data are spread across diverse compilations, the number of publications on new measurements is continuously increasing and of heterogeneous quality. The applicability of experimental data to specific locations or reservoir units is questionable if information on the lithology, stratigraphy, porosity, pore fluid properties, rock anisotropy, measuring method and lab or in-situ conditions are too sparse or even lacking.

Therefore, we developed a database of published petrophysical properties. It provides easily accessible, peer-reviewed experimental data on various petrophysical properties in one single compilation. Each measured value is complemented by relevant meta-information such as the corresponding sample location, lithology, chronostratigraphic age and, most importantly, original citation. The original stratigraphic and lithologic descriptions are transferred to standardized catalogues following a hierarchical structure ensuring intercomparability for statistical analysis. In addition, information on the experimental setup and the measurement conditions are given for quality control.

Thus, the petrophysical properties collected including hydraulic, thermophysical and mechanical properties and, in addition, electrical resistivity and magnetic susceptibility can directly be correlated with each other or to in-situ conditions to derive specific parameters relevant for simulating the subsurface or interpreting geophysical data. We describe the structure, content and status quo of the database and show lithology dependent empirical correlations.

Keywords: rock physical properties, experimental data, reservoir characterization, correlation between thermal and other petrophysical properties.

3-D lithospheric-scale temperature modeling: application for the Hungarian part of the Pannonian Basin

Eszter Békési¹, László Lenkey², Jon Limberger¹, Damien Bonté¹, Mark Vrijlandt⁴, Ferenc Horváth^{2,3}, Sierd Cloetingh¹
and Jan-Diederik van Wees^{1,4}

¹Department of Earth Sciences, Utrecht University, Budapestlaan 4, 3584 CD Utrecht, Netherlands

²Department of Geophysics and Space Science, Eötvös Loránd University, Pázmány Péter sétány 1/c, 1117 Budapest, Hungary

³Geomega Ltd, Zsil u. 1, 1093 Budapest, Hungary

⁴TNO Utrecht, Princetonlaan 6, 3584 CB Utrecht, Netherlands

E-mail: e.bekesi@uu.nl

Hungary is one of the most suitable countries in Europe for geothermal development, as a result of large amounts of Miocene extension and associated thermal attenuation of the lithosphere. For geothermal exploration, it is crucial to have an insight into the subsurface temperature distribution.

Hereby a new thermal model of Hungary is presented extending from the surface down to the lithosphere-asthenosphere boundary (LAB). Subsurface temperatures were calculated through a regular 3D grid with a horizontal resolution of 2.5 km, a vertical resolution of 200 m for the uppermost 7 km, and 3 km down to the depth of the LAB. The model solves the heat equation in steady-state, assuming conduction as the main heat transfer mechanism. At the top and the base, it adopts a constant surface temperature and basal heat flow condition. For the calibration of the model, temperature measurements were collected from the Geothermal Database of Hungary. The model is built up by six sedimentary layers, upper crust, lower crust, and lithospheric mantle, where each layer has its own thermal properties. The prior thermal properties and basal condition of the model is updated through the ensemble smoother with multiple data assimilation technique.

The prior model shows a misfit with the observed temperatures, which is explained fundamentally by groundwater flow in Mesozoic carbonates and other porous sedimentary rocks. The updated models considerably improve the prior model, showing a better fit with measured records. The updated models mimic the effect of convection by modifying the thermal conductivity of the layers. Additionally, the updated models are capable to reproduce the thermal effect of lithospheric extension and the sedimentary infill of the Pannonian Basin. Results indicate that the hottest areas below 3 km are linked to the basement highs surrounded by deep sub-basins of the Great Hungarian Plain. Our models provide an indication on the potential sites for future EGS in Hungary and can serve as an input for geothermal resource assessment.

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

Caterina Bianco

Department of Earth and Geoenvironmental Sciences, Bari, Italy

E-mail: caterina.bianco@uniba.it

Geothermal fluid flow, geological structures and properties of rocks are closely linked. In fact, migration of crustal fluids is controlled by faults. These relationships are well evident within the fossil geothermal systems typically represented by epithermal mineralization as in the case of Elba Island. Here, a good example of exhumed geothermal system crops out and it can be considered the analogue of the Larderello active one, since they have several similarities, concerning their stratigraphy, tectonics and magmatic activity, and mineral phases. On Elba Island, the Monte Capanne and the Porto Azzurro monzogranite intrusions gave rise to an important hydrothermal activity during their cooling, producing diffuse epithermal and mesothermal mineralizations. In particular, Eastern Elba Island is characterized by Fe-oxides and sulphides ore deposits.

In this PhD research, a detailed structural analysis of the eastern Elba Island exhumed geothermal system (about 5-6 Ma old), is proposed. The aim of the work is to contribute to a better understanding of the relationships between geological structures and hydrothermal fluid flow. To follow this goal, the structural and geometric features of the geological bodies and the tectonic evolution of the area represent preliminary key- factors.

The first step of the work has regarded the revision of Elba Island tectonic units and its implications for the tectonic evolution of the Island, then the relationships between the detected geological structures and the hydrothermal mineralization have been investigated. Therefore, seven tectonic units have been distinguished and they belong both to continental (Tuscan Domain) and oceanic (Ligurian Domain) environments and pointing to several differences with respect to the tectono-stratigraphic models proposed in the previous works. The results of the carried out geologic survey have been reported in a general geologic map. Taking into account the geometric correlations among the geological bodies, the recognized geologic structures and the similarities with the inner portion of the Northern Apennines, the proposed tectonic evolution for the eastern Elba Island can be summarized as follows: 1) Late Oligocene -Early Miocene compressive phase resulted in an eastward stacking of Ligurian and Tuscan derived Units. The process caused a thickening of the continental crust experiencing HP-LT metamorphism in its deep-seated units; 2) Early-middle Miocene to Present this tectonic pile has been dismembered as a consequence of the extensional tectonics that affected the Northern Apennines belt. Extension, accompanied by exhumation and magmatism, determined a widespread tectonic delamination in the stacked units, generating a strong elision. Subsequently, all the previous structures are cross-cut by the high-angle normal and oblique slip faults, the latter mainly SW-NE oriented. Mineralization is mostly concentrated along these structures and mineralized shear veins have been extensively recognized in the fault-slip surfaces and related damage zones. It has been noticed that hydrothermal fluid flow occurs, most commonly, at the terminations of individual faults and/or where multiple faults interact, resulting in high permeable volume of rocks.

Fluid flow affecting both the cataclasite and the permeable geologic bodies, hydraulically connected with the shear zones, are accompanied by metasomatic processes. Consequently, the main mining activities were located along the SW-NE shear zones or in the surrounding geological bodies. Therefore, we can assume that the faults have played the role of conduits for the fluid flow, while the permeable geologic bodies, surrounding the shear zones, stored the hydrothermal fluids. In particular, these reservoirs are preferentially located within the Triassic quartzite (Verrucano Group).

Concluding, this study can be considered precursor for a deeper understanding of the relation between fault systems and hydrothermal (mineralizing) fluid migration through the upper crust of Eastern Elba Island.

The research leading to these results has received funding from the EC 7th Framework Program, under grant agreement no. 608553 (Project IMAGE).

Vertical seismic profiling survey at the Thonex Well (Geneva)

A. Bitri¹, L. Guglielmetti², C. Nawratil de Bono³, F. Martin³, F. Reiser⁴, C. Schmelzbach⁴

¹French Geological Survey, ²University of Geneva, ³Geneva Industrial Services, ⁴Institute of Geophysics, ETH Zurich, Switzerland

Vertical seismic profiling (VSP) is a field measurement procedure in which the seismic source is activated at a fix surface position and the seismic signal is recorded by sensors located in a well at successive depth levels. It differs from surface seismic both by being higher in resolution and by giving the ability to analyze wave-fields in-situ. VSP can be applied to identify reflections. It provides information about reflectors orientation and exact location when they intersect the bore-hole. It allows to directly link borehole geology to surface seismic data.

A zero offset, 4 offsets and 5 walk above (WAB) VSP were recorded in Thonex well near Geneva in Switzerland, from October 6th to 19th 2016. The Thonex well was drilled in 1993 with the goal to reach deep thermal aquifers in the Jurassic formations for providing heat to district heating plant. A true vertical depth of 2530 m was reached with a deviated geometry towards NE. The well testing via air lift indicated a stabilized flowrate of 11 m³/h, originating from the upper Jurassic limestones at a depth of about 1900 m with a fluid temperature of 70°C. In 2007, an inspection found an obstruction at about 1100 m depth. Unfortunately, cleaning hole process by coiled-tubing method allowed to give access only to the first 1500 m.

The VSP acquisition aimed to determine the velocity depth profile in order to generally improve the geological model, and to specifically characterize the carbonate formation, highlight possible fault zones and develop an acquisition approach which can be applied for the further wells. The acquisition campaign was carried out by OGS using two levels /three components (3C) VSP tool string from Avalone sciences Ltd. The energy source for this survey was a Prakla vibroseis. Below 700m depth the quality of data is good with evidence of direct arrivals and reflections. Above this depth, along the vertical section of the borehole, we observe effects due to condition of the casing or troubles in the cement bonding. Vertical component of data was processed using Schlumberger Vista software.

Figure 1 shows the migration result of all VSP's data inserted in the Thonex-2 surface seismic section after depth conversion using zero offset VSP velocity function. VSP migration has a higher resolution than surface's seismic because one recorded direct wave-fields arrivals from the surface. In the surface seismic survey, high frequency signal is attenuated by the two way travel paths. Full waveform inversion (FWI) is a powerful method to image the subsurface. The FWI tests on Thonex VSP data show encouraging results for application of this method in geothermal context (Fig 2).

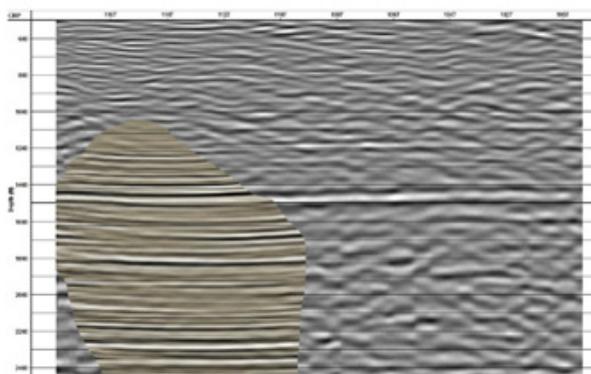


Figure 1: Kirchhoff migration of VSP's data inserted in the Thonex-2 depth surface seismic section.

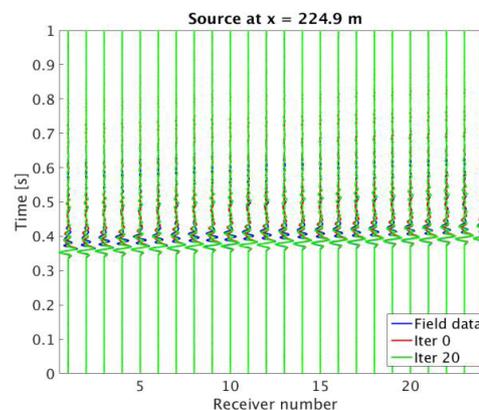


Figure 2: Seismogram comparison of WAB data (blue) initial model (red) and final FWI result (green).

Seismotectonics of the Geysir area in South Iceland during the years 1995 to 2001, revealed with relative earthquake locations

Ingi Th. Bjarnason and Bergthóra S. Thorbjarnardóttir

Institute of Earth Sciences, Science Institute, University of Iceland, Reykjavík, Iceland

We present earthquake relocations with good relative accuracy for an extended area (27x27 km²) around and north of the Geysir geothermal field in Iceland. The data were received from the earthquake catalog of the Iceland Meteorology Office for the years 1995–2001. The area encloses seismicity 7 km south and 20 km north of Geysir, in a zone extending into the neovolcanic zone in the west. Seismicity in the area was moderately active during the years 1995 up to 16 June 2000, but became highly induced following the two large earthquakes in the South Iceland Seismic Zone (SISZ) in June 2000. Geysir is some 40 km north and north-north-east of the mainshocks. The rate of seismicity tapered down in year 2001, but was still significantly higher than prior to the June 2000 events (200 earthquakes recorded in 2001, compared to 380 in the time period 1995 to 16 June 2000, and 1300 from 17 June 2000 to the end of 2000).

Seismic lineation suggests two main fault populations in the study area, i.e. approximately NE-SW striking near vertical fault segments up to ~4 km long (possibly ~10 km long but not delineated the whole length), and less frequent ~ENE-WSW striking segments with lengths up to ~2.5 km. The ENE segments are also near-vertical in the depth range 4–8 km. Right-lateral strike-slip movement has been determined on the NE striking fault segments in the extended Geysir area, a sense of motion comparable to N-S strike-slip faults observed in the SISZ. Assuming the same stress field source for the ENE segments, they are likely to be left-lateral strike slip faults in an echelon arrangement.

In the vicinity of the Geysir geothermal field, within 3–4 km distance, we observe numerous near-vertical ~NE-SW striking seismic patterns, that suggest movement along correspondingly oriented faults. The hypocenter depths are well-constrained in this area due to the proximity of a seismic station. Most of the seismicity lies at 0–2.5 km depth, which is unusually shallow for well-defined tectonic faults in South Iceland, and may require additional explanation than tectonic loading. However, east and northeast of Geysir, the depth range of earthquakes is 4–6 km. The presumed fault feeding the Geysir geothermal field is, however, not observed in seismicity during this time period.

In the northern part of the study area, within the neovolcanic zone, we observed a near-vertical seismic pattern, with strike identical to the orientation of the rift in the area, that occurred within days after the 2000 mainshocks. The depth is ~3–6 km, but the constraint is uncertain. We suggest that the strain from the mainshocks extended ~40–50 km north and induced movement on a vertical plane of weakness oriented in the same direction as presumed vertical dykes in the rift zone, even though they are not orientated in the plane of maximum shear stress. The pattern of the original vertical dyke emplacements in the crust may be the main source of weakness planes for the development of strike-slip faults in the SISZ.

About 10–15 km north of the Geysir geothermal field (~2–7 km north of mount Sandfell), diffused patterns of seismicity are observed at a depth of 4–8 km, the largest extending ~1.5 and 4.5 km laterally. These patterns may have shallower dip than the commonly observed near-vertical dips in the study area, but constraining the dip direction requires further analysis. The predominant strike direction of these patterns seems to be ~ENE-WSW, similar to well developed but usually inactive faults observed in South Iceland (e.g. in Vörðufell and Búrfell). A possible exception of an active ~ENE-WSW fault is in Ölfus, Southwest Iceland. The seismicity north of mount Sandfell was more persistent during the entire time period 1995–2001 than other parts of the study area, and has up to now continued to be so.

Temperature in the subsurface of the Netherlands from new data and novel modelling methodology

Damien Bonté¹, Maartje Struijk², Eszter Békési¹, Jon Limberger¹, Jeroen Smit¹, Fred Beekman¹, Sierd Cloetingh¹
and Jan-Diederik van Wees^{1,2}

¹Utrecht University, Department of Earth Sciences, PO Box 80021, 3508 TA Utrecht, The Netherlands

²TNO, P.O. Box 80015, 3508 TA Utrecht, The Netherlands

Deep geothermal energy has grown in interest in Western Europe in the last decades, for direct use but also, as the knowledge of the subsurface improves, for electricity generation. In the Netherlands, where the sector took off with the first system in 2005, geothermal energy is seen as a key player for a sustainable future. The knowledge of the temperature subsurface, together with the available flow from the reservoir, is an important factor that can determine the success of a geothermal energy project. To support the development of deep geothermal energy system in the Netherlands, we have made a first assessment of the subsurface temperature based on thermal data but also on geological elements (Bonté et al, 2012). An outcome of this work was ThermoGIS that uses the temperature model.

This work is a significant progress on the work published in 2012. The improvement from the first model are multiple, we have been improving not only the dataset used for the calibration and structural model, but also the methodology through an improved software (called b3t). The temperature dataset has been updated by integrating temperature on the newly accessible wells since the last compilation. The sedimentary description in the basin has been improved by using an updated and refined structural model and an improved lithological definition. A major improvement is from the methodology used to perform the modelling, with b3t the calibration is made not only using the lithospheric parameters but also using the thermal conductivity of the sediments. The result is a much more accurate definition of the parameters for the model and a perfected handling of the calibration process.

The result obtained is a precise and improved temperature model of the Netherlands. The thermal conductivity variation in the sediments associated with geometry of the layers is an important factor of temperature variations and the influence of the Zechstein salt in the north of the country is important. In addition, the radiogenic heat production in the crust shows a significant impact. The most interesting result is however the obtained temperature in the deeper part of the basin where deep convective systems have been identified and could become a major geothermal energy target in the future.

Characterizing permeable structures in geothermal fields – A case study in Lahendong

Maren Brehme¹, Guido Blöcher¹, Simona Regenspurg¹, Inga Moeck², Günter Zimmermann¹, Martin Sauter³ and Ernst Huenges¹

¹Helmholtz Centre Potsdam - GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany

²Leibniz Institute for Applied Geophysics, Stilleweg 2D-30655 Hannover

³Applied Geology, University of Göttingen, Goldschmidtstraße. 3, 37077 Göttingen, Germany

Email: brehme@gfz-potsdam.de

Productivity of geothermal fields strongly depends on permeable structures in the subsurface such as fractures and fault zones. Wells targeting these structures show high productivity independent of temperature. This study shows an approach how to find these high productive zones in the underground. The approach uses advanced exploration methods including field studies, fluid-rock interaction analysis and numerical simulation.

Our test ground is the Lahendong geothermal field located in Sulawesi, Indonesia. It is a water-dominated magmatic structurally controlled system. 25 wells have been drilled from which only 12 sufficiently produce hot water. At time of drilling faults and fractures were not appropriately mapped in the area. However, this study shows that the highest productivity occurs in wells near to faults. Faults generally act as across-fault fluid barriers and along-fault fluid conductors. As a result, hot springs mainly appear on the top of vertically permeable faults at the surface. Available numerous drilling and surface measurements allowed a detailed characterization of the geological and hydrogeological setting of the area.

A multi-disciplinary approach combining measurements of geochemical and hydraulic properties of reservoir fluid and rocks with hydro-chemical numerical modeling was applied. The models show that the geothermal field consists of two geochemically distinct reservoir sections. One section is characterized by highly acidic water, considerable gas discharge and high well productivities. The other section is characterized by neutral water and lower productivities. The two reservoir sections are separated by faults, which are less permeable across strike than along strike.

Increased fluid flow in the highly fractured and permeable areas enhances chemical reaction rates. This results in strong alteration of their surrounding rocks. Numerical models of reactions between water and rock at Lahendong indicate the main alteration products are clay minerals. A geochemical conceptual model illustrates the relation between geochemistry and permeability and their distribution within the area.

Furthermore, pressure and temperature fields have been simulated to elaborate on the influence of permeability on subsurface fluid flow in the Lahendong geothermal reservoir. The model identified a deep-seated fault that has previously not been traced at the surface. Simulated temperature distribution suggests a prominent convective heat flow, driven by an upward migrating and SW–NE oriented fluid flow. This hydraulic gradient causes a pressure drop along the reservoir. High-pressure patterns are used to constrain recharge areas, in addition to infiltration measurements. Discharge flow occurs from SW to NE migrating also upward toward the hot springs. In that frame, thermal–hydraulic simulations identified previously unresolved subsurface faults, which now allow a better understanding of the subsurface permeability distribution and its influence on fluid flow.

The main conclusion of this study is the proposed workflow to characterize permeable structures by combining structural geological mapping with hydrogeological investigations. Furthermore, geohydrochemical analysis of fluids and rocks broadens the understanding of flow directions and of quantity of fluid flow while numerical simulations allow predicting the permeability distribution in sparsely sampled spots of the target area. Generally, detailed investigation of permeable structures is a crucial step for site selection and smart drilling strategies avoiding drilling into less productive areas. Although the target area is Lahendong, our approaches are applicable for other geothermal sites in the world.

3D reconstruction of the electric resistivity with land CSEM

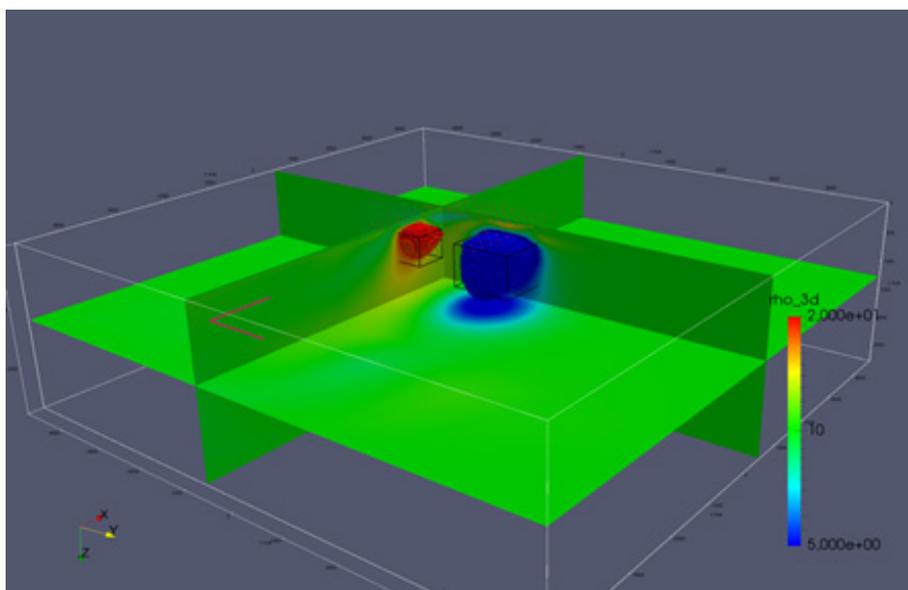
Numerical developments and application to geothermal prospection

F. Bretaudeau, S. Penz, N. Coppo, P. Wawrzyniak, M. Darnet

BRGM, France

Electromagnetic sounding techniques such as Magneto-Telluric (MT) and Controlled-Source Electromagnetic (CSEM) are potential method for structural mapping and fluid identification for deep geothermal prospection and monitoring, as they are sensitive to the electrical resistivity of the rocks and fluids. However, MT is usually not applicable to those contexts because high level of cultural noise general contaminates the MT signal. By using powerful controlled currents injected directly into the ground, CSEM is an interesting alternative to overcome the problem of cultural noise. But even though CSEM is now commonly used off-shore to detect resistive hydrocarbons, the way to successively acquire and process land based CSEM data to image deep conductive targets is still not well established. In particular, due to logistical and cost constrains, land based CSEM surveys are usually acquired with a limited number of transmitters and stations thus degrading the quality of the illumination. It is not clear yet how to reconstruct a reliable 3D resistivity model and what can be reconstructed with such incomplete illuminations.

In the framework of the IMAGE project, BRGM have developed a versatile 3D CSEM and MT modeling and inversion algorithm (POLYEM3D) with the aim of applying CSEM on on-shore context with potentially decimated acquisition. We present here the main aspects of its development. We proposed a specific inversion framework based on Gauss-Newton optimization, preconditioning and specific data formulation, that we found to be efficient for 3D reconstruction even with partial illumination. We illustrate its application on a pathologic synthetic case and then show the application to a real CSEM dataset acquired in a noisy area.



3D CSEM inversion of electrical resistivity using POLYEM3D on a synthetic case with a single transmitter position and 100 stations.

Stress field from fault data inversion in North-East Iceland

Andrea Brogi¹, Domenico Liotta¹, Sigurveig Árnadóttir²

¹Dipartimento di Scienze della Terra e Geoambientali, Università di Bari, Italy

²ÍSOR, Akureyri, Iceland

The state of stress in Iceland has been recently summarized by Ziegler et al. (2016) on the basis of several and different datasets. Nevertheless North-eastern and central part of Iceland are areas with scarcity of data. In order to contribute to fill up this gap, we collected geometric and kinematic data on faults affecting rock volumes younger than 2 Ma. In particular we have considered those faults associated to geothermal manifestations (thermal springs, gas vents and hydrothermal alterations).

The investigated area is encompassed between Skagi and Tröllaskagi peninsulas and Hveravellir area. In this sector, interacting N-S and NW trending faults systems are related to the evolution of the oceanic rift and associated transform zone.

The adopted methodology followed the classical approach of structural geology based on the analysis of data collected in structural stations. These were located along the main structural lineaments, where outcrops showed clear fracture systems. The kinematic indicators mainly consist of slickenlines and grooves, even if calcite or Fe-hydroxides shear veins have been rarely observed. The trend of the extensional fractures controlling gas vents, thermal springs, hydrothermal alteration zones and lava emission (lava fissures) have also been collected and integrated with the faults data.

The distribution of stress axes is in agreement with almost NNE-SSW orientation of the fissure lava swarms and alignments of thermal springs. Associated to this main trend, NW-SE faults and fractures have also been recognized. The latter are therefore interpreted as evidence of an active NW-SE transform zone, coeval with the oceanic rift evolution.

These results can be integrated in the Ziegler et al.'s (2016) map, without having significant differences from the present knowledge. Finally, on the basis of the main results from this new dataset, the consideration of the Skagafjörður as an inactive rift zone should be re-considered.

The research leading to these results has received funding from the EC 7th Framework Program, under grant agreement no. 608553 (Project IMAGE).

Kinematic data of the NE-trending shear zone affecting the Larderello geothermal area (southern Tuscany, Italy) and comparison with local focal mechanisms

A. Brogi and D. Liotta

Dipartimento di Scienze della Terra e Geoambientali, Bari (Italy)

We have refined the structural setting of a key-area passing through the Larderello geothermal field. Thus, we present a new structural and geological map integrated with public boreholes and geophysical data (by ENEL GreenPower) where the NE-striking structure has been 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 calcite slickenfibers 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. The occurrence of a cooling magmatic body, located at 6-7km below the surface, in the pull-apart basin developed within such a shear zone (as indicated by geophysical data), accounts for the possible control exerted by the NE-trending shear zone on the location of the heat flow anomaly (up to 1000 mW/m²) reflected in the location of the geothermal resources. The kinematic analysis on fault surfaces shed light on the apparent contradictory focal mechanisms characterizing the geothermal area and switching from normal to oblique slip. This variation is a consequence of the orientation (NW and NE trending) of different fault planes active under the same stress field through time.

The research leading to these results has received funding from the EC 7th Framework Program, under grant agreement no. 608553 (Project IMAGE).

Low-cost geothermal exploration through reprocessing of vintage seismic data with a new edge-preserving de-noising algorithm

Stefan Carpentier, Philippe Steeghs

TNO, Utrecht, The Netherlands

European ambitions in the development of sustainable energy are pushing innovations in exploitation of geothermal energy. Seismic imaging is currently the method of highest resolution with respect to depth penetration. In de-risking geothermal plays, there is great need for the use of seismic data to characterize and estimate geothermal reservoir properties. Acquisition, processing and interpretation of seismic data is often a costly affair, hence the desire for low-cost exploration.

For this reason, a new continuity enhancing, edge preserving seismic denoising algorithm was developed and applied for re-processing vintage seismic data in an ultra-deep geothermal case. The Non Local Means (NLM) algorithm is suitable for any type of seismic data (2D, 3D, poststack, prestack, land, marine). The NLM re-processing algorithm developed is in fact so general, that it can be applied to any seismic data and for that matter, any type of gridded/matrix/vector data. A test of the NLM algorithm on satellite images revealed that surfacing faults can be enhanced and isolated.

Semi-automated horizon interpretations were enhanced by the use on the NLM re-processed vintage seismic data and semi-automated fault interpretation, extraction and internal scaling relations were developed and applied to the NLM re-processed vintage seismic data. The re-processing and automated horizon and fault interpretation on vintage 2D and 3D seismic data renewed the vintage data to such a high level that industry standards were achieved. As such, the ultra-deep geothermal case was de-risked significantly at a fraction of the costs associated with new data acquisition or raw data prestack reprocessing. Low cost exploration has made a major step forward with these results.

Worldwide libraries exist of vintage 2D and 3D seismic data originating from the rich history of petroleum exploration. Thinking of these vast amounts of low-cost data and the ability of the NLM algorithm to tackle all of these data at relatively low computational costs, it is not hard to envisage the breakthrough that this technology can provide for the geothermal industry.

The research leading to these results has received funding from the European Community's Seventh Framework Programme under grant agreement No. 608553 (Project IMAGE).

Imaging the resistivity structure of the Reykjanes high-enthalpy geothermal field with the Controlled-Source Electro-Magnetic method

Mathieu Darnet¹, Nicolas Coppo¹, Pierre Wawrzyniak¹, Eva Schill², Nadine Haaf², Steinthor Nielsson³

¹BRGM, France

²KIT, Germany

³ISOR, Iceland

The Reykjanes geothermal field is located at the tip of the Reykjanes Peninsula. It is part of the Reykjanes fissure swarm, which is the sub-aerial extension of the Reykjanes Ridge. The South-western tip of the Reykjanes Peninsula is mostly covered by sub-aerial basaltic lavas and to a lesser degree by hyaloclastites. Hot ground and surface alteration at the Reykjanes geothermal field extends over an area of about 1.5 km². In this zone, there are also numerous fumaroles and mud pots indicating a buried high temperature field. A geothermal plume reaches to about 900 m depth and below the reservoir expands to at least 4 km² at 2 km depth with borehole temperatures exceeding 300°C.

As part of the EU H2020-funded DEEPEGS project, the IDDP2 well has been drilled into the Reykjanes geothermal field and is currently being stimulated. In an attempt to monitor the massive and soft hydraulic stimulations, we undertook a 4D Controlled-Source Electromagnetic (CSEM) monitoring experiment to sense and map from surface EM measurements electrical resistivity changes occurring within the geothermal reservoir as a result of the stimulations.

In this paper, we will report out the results of the baseline 3D CSEM survey acquired in 2016 and covering the Reykjanes geothermal field. We will show that despite the presence of high industrial electromagnetic noise, we managed to recover a reliable 3D resistivity image of the geothermal field but also achieved a CSEM data quality sufficient to be able to measure resistivity changes occurring at reservoir depth during the stimulations, if any. These should ultimately help us mapping the areas of the subsurface where resistivity has changed due the stimulations of the reservoir and hence mapping the fluid flow pathway within the supercritical geothermal system.

The DEEPEGS project has received funding from the European Union's HORIZON 2020 research and innovation programme under grant agreement No. 690771

Advances in geophysical methods for geothermal exploration in deep sedimentary and basement areas

M. Darnet, A. Bitri, M. Delatre, A. Lemoine, A. Imtiaz, N. Coppo, P. Wawrzyniak, F. Bretaudeau, S. Penz, J. Brives, L. Grabenstaetter and C. Dezayes

BRGM, France

The main targets for an extended geothermal resource base in the sedimentary basins are hot systems with insufficient natural permeability suitable for the development of reliable Enhanced Geothermal Systems (EGS). Barriers in the utilization of this resource are primarily connected to the financial risk of drilling a non-exploitable well. The risk for such a failure is related to pre-drill uncertainty in the assessment of the following critical exploration parameters: resource temperature, depth, fracture permeability and connectivity, extension and recharge, quality (geochemical parameters, pressure) and seismogenic properties and stress. Within the frame of the IMAGE project, we undertook to develop geophysical exploration methods that can quantify these parameters with the greatest possible accuracy. We worked both on improving well-established exploration techniques beyond the current state of the art and on testing new methods, namely:

- Electro-Magnetic sounding techniques (CSEM and MT) for structural mapping and fluid identification
- Vertical Seismic Profiling (VSP) for structural/fault mapping near the well bore
- Passive seismic H/V method for structural mapping
- Teleseismic receiver functions for structural mapping

Significant progress has been made both in terms of increasing the maturity of existing techniques and demonstrating that new concept can work:

- The EM pilot surveys performed in Czech Republic and France have shown that these techniques can be routinely deployed in highly industrialized areas for deep resistivity mapping despite the presence of strong noise, although some limitations still exists in terms of depth of penetration.
- The Walk-Above VSP survey acquired in Switzerland has shown that this type of seismic acquisition leads to higher resolution images than 2D surface seismic lines and provides the elusive link between synthetic seismograms and actual seismic records.
- The passive seismic study in the Upper Rhine Graben looked into how H/V measurements can complement long-range seismic noise correlations used for the tomography of the sedimentary cover. We showed that the joint inversion of dispersion curves of surface waves and H/V curves leads to an improved accuracy on both velocities and interface depths compared to the inversion of the surface waves only. A detailed analysis of the H/V curves also hints at the possibility of tracking lateral depth changes and hence detecting the presence of faults.
- For teleseismic receiver functions, the preliminary results from the Upper Rhine Graben have shown some promising indications for shallow crust imaging (deeper resolution than other passive methods), although it probably requires a dedicated receiver area in suburban to improve signal to ratio.

In this paper, we will present the achievements made as well as discuss the current limitations of the aforementioned methods for deep geothermal exploration in sedimentary and basement areas.

3-D geological-geophysical model and synthetic seismic reflection modelling along CROP-18A line in the Larderello area

R. de Franco¹, L. Petracchini², G. Caielli¹, D. Scrocca², A. Santilano³, A. Manzella³, G. Montegrossi⁴, G. Norini¹, G. Groppelli¹

¹CNR-IDPA, Milano, Italy; ²CNR-IGAG, Roma, Italy; ³CNR-IGG, Pisa, Italy; ⁴CNR-IGG, Florence, Italy

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, which is one of the tasks of the IMAGE FP7 European project.

The deep reservoir of Larderello geothermal field, Tuscany Italy, is hosted in the metamorphic basement (Batini et al., 2003; Bertini et al., 1996), and is characterized by a strong amplitude reflective signal, the well-known K-horizon, widely observed in several seismic lines (Batini et al., 1978, Accaino et al., 2005) and probably drilled by the San Pompeo 2 well (Gianelli et al., 1997).

In this study, geological and geophysical available data have been integrated to develop a new 3D geological-geophysical model of the portion of the Larderello geothermal field drilled by the San Pompeo 2 well. The geological-geophysical 3D modelling, performed using Petrel software, has been used to generate a 2D model for the synthetic seismic modelling of the main seismic units up to the K-horizon along the CROP-18A seismic reflection line acquired within the CROP project (Scrocca et al., 2003). The exploding reflector approach, developed in Matlab by the CREWES consortium and partly modified by us in this project, has been used to generate the synthetic seismic sections.

The geological units defined for the velocity model are respectively the Neogene Unit, the Ligurian Flysch Complex, the Tuscan Units plus Tectonic Wedge Complex and the Metamorphic Units. We have assigned to these units Vp velocity values of 2700 m/s, 3850 m/s, 5500 m/s and 4800 m/s respectively, derived from literature (Batini et al., 1978, Accaino et al., 2005).

Besides an acceptable calibration of the line CROP-18A with homogeneous units characterized by the previous seismic velocities, the seismic modelling allows to hypothesize a productive geothermal horizon at depth probably constituted by a "Physical perturbed layer - PPL". The PPL is characterized by a symmetric and/or asymmetric randomized velocity distribution (around the velocity of the host rock) simulating a rock physics model with fluid inclusions corresponding to the K-horizon.

The homogeneous unit seismic response indicates that:

- the deeper reflected events are significantly influenced by the articulated shallow morphology of Neogene and Ligurian units;
- the wedge geometry allows the fit of the line-drawing performed on the stacked section related to the top of the productive K-horizon.

The responses with the PPL model indicate that:

- PPL could explain the reflectivity features and pattern of productive horizons observed in the Tuscan geothermal area;
- asymmetric velocity distribution (a general decrease in velocity in PPL) generates a pseudo-layer which exhibits both reflection events at the top and bottom of PPL (sometime observed as typical pattern of reflectivity);
- in the case of thin layer (about 100 m) to observe diffuse reflectivity, the PPL must be characterized by symmetric randomized velocity distribution, otherwise it exhibits a response similar to a homogeneous layer;
- both symmetric and asymmetric velocity distribution with a PPL thicknesses greater than 100 m generally shows responses characterized by diffuse reflectivity.

Acknowledgements

The research leading to these results has received funding from the EC Seventh Framework Programme under grant agreement No. 608553 (Project IMAGE).

Improving the depth penetration of seismic surface wave based methods with H/V methods for sedimentary basins

M. Delatre, J. Brives, A. Lemoine, A. Imtiaz, L. Grabenstaetter, C. Dezayes

Rhine and Molasse sedimentary basins have been identified as potential good candidates for EGS exploitations in Europe as they are near large populated and industrial areas and exhibit thermal anomalies already exploited by pilot plants such as Souz-Sous-Forêt (France) or Landau (Germany). It is believed that the sediment-bedrock interface deep below the surface will provide favorable conditions to EGS, and better knowledge of this interface through new geophysical methods leads to less financial risks with the drilling process – provided the geophysical methods can be cost-effective.

In seismology, sedimentary basins are known to generate what is called “site effect”, e.g. seismic wave amplification at certain frequencies. This phenomenon is easily explained by the constructive interference built by seismic waves bouncing back and forth between the surface and the base of the sediments ; in this case, the frequency and the amplitude of the amplification are linked to the seismic wave speed in the sediment and bedrock and the thickness of the sedimentary layer. Site effects can be evaluated using seismic ambient noise with the H/V method (Bonnefoy et al 2006)

We propose in this study to show in a practical study how H/V measurements can complement long-range seismic noise correlations used for tomography studies (Campillo and Shapiro 2004). Long-range noise correlations are used to extract surface waves from the noise and are thus limited in depth by the highest wavelength that can be recorded fixed by the distance between the seismic recorders ; H/V method for sedimentary basins relies on single-station measurements and are only limited by the frequency range of the sensor, which means that in several cases it can give a clue about the main interface depth and therefore help the inversion process to get the speed profile.

This idea was applied on the test site west of Strasbourg in the Upper Rhine Graben, one of the sedimentary basins considered for EGS systems. A temporary network of 8 broadband three component velocimeters was deployed for 6 months, with the initial goal of testing seismic noise tomographic methods. The estimated depth of the sedimentary-bedrock interface (4 km) was underestimated during the design phase, leading to several stations too close for the wavelength criterion.

The study extracted the surface waves using long-range correlation and inverted the dispersion curves for a first estimate of the velocity profile with the GEOPSY software (Wathelet et al 2004). H/V curves were then measured using the same datas and were added to the inversion process, leading to improved accuracy on both velocities and interface depths ; a detailed analysis of the H/V curves also hints at the possibility to track depth differences and detect the position of one of the N/S normal faults in the area. We show therefore the usefulness of H/V to enhance results obtained by noise correlations, with a minimal cost as the same datasets and stations are used.

3D Geological and temperature models in the Strasbourg area (Upper Rhine Graben, France)

C. Dezayes¹, P. Calcagno¹, J. Freymark²

¹BRGM, 3 avenue Claude Guillemin, 45060 Orléans Cedex 2, France

²GFZ, Telegrafenberg, 14473 Potsdam, Germany

The Upper Rhine Graben is defined as brown site in the IMAGE project, as it is an established geothermal area, where a solid experience with standard exploration tools and a database exists. A 3D local geological model has been built on the area. Located between Strasbourg and northern Sélestat, it covers a 35 km x 45 km horizontal zone with a 7 km vertical extension. Based on a detailed geological study combining data derived from 15 previous oil boreholes and more than 200km 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 (Dezayes et al., 2010). Therefore, seven formations have been modelled. They are limited by the following six geological interfaces:

- Base of the Oligo-Miocene (Top of the Pechelbronn Formation)
- Base of the Tertiary sediments
- Base of the Upper Jurassic (Top of the Aalenian)
- Base of the Upper Triassic (Base of the Keuper)
- Base of the Muschelkalk
- Base of the Buntsandstein

The selected seismic lines have been reprocessed and interpreted in order to determine the geometry of the main interfaces of the geological formations. After converting the time of the seismic interpretation into depth, the location of these interfaces has been imported in the GeoModeller software developed by BRGM. Faults have been identified on each seismic profile. Then a coherent 3D correlation has been done between all profiles. After building a consistent fault pattern, the formation interfaces have been interpolated using the potential field cokriging method and geological rules (Lajaunie et al., 1997; Calcagno et al., 2008). In this method, interface locations, orientation data, fault influence, and geological history have been taken simultaneously into account.

Associate to this geological model, the conductive results of a larger thermal model (Freymark et al., 2016) and the bottom hole temperature interpolation (Carré, 2011) have been set in the same 3D space. This allows comparing isotherm with the lithology along cross-sections and maps everywhere throughout the model.

References

- Calcagno, P., Chilès, J.P., Courrioux, G., Guillen, A. (2008): Geological modelling from field data and geological knowledge, Part I – Modelling method coupling 3D potential-field interpolation and geological rules. *Physics of the Earth and Planetary Interiors*, 171, 147–157.
- Carré C. (2011) – Cartographies thermiques du Graben du Rhin. Rapport de Master 2 Réservoirs Géologiques. BRGM-Université de Montpellier.
- Dezayes C., Thion I., Courrioux G., Haffen S., Bouchot V. (2010) – Towards a better knowledge of the Lower Triassic reservoirs in the Upper Rhine Graben. WGC Bali, Indonesia, 25-29 avril 2010.
- Lajaunie C., Courrioux G. and Manuel L. (1997): Foliation fields and 3D cartography in geology: principles of a method based on potential interpolation (*Mathematical Geology*, v. 29 no. 4, p. 571–584)
- Freymark, J., Sippel, J., Scheck-Wenderoth, M., Bär, K., Stiller, M., Fritsche, J.-G. and Kracht, M. (2016): The deep thermal field of the Upper Rhine Graben (Tectonophysics, in review).

Impact of thermal stressing on the strength and permeability in reservoir rocks at Krafla volcano

GUÐJÓN H. EGGERTSSON¹, YAN LAVALLÉE¹, JACKIE E. KENDRICK¹,

Department of Earth, Ocean and Ecological Sciences, University of Liverpool, 4 Brownlow Street, Liverpool, U.K.

E-mail: g.eggertsson@liverpool.ac.uk

Here we present the results of experiments aiming to constrain the thermo-mechanical behaviour of reservoir rocks at Krafla, to constrain conditions favouring the generation of fracture and improve our ability to enhance fluid flow via thermo-mechanical stimulations. Geological survey and drilling activity have helped identify the presence of six main rock types in the hydrothermal reservoir: basalts (5-60% porosity), hyaloclastites (<35-45% porosity), obsidians (0.25-5% porosity), ignimbrites (13-18% porosity), and intrusive felsites and microgabbros (9-16% porosity). These samples were selected for mechanical testing, and their porosities were determined with a helium pycnometer. Samples were collected primarily from surface exposures, but selected samples were taken from cores drilled within the Krafla caldera.

Thermal expansion coefficients for dense basalt, hyaloclastite and felsite were measured using a thermomechanical analyser. The data shows a range of expansivities depending on the lithologies. The basalt expands uniformly with temperature, whereas the felsite shows different expansion below and above the alpha – beta transition of quartz at around 575°C. The hyaloclastite, however, shows a strong contraction resulting from mineral breakdown during heating.

Uniaxial and triaxial deformation tests were used to constrain the strength, Poisson's ratio and Young's modulus of each rock type. The results show that the rock strength is inversely proportional to the porosity and is strongly affected by the abundance of micro cracks; some of the rocks are unusually weak considering their porosities, especially at low effective pressure as constrained at Krafla. The presence of cracks also strongly influences the rock permeability, which was measured in a hydrostatic cell at pressure conditions relevant for the Krafla hydrothermal system. Thermal stressing variably impacts the strength of rocks, depending of the resilience of the mineralogy at high temperatures.

The data allows a complete description of the rocks' thermo-mechanical and permeability properties, and suggests that moderate temperature fluctuations induce sufficient thermal stresses and/ or mineral reactions, which generate thermal cracks and voids that affect the resultant permeability. We will discuss how the data may be integrated to into future fluid flow simulations to increase our understanding and exploitation of the hydrothermal reservoirs for geothermal energy.

Petrophysical and mineralogical characterization of IDDP-2 mini-core samples from depths of 3650 to 4650 m

David Escobedo¹, Benoit Gibert¹, Fleurice Parat¹, Didier Loggia¹, Léa Levy^{2,3}, Gudmundur Omar Fridleifsson⁴, Robert A. Zierenberg⁵

¹Laboratoire Géosciences Montpellier, Université de Montpellier, France

²Ecole Normale Supérieure, Paris, France

³University of Iceland

⁴IDDP office and HS Orka, Iceland

⁵UC-Davis, USA

As part of the exploration of supercritical geothermal reservoirs at the Reykjanes Peninsula, SW Iceland, the IDDP-2 consortium have accomplished a series of exploratory drillings and coring in order to investigate the physical conditions at depths of 4-5 km, governed by high temperature-high pressure environments. A set of 13 centimetric cylindrical mini-cores samples extracted from cores drilled at depths from 3638 m to 4654 m were studied to identify their alteration mineralogy and related physical properties. Optical and SEM observations on thin sections indicate that samples are medium to fine grained diabase intrusions showing granular holocrystalline textures. Composition from XRD on powders and combined EDS/EBSD analysis on a SEM indicate that the rocks are mostly composed of plagioclase and hornblende, which replaces primary augite phenocrysts (80 to 90% of rock composition). Unaltered augite phenocrysts are almost absent within the shallower sample (2%<), but became more abundant downwards (5-15%). Accessory minerals found are magnetite, ilmenite, enstatite and secondary quartz and biotite, which are more abundant at the lowest depth (5%). The primary alteration is replacement of pyroxene by hornblende with low amounts of epidote in the shallowest samples and biotite in the deepest samples. EBSD analysis performed on a SEM on 6 samples did not display any crystal preferred orientation, indicating that the samples should be isotropic at depth. Petrophysical properties such as porosity, acoustic velocity (V_p - V_s) and electrical conductivity were measured on all the samples at room conditions in dry and saturated conditions. All the samples show low porosity, ranging from 1 to 4%. Macroscopic observations as well as SEM observations indicate that the porous network is principally due to open – non mineralized- fractures developed during drilling operation under the combined effects of drastic cooling and decompression. These effects are stronger as depth increases. On some samples, principally at deeper depth, intergranular, equant micropores are also present. P-wave velocities under dry conditions range from 4 to 6 km/s at depths intervals of 3650 to 4300 m and are only 2.5 km/s at higher depths (4640 m - 4653 m). Under saturated conditions p-waves velocities increase by about 1 to 1.5 km/s. Samples with the smallest grain-size have the lowest porosity as well as the highest velocities. This preliminary characterization indicates that microfracturing of the rock induced by drilling operations has a strong influence on the physical properties of reservoir rocks, in particular at deeper depth. Further investigations are planned in order to examine the effect on the physical properties of the reservoir rocks of the fracture reduction or enhancement under varying conditions of temperature and pressure.

The research leading to these results has received funding from the European Community's Seventh Framework Program under grant agreement No. 608553 (Project IMAGE). We are grateful to HS Orka power company for making available IDDP core samples from the Reykjanes geothermal system for scientific studies, and to the International Continental Scientific Drilling Program (ICDP) and the US National Science Foundation (NSF) (Grant No. 05076725) for financial support for the core drilling at Reykjanes.

New tracers: Krafla field test

A. Gadalía¹, G. P. Hersir², F. Óskarsson²

¹BRGM, France

²ÍSOR-Iceland GeoSurvey, Iceland

The main objectives of this new tracing test at Krafla geothermal field were (i) to assess the geometry of the flow paths and (ii) to compare a supposedly conservative tracer and tracers which were known to degrade at high temperatures. Potassium iodide (KI) was selected as the reference conservative tracer of the liquid phase and the two most thermally stable naphthalene disulfonate molecules (2,6- and 2,7-NDS), liquid-phase tracers as well, were chosen as possibly degrading molecules. The tracers were injected in equal amounts; 200 kg of each.

Means and methods

The NDS solutions were injected together with the KI brine into the Krafla re-injection well K-39. Utmost precautions were taken to minimize the contamination risks when preparing the injection blend. The monitoring operations were carried out from June, 21st to August, 17th through scheduled sampling. The monitored production wells were located in various areas of the field and tapping different parts of the reservoir. Two out of the five wells produced a steam phase enriched, excess enthalpy fluid so that (i) the sampling procedure had to be adjusted and (ii) some corrections made. The chloride concentration and the conductivity, both closely consistent, were used to take into account the possible dilution resulting from mixing with steam condensate. ÍSOR and BRGM Laboratories analyzed respectively NDS molecules and total iodine concentration.

Results and discussion

The three tracers were detected only in one well. The monitoring of the five wells displayed that (i) the NDS background remained below the quantification threshold whereas (ii) the iodine background was relatively variable as a result of the chemical heterogeneity of the Krafla field. A release of iodide resulting from previous tracer tests was rejected as this variation was already observed at least before the 2005-2007 tests.

The presence of condensate during the first period of sampling leads to some uncertainty on the tracers breakthrough times (24 h for iodine and 72 h for the NDS molecules), values that may be shorter. The occurrence of the tracer peaks is more constrained; the iodine peak arrives slightly later than the NDS one (15-20 vs. 14-18 days, respectively). This may suggest a slight difference in the diffusion/transport properties of the two tracer types in the Krafla reservoir context. The peaks for the two tracer types have similar amplitudes (600 µg/L for KI vs. 620 µg/L for either NDS molecule).

The calculated iodide restitution rate is lower than during the previous Krafla tracer tests. Besides a possible impact of the short testing time, it could indicate a higher flow rate as the main direction of the faulted rift is concerned. Nevertheless, 2,6-NDS was not detected in the 2013-2015 test, which used the same wells and the same liquid phase tracer. In 2009, a particular behavior of tracers, including 2,6-NDS, in the well K-39 (productive at that time) was attributed to thermal degradation. No degradation of the injected NDS molecules can be inferred from the 2016 test. As the selected NDS molecules were supposed to remain stable up to 340°C, this could result from the decreasing enthalpy of K-19 or the possible cooling of the K-39 part of the geothermal reservoir.

Calculation of the apparent linear velocities (ALV) gives values of the same order than in the 2013-2015 tests confirming a high flow rate within the Krafla geothermal reservoir.

On a relatively short monitoring period, this tracer test brought information on tracer properties, on the evolution of the field conditions and on flow pathways.

Contributions by: I. Nardini, A. Orlando, G. Ruggieri (CNR – Pisa - Italy); E. Júlíusson, M. E. Ruben (Landsvirkjun - Iceland); R. St. Ásgeirsdóttir, S. R. Guðjónsdóttir, S. Halldórsdóttir, I. M. Gałeczka, E. I. Eyjólfsdóttir, S. I. Svavarsdóttir (ÍSOR - Iceland); J. Muller, S. Opsahl Viig (IFE - Norway); G. Braibant, E. Decouchon, A. Chevallier, T. Conte, K. Hadria (BRGM - France).

A new research project on interaction of geothermal, tectonic, and magmatic processes in the Hengill area

Halldór Geirsson¹, Þóra Árnadóttir¹, Kristín Vogfjörð², Daniel Juncu¹, Hanna Blanck^{3,1}, Cecile Ducrocq¹, Bjarni Reykr Kristjánsson⁴, Gunnar Gunnarsson⁴, Vincent Drouin¹, Freysteinn Sigmundsson¹, Benedikt G. Ófeigsson², Kristín Jónsdóttir², Björn Lund⁵, and Gunnar B. Guðmundsson²

¹Institute of Earth Sciences, University of Iceland, Reykjavík, Iceland

²Icelandic Meteorological Office, Reykjavík, Iceland

³ÍSOR - Iceland Geosurvey, Reykjavík, Iceland

⁴Reykjavík Energy, Reykjavík, Iceland

⁵Uppsala University, Uppsala, Sweden

It is generally agreed that high-temperature geothermal fields owe their existence to magmatic supply (i.e. intrusions) and that tectonically driven faulting provides high-permeability fluid flowpaths that are necessary for geothermal energy production. It is also surmised that geothermal utilization causes permanent changes in crustal stress and fluid pressure, which affect nearby seismicity and fault movements. Stress changes can in general also affect magmatic movements, such as dike propagation, dike arrest, and formation and growth of magma chambers. The objective of the project is to study stress interactions of geothermal, tectonic, and magmatic processes, with special focus on the Hengill area. Significant changes in geothermal production in the Hengill area commenced in 2016 when production started in the Hverahlíð geothermal area, predictably causing changes in deformation, fluid pressures, and stresses. We will use existing and new geodetic, seismic, and reservoir monitoring data to model deformation processes and associated stress changes; estimate in-situ stress changes from earthquakes; map faults activated using relative earthquake relocations; and combine our observations with existing numerical reservoir models in the area. The resulting conceptual picture is expected to increase understanding of the origins and sustainability of geothermal reservoirs, as well as dynamics of one of Iceland's most seismically active volcanic systems. The study is a 3-year project funded by RANNÍS and started in 2017. Two new PhD students studying seismicity and deformation started in the fall of 2017, and will carry a large part of the research work. Three new continuous GPS stations were installed in the summer of 2017 near the center of the three main geothermal production areas in Hengill: at Nesjavellir, Hellisskarð, and Hverahlíð. Preliminary analysis of Sentinel InSAR data extending into 2017 show mild subsidence in the Hverahlíð region, in a broad correspondence with the limited mass outtake in the region.

Electrical conductivity of basaltic and rhyolitic melts from Krafla central volcano, Iceland

Gibert B.¹, L. Levy^{2,3,4}, F. Sigmundsson³, G. P. Hersir⁴, O. G. Flovenz⁴

¹Laboratoire Géosciences Montpellier, Université de Montpellier, France

²Ecole Normale Supérieure, Paris, France

³Earth Sciences Institute, University of Iceland, Reykjavík, Iceland

⁴ÍSOR-Iceland GeoSurvey, Reykjavík, Iceland

As part of the exploration of supercritical geothermal reservoirs, the IDDP-1 borehole drilled in the Krafla caldera in 2009 has intersected a magma body of rhyolitic composition at 2.1 km depth. This unexpected encounter with a shallow magma intrusion demonstrate the difficulty to detect magma bodies using geophysical methods, in particular electromagnetic surveys that are widely used in geothermal research. The IDDP-1 operations indicate also the possibility for exploiting very high enthalpy fluids at the contact with such intrusions.

In order to better interpret the geophysical investigations that have been acquired on the Krafla caldera, electrical conductivity of two types of magma that can be encountered in this area have been investigated. Rhyolitic samples from the obsidian lava flow in Hrafninnuhryggur and basaltic samples from the recent Krafla fires have been collected.

Electrical conductivity of these samples have been measured from 400°C to 1250°C at a pressure at 50 MPa to 150 MPa in the Paterson gas pressure apparatus of the Laboratoire Géosciences Montpellier. The impedance of cylindrical samples was measured as a function of frequency using a 2-poles configuration with parallel planar electrodes. The glassy obsidian was directly investigated, while the basaltic samples were first melted at 1400°C and cooled down in air in order to obtain a homogeneous, bubble-free glass sample. The obsidian sample displays a linear increase of the logarithm of conductivity as a function of reciprocal temperature from 400°C to 1100°C, indicating an Arrhenian behaviour with a single conduction mechanism in the glass and melt region. The resulting activation energy is 75 kJ.mol⁻¹ and is compatible with a conduction due to sodium mobility. Absolute values at estimated in-situ temperatures (900-1000°C) are about $1 \pm 0,2$ S.m⁻¹ and are very close to the one obtained by Gaillard (2004) on a dry obsidian. The conductivity of the basaltic sample has been measured between 1175 and 1250°C in order to avoid rapid cristallization at lower temperature. In this temperature range, it displays arrhenian behaviour and conductivity varies between 0,6 and 2 S.m⁻¹. These values are very comparable with previous experiments on basaltic samples, for instance by Tyburcsy and Waff (1983).

This very preliminary study indicates that the conductivity contrast between a rhyolitic melt at 900-1000°C and a basaltic melt at 1250°C is quite limited, making difficult to discriminate the type of melts from electromagnetic investigations. In addition, comparison with the measured conductivity of saturated altered rocks at 250-350°C (Nono et al., 2016) indicates that the conductivity contrast between magmas and reservoir rocks can be highly variable and strongly dependent on the rock composition and porosity, and pore fluid salinity. Depending on reservoir conditions and lithology, electromagnetic investigations may be carefully interpreted for imaging magmas intrusions within geothermal reservoirs.

Gaillard, F., 2004. Laboratory measurements of electrical conductivity of hydrous and dry silicic melts under pressure. *Earth Planet. Sci. Lett.*, 218: 215-228.

Nono F., Gibert B., Parat F., Loggia D, Azais, P., Cichy, S.B., 2016: Electrical conductivity of Icelandic deep geothermal reservoirs: insight from HT-HP experiments, EGU 2016, Vienna.

Tyburcsy, J.A. and Waff H.S., 1983. Electrical conductivity of molten basalt and andesite to 25 kilobars pressure: Geophysical significance and implications for charge transport and melt structure, *Journal of Geophysical Research*, volume 88-B3, 2413-2430.

The research leading to these results has received funding from the European Community's Seventh Framework Program under grant agreement No. 608553 (Project IMAGE).

Exploring the geothermal heat: Seismic properties as a function of reservoir conditions

Melchior Grab¹, Hansruedi Maurer¹, Stewart Greenhalgh²

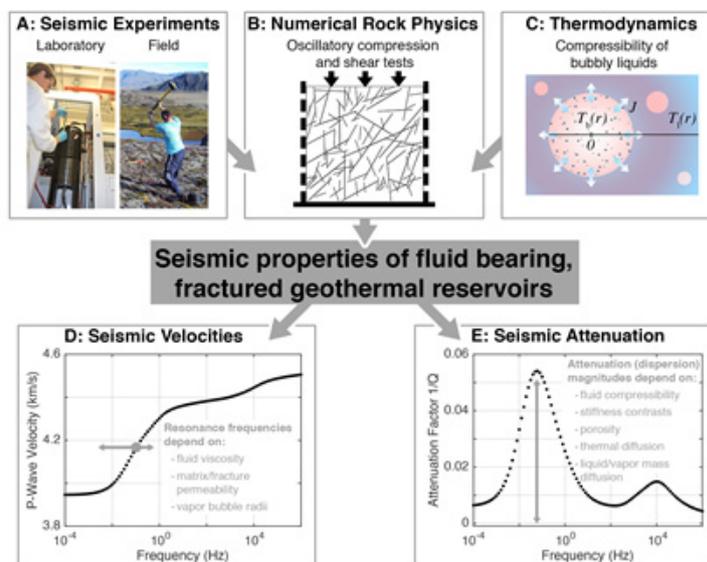
¹Institute of Geophysics, ETH Zürich, Switzerland

²Department of Earth Science, King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia

In contrast to other renewable energy resources, geothermal reservoirs are hidden at several kilometers depth. During the past decades, seismic exploration methods have been established as a common non-invasive tool to observe the Earth's interior. To enable the investigation of geothermal reservoirs with seismic techniques, we have established how seismic parameters are linked with the hydraulic permeability of the rocks and the energetic state of the saturating fluids.

Quantities measured with seismic techniques are the seismic velocities of geological formations, which control the travel time of the seismic waves, and the seismic attenuation factors, which cause the decay of the wave amplitude with distance/time. In our work we have investigated how these quantities depend on reservoir permeability and fluid properties. Seismic experiments under known ambient and in-situ pressure and temperature conditions (laboratory) and at reservoir-scales (field-experiments) were conducted. This provides input parameters for numerical modeling techniques, which are used to compute the seismic properties of fractured geothermal reservoirs at variable scales. To account for varying fluid conditions, ranging from the liquid to the boiling and ultimately to the vapor state, thermodynamic relationships are implemented into the rock physics model.

The combined experimental, numeric-petrophysical, and thermodynamic investigations deliver frequency-dependent seismic properties as a function of the hydraulic rock structure and fluid properties. We have shown that on one hand the resonance frequency, at which the seismic velocities show marked dispersion and at which the seismic attenuation is strongly increased, depends on the hydraulic permeability of the rock matrix and fractures, on the viscosity of the pore fluids, and on the diameter of vapor bubbles. On the other hand, the magnitude of the attenuation and dispersion varies as a function of fluid compressibility, thermal/mass diffusion in a multi-phase fluid, porosity, and stiffness-contrasts within the host rock. Such relationships help to interpret seismic reflection and travel-time tomograms in terms of reservoir parameters.



The integrated approach, consisting of (A) experimental investigations in the laboratory and in-situ in the field, (B) numerical rock physics modeling, and (C) thermodynamic fluid physics calculations, enables to link seismic velocities (D) and attenuation (E) with the hydrothermal key parameters of a geothermal reservoir.

References:

- Grab, M., Zürcher, B., Maurer, H., & Greenhalgh, S. (2015). Seismic velocity structure of a fossilized Icelandic geothermal system: A combined laboratory and field study. *Geothermics*, 57, 84-94.
- Grab, M., Quintal, B., Caspari, E., Maurer, H., & Greenhalgh, S. (2017). Numerical modeling of fluid effects on seismic properties of fractured magmatic geothermal reservoirs. *Solid Earth*, 8(1), 255.
- Grab, M., Quintal, B., Caspari, E., Deuber, C. Maurer, H., & Greenhalgh, S. The effect of boiling on seismic properties of water-saturated fractured rock. *JGR-Solid Earth* (Sep. 2017, accepted with minor revisions)

A 3D mechanical model to help locating the deep geothermal resource

T. Guillon¹, M. Peter-Borie¹, S. Gentier², A. Blaisonneau¹,

¹BRGM – DGR/DES, 3 Avenue C. Guillemin, BP 36009, 45060 Orléans Cedex 2, France

²BRGM – DSR/DIR, 3 Avenue C. Guillemin, BP 36009, 45060 Orléans Cedex 2, France

Among other objectives, the FP7-IMAGE project aims to understand “the processes and properties that control the spatial distribution of critical exploration parameters”. Such an understanding would help reducing the uncertainty on the localization of the geothermal resource, and hence, mitigating the pre-drill risk. The information leading to delineation of preferential target areas (i.e., areas where the resource has best chances to be located) should be collected from various disciplines such as, e.g., geology or geophysics, in order to improve the confidence in the predicted locations by cross-checking. This information can originate from in situ data and/or predictions of analytical/numerical models.

As far as geomechanics is concerned, the spatial distribution of the stress state is a key-parameter since it affects the possible creation of flowpaths within the rock matrix (pore and fracture networks) or through regional fault zone networks. In most cases, in situ stress data is scarce and poorly interpolable due to a strong sensitivity to local irregularities (discontinuities, material heterogeneities and anthropic activities). By integrating heterogeneities, physically-based models can give an overview of the stress distribution through the rock mass. In particular, fault zones are expected to play a key-role on the local stress redistributions. Besides, fault zones can be responsible for regional circulations – including upflow of previously heated fluids – and should be accounted for in the models.

In this study, we propose to estimate stress distributions through a rock mass using the DEM-based software 3DECTM (DEM: Distinct Element Method). In 3DECTM, fully deformable blocks represent the rock mass and are interacting through mechanically-active joints that depict the fault zones. The first step of setting up the numerical model is to build its geometry. The geometry is built according to a structural analysis of the fault zones evidenced by active seismic campaigns or by previous structural studies. Additional processing is performed with the help of structural tools (e.g., Riedel systems for assessing fault priority rules). Then, the physical model can be completed, and includes determining the initial state, the model boundary conditions, the constitutive equations for the fault zones and the rock mass as well as the corresponding parameters. Once the predicted stress distributions are obtained, a criterion can be used to highlight preferential zones within the rock mass.

The overall model will be illustrated using a case study located in the Upper Rhine Graben, with specific focus on the following key-aspects: building of the model, presentation of DEM-specific results, and qualitative analysis of impact of the chosen criterion on the delineation of preferential target areas.

Wave-length of the crustal stress pattern in Western Europe and the Mediterranean

Oliver Heidbach¹, Moritz Ziegler^{1,2}, Mojtaba Rajabi³, Karsten Reiter⁴ and the WSM Team

¹Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany

²University of Potsdam, Inst. of Earth and Environmental Science, Karl-Liebknecht-Str. 24-25, 14476 Potsdam, Germany

³Australian School of Petroleum, The University of Adelaide, Adelaide, SA 5005, Australia

⁴TU Darmstadt, Institute of Applied Geosciences, Schnittspahnstr. 9, 64287 Darmstadt, Germany

For the 30th anniversary the database of the World Stress Map (WSM) Project that compiles data on the orientation of the maximum horizontal stress in the earth's crust has been completely revised and updated. In particular we increased the number of stress data records from 21,750 to 42,410. The stress data records originate from a wide range of stress indicators such as borehole data (e.g. hydraulic fracturing, drilling induced tensile fractures, borehole breakouts), earthquake focal mechanism solutions and stress inversions from these, engineering methods (overcoring, borehole slotter) and geological data (e.g. volcanic alignment, inversion of fault slip data). To guarantee the comparability of the orientations derived from different stress indicators each data record is quality-ranked using the WSM quality ranking scheme. The increase in data records and coverage enables us identifying the regional and local variability of the stress pattern worldwide. In Western Europe and the Mediterranean in the framework of the anniversary of the WSM the number of data records has been increased from 3877 to 8192. Based on this new compilation we analysed the wave-length of the stress pattern by determining the mean orientation of the maximum horizontal stress SHmax on a regular grid using the Matlab script of Ziegler and Heidbach [2017]. The results show that the Africa-Eurasia plate convergence is a key control of the overall stress pattern. However, given the complex tectonic setting in particular due to the indentation/collision of the Adriatic micro block, the Alpine topography, as well as forces that control the movement of the Anatolian and Aegean block, the stress pattern shows in these regions significant changes in the mean SHmax orientation as well as in the tectonic regime. The wave-length of the crustal stress pattern correlates well with tectonic activity. Thus in the Mediterranean the wave-length is in general shorter than 200 km whereas north of the Alps the wave-length is increasing to higher values between 300-500 km. This indicates that in young tectonic areas local stress sources due to density and strength contrasts as well as the superposition of plate boundary forces that act in different orientations lead to a higher variability of the stress orientations. In regions that are tectonically less active the overall stress pattern is mainly controlled by plate boundary forces that result from continental collision and ridge push.

Alteration Minerals and Fluid Inclusions in Garnet from Geitafell, SE-Iceland

Helga Margrét Helgadóttir¹, Giovanni Ruggieri² and Valentina Rimondi²

¹Iceland Geosurvey (ÍSOR), ²National Research Council of Italy (CNR-IGG)

In May 2016 fluid inclusion analyses of garnet samples from the exhumed geothermal system in Geitafell, SE-Iceland, were carried out. Furthermore, microprobe analyses were made to confirm the existence of alteration minerals formed at supercritical or superheated conditions. Preceding the analyses, twelve thin sections were prepared for petrographic analyses from samples that had been taken from cores that were drilled into the eastern side of the alteration aureole surrounding the Geitafell gabbro in May 2014.

The analysis of fluid inclusions in garnet suggests the occurrence of supercritical or superheated fluid during the deposition of this particular phase. Petrographic observation and results from electron microprobe analyses (EMPA) confirm the occurrence of secondary clinopyroxene with an intermediate composition between diopside and hedenbergite (salite and ferrosalite) in association with a high temperature mineral assemblage in veins, including actinolite, garnet etc., developed during the contact metamorphic event at the Geitafell volcano. The EMPA results are comparable with previous analyses from Friðleifsson (1983; 1984) although two differences were noted. Friðleifsson found Fe rich hedenbergite which was not found in the current study whereas this study revealed Mg rich clinopyroxene which was not reported in Friðleifsson. The textural relations of the Mg rich clinopyroxene need further examination.

Low-temperature geothermal exploration in Hoffell, southeastern Iceland Hot water for the municipality of Hornafjörður

Heimir Ingimarsson, Sigurður G. Kristinsson, Sigurveig Árnadóttir and Magnús Ólafsson

Iceland GeoSurvey (ÍSOR), Reykjavík, Iceland

E-mail: heimir.ingimarsson@isor.is

A good progress have been achieved in recent years in drilling of exploration/production wells in Hoffell/Miðfell in Hornafjörður, SE-Iceland. Low-temperature geothermal exploration began in the county of Austur-Skaftafellssýsla at the initiative of the municipalities in 1992. A noticeable heat anomaly was observed in Hoffell with a geothermal gradient of 186°C. Chemical analysis indicated that the temperature in the geothermal system might reach 70-80°C. Exploration in Hoffell was under the supervision of Jarðfræðistofan Stapi until 2012 when Iceland State Electricity (RARÍK) got the geothermal utilization right in the area. Thereafter, Iceland GeoSurvey (ÍSOR) began the exploration of the area. Lithological measurements were conducted in selected boreholes as well as acoustic televiwer logging. Interpretation of these logs changed the previous ideas, which experts had, about the geothermal system and results showed that it was more complicated than initially considered. On the basis of these measurements, production well HF-1 (1608 m deep) was drilled south-east of the N-S heat anomaly with acceptable results, but more water was still needed for the district heating of Höfn, the main town in the area.

A production well HF-2 (1684 m deep) was drilled in late 2014. The location of the well was decided in a similar manner as customary in Iceland, taking into account the temperature gradients in shallow exploration wells and then drilling straight into the area with the maximum temperature gradient. The result of that drilling did not meet the expectations. Based on that all assumptions were thoroughly reconsidered. A heat anomaly seen to the east with quite a flat peak was taken into further investigation and as a result, several shallow exploration wells were drilled to better determine the orientation of this anomaly. The hypothesis is that the main convection of geothermal water in the system is connected with NE-SW striking fractures dipping to the SE and extending NE from where production wells HF-1 and HF-2 were drilled.

Several exploration wells were drilled in 2015 and 2016 in the northeast part of the area to further explore the inner part of the geothermal system. Imaging with acoustic televiwer among other lithological measurements in these wells have strengthen the hypothesis that the main convection of water is in northeasterly striking fractures and that the geothermal system is much bigger than previously anticipated. Information derived from acoustic televiwer images have been crucial in locating production wells with greater accuracy and thus increasing the likelihood that the wells will intercept open fractures at the right depth. Production well HF-3 (1084 m deep) was drilled in early 2016 and drilling of HF-4 (1750 m deep) was finished in middle of July 2017. Both of them were very successful and have increased the possibility that sufficient water for the district heating in Höfn can be obtained. Well HF-4 is the easternmost production well in the area and is showing the highest temperature, which indicates that it, is closer to the main convection in the system.

References:

- Heimir Ingimarsson, Sigurður G. Kristinsson, Sigurveig Árnadóttir, Magnús Ólafsson, Friðgeir Pétursson (2017). Hoffell í Nesjum – Borun holna ASK-129 og ASK-130 og staðsetning næstu holu. Ísleskar orkurannsóknir, ÍSOR-2017/006, 34 p.
- Sigurður G. Kristinsson, Helga Margrét Helgadóttir, Halldór Ö. Stefánsson, Hörður Tryggva-son, Friðgeir Pétursson, Magnús Ólafsson (2013). Borun holu HF-1 við Hoffell í Nesjum. Íslenskar orkurannsóknir, ÍSOR-2013/030, 49 p.
- Sigurður G. Kristinsson, Helga Margrét Helgadóttir, Sigurveig Árnadóttir, Halldór Ö. Stefánsson, Þórólfur H. Hafstað, Magnús Ólafsson (2015). Hoffell í Nesjum – Hóla HF-2. Borsaga, jarðfræði og mælingar. Íslenskar orkurannsóknir, ÍSOR-2015/027, 30 p. Sigurður G. Kristinsson, Heimir Ingimarsson, Bastien R. Poux, Þórólfur H. Hafstað, Halldór Ö. Stefánsson, Halldór Ingólfsson, Friðgeir Pétursson, Magnús Ólafsson (2016). Hoffell í Nesjum – Hóla HF-3. Borsaga, jarðfræði, afköst og mælingar. Íslenskar orkurannsóknir, ÍSOR-2016/033, 43 p.
- Stapi-Jarðfræðistofa (1993). Jarðhitaleit í Austur-Skaftafellssýslu árið 1992. Sýslunefnd Austur-Skaftafellssýslu, 88 p.
- Stapi-Jarðfræðistofa (1994). Jarðhitaleit í Austur-Skaftafellssýslu árin 1993–1994. Sýslunefnd Austur-Skaftafellssýslu, 200 p.
- Stapi-Jarðfræðistofa (2002). Hornafjörður–Hoffell. Jarðhitaleit árið 2002. Greinargerð ÓBS/02-11, 18 p.
- Stapi-Jarðfræðistofa (2005). Hornafjörður–Hoffell. Jarðhitaleit árið 2003–2004. Greinargerð ÓBS/05-01, 19 p.
- Stapi-Jarðfræðistofa (2006). Jarðhitaleit við Hoffell árið 2005–2006. Greinargerð ÓBS/06-07, 9 p.

Exploring the potential of imaging a peri-urban geothermal site by using teleseismic receiver functions

A. Imtiaz, A. Lemoine, M. Delatre, C. Dezayes, A. Roulle

BRGM, France

E-mail: a.imtiaz@brgm.fr

The uncertainty involved in localizing geothermal reservoirs has been a significant impediment in the exploitation of potential geothermal energy. More research is needed to explore imaging tools in order to characterize the first few kilometers of the subsurface. In parallel to a multidisciplinary approach, ability of teleseismic earthquakes waveforms in characterizing the first few kilometers of a continental sedimentary site is assessed in the current research work.

The Receiver Function (RF) method is a classical technique for studying the discontinuities beneath seismic stations, particularly for imaging deeper interfaces (e.g., moho). It is based on the idea that the recorded teleseismic long-period body waves contain information about crustal structure near the receiver. Source, path and instrument effects are carried out through deconvolutions. The receiver function exhibits the response of the crust and upper mantle (Langston, 1979). The regular deconvolution methods for RF calculation require high signal-to-noise ratio (SNR) of the recorded waveforms. However, some approaches (e.g. Ligorria and Ammon, 1999) offer effective solution the problem associated to SNR. Since our objective is to characterize the capacity of RFs to constrain the interfaces (sediments/bedrock) at a relatively shallow depth (few km) and the target site is located near an urban area, this method is deemed as suitable for its capacity to remove anthropic noise.

The present study takes place in the Upper Rhine Graben, created during the Oligocene and the Miocene and filled with thick (>4km) tertiary to quaternary deposits. The main formations of geothermal interest are found in these Mesozoic formations. It is close to the city of Strasbourg and has a deep sediment-basement interface, exposing it to the expected conditions of future geothermal projects. A temporary network of 8 broadband three component velocimeters was deployed for 6 months, with the goal of testing seismic noise tomographic methods. Additionally, data from a broadband permanent station belonging to the French national network RESIF was used.

To estimate the RFs, seismograms from teleseismic earthquakes of magnitude $M_w > 5.5$ with epicentral distances between 30° and 90° are used. As recorded data are generally noisy, a visual quality control was applied. This operation reduces drastically the number of exploitable waveforms. As a preliminary step, 14 good quality, M_w 6-8, events and 7 stations have been selected for the analysis. RF computation is performed by the iterative time domain deconvolution approach (Ligorria and Ammon, 1999). The program code 'saciterd', written by Dr. Charles J. Ammon, provided in Computer Programs in Seismology package (Herrmann, 2013), was used. The RFs are then processed by using the stacking techniques Common-Conversion-Point (Zhu, 2000) and H- κ stacking (Zhu and Kanamori, 2000) to estimate the Moho depth and the bulk crust ratio V_p/V_s . The processing is done using an interactive toolbox, 'Funclab' (Eager and Fouche, 2012). The final results are analyzed and interpreted to identify the probable impedance contrasts in the underlying structure, and to compare with the observations coming from other site characterization approaches.

The geometry of the station network is not ideal for RFs, and the data are noisy for moderate earthquakes (workable frequency domain for few kilometers resolution at depth seem not to be associated to good enough SNR because of the suburban site conditions). Nevertheless, the preliminary results show some promising indications (deeper resolution than other passive methods) for shallow crust imaging.

Structural-geological impact on soil gas composition at Los Humeros Volcanic Complex

Anna Jentsch, Egbert Jolie

GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany

E-mail: ajentsch@gfz-potsdam.de

Mexico is known for its excellent geothermal resources. The Trans-Mexican Volcanic Belt (TMVB), a region characterized by Pliocene-Quaternary volcanism, is hosting two of the four geothermal production fields in Mexico used for power generation. One of them is the Los Humeros Volcanic Complex (LHVC), situated 180 km E of Mexico City in the eastern portion of the TMVB. The Los Humeros caldera with a diameter of ~ 18 km is composed of a 2200 m Quaternary volcanic succession, which is related to at least two major caldera-forming eruptions as well as abundant monogenetic eruptive centers. Experiences from the operation of the Los Humeros geothermal field indicate the existence of a superhot geothermal reservoir with temperatures > 380°C, which is not yet used for power generation.

The focus of the study is on the structural control on migration pathways of geothermal volcanic fluids to identify and assess hydraulically active (permeable) fault segments or buried discontinuities along major fault zones. Especially in low permeable reservoirs, fault zone architecture and its permeable structures form primary controls of fluid flow. Therefore, a detailed analysis of the structural-geological characteristics is required for a comprehensive understanding of fluid migration in the subsurface.

Techniques for diffuse degassing measurements provide important tools for the determination and quantification of volcanic gases. During the first field campaign in May/June 2017, 2600 CO₂ flux measurements were taken in an area of 3x6 km based on a regular sampling grid within the caldera. The same area is also covered by gamma spectrometry to determine the local dose rates based on the solid nuclides (²¹⁴Bi, ²⁰⁸Tl, ⁴⁰K), a presumed indicator for deep reaching fault zones. At 10 selected sites δ¹³C isotope samples were collected to distinguish between biogenic and magmatic/hydrothermal origin of CO₂ flux anomalies.

Preliminary results of both methods, CO₂ flux as well as gamma spectrometry, show an anomaly pattern that partly correlates to already known structures. Elevated values also occur in areas without obvious evidence for faults and could be interpreted as indicators of permeable segments. Further soil gas analysis, such as alpha spectrometry (²²²Rn, ²²⁰Rn), Micro Gas Chromatography (N₂, O₂, H₂, Ne, etc.) and Quadrupole Mass Spectrometry (He, Ar) will be performed within the project. Isotopic analyses of ³He/⁴He ratios will be conducted for the identification of possible mantle signatures. The goal of this approach is to put surface gas emissions in context to the geothermal-volcanic system to understand and explore it.

Integrated geophysical imaging of Reykjanes, SW Iceland

P. Jousset¹, H. Blanck², M. Metz^{1,3}, V. N. Djotsa^{1,3}, S. Franke⁴, K. Ágústsson², R. Karlsdóttir², T. Ryberg¹, T. Toledo¹, G. P. Hersir², C. Weemstra⁵, J. Martins⁶, A. Verdel⁶, B. Gibert⁷ and D. Bruhn¹

¹GFZ Potsdam, Germany

²ÍSOR, Iceland

³University of Potsdam, Germany

⁴Alfred Wegener Institute, Germany

⁵University of Delft, Netherlands

⁶TNO, Netherlands

⁷Université de Montpellier, France

The direct observation of hydrothermal fossil systems outcrops or the simulation of 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 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 results from the integration models obtained from seismic tomography and resistivity tomography around Reykjanes geothermal reservoir located along the Medio-Oceanic Ridge and Reykjanes, SW-Iceland. We deployed a network of 30 seismic stations and 24 Ocean Bottom Seismometers, between April 2014 and August 2015. 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 computed the accuracy we can obtain for the deployed network with a recent network analysis method.

We used local earthquakes recorded by a network of 84 stations (including the IMAGE network - 54 stations - and additional networks, e.g., 7 stations from the Iceland Meteorological Office, 15 stations from the Czech Academy of Science, and 8 stations from the ISOR/Hs Orka network). We performed first travel time tomography. The processing includes first arrival picking of P- and S- phases using an automatic detection and picking technique based on Akaike Information Criteria. The picks were then manually checked and improved. We locate earthquakes by using a non-linear localization technique, as a priori information for deriving a 1D velocity model. Our model confirms previous models obtained in the area, with enhanced details. We then computed a 3D velocity model by joint inversion of earthquakes location and velocity anomalies of the 1D model.

We also used ambient noise cross-correlation techniques in order to derive a complementary velocity model, especially to cover locations where earthquakes did not occur. Cross-correlation techniques involve the computation of stacked cross-correlation of station-pair recordings, from which Green's function are extracted. Surface wave inversion of the Green's functions through tomography allows a further derivation of S wave velocity-depth profiles.

We performed integration with other structural information like resistivity models and other models before drilling the IDDP-2 well. Results obtained from rock analysis drilling confirm our results.

Injection-induced surface deformation and seismicity at the Hellisheidi geothermal field, Iceland

D. Juncu¹, T. Árnadóttir¹, H. Geirsson¹, G. B. Guðmundsson², B. Lund³, G. Gunnarsson⁴, A. Hooper⁵, S. Hreinsdóttir⁶,

K. Michalczevska¹

¹Nordic Volcanological Center, Institute of Earth Sciences, University of Iceland, Reykjavik, Iceland

²Icelandic Meteorological Office, Reykjavik, Iceland

³Department of Earth Sciences, Uppsala University, Uppsala, Sweden

⁴OR – Reykjavik Energy, Reykjavik, Iceland

⁵COMET, School of Earth and Environment, University of Leeds, Leeds, UK

⁶GNS Science, Lower Hutt, New Zealand

Induced seismicity is often associated with fluid injection but only rarely linked to surface deformation. We observe 2 cm of surface deformation as well as a strong increase in seismicity during the initial phase of geothermal wastewater reinjection at the Hellisheidi geothermal power plant in south-west Iceland. Reinjection started in September 2011 with a flow rate of around 500 kg/s. Micro-seismicity increased immediately in the area north of the injection sites, with the largest seismic events in the sequence being two M4 earthquakes on 15 October 2011. Semi-continuous GPS sites installed in October and November 2011 reveal a transient signal which indicates that most of the deformation occurred in the first months after the start of the injection. The surface deformation is evident in SAR interferograms as well, in the time interval between June 2011 to May 2012. We use an inverse modelling approach and simulate the geodetic data (InSAR and GPS) to find the most plausible cause of the deformation signal and investigate how surface deformation, seismicity and fluid injection may be connected to each other. We argue that fluid injection caused an increase in pore pressure which resulted in increased seismicity and fault slip. Both pore pressure increase and fault slip contribute to the surface deformation.

Surface and body waves ambient noise tomography near Soultz-sous-forêts (France) using the dense EstOF seismic array

Maximilien Lehujeur¹, Jérôme Vergne¹, Adrien Le Chenadec¹, Jean Schmittbuhl¹ and the EstOf-Team^{1,2,3}

¹EOST-IPGS, Université de Strasbourg/CNRS, 5 rue René Descartes, F-67084 Strasbourg Cedex, France

²ES-Géothermie, 3A, chemin du gaz, 67500 Haguenau, France

³GEIE-EMC, Route de Soultz, BP 40038, F-67250 Kutzenhausen, France

lehujeur@unistra.fr

In September 2014, a dense temporary network (EstOf) including 288 vertical component geophones was deployed during 30 days in the Outre-Forêt region of the Upper Rhine Graben (France), where two deep geothermal projects - Soultz-sous-Forêts (GEIE-EMC) and Rittershoffen - are currently in operation. We applied ambient seismic noise correlation to determine the empirical Green's functions between the ~41200 station pairs. This network significantly improved the spatial and azimuthal coverage relative to the sparse long-term networks settled in the area mostly to monitor the induced seismic activity. Both the fundamental mode and the first overtone of the Rayleigh waves could be identified between most station pairs in a period range between 1 and 5 seconds. These waves were analyzed to build dispersion maps at various periods which are then inverted to depth to build a 3 dimensional S-wave velocity model. Although less prominent, P waves have also been identified in the correlations at periods around 1s and were used to build a preliminary 3 dimensional P-wave velocity model of the area. Due to the increase in P wave velocity at the transition from the sedimentary pile to the crystalline basement, where lie the geothermal reservoirs, the resolution peaks at that depths. The main geological structures emerge from the tomographic models, which reflects their validity and supports the use of such techniques for the exploration and the characterization of deep geothermal reservoirs.

The role of smectites in the electrical conductivity of active hydrothermal systems: electrical properties of core samples from Krafla volcano, Iceland

L. Lévy^{1,2,3}, B. Gibert⁴, F. Sigmundsson², G. P. Hersir³, Ó. G. Flóvenz³, P. Briole¹ and P. Pezard⁴

¹Laboratoire de Géologie, Ecole Normale Supérieure - PSL Research University, CNRS, UMR 8538, Paris, France

²Nordic Volcanological Center, Institute of Earth Sciences, University of Iceland, 101 Reykjavík, Iceland

³ÍSOR - Iceland Geosurvey, Grensásvegur 9, 108 Reykjavík, Iceland

⁴CNRS, Géosciences Montpellier, UM2 5243-CC60, Université Montpellier, Montpellier, France

Alteration minerals, in particular clay minerals (smectite, chlorite), are used to estimate the temperature of geothermal reservoirs given their different ranges of temperature stability. Permeable and active horizons of geothermal reservoirs are also often associated with the presence of expandable clay minerals outside their normal temperature range. Expandable clay minerals, such as smectite, are good electrical conductors but their quantitative influence on the total electrical signal, as well as the physical processes responsible for their electrical properties, are still open questions. This study explores the quantitative relationship between smectite content and electrical response of igneous basaltic rocks. We present laboratory measurements of a large range of properties (Cation Exchange Capacity (CEC), X-Ray Diffraction (XRD), porosity, electrical properties) on 88 core samples from four boreholes in the Krafla high-temperature geothermal field, Northeast Iceland.

We first show that the Cation Exchange Capacity (CEC), measured by the Copper-triethylenetetramine method, is a reliable measure of the smectite weight content in complex volcanic samples by addressing separately the contribution of zeolites, chlorite and mixed-layer to the CEC, as well as by comparing the CEC measurements to an independent quantification of the smectite content by Rietveld-refinements of XRD patterns.

We focus in this study on the real "in-phase" part of the complex conductivity signal, which contains two distinct contributions: from the fluid and from the solid (the expandable minerals). We adopt a similar approach to that of Waxman & Smits (1968), elaborating a function that best fit the data at all salinities, discussing the physical processes involved and finally studying the applicability to geothermal exploration. In addition, the use of altered igneous samples enables to reach much higher volumetric quantities of expandable minerals than in previous studies. While the fluid contribution to the conductivity is dominating in samples with a little amount of expandable minerals, both fluid and solid contributions are important for samples with more expandable minerals. We explore the non-linear salinity-dependence of the conductivity signal for samples with high content in expandable minerals and suggest simple equations to fit the data. We then compare the parameters derived from the fits to two independently measured parameters: the content in expandable minerals and the porosity. We observe that these two parameters are necessary to describe the conductivity of rocks at a given temperature and salinity, but also interrelated. Finally, we analyze the applicability and limits of our results to the field scale, by comparing the parameters measured on cores to borehole logs.

The research leading to these results has received funding from the EU Seventh Framework Programme under grant agreement No. 608553 (Project IMAGE).

Thermo-mechanical characterization of the European lithosphere for geothermal exploration

Jon Limberger¹, Jan-Diederik van Wees^{1,2}, Magdala Tesauro^{1,3}, Jeroen Smit¹, Damien Bonté¹, Eszter Békési^{1,2}, Maarten Pluymaekers², Maartje Struijk², Mark Vrijlandt², Fred Beekman¹ and Sierd Cloetingh¹

¹Utrecht University, Department of Earth Sciences, PO Box 80021, 3508 TA Utrecht, The Netherlands

²TNO, P.O. Box 80015, 3508 TA Utrecht, The Netherlands

³Università degli Studi di Trieste, via Weiss 1, Palazzina C 34127 Trieste, Italy

In order to bridge the gap between large-scale geophysical models and more detailed basin-scale models, we have constructed a 3D thermal model of the European lithosphere with differentiated thermal properties for the sedimentary layer and the layered thermal property structure for deeper parts of the lithosphere. Physics-based reference models and underlying properties, compositional reference models, boundary conditions, and observational data constraints are used for thermal and mechanical characterization of the lithosphere. To improve model robustness, the lower boundary condition and main thermal parameters are stochastically varied using an Ensemble Smoother Multiple with Data Assimilation (ES-MDA) technique, resulting in a good fit with available temperature data.

Lacking a European centralized and public database of temperature measurements, the thermal model is calibrated with temperature data points extracted from regional temperature models. Misfits between the prior and posterior thermal model can partly be attributed to generalization and discretization required for building a European-scale model and to a-priori assumptions on thermal properties and model boundary conditions. Other misfits can be related to transient thermal effect or to areas where a significant amounts of non-conductive heat transfer is occurring such as regions with active tectonics or volcanism. These misfits can be used to study thermal properties of the lithosphere as well as the contribution of non-conductive heat transfer to surface heat flow. Using the ES-MDA technique, misfits are reduced by varying the model parameters within a predefined bandwidth. Conduction is the dominant heat transfer mechanism within the lithosphere and together with the a-priori structural and compositional model it can explain most large-scale variation observed in the thermal structure of the lithosphere. The conductive thermal field can regionally and locally be disturbed by active tectonic processes, volcanism, buoyancy-driven thermal convection, and advective groundwater flow.

The thermal state of the lithosphere, rheology, and stress regime control the integrated strength of the lithosphere and determine the style of deformation. Based on our high resolution 3D thermal model, we have updated strength estimates for Europe, in particular affecting the upper part of the lithosphere. An improved understanding of the thermo-mechanical state of the lithosphere can aid in geothermal resource assessments.

Normal faults and transfer zones during Late Miocene mineralization in eastern Elba Island (Italy)

D. Liotta¹, A. Brogi¹, A. Dini², C. Bianco¹, G. Ruggieri³

¹Department of Earth and Geoenvironmental Sciences, University of Bari "Aldo Moro", Via Orabona 4, Bari, Italy

²CNR-IGG National Council of Research, Geosciences and Georesources Institute, Pisa, Italy

³CNR-IGG National Council of Research, Geosciences and Georesources Institute, Florence, Italy

The kinematic and chronological relationships among low angle normal faults and high angle strike- to oblique-slip faults in an exhumed mineralized area are presented. Shear veins and minor associated structures filled with the same mineral assemblage are interpreted as indicators of coeval fault activities. The study area is located in 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 favoring 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.

The research leading to these results has received funding from the European Community's Seventh Framework Programme under grant agreement no. 608553 (Project IMAGE).

Fractures analysis and hydrothermal mineralization in the Neogene Geitafell central volcano (Iceland): insights for fluid pathways in the fossil geothermal system

Domenico Liotta¹, Andrea Brogi¹, Giovanni Ruggieri², Valentina Rimondi², David Baumann³, Thomas Driesner³, Guðmundur Ómar Friðleifsson⁴, Helga Margrét Helgadóttir⁵, Massimiliano Ciacci¹, Martina Zucchi¹

¹Dipartimento di Scienze della Terra e Geoambientali, Università di Bari (Italy)

²Centro Nazionale delle Ricerche, IGG, Firenze (Italy)

³ETH, Zurich (Switzerland)

⁴HS Orka, Reykjavik (Iceland)

⁵ÍSOR-Iceland GeoSurvey, Reykjavík, (Iceland)

The research on the geothermal fluids pathways and its tectonic control represents one of the most attractive and continuous task for the improvement of exploration and exploitation in Iceland. Several methodologies have been proposed to this goal: from numerical simulations of fluid circulation to geochemical, geophysical and structural data. The integration among these approaches leads to fluid flow models describing the relationships between crustal structures and geothermal resources with a crucial role for assessing successive strategies. However, given the complexity of the natural system, the resulting hydrological model almost always contains uncertainties on the fluid pathways. In order to contribute to this understanding, we present an integrated approach between structural - kinematic study and fluid inclusions analyses carried out on a fossil, exhumed, geothermal system located at Geitafell area (SE Iceland), that is considered as a proxy of the deep structure characterizing the present geothermal areas of Iceland. Our work is addressed to the reconstruction of the relationships between the main structures and the geothermal fluids circulation at the boundary between the magmatic chamber and hosting rocks, in order to get information on factors having controlled the geothermal fluids flow, its storage and the rocks-fluids interaction, at 1-2 km depth crustal level. The results allow us to reconstruct the main conduits favoring the geothermal paleo-fluids circulation, corresponding to fault zones parallel and orthogonal to the rift-trend, and to investigate the lateral traps, consisting of porous lava levels, where the fluids mostly with low-salinity (< 1 wt.% NaCl eq.) and temperatures mainly in the 150 -360°C range, were stored. We finally encourage the study of fossil geothermal systems as a key for having parameters, commonly got after drillings.

The research leading to these results has received funding from the EC 7th Framework Program, under grant agreement no. 608553 (Project IMAGE)

NW-TRENDING TECTONIC STRUCTURES IN KRAFLA GEOTHERMAL AREA

Domenico Liotta¹, Andrea Brogi¹, Sigurveig Árnadóttir²

¹Dipartimento di Scienze della Terra e Geoambientali, Università di Bari, Italy

²ÍSOR, Akureyri, Iceland

The tectonic evolution of North-eastern Iceland is controlled by the coeval activity of N-S trending normal and NW-trending oblique faults, related to the oceanic rift and associated transform zone evolution, respectively. The northern transform zone comprehends the Husavik-Flatey fault zone and it is documented by structural data and epicentral distribution. Along this zone volcanic and geothermal manifestations have been described, as well as along the normal faults associated to the oceanic rift. The interplay between these two fault systems is presently described up to the south of Tjörnes where it is interrupted by the N-S trending faults. Differently, our survey documented alignment of geothermal manifestations and lava fissure systems further to the east, along the same trend of the transfer zone up to the Krafla geothermal area, where these represent minor structures coeval with the regional structures, dominantly N-S oriented.

We interpret these evidence as an incipient migration of the Husavik-Flatey fault zone further to the east, in the frame of the extensional tectonic evolution of Iceland. In this view, the location of the Krafla geothermal system appears to be controlled by the increase of secondary permeability deriving by the cross-cutting relationships between the two main tectonic trends characterizing the area.

The research leading to these results has received funding from the EC 7th Framework Program, under grant agreement no. 608553 (Project IMAGE).

Supercritical geothermal resources in Europe: how to IMAGE them?

Adele Manzella¹, Gylfi Páll Hersir², Jan Diederik van Wees^{3,6}, David Bruhn⁴, Domenico Liotta⁵, Serena Botteghi¹, Gianluca Gola¹, Ólafur G. Flóvenz², Jon Limberger⁶, Alessandro Santilano¹, Eugenio Trumpy¹

¹CNR-IGG (Italy), ²ÍSOR (Iceland), ³TNO (The Netherlands), ⁴GFZ (Germany), ⁵University of Bari (Italy), ⁶Utrecht University (The Netherlands)

Very high-temperature reservoirs are a possible target for future geothermal exploration either through the direct exploitation of super-critical fluids or as a potential high-temperature reservoir for Enhanced Geothermal Systems. By exploiting subsurface fluids at super-critical conditions, i.e. high temperature (>375 °C) and high pressure (>22 MPa), the energy output per well will increase by a factor of ~10. This will reduce development costs by decreasing the number of wells needed (IEA Technology Roadmap 2011).

In order to contribute to the EU strategic energy and climate targets for 2020 and 2050 by fostering increased growth in the geothermal energy market through enhanced awareness of the potential of geothermal energy production, a database of potential supercritical resources has been launched by the IMAGE project.

Superhot and supercritical resources are expected in the surrounding of still hot magmatic intrusions in the crust. A large part of the IMAGE activity focused on understanding what are the favorable conditions at a few km depth for shallow magmatic emplacement, beside improving exploration and investigation techniques for their detection and the related hot water circulation. In a typical crust with an average thermal gradient of the order of 30-35 °C/km the critical temperature of a brine (temperature above 450 °C) is reached at depth greater than 12-15 km. However, in many sites around the world (e.g. Larderello and Phlegraean Fields in Italy, Nesjavellir in Iceland, The Geysers in California) where exploratory boreholes were drilled in high-temperature geothermal system (T > 370 °C), reservoir pressures above supercritical conditions (>22.1 MPa) were encountered. These evidences confirm that geothermal reservoirs in supercritical conditions, both in temperature and pressure, exist in the vicinity of cooling magmatic intrusions. Volcanic rifts, extensional basins and/or subduction zones with related shallow crustal magma emplacements, are the more promising environments in which supercritical conditions may be found in the upper to middle crust levels,

The compilation of a European database of the favourable indicators of the presence of supercritical geothermal resources has been a main task in the IMAGE project. The objective is to define areas in Europe where supercritical fluids occur at a drillable depth with a manageable chemistry composition can be found. Where do we find fluids at 4-5 km depth with a temperature exceeding 400 °C? In various regions in Europe, including Iceland, Italy, Azores, Montserrat, Canary Island. What characterizes these areas? Can we find other areas with similar features at greater depth? We focus on Iceland, where these resources have been searched and studied in the last decade. We used the experience of research in Larderello, described in detail in other IMAGE deliverables (e.g. D5.01), to look for indicators applicable over broad areas, in search of potential supercritical resources in continental Europe. Since temperature is the key parameter controlling the presence of supercritical reservoirs at (relatively) shallow depth, mapping of supercritical resources was mainly driven by thermal models derived from crustal and lithospheric constraints and data interpolation from available deep wells. Other information providing indirect indication of crustal thinning and shallow magmatic emplacement have been searched and analyzed. In particular, we mapped the following indicators: the depth of 400 °C isotherm; the MOHO depth and crustal thickness; the earthquake density combined with the estimated depth of the Brittle-Ductile Transition in Europe. Other interesting indicators, e.g. He3/He4 ratio values from which fluids of crustal origin may be inferred, or Curie Point depth that refers to deep temperature regime, are available only for local areas, and are too restricted to be of use at regional and European scale. The location of recent (Pleistocene-Holocene) volcanism, also dispersed, was mapped since it provides useful information, but was not used in the computation of final maps.

After defining the indicators, their spatial correlation was established by Geographic Information System (GIS) models, and a database was organized. By prioritizing favourable conditions using GIS spatial analysis methods, the "favourability" map of geothermal resources at supercritical condition was then obtained. It provides a clear overview of the distribution of potential resources in Europe, based on analytical data.

Acknowledgements

The research leading to these results has received funding from the EC Seventh Framework Programme under grant agreement No. 608553 (Project IMAGE).

Surface-Wave Tomography by Ambient Noise Seismic Interferometry to image volcanic and geothermal systems in South Iceland

Joana E. Martins^{1,2}, Elmer Ruigrok³, Cornelis Weemstra², Arie Verdel¹, Philippe Jousset⁴, Gylfi P. Hersir⁵, Deyan Draganov², Andrew Hooper⁶, Ramon Hansen², Robert White⁷, Heidi Soosalu⁸

¹TNO, Utrecht, The Netherlands

²Delft University of Technology, Delft, The Netherlands

³KNMI, Utrecht, The Netherlands

⁴GFZ, Potsdam, Germany

⁵ÍSOR, Reykjavik, Iceland

⁶University of Leeds, Leeds, United Kingdom

⁷Cambridge University, Cambridge, United Kingdom

⁸Tallinn University of Technology, Estonia

Tomographic studies based on passive seismic measurements have proven to be a powerful tool to image the subsurface. This especially holds in areas like Iceland, where the microseism coverage arriving from the Ocean is excellent.

In this study, we apply Ambient Noise Seismic Interferometry (ANSI) to generate a tomographic image of Rayleigh waves velocity anomalies and further inversion to S-wave anomalies at two Icelandic locations. We derive a tomographic image over Reykjanes Peninsula geothermal system using 30 Broad-Band (BB) stations deployed under IMAGE project framework and operating for approximately one year and a half. In the other case study, we derive a tomographic image of Torfajökull volcano using 23 BB seismometers recording ambient noise for ~100 days acquired in 2005 by Cambridge University.

We retrieve the surface-wave part of the Green's functions by cross-correlation between station pairs and consecutive stacking of the cross-correlations to obtain coherent ballistic surface waves (BSW). We pick the arrival times of the BSW, which are the input for the tomographic analysis. Both datasets show remarkably high signal-to-noise-ratio of surface-wave arrivals between 0.1 and 0.5 Hz, even with only ~100 days of recorded ambient noise. A beamforming analysis indicates a broad azimuthal coverage with persistent ambient noise arrives within three azimuthal quadrants, between 90 and 360 degrees. The highly coherent surface waves retrieval and the wide azimuthal coverage of the microseismicity arrival explain the success of ANSI techniques in Iceland.

For the tomographic inversion, we use a Tikhonov and a statistical regularisation to invert the ballistic surface-wave time arrivals to a 3D frequency dependent velocity variations. We detect low and high-velocity anomalies with changes between -15% and 15% from an estimated average velocity, which we interpret as possible old dyke intrusions and heat sources.

The research leading to these results has received funding from the European Community's Seventh Framework Programme under grant agreement No. 608553 (Project IMAGE)

The importance of borehole imaging logs in revealing volcanic facies and structure: Examples from Hawai'i and Iceland

John M. Millett^{1,2}, Sverre Planke^{1,3}, Dougal A. Jerram^{3,4}, Anett Blischke⁵, Sigurveig Árnadóttir⁵, Simona Pierdominici⁶, Jochem Kück⁶

¹VBPR AS, Oslo Science Park, Norway (j.millett@abdn.ac.uk)

²Department of Geology & Petroleum Geology, University of Aberdeen, U.K.

³CEED, University of Oslo, Norway

⁴DougalEARTH Ltd., Solihull, U.K.

⁵ÍSOR-Iceland GeoSurvey, Akureyri Branch, Iceland

⁶OSG at Helmholtz Center Potsdam - GFZ German Research Center for Geosciences, Germany

Volcanic systems incorporate a huge diversity of volcanic facies which in turn host a similar diversity and range of physical properties. Where volcanic systems form sub-surface exploration targets for geothermal energy, hydrocarbons or aquifers, interpreting the volcanic geology from borehole data is integral to developing robust geological models. This is especially important in terms of multi-borehole correlation, and where volcanic facies e.g. permeable lava flow margins, hyaloclastites or fractured intrusions, impart strong controls onto fluid flow pathways and connectivity, additional to those associated with fracturing. Within this presentation we focus on the application of the borehole televiewer tool (BHTV) for volcanic facies determination. The BHTV can acquire high resolution acoustic images of open borehole sections and is commonly utilized for both structural and facies analysis by interpretation of contrasts in travel time and amplitude.

To highlight the potential of the BHTV log for volcanic facies analysis, we focus on results from borehole logging operations in a fully cored c. 1.5 km deep borehole, PTA2, from the Big Island of Hawai'i. The borehole was drilled as part of the Humu'ula Groundwater Research Project (HGRP) and penetrates a basaltic lava dominated sequence with a complex history of hydrothermal alteration. BHTV data along with sonic, spectral gamma and magnetic susceptibility were collected for the open hole section from 889-1568 m depth, with the BHTV set to the highest resolution settings and run at optimized logging speed for gaining the best possible imagery. By comparison with the core data, the potential for BHTV imaging to reveal spectacular intra-facies features including individual vesicles, vesicle segregations, 'a'a rubble zones, intrusive contacts, and intricate pāhoehoe lava flow lobe morphologies is demonstrated. The calibration of BHTV imagery with the high quality full core from PTA2 enables improved interpretation of volcanic reservoir features in the more common exploration scenario where core is absent.

A number of factors including tool settings, logging speed, temperature and hole conditions can deteriorate the quality of images returned by the BHTV. To highlight some of these influences, we compare data from the K18 borehole within the Krafla high temperature field, where challenging logging conditions associated in part to the high temperature nature of the borehole, resulted in mixed but generally poor BHTV results. We conclude that the benefits of good quality BHTV data can be significant in terms of improved understanding of volcanic reservoirs, and that where possible, acquiring high resolution BHTV data should form a priority for geothermal exploration in volcanic settings.

Supercritical fluid flow close to shallow magma intrusions: suggestions from analogue modelling

Domenico Montanari, Marco Bonini, Giacomo Corti, and Andrea Agostini

Institute of Geosciences and Earth Resources, National Research Council of Italy (CNR), Florence, Italy

Magma emplacing at shallow crustal levels may cause significant deformation in the overlying country rock (i.e., forced folding, fracturing and faulting), both at a local and/or regional scale). To get insights into these processes, we investigated in the laboratory the development of forced folds and associated fracture/fault networks. An analogue magma, simulated by polyglycerols, was intruded into a sand pack representing the brittle crust. The scaled analogue models reproduced different 3D deformation structures depending on the model parameters (e.g., magma viscosity, injection rate, volumetric flux, and the rheology and thickness of the host and cover rocks). However, all models were invariably dominated by forced folding and associated brittle faulting/fracturing. Although the models involve simplifications, these results provide useful hints for geothermal research, as fractures and faults associated with magma emplacement can significantly influence the distribution and migration of superhot geothermal fluids. These structures can therefore be considered potential targets for geothermal and/or ore deposit exploration. In this perspective, the results of analogue models may provide useful geometric constraints for field work, numerical modeling, and particularly seismic interpretation, allowing production and a better understanding of integrated conceptual models concerning the circulation of supercritical fluids.

The research leading to these results has received funding from the European Community's Seventh Framework Programme under grant agreement No. 608553 (Project IMAGE). Spiga Nord S.p.A is acknowledged for kindly providing us the polyglycerols used in our experiments.

Characterization of deep geothermal reservoir using fractal models and linking observed fractures, stress heterogeneities and micro-seismic observations

Mohammad Moein¹, Keith F. Evans¹, Thessa Tormann², Stefan Wiemer², Marcus Herrmann², Dimitrios Karvounis², Benoît Valley³

¹Geological Institute, ETH Zürich, SWITZERLAND

²Swiss Seismological Survey, ETH Zürich, SWITZERLAND

³CHYN, University of Neuchâtel, SWITZERLAND

Fracture network characteristics and stress heterogeneities are believed to be key parameters controlling the micro-seismicity development during hydraulic stimulation of deep geothermal reservoirs. These parameters are difficult to estimate, particularly at early project stage when only a single exploration well may be available. In this contribution, we explore the possible linkage between these parameters with the objective of producing a better characterization of the reservoir if fracturing, stress and microseismic characterization are considered jointly.

The data sets available in deep geothermal reservoirs are typically too sparse to infer deterministically systematic links between fracturing, stresses and microseismicity within the reservoir volume. Thus, we pursued a probabilistic approach taking advantage of the fact that scale invariant power law distributions, also referred as fractal distributions, are present in all three considered data sets.

Fractal patterns in natural fracture networks have been widely recognized. However, the characterization of the fractal parameters of a fracture network from deep borehole datasets encounters two major difficulties. 1) stereological relationships of fractal parameters when shifting from 1D observations along a borehole to 3D are not well understood, and 2) fracture lengths are not constrained by single borehole data, thereby preventing the estimation of the exponent in the power law that describes fracture length variations in the fracture network distribution. We addressed the first problem by performing stereological analyses on synthetic fracture network and then applied these findings to actual fracture data sets derived from the geothermal projects at Basel and Soultz. We explored the possibility of constraining the fracture length parameters using inputs from the stress heterogeneities and microseismicity data.

The stress heterogeneities in the reservoir are best highlighted by studying the variability in observed wellbore failure. Where present, wellbore failure provides a direct indication of the in-situ principal stress direction. In contrast to other borehole stress measurement techniques that are essentially point measurements, wellbore failure, if quasi-continuous over significant lengths of a borehole, allows the variability of stress orientation along the borehole to be examined, and the fractal characteristics of these variations evaluated. The fact that borehole failure is often discontinuous brings a difficulty in these analyses, as it is not trivial to extract unbiased fractal parameters from discontinuous data series. We tested a number of approaches on synthetic data and then applied the most robust methods to evaluate the fractal parameter of data sets from Basel and Soultz and to assess the uncertainty on these estimators.

To investigate the fractal properties of injection induced micro-seismicity, we performed a re-analysis of the Basel data set, using a template-matching and cross-correlation based approach. This allows us to substantially lower the detection threshold, improve the location accuracy and the homogeneity of the micro-seismicity record, thus providing a much-improved database for analyzing the size distribution as well as the spatial distribution of events. The time-evolution of the relative earthquake size distribution, or b-value, reveals that the fracture network activated during different phases of the stimulation and post-stimulation periods varies significantly.

Joint analyses of these parameters are still on-going. They will bring additional insight compared to analyses with these key reservoir characteristics considered in isolation, and in turn will provide more reliable inputs for reservoir simulations.

Geochemical model of high temperature gas-water-rock interaction

Giordano Montegrossi¹, Giovanni Ruggieri¹, Barbara Cantucci²

¹C.N.R. -I.G.G.-U.O.S. Firenze (Italy)

²I.N.G.V. Roma (Italy)

The study carried out in the framework of the IMAGE FP7 (grant agreement no. 608553) project was focused on modeling two different kind of high temperature systems. The first one is a high-temperature system related to the flowing of B-rich fluid of magmatic origin within biotite-rich micaschist of eastern Elba Island. This system is considered a fossil system analogue to an active high-temperature system present at depth below the present-day exploited Larderello geothermal field. The high-temperature system was investigated by using the state-of-art geochemical modeling codes and data, and the resulting model shows that with the current knowledge, it is possible to reproduce a real case of tourmalinization and magnetite ore deposition (similar to that found in eastern Elba Island) related to the circulation of B-rich fluid that interacted with biotite. The model starts by evaluating the field mineralogy and integrating the thermodynamic data already present in the database with the key minerals (e.g. Schorl and Dravite) and constraining the model on the basis of the field observation. The model succeeded in reproducing the deposition processes observed in the field, thus providing a deeper insight of the system.

The second system deals with the alteration of basalts, studying samples from Geitafell, Iceland. This is a fossil hydrothermal system analogue to the active Krafla geothermal field, characterized by low-salinity fluid. The investigation start from the analysis of the basalt. To model an ideal gas phase, as often encountered in geothermal and volcanic system, some assumption on the dominant redox buffer have been introduced: NNO, FeO1.5 or sulfur buffers. Such three main buffers have an overlapping region, around $\log f(O_2) = 16.9$. In this case, we could use iron and sulfur present in the basalt as dominant buffers. Thus, we compute the gas speciation and add different amount of gases to compute the secondary mineral assemblage, and then validate the model by comparison of the resulting water composition with the ones present at depth in the Krafla geothermal system.

3D Numerical Model of Larderello Area

Giordano Montegrossi¹, Marina Agostini², Davide Scrocca³, Giovanni Ruggieri¹, Adele Manzella⁴, Alessandro Santilano⁴, Lorenzo Petracchini³, Eugenio Trumpy⁴, Roberto De Franco⁵, Grazia Caielli⁵

¹C.N.R. –I.G.G.–U.O.S. Firenze (Italy)

²University of Florence, Dept. Earth Sciences, Firenze (Italy)

³C.N.R. – I.G.A.G. Roma (Italy)

⁴C.N.R. –I.G.G.–U.O.S. Pisa (Italy)

⁵C.N.R. – I.D.P.A. Milano (Italy)

A 3D numerical model of the natural state of a selected area within the Larderello Geothermal system was developed by using the main results obtained during the IMAGE project, as well as from literature review.

The main source of well data, such as stratigraphy, permeability and temperature, is the geothermal database hosted at CNR-IGG (namely BNDG). The 3D geological model describe the following geological units: Neogene sediments, Ligurian Flysh Complex, Tuscan Nappe plus Tectonic Wedge Complex and Metamorphic Units. Petrophysical information have been also collected from representative samples of the different rock types outcropping (according to geological data) analogue to those occurring in the Larderello area at depth, and in particular, representative of the main rock types found in the Lago area wells. The various lithological units of the shallow geological formations (i.e. Neogene sediments, Tuscan Nappe, Tectonic Wedges and Phyllitic-quartzitic complex of the Methamorphic Units) are outcropping at the border of or within the geothermal area, whereas the deep portions of the Metamorphic Units (e.g. granite, micaschists) are exposed at Elba Islands. The petrophysical measurements were performed thanks to the courtesy of Aachen RWTH and ERASMUS+ traineeship 2016-2017.

By integrating this information in the general framework obtained in the IMAGE project, we were able to elaborate a 3D reservoir-numerical model of the Larderello geothermal reservoir spanning from below K-horizon up to the surface. The temperature range overpasses the water critical point, and to compute the steady state for this model we used the IAPWS97 extension for pure water developed in the DESCRAMBLE H2020 project (**grant agreement N°640573**). CO₂ is not included in this model.

The results of the seismic modeling of K-horizon and integrated information (see De Franco et al., 2017 presented in this volume) suggest that the structure of K-seismic reflector is an impermeable horizon that includes several pockets of high pressure / high temperature fluids. Going deeper, considering the temperature gradient encountered just above k-horizon, a temperature of about 650°C is quickly reached, which is close to granite partial melting/last crystallization temperature. Such temperature is then referred to the bottom of the model. The final modelling results provide important information regarding the multiple-reservoir (hydrothermal and supercritical) system of Larderello.

The research leading to these results has received funding from the European Community's Seventh Framework Programme under grant agreement no. 608553 (Project IMAGE).

What can we learn from laboratory experiments on tracer behavior?

Jiri Muller, Sissel Opsahl Viig, Per Arne Hubred, Øyvind Brandvoll, Odd Benny Haugen

Institute for Energy Technology - IFE, Norway

Laboratory experiments have been performed at testing stability of perfluorinated cyclic hydrocarbon (PFC) gas tracers at supercritical conditions. Both static and dynamic tests have been performed at a specially constructed equipment which can tolerate such hard conditions (>374 °C, >218 bar). Static stability results indicate no rapid thermal degradation of the tested tracer candidates within the time frame of the performed stability test (2 months). However, the dynamic flooding experiments using crushed rock from the Krafla IDDP-1 field on Iceland indicate interactions between the rock material and the tracer candidates. This is an interesting result because PFC tracers have been detected in earlier studies in the Krafla field.

Ambient seismic noise monitoring during the injection phases at the deep geothermal projects in Basel and St. Gallen, Switzerland

Anne Obermann¹, Gregor Hillers², Toni Kraft¹, Stefan Wiemer¹

¹Schweizerischer Erdbebendienst (SED), ETH Zürich, Switzerland

²ISTerre, Université Joseph Fourier, Grenoble, France

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.

The first visionary Swiss EGS project was within the city limits of Basel. In December 2006, a hydraulic stimulation of the crystalline basement at a depth of 5 km took place. The stimulation was accompanied by more than 10,500 earthquakes in the vicinity of the injection point in the first 6 days. These high rates of induced seismicity led operators to stop the stimulation after 6 of 21 originally planned days. A ML3.4 earthquake occurred 5 h after shut-in, causing slight structural damages that lead to insurance claims exceeding U.S. \$7 million. In the following 56 days three “aftershocks” of ML>3 followed and resulted in the final closure of the project.

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.

We report our results from monitoring the injection phases of these two very different projects with ambient noise cross-correlations. In the case of Basel, we observe a pronounced lapse time change that we interpret as an aseismic transient deformation related to the stimulation. In the case of St. Gallen, we observe a significant loss of waveform coherence that starts with the onset of the fluid injections 4 days prior to the gas kick. We interpret the loss of coherence as an infiltration of the gas in the formation.

Both case studies show that ambient noise correlations can be used to assess the aseismic response of the subsurface to geomechanical well operations, yielding additional important information on the reservoir dynamics.

References:

- Hillers, G., Husen, S., Obermann, A., Planès, T., Campillo, M., Larose, E., (2015) Noise based monitoring and imaging of aseismic transient deformations induced by the 2006 Basel reservoir stimulations, *Geophysics*, 80, 4, doi: 10.1190/GEO2014-0455.1
- Obermann, A., Kraft, T., Larose, E., Wiemer, S., (2015) Potential of ambient seismic noise techniques to monitor reservoir dynamics at the St. Gallen geothermal site (Switzerland), *JGR*, 120 (6), 4301-4316, doi: 10.1002/2014JB011817

3D-ambient noise Rayleigh wave tomography of Snæfellsjökull volcano, Iceland

Anne Obermann¹, Matteo Lupi², Aurélien Mordret³, Steinunn Jakobsdóttir⁴

¹Schweizerischer Erdbebendienst (SED), ETH Zurich, Switzerland

²ETH Zurich, Switzerland

³MIT, Cambridge, USA

⁴University of Iceland, Reykjavík, Iceland

From May to September 2013, 21 seismic stations were deployed around the Snæfellsjökull volcano, Iceland. We cross-correlate the five months of seismic noise and measure the Rayleigh wave group velocity dispersion curves to gain more information about the geological structure of the Snæfellsjökull volcano. In particular, we investigate the occurrence of seismic wave anomalies in the first 6 km of crust. We regionalize the group velocity dispersion curves into 2-D velocity maps between 0.9 and 4.8 s. With a neighborhood algorithm we then locally invert the velocity maps to obtain accurate shear-velocity models down to 6 km depth. Our study highlights three seismic wave anomalies. The deepest, located between approximately 3.3 and 5.5 km depth, is a high velocity anomaly, possibly representing a solidified magma chamber. The second anomaly is also a high velocity anomaly east of the central volcano that starts at the surface and reaches approximately 2.5 km depth. It may represent a gabbroic intrusion or a dense swarm of inclined magmatic sheets (similar to the dike swarms found in the ophiolites), typical of Icelandic volcanic systems. The third anomaly is a low velocity anomaly extending up to 1.5 km depth. This anomaly, located directly below the volcanic edifice, may be interpreted either as a shallow magmatic reservoir (typical of Icelandic central volcanoes), or alternatively as a shallow hydrothermal system developed above the cooling magmatic reservoir.

References:

Obermann, A., Lupi, M., Mordret, A., Jakobsdóttir, S., Miller, S. (2016) 3D-ambient noise Rayleigh wave tomography of Snæfellsjökull volcano, Iceland, *Journal of Volcanology and Geothermal Research*, 317, 42-52, doi: 10.1016/j.jvolgeores.2016.02.013

Probabilistic sensitivity kernels to image lapse time changes

Anne Obermann¹, Thomas Planès², Alejandro Duran¹, Roel Snieder², Céline Hadziioannou³, Michel Campillo⁴

¹Schweizerischer Erdbebendienst (SED), ETH Zürich, Switzerland

²Colorado School of Mines, Colorado, USA

³Ludwig Maximilians Universität, Munich, Germany

⁴ISTerre, Université Joseph Fourier, Grenoble, France

In coda wave interferometry one uses the long wave paths of coda waves to detect minute changes in the velocity. When the relative velocity perturbation is constant in space, it is related to the travel time change dt by $dv/v = -dt/t$. But when the velocity change depends on space, the relation between the measured travel time change and the velocity change is more complicated. It has been shown that in that case the estimation of velocity changes can be formulated as a standard linear inverse problem. The sensitivity kernel that relates the travel time change to the velocity depends on the intensity of the coda waves in space.

There are different ways to compute the sensitivity kernels. The first way to do this, is to model the intensities of the coda waves by solving the diffusion equation for the intensity. This approach presumes that one knows the diffusion constant for a given model of the random medium that generates the wave scattering. In the presence of a free surface--the Earth has a free surface--one also needs to account for the energy carried by surface wave modes compared to the energy of body waves. We used this approach to model the depth sensitivity of coda waves 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.

An alternative is to numerically model the wavefield instead of the intensity, and to compute the intensity from these wavefield simulations. Since for a given realization of a random medium the wavefield has statistical fluctuations, one may have to average the intensity computed for several realization of the random medium. This approach was taken by Kanu and Snieder (2015) who show examples for acoustic media whose statistical properties are not constant in space. We extend this approach to elastic media. We show that we can compute the total intensity as a decomposition in contributions from P- and S-waves and illustrate this with numerical examples.

References:

- Obermann, A., Planès, T., Hadziioannou, C., Campillo, M. (2016) Lapse-time dependent coda wave depth sensitivity to local velocity perturbations in 3-D heterogeneous elastic media, *Geophysical Journal International*, 207, 59-66, doi: 10.1093/gji/ggw264
- Kanu, C. and Snieder, R. (2015) Numerical computation of the sensitivity kernel for monitoring weak changes with multiply scattered acoustic waves. *Geophys. J. Int.*, 203:1923–1936.
- Snieder, R., Duran, A., Obermann, A. Locating velocity changes in elastic media from coda wave interferometry, submitted

What seismic studies reveal about LUSI, a clastic dominated geysering system in Java, Indonesia

Anne Obermann¹, Karyono Karyono^{2,3}, Mohammad Fallahi², Matteo Lupi⁴, Adriano Mazzini²

¹Schweizerischer Erdbebendienst (SED), ETH Zürich, Switzerland

²CEED, University of Oslo, Norway

³Agency for Meteorology, Climatology and Geophysics (BMKG), Jakarta, Indonesia

⁴Department of Earth Sciences, University of Geneva, Switzerland

The spectacular eruption of Lusi began in NE Java, Indonesia, on 29 May 2006 and is still ongoing. Since its birth, Lusi has presented a pulsating activity marked by frequent eruptions of gas, water, mud and clasts. We use data from temporary seismic deployments to study this unique system under different angles:

1) Tremors. Based on visual observations from 2014 to 2015, Lusi's erupting activity is characterised by four recurrent phases: (1) regular bubbling activity; (2) clastic geysering; (3) clastic geysering with mud bursts and intense vapour discharge; (4) quiescent phase. With a temporary network of five seismic stations deployed around the crater, we could identify tremor events related to phases 2 and 3. One of the tremor types shows periodic overtones that we associate with mud wagging in the feeder conduit. On the basis of our observations, we would describe Lusi as a sedimentary-hosted hydrothermal system with clastic-dominated geysering activity.

2) Local seismicity. We study the local seismicity around the spectacular Lusi eruption and the adjacent Arjuno-Welirang volcanic complex. During a period of 17 months, we observed 289 micro-seismic earthquakes with local magnitudes ranging from ML0.5 to ML1.7. The events predominantly nucleate at depths of 8-13 km below the Arjuno-Welirang volcanic complex. Despite the geological evidence of active tectonic deformation and faulting observed at the surface, little to no seismicity is observed in the sedimentary basin hosting Lusi. Although we cannot entirely rule out artifacts due to a significantly increased detection threshold in the sedimentary basin, the deficit in seismicity suggests aseismic deformation beneath Lusi due to the large amount of fluids that may lubricate the fault system. An analysis of focal mechanisms of seven selected events around the Arjuno-Welirang volcanic complex indicate predominantly strike-slip faulting activity in the region SW of Lusi. This type of activity is consistent with the orientation and the movements observed for the Watukosek fault system that extends from the volcanic complex towards the NE of Java. Our results suggest that the tectonic deformation of the region is characterized by scattered faulting, rather than localized along a distinct fault plane.

3) Ambient noise tomography. We use 10 months of ambient seismic noise cross-correlations from 31 temporary seismic stations to obtain a 3D model of shear wave velocity anomalies beneath Lusi, the neighbouring Arjuno-Welirang volcanic complex, and the Watukosek fault system intersecting the two. Our work reveals a hydrothermal plume, rooted at least at 6 km depth that reaches the surface at the Lusi site. Further, the inversion shows that this vertical anomaly is connected with the adjacent volcanic complex through a narrow low velocity corridor slicing the survey area at a depth of ~4-6 km. The NE-SW direction of this elongated zone is matching the strike of the Watukosek fault system. Distinct magmatic chambers are also inferred below the active volcanoes. The obtained large-scale tomography features an exceptional example of a subsurface connection between a volcanic system and a solitary erupting hydrothermal system hosted in a hydrocarbon rich sedimentary basin.

These results are consistent with a scenario where deep-seated fluids (e.g. magmas, released hydrothermal fluids) flow along a region of enhanced transmissivity (i.e. the Watukosek fault system damage zone) from the volcanic arc to the back arc basin where Lusi resides. The triggered metamorphic reactions occurring at depth in the organic-rich sediments generated significant overpressure that is today released at the spectacular Lusi eruption site.

References :

- Karyono, K.*, Obermann, A., Lupi, M., Masturyono, M., Hadi, S., Syafri, I., Abdurrokhim, A., Mazzini, A. Lusi, a clastic dominated geysering system in Indonesia recently explored by surface and subsurface observations, *Terra Nova*, 29 (1), 13-19, doi: 10.1111/ter.12239
- Obermann, A., Karyono, K., Diehl, T., Lupi, M., Mazzini, A. Seismicity at Lusi and the adjacent volcanic complex, Java, Indonesia, submitted to *Marine and Petroleum Geology*
- Fallahi, M., Obermann, A., Lupi, M., Karyono, K., Mazzini, A. The Lusi eruption plumbing system revealed by ambient noise tomography, submitted

Synthesis of tourmaline under upper crustal conditions: a clue to understand processes occurring in both fossil and active geothermal areas

Andrea Orlando, Giovanni Ruggieri, Laura Chiarantini, Giordano Montegrossi, Valentina Rimondi

C.N.R. -I.G.G.-U.O.S. Firenze (Italy)

Fluid – rock interaction experiments are a precious tool to investigate reactions occurring in geothermal areas, integrating information got through thermodynamic modelling. In the framework of IMAGE project, we performed such experiments in order to improve the knowledge of geological processes active in the Larderello geothermal field (Central Italy), in which quartz and tourmaline fragments were ejected at the surface during a deepening of a well approaching a super-hot reservoir. The same minerals are found in veins and masses cutting a biotite rich schist in Mt Calamita (Elba Island), 70 km SW from Larderello. This is not an active geothermal area but it is considered a possible exposed proxy of the deepest part of the Larderello geothermal field. Thus, the investigation of the reactions which led to tourmaline crystallization are crucial to understand reactions currently occurring in the super-hot reservoir. This was done through fluid – rock interaction experiments between a biotite-rich schist (from Mt. Calamita Formation) and B-bearing aqueous fluids (with 20 wt% NaCl or NaCl- free) at 500-600 °C and 100-130 MPa for a duration of 1 week. Experimental products revealed that tourmaline crystallized at the expenses of biotite when H₃BO₃ concentration in fluid is greater than 1.6 M. Furthermore, the chemistry of formed tourmalines depends upon the salinity of the fluid; they are dravitic (Mg-rich) if saline fluid was used in the runs or schorlitic if NaCl free solutions were considered. Complementarily, the fluid chemistry of the fluids after interactions show significant differences that depend on its initial salinity; in particular, saline fluids can transport high Fe contents (up to 2700 ppm) due to the presence of Cl, which acts as complexing agent forming different Fe(II)- and Fe(III)-complexes. This process, besides having played a crucial role in the genesis of Fe deposits in Elba Island, it can nowadays active in the deepest area of Larderello geothermal area. The finding of tourmalines in Larderello geothermal wells can thus reveal the existence of this interaction process interesting mica-rich formations. Moreover, the Mg and Fe contents in this mineral may give precious clues about the salinity of fluids circulating in the deepest part of Larderello geothermal area.

The research leading to these results has received funding from the European Community's Seventh Framework Programme under grant agreement no. 608553 (Project IMAGE).

Practical methods to transfer rock mass fracturing field data to quantifiable values for modelling

Mariane Peter-Borie¹, Chrystel Dezayes¹, Jonathan Siaux², Benoît Valley²

¹BRGM, Orléans, FRANCE

²CHYN, University of Neuchâtel, SWITZERLAND

On the field, numerous data and information on the rock mass can be measured by the geologist, but their conversion to relevant input parameters for numerical models is often not obvious. In particular, discontinuities play a role in the rock mass behavior (mechanical and hydrogeological behaviors), and numerical simulations need to take them into account, either explicitly (for example for hydraulic transport and flow, mechanical and/or thermal modellings of complex zones such as fault zones) using the Discrete Fracture Network approach (DFN), or by homogenizing the medium using continuous approaches. In this presentation, we focus and detail the development of practical methods to transfer field data to quantifiable values for models based on the DFN approach. In DFN models, each discontinuity is explicitly represented with all its geometric (i.e. discontinuity shape, length, orientation...) and physical parameters (hydraulic properties such as aperture, porosity; and/or mechanical properties such as rigidity, friction angle, dilatance; and/or thermal properties such as thermal conductivity). The geometric parameters used to describe discontinuity networks can be deterministic (parameters such as size, center coordinates/spatial position, plan orientation for each discontinuity) and/or stochastic (size distribution, density, and orientation distribution). These parameters can be given for each discontinuity set or for the whole discontinuities with a fractal, poissonian or geostatistical approach.

The key questions are which data must be transferred from field data to quantifiable values for the models, and how they can be transferred. For a long time, it has been well known that the discontinuities properties having the greatest influence on the rock mass behavior are:

- orientation
- size (here size refers to the extension of the discontinuity)
- frequency
- surface geometry
- genetic type
- infill material

Although it is a standard procedure for the geologist to collect such pieces of information, there is still a gap between the descriptive methods of the geologist (whatever the data sources: aerial photographs and satellite images, outcrops, borehole logging...) and the quantitative data required for modeling. In addition, some of these parameters (e.g. size and shape of discontinuities in 3D) are always difficult to quantify on the field, even using new technologies like photogrammetry or laser scan of the outcrops. We present here a methodology to try to fill the gap by applying mathematical methods. Three main themes, corresponding to the three main steps of the workflow, will be developed here: upstream work, data acquisition on field and post-processing. The workflow will be in part illustrated using data collected on an outcrop in the Mesozoic limestones at Éclèpens, Switzerland.

Key situations to lead an optimized and adapted exploration

Mariane Peter-Borie, Arnold Blaisonneau, Sylvie Gentier, Théophile Guillon

BRGM, Orléans, FRANCE

The widespread exploitation of the in-depth heat by EGS (Engineered Geothermal System) techniques requires re-thinking the approaches to move towards an optimized and adapted exploration designed to minimize the “geological” risk. The present-day prospected resources correspond often to deep hydraulic systems more or less continuous, heterogeneous and localized; globally, they show no real geothermal manifestations at surface. In this context, the difficulty is then to identify the most favourable areas before any significant capital investment. In these specific contexts, favourable areas cover the prospected temperature depending on the final use and the initial hydraulic potential to minimize the subsequent potential risks due to the enhancement of the injection/production flow rate of the exploitation wells.

In recent years, the ongoing work on the EGS and on the characterization of the associated potential resource leads us to try to define “key situations”. The goal of these “key situations” is to try to understand how they allow an initial discrimination during the exploration phase to choose the location of the first exploratory drillings. In this context, key situations could be defined as patterns that suggest that there is a resource having sufficient temperature and flow at an economically viable depth (optimization of the depth to reduce the drilling cost). The understanding of the key situations and their interaction will help to develop guides 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).

In a first step, we propose to present known situations, compiled and analysed through literature reviewing. This step allows the identification and the definition of a set of elementary situations and of combined situations. Elementary situations can be related to lithology, structural geology, temperature, fluid content, stress state... In a second step, 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 modelling (mechanical, thermal, hydraulic...) that allow quantitative evaluations of the favourable characteristics and a better understanding as to which parameters or conditions of the key-situations can be used for guiding the exploration phase.

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 third phase, the study of combinations of the different favourable patterns to understand interactions between the key situations.

Seismic imaging and interpretation of basaltic complexes

Sverre Planke^{1,2}, John M. Millett^{1,3}, and Dougal A. Jerram^{2,4}

¹Volcanic Basin Petroleum Research AS, Oslo Science Park, Norway

²Centre for Earth Evolution and Dynamics (CEED), University of Oslo, Norway

³Department of Geology and Petroleum Geology, University of Aberdeen, U.K.

⁴DougalEARTH Ltd., Solihull, U.K.

E-mail: planke@vbpr.no

Basalt and sub-basalt seismic imaging represent a major challenge for the petroleum industry when exploring volcanic basins. Similar challenges are also experienced for seismic imaging of geothermal reservoirs or potential future carbon sequestration sites in basalt terrains. The imaging difficulties are partly related to the very heterogeneous seismic properties of the basalt complexes. Massive basalts and basaltic intrusions have typically P-wave velocities of 6-7 km/s. However, the velocities are much lower in vesicular or fractures basalts, basaltic hyaloclastites, and tuffs, ranging from 2 to 6 km/s. In addition, basaltic rocks are commonly altered to clays and iron hydroxides, further reducing the velocity. Field and borehole observations, wireline logs, and petrophysical data from Iceland and other basaltic terrains are important for understanding the characteristic seismic properties of various volcanic complexes. Vertical seismic profiling data from the Krafla K-18 borehole and boreholes in Eyjafjardar region, northern Iceland, show that seismic waves propagate through basalt sequences and generate reflections from major stratigraphic boundaries. Offshore mid-Norway, new high-quality 3D seismic data reveal major improvement in intra and sub-basalt imaging of Paleogene basalts. Spectacular lava flow fields are identified on the top basalt horizon using the methods of igneous seismic geomorphology. Intra-basalt reflections displays distinctly different seismic facies units, such as prograding Lava Delta and divergent Seaward Dipping Reflections (SDRs) facies units. On recent high-quality data, the base basalt reflection and sub-basalt sequences are also interpreted with confidence. The volcanological interpretation of the extensive offshore seismic database is hampered by the scarcity of boreholes. Integration of results from onshore basaltic provinces, such as Iceland, has led to a new understanding of the nature of the volcanic complexes imaged offshore, and we can confidently identify e.g. subaerial basalt sequences, hyaloclastite deltas, and saucer-shaped sills in the seismic reflection data. In contrast, knowledge from new offshore seismic data are important for understanding lower-quality onshore seismic images, as few high-quality seismic reflection data exist here. We argue that improvements in seismic acquisition and processing technologies developed by the petroleum industry may have an important role to play for future application of seismic data for onshore reservoir imaging and well planning in basaltic terrains.

General stratigraphy, volcanic evolution and geomechanical characterization of Pleistocene hydrothermal-altered rhyolitic lavas of the Acoculco Caldera Complex, central Mexico

Pola, A.,¹ Macias, J.L.², Martínez-Martínez, J.³, Avellán, D.R.,^b Cisneros-Máximo, G.²

¹Escuela Nacional de Estudios Superiores – Unidad Morelia, Universidad Nacional Autónoma de México. Antigua carretera a Pátzcuaro 8701, 58190 Morelia, Michoacán, México

²Instituto de Geofísica, Universidad Nacional Autónoma de México, Unidad Michoacán. Antigua carretera a Pátzcuaro 8701, 58190 Morelia, Michoacán, México

³Instituto Geológico y Minero de España (IGME). Ríos Rosas 23, 28003 Madrid, España.

E-mail: antoniopolavilla@gmail.com, telephone: +52 443 3222777 ext. 42666

General stratigraphy and general geological evolution of the Acoculco Caldera Complex was constructed by assigning the spatial and temporal distribution of each lithostratigraphic unit. Based on the characteristics of the unconformities bounded units (e.g. erosional phases, abrupt change of eruptive styles), together with new and extended radiometric dating, the complex was divided into five different eruptive phases: 1) the pre-caldera eruptive phase, 2) the syn-caldera eruptive phase, 3) the early post-caldera eruptive phase, 4) The late post-caldera eruptive phase, and 5) the final phase or late activity. Particularly, the late post-caldera eruptive phase is part composed by Pleistocene hydrothermal-altered rhyolitic lavas in which we performed a general geomechanical characterization. One of the main purposes of the study is to highlight the interaction between properties: for example the influence of hydrothermal alteration on the strength and deformability were explored by a series of uniaxial compressive tests, while the relationship of the pore system and permeability was explored by mercury porosimeter and by measuring the coefficient of permeability, respectively. Finally, the study also pretend to be part of a database, very useful for the construction of different conceptual models, which in turn, and together with other studies, as geophysical studies will help to identify new zones of geothermal interests.

Geological expression on Flores Island in Indonesia: the transition from oceanic to continental plateau subduction

Ahmad Fauzi Purwandono^{1,2}, Damien Bonté¹, Agung Harijoko², Fred Beekman¹ and Jan Diederik van Wees^{1,3}

¹Utrecht University (NL)

²Universitas Gadjah Mada (IDN)

³TNO Utrecht (NL)

E-mail: a.f.purwandono@uu.nl

The Sunda-Banda Arc, in Indonesia, is part of the plate margin where the Indo-Australian plate is subducted beneath the Eurasian plate. The Flores Island is located at the transition between the Sunda Arc and the Banda Arc. The interest of Flores Island lies in the transition from a subduction of the Indo-Australian oceanic crust to the west to the Australian continental plateau to the east. In this project, we investigate how this transition in the subduction controls the large-scale volcano-tectonic structure and deformation of Flores Island, and how this affects the geothermal resource characteristics and potential. The key objective is to obtain a better understanding of the tectonic setting of Flores Island, and its effects and controls on magmatism. As a result of the transition, the volcanic arc form a linear volcanic segment with the other volcanoes from eastern Java through central part of Flores, while from central part of Flores to the east formed an echelon structures. Geologically, the northwest part of Flores is composed of volcano-sedimentary, and sedimentary tertiary rocks while the southwest and east is dominated by quaternary volcanism. From past investigation, the identified geothermal systems in Flores Island are closely related with the existence of volcanism. There are currently 13 geothermal systems on the Flores Island directly related with volcanic systems, which are associated with faults, post volcanic features, and caldera structures.

Testing vertical seismic profiling (VSP) as a subsurface mapping method at the Krafla volcanic geothermal field in Iceland

Reiser F.¹, Schmelzbach C.¹, Maurer H.¹, Greenhalgh S.^{1,2}, Planke S.³, Hersir, G.P.⁴, Halldórsdóttir S.⁴, Giese R.⁵, Kästner F.⁴.

¹ETH Zurich, Institute of Geophysics, Switzerland

²King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia

³Volcanic Basin Petroleum Research (VBPR), Oslo, Norway

⁴Iceland GeoSurvey (ISOR), Reykjavík, Iceland

⁵GeoForschungsZentrum Potsdam (GFZ), Potsdam, Germany

Geothermal resources play a major role in the energy supplies of Iceland. Geophysical exploration of geothermal fields is important to assess and optimize the exploitation of these natural heat sources. Seismic reflection imaging, which is the geophysical exploration method providing the highest resolution at depth, is challenging in highly heterogeneous volcanic rocks such as found in Iceland due to intense scattering of seismic waves. So far, only a few surface-based seismic reflection surveys have been acquired in Iceland, with essentially all resulting in very little coherent reflections being recorded. Since vertical seismic profiling (VSP) suffers less from absorption of signals in the near-surface zone compared to surface-based seismic surveying and the down-hole receivers are placed closer to the target area, VSP offers means to image structures in the vicinity of a well in complex environments in high resolution. In this study, VSP was tested for mapping volcanic stratigraphy, fractures, dykes, fluid, steam and magma in the geothermal area of Krafla in Iceland.

The VSP survey in Krafla was conducted around two wells, for each of which zero-offset, far-offset and walk-away data were recorded. A standard seismic-reflection processing flow was used to process the zero-offset data to a corridor stack. To obtain structural information away from the borehole, traveltime tomography with the complete dataset was performed. Different inversion parameters (e.g., starting models, damping and smoothing parameters) were tested to assess the robustness of the final seismic velocity models. The resultant velocity model of this primarily data-driven inversion approach is shown in Fig. 1a where the transition between volcanic layering and intrusions is resolved (final RMS misfit of 6.3 ms). As a next step, an initial model was constructed based on an existing borehole-based geological model (Fig. 1b) which included several layers of basalt lava flows and hyaloclastites. We tested whether a geophysical model can be found that explains the traveltime data compared to the model shown in Fig. 1a equally well in terms of RMS misfit but honors the geological constraints. The resultant model shown in Fig. 1c exhibits more fine-scale structures than the primarily data-driven inversion result (Fig. 1a). For the geological interpretation of the geophysical model, the velocity values were assigned to different bins. The bins were defined based on histogram plots and petrophysical information. The resulting composite model in Fig. 1d generally resembles the geological model and shows those small-scale units that are consistent with inverted velocity variations. For comparison, the zero-offset corridor stacks are displayed next to the composite model. The observed reflections correlate overall well with the main lithological boundaries (indicated with the red rectangles).

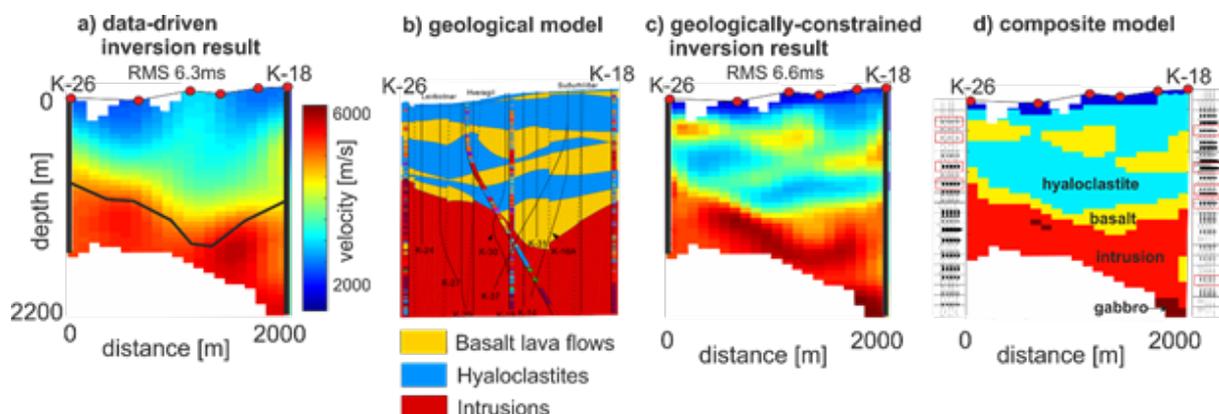


Figure 1: a) Inversion result with little geological constraints. b) Existing geological model. c) Inversion result using a starting model based on the geological model in b). d) Geological interpretation based on the seismic-velocity model in c). The corridor stacks shown to the left and right correlate well with the main lithological boundaries (red rectangles).

Temperature measurement tests in geothermal wells by using synthetic fluid inclusions

Giovanni Ruggieri¹, Andrea Orlando¹, Laura Chiarantini¹, Valentina Rimondi¹, Tobias B. Weisenberger²

¹IGG-CNR, Florence, Italy

²Iceland GeoSurvey (ÍSOR), Reykjavík, Iceland

Super-hot geothermal systems in magmatic areas are a possible target for the future geothermal exploration either for the direct exploitation of fluids or as a potential reservoirs of Enhanced Geothermal Systems. Reservoir temperature (T) measurements are crucial for the assessment of the geothermal resources, however high-T determination (>380°C) in super-hot geothermal systems is difficult or impossible by using either mechanical temperature and pressure gauges (Kuster device) and electronic devices. A method based on the production of synthetic fluid inclusions (F.I.), by using stainless steel micro-reactors to be placed to in geothermal wells, was elaborated during IMAGE project for high-T reservoirs. Laboratory experiments demonstrated that synthetic F.I. form within a relatively short time (even in 48 hours) and that their trapping T gives a good estimate of experimental T. After these encouraging results, in-hole experiments has been carried out in two geothermal wells of Iceland and Italy.

The micro-reactors used for in-hole experiments hosted gold capsules which contained: i) pre-fractured quartz fragments in which synthetic F.I. will be trapped, ii) the solution that will be trapped in synthetic F.I. (an aqueous solution with 9.1 wt.% NaCl and 0.4 wt.% NaOH), and iii) powdered silica. The micro-reactors were partially filled with an amount of distilled water such that the P-T conditions in the micro-reactors will follow the liquid-vapor curve of H₂O and critical isochore of H₂O above the critical point of H₂O.

In the KJ-35 geothermal well of the Krafla geothermal field (North Iceland) bore-hole test was performed by lowering two micro-reactors, inserted in a bigger stainless steel tube, at about 1750 m below the ground level. T around 336°C was measured by ÍSOR in KJ-35 well at 1750 m depth by conventional method a few weeks before the experiment. The micro-reactors were left for about 69 h in the well. In the Lumiera 1 well of the Larderello geothermal field (Tuscany, Italy) one micro-reactor, inserted in a stainless steel tube, was lowered at a depth of about 920 m and left for about 168 h. T around 249°C was measured by ENEL-GreenPower at the depth of the test few days before the experiments by conventional method.

Synthetic F.I. formed in all quartz chips recovered from the gold capsules of both test sites. Homogenization T of newly formed synthetic F.I. formed in KJ-35 well varies from 338 to 342°C. Trapping T ($341 \pm 2^\circ\text{C}$), computed by the intersections between isochores of synthetic F.I. and the liquid-vapour curve of water, are rather close to the measured T (336°C). Synthetic F.I. formed in the Larderello test site showed homogenization T between about 250 and 252°C. Calculated trapping T ($251 \pm 1^\circ\text{C}$) is nearly equal to the homogenization T and almost match the measured T (249°C).

In conclusions, F.I. successfully synthesized in geothermal wells both at Krafla and Larderello. T gives a rather accurate estimate of wells T, indicating that the proposed method is highly valuable for estimating T in geothermal wells. The Larderello test showed that the method also worked at "relatively low-T". Moreover, F.I. synthesized by using the micro-reactor can be potentially applied for temperature measurements of geothermal well with temperature up to 424°C (i.e. the working temperature limit of the utilized commercial micro-reactor). At high T, fluid inclusions forms quickly, so the time necessary to keep the micro-reactor into the wells should be lower.

The research leading to these results has received funding from the European Community's Seventh Framework Programme under grant agreement no. 608553 (Project IMAGE).

Deep exploration of the Larderello geothermal field (Italy) by means of electromagnetic methods: integrated models and inversion

Alessandro Santilano¹, Adele Manzella¹, Alberto Godio², Serena Botteghi¹, Enrico Calvi¹, Assunta Donato¹, Gianluca Gola¹,

Giordano Montegrossi¹, Sandra Trifirò¹, Eugenio Trumpy¹, Enzo Rizzo³

¹CNR-IGG (Italy), ²Politecnico di Torino (Italy), ³CNR-IMAA (Italy)

The intrinsic complexity of geothermal systems and the need of an accurate integration of the geophysical parameters with the geological properties of the systems still represent a challenge of the exploration geophysics. In such a scenario, we focused our research on the Larderello- geothermal field (Tuscany, Italy), to relate the results of electromagnetic (EM) surveys with an integrated modelling of the geothermal system. To this aim in 2016 we acquired new magnetotelluric (MT) and Time Domain EM (TDEM) data. These data integrate the MT datasets previously acquired in adjacent areas, in the frame of other exploration and scientific projects.

The main target of our research has been the improvement of the knowledge of the deep structures of Larderello field, with a focus on the Lago Boracifero area which is its hottest sector. In particular, we were interested in understanding the heat source of the system (shallow magmatic intrusions), the tectonics and its relation with the hydrothermal circulation.

The focus of our study has been the integrated modelling. To improve the reliability of the 2D MT inversion models we performed an integrated approach, by using external information from an integrated 3D model of the field as well as an innovative probabilistic analysis of the MT data. The external data integration implied the organization of a large quantity of geological and geophysical data, such as wells and seismic data, in Petrel (Schlumberger) environment.

We treated the 1D magnetotelluric inverse problem with a probabilistic approach, by adopting the Particle Swarm Optimization (PSO), a heuristic method based on the concept of the adaptive behavior to solve complex problems. We tested this approach on theoretical and measured MT data, and results were promising, also for the possibility to implement different schemes of constrained as well as joint optimization (e.g. MT and TDEM). The 1D models were then interpolated along main profiles to obtain pseudo-2D models, which have been used as a-priori models for 2D MT data inversions.

2D MT data inversion modeling was then carried out along chosen profiles using various input as a-priori information: a) homogeneous half spaces, b) geological information from the integrated 3D model; c) the surface-hole deep electrical resistivity tomography (SHDERT, see Rizzo et al. 2017, in this same volume); d) the pseudo-2D resistivity models from interpolated 1D PSO models. The integrated analysis improved our understanding of the deep structures of the geothermal system of Larderello, with a relevant impact on the conceptual geothermal model.

In Micaschist and Gneiss complexes we observed a generally high electrical resistivity response, locally interrupted by low resistivity anomalies that are well correlated with the most productive sectors of the field. A still partial melted igneous intrusion beneath the Lago Boracifero sector was detected based on the interpretation of the low resistivity anomalies located at a mid-crustal level (>6 km). New insights on the tectonics are proposed in this research. The fundamental role of a large tectonic structure, i.e. the Cornia Fault, located along the homonymous river, was highlighted. This fault played an important role in the geothermal evolution of the Lago Boracifero sector, possibly favoring both the hydrothermal circulation and the emplacement of magma bodies.

Acknowledgements: The research has received funding from the EC Seventh Framework Programme under grant agreement No. 608553 (Project IMAGE). A part of the study was carried out in the frame of a PhD program at the Politecnico di Torino, Italy.

Real-time seismic monitoring of operational changes at the Hellisheiði geothermal power plant

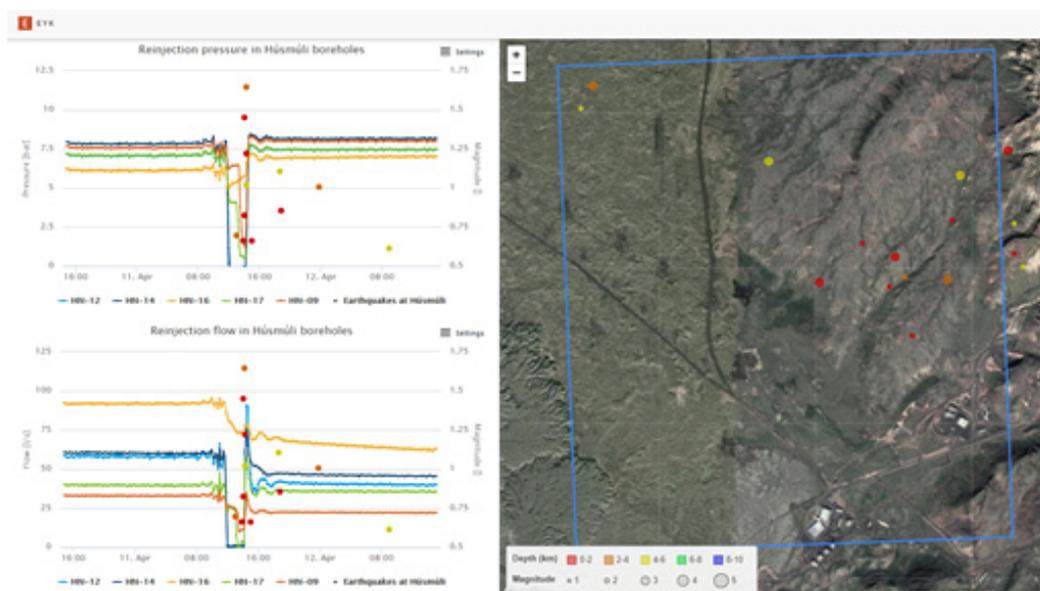
Bergur Sigfússon

Reykjavik Energy, Iceland

Reykjavik Energy operates the Hellisheiði co-generation power plant with an installed capacity of 303 MWe and 133 MWth. The powerplant is located on the South-Western flanks of the Hengill central volcano. The spent geothermal fluids from the power plant are re-injected into the reservoir through 15–20 re-injection wells at a combined rate of approximately 800–900 l/s. The re-injection zones are located in a variable tectonic setting and have responded differently to the re-injection during the last 11 years of operation.

Complementing the national seismic network in Iceland, 6 seismic monitoring stations were installed near the re-injection zones of the power plant. The new seismic network enables real-time observation of earthquakes occurring near re-injection wells during operation. Furthermore, it provides a validation opportunity of the procedures established by Reykjavik Energy to minimize induced seismicity.

Since the seismic network was established in September 2017, a few large disturbances have been experienced in the national power grid resulting in unexpected shutdown of parts of the Hellisheiði powerplant. These disturbances can lead to very rapid changes in re-injection rates resulting in notable pressure changes in the adjacent reservoirs. This contribution shows examples of observed earthquakes following some of these events. Figure 1 shows observed seismicity during an interruption and restoration to normal flows of re-injection waters over a 48 h period in April 2017.



Observed seismicity during an interruption and restoration to normal flows of Hellisheiði re-injection waters over a 48 h period in April 2017.

It is anticipated the operation of the seismic network will become integral part of the daily monitoring of the power plant. Furthermore, it is anticipated that the data series from the seismic network will be used to better characterise the Hellisheiði geothermal reservoir for the future resource utilization.

Geodetic imaging of changes in geothermal reservoirs and magma transfer: Towards improved modeling of volcanic and geothermal processes

Freysteinn Sigmundsson¹, Vincent Drouin¹, Michelle Parks^{1,2}, Siqi Li¹, Sigrún Hreinsdóttir³, Halldór Geirsson¹, Þóra Árnadóttir¹,
Daniel Juncu¹, Andy Hooper⁴, Benedikt G. Ófeigsson², and Ingvar Þór Magnússon⁵

¹Nordic Volcanological Center, Institute of Earth Sciences, University of Iceland

²Icelandic Meteorological Office, Reykjavík, Iceland

³GNS Science, New Zealand

⁴COMET, School of Earth and Environment, University of Leeds

⁵ÍSOR - Iceland GeoSurvey, Reykjavík, Iceland

New satellite acquisitions, and extensive backlog, of synthetic aperture radar (SAR) images over Icelandic geothermal areas in volcanic regions allows detailed time series analysis of ground deformation through InSAR, interferometric analysis of SAR images. Such studies can be combined with other available geodetic measurements including GNSS measurements (Global Navigation and Satellite System, primarily GPS in the past) and leveling, in order to achieve both high spatial and temporal resolution of ground deformation. Such studies have been carried out over a number of the geothermal areas in Iceland, including Krafla, Bjarnarflag, Peistareykir, Reykjanes, Krísuvík, Hengill, Torfajökull and Askja. Overview of measurements and results will be presented. In addition to pressure changes in geothermal reservoir causing ground deformation, we explore the possibility that gradual cooling of host rock may be responsible for steady deformation observed in geothermal areas over years or decades during periods of relatively stable pressure conditions. This has e.g. been suggested as a cause for deformation at the Krafla geothermal area (Drouin et al., 2017), as there measured pressure change is insignificant but gradual cooling of about 0.5°C/yr has been observed in a monitoring well. Such minor cooling, if affecting a crustal volume corresponding to a sphere with radius 1.5 km, approximating a geothermal reservoir, could fully explain the observed present subsidence of ~5 mm/yr at Krafla, inferred to be related to geothermal processes and utilization.

Reference:

Drouin, V., Sigmundsson, F., Verhagen, S., Ófeigsson, B. G., Spaans, K., Hreinsdóttir, S. (2017), Deformation at Krafla and Bjarnarflag geothermal areas, Northern Volcanic Zone of Iceland, 1993–2015, *J. Volc. Geotherm. Res.*, Online.

Brief over view of the Icelandic deep drilling RN-15/IDDP-2 at Reykjanes, Iceland

Omar Sigurdsson, Gudmundur O. Fridleifsson, Ari Stefansson, Þor Gislason

HS-Orka, Iceland

Drilling operations for deepening well RN-15 at the Reykjanes field began 11th August 2016. The 2.5 km deep production well RN-15 was quenched and cooled down in the preparation for deepening to 5 km as Phase 2 of the Iceland Deep Drilling Project (IDDP). The IDDP aim is to attempt to sample and produce high temperature geothermal fluids from supercritical pressure-temperature conditions with the goal of using it for energy production. Furthermore, the aim was to investigate the deep roots of the overlying geothermal system. Deep injection of fluid may be necessary to create a permeable EGS system for that purpose. The Reykjanes Geothermal Field is recharged by seawater and is a geochemical analogue to seafloor "black smoker" that are found on the World's Ocean Ridges.

Well RN-15 was drilled vertically in 2004 to 2507m depth with 13 3/8" production casing set to 794 m and a 12 1/4" open hole below. The main feed zone was at approximately 2400m with formation temperature of ~290°C. The well supplied some 2-3 MWe to the Reykjanes power plant. The hole is located north of the main upflow zone of Reykjanes field so a slightly deviated drill hole should intersect the zone at target depth of 5000m. The Bentec Euro Rig 350, Þór, operated by Iceland Drilling Company (IDC) was on site in July. The well was cooled and logged in preparation for deepening to 3000m before casing with 9 7/8" and 9 5/8" casings. Total circulation loss in the hole during drilling prevented return of drill cuttings to the surface. The well was deviated in the direction 210° at a kick off depth at 2750m with the intention of building inclination to 16° from vertical. Depth of 3000m was reached on August 22nd. Casing was run to 2941.4m along with thermocouple cables and a fiberoptic cable attached to the outside of the casing to measure temperatures at various depths. Use of such cables outside casing is quite new in Iceland. The casing was cemented to surface with reverse cementing method completed on Sept. 6th.

Drilling continued with downhole motor, MWD tool and an 8 1/2" bit. Circulation losses quickly increased to total losses in the first 200 m interval below the casing. About 12 cement plugs were set in an attempt to cure the losses with limited results. At 3185 m a decision was taken to continue drilling in total circulation losses as deep as possible. The well was drilled to 4626 m and a 7" perforated liner was set to 4600 m as well as a sacrificial 7" casing to 1304 m and cemented to surface. A T/P log measured after setting the liner on Jan. 3rd gave 426°C and 340 bar at 4560 m depth which is above the critical point for seawater. A total of 13 coring runs were made that gave in average about 51% return. For the last cores the well was drilled with 6" bits to 4659 m. Geophysical logs were obtained by special tripping with LWD tools to 4623 m.

At end of drilling short stimulation with thermal cycling and pressurization was carried out that increased the indicated injectivity to about 3 L/s per bar. The drilling operation was completed on January 25th, 2017 by installing a 3 1/2" pipe to about 4590 m depth for further stimulation. Since then the well has been cooled and short thermal cycles carried out where the well temperature has been oscillated by 200-250°C. Fluid blocking material has also been used to divert the cool injection to the lesser permeable zones.

Currently, preparation for hydraulic fracturing in the interval below 4630 m is being carried out. Then plans are to cool the deep formation further by fresh water injection till autumn 2017.

The Characteristic of Sumatran Geothermal Systems from Geological Perspective

Lukman Sutrisno¹, Damien Bonte¹, Yunus Daud², Fred Beekman¹, Jan Diederik van Wees^{1,3}

¹Utrecht University

²Universitas Indonesia

³TNO

E-mail: l.sutrisno@uu.nl

The current producing fields and proven geothermal resources on Sumatra (Indonesia) are associated with convective systems, classified as (i) magmatic/plutonic plays and/or (ii) extensional plays, according to the scheme by Moeck and Beardsmore (2014). These two end members are controlled by the interplay between major strike-slip faulting, Sumatran Fault (Sieh and Natawidjaja, 2000), Quaternary volcanism occurring along the fault corridor, and the pre-existing basement fabric and composition. In this project, we investigate the potential of these 2 convective play types as well as another geothermal play type, (iii) conductive system, which has not yet been assessed properly for Sumatra. We will characterise Sumatra's geothermal resource potential through a regional tectonic-based approach.

First results show that the structural trends do not always have NW-SE orientation, parallel to the Sumatran Fault System, but are rather determined by the distance to the fault corridor, local structural setting, and basement configuration. The pre-existing basement configuration controls the permeability distribution and the thickness of more porous Quaternary volcanic rock, and therefore defines potential convection pathways and lateral field extensions. The geothermal systems within or close to the main Sumatra fault corridor are strongly affected by the dynamics of volcano-tectonic processes, indicated by an elongated resistivity structure. The systems further away from the fault corridor are less affected by the faulting, and tend to have a resistivity doming structure commonly observed in volcanic-related hydrothermal systems. Active deformation is responsible for the influx of cold meteoric-water into the system which is indicated by the alteration mineralogy and fluid chemistry. Another distinctive feature is that surface thermal manifestations are located close or above the system' margins, rather than on top of the centre of the system.

Topography, faults, and lithology control the non-magmatic hydrothermal system of the Têt Valley, Eastern Pyrénées (France)

Taillefer A.¹, Soliva R.¹, Guillou-Frottier L.², Le Goff E.³, Ladouche B.³, Lopez S.², Courrioux G.², Millot R.²

¹Géosciences Montpellier, Université Montpellier (France)

²BRGM, Orléans (France)

³BRGM, Montpellier (France)

E-mail: audrey.taillefer@gmail.com

Although non-magmatic hydrothermal systems in mountain ranges likely involve similar processes than those highlighted for other hydro-geothermal continental systems, questions remain about : 1) the water origin and the structures responsible for efficient infiltrations, 2) the geometry and amplitude of the thermal anomalies and subsequent rock-fluid interactions in the deep transfer zone, 3) the type of pathways from depth to the hot springs, and the conservation of the draining capacity.

In Eastern Pyrénées (France), the alignment of 39 hot springs (29-73°C) along the brittle Têt fault and its related high topography allows studying these processes. The integrative analysis of remote sensing, multi-scale geological field observations and the fluid geochemistry, provides strong constraints for establish a realistic 3D numerical model coupling heat transfers with fluid flows. From the infiltration areas to the springs, we show that :

1. The hydrothermal fluids have a meteoric origin and infiltrate in high altitude (around 2000 m). They require efficient structures to transfer fluids through the crust to the hot springs. Three intersecting fracture sets, resulting from three consecutive tectonic stages, pervasively distribute on the infiltration areas.
2. Ionic composition of hydrothermal fluids indicates similar rock-water interactions for the whole springs, suggesting a common transfer zone. In numerical models, flow lines come from high reliefs in the fault footwall, or circulate along it. The proportion of springs supplying fluid flows coming from the basement and/or the fault depends on the permeability ratio of these two compartments. Variations of deep temperatures measured by geothermometry correlates with variations of hot spring temperatures. The highest temperatures locate where the scarp and the mean topography profile of the fault footwall are the highest, and decrease away from it.
3. Hot springs mostly locate in the Têt fault footwall, at the base of the most elevated topography, close to the fault. They always localize in crystalline rocks, at the contact with metasediments, related to unfaulted or faulted contacts by brittle or old ductile faults. Hot spring locations also match with intersections of brittle fault-damage zones. Differences of temperature between hot springs in a same cluster are not linked to melting with superficial water, suggesting multiple pathways deriving from a single thermal anomaly.

Seismic network survey design and performance

Toledo T.¹, Jousset P.¹, Krawczyk C.¹, Maurer H.²

¹GFZ German Research Center for Geosciences

²Swiss Federal Institute of Technology, Zürich, Switzerland

Local seismic network deployment and monitoring are a common practice among several applied areas such as oil, gas, and geothermal energy production, and underground storage to identify and mitigate induced seismicity. Although considerable effort is dedicated to the development of standardized data-acquisition and inversion techniques, seldom a times is an adequate survey design analysis performed previous to deployment. However the success of a microseismicity study and an accurate structural interpretation relies on well constrained event locations.

The experimental design (ED) technique hereby used has been successfully implemented in electromagnetic problems, geoelectrics, seismic crosshole applications, near-surface full waveform inversion 2D profiles, and optimal aftershock recordings. It consists of searching for optimal locations that minimize a cost function related to the condition number of the inverse problem. The overall aim is to better constrain a set of expected earthquake targets with a fixed number of stations. Thus, we used the developed ED algorithm to design a seismic network for a Mexican (Los Humeros) and an Icelandic (Theistareykir) geothermal fields. On a similar tone, the same principles were used to qualify the Reykjanes network performance as a function of number of stations and additionally obtain hypothetical event accuracies throughout the domain.

Influence of the geothermal fluid rheology in the large scale hydro-thermal circulation in Soultz-sous-Forêts reservoir, France

B Vallier¹, V Magnenet², C Fond², J Schmittbuhl¹

¹EOST, Université de Strasbourg / CNRS, 5 rue René Descartes, Strasbourg, FRANCE

²ICUBE, Université de Strasbourg / CNRS, 72 Route du Rhin, Illkirch, FRANCE

Many numerical models have been developed in deep geothermal reservoir engineering to interpret field measurements of the natural hydro-thermal circulations or to predict exploitation scenarios. They typically aim at analyzing the Thermo-Hydro-Mechanical and Chemical (THMC) coupling including complex rheologies of the rock matrix like thermo-poro-elasticity and the influence of large geological structure like the sedimentary cover/basement transition or the large regional faults. Few approaches address in details the role of the fluid rheology and more specifically the non-linear sensitivity of the brine rheology with temperature and pressure. Here we use the finite element Code_Aster to solve the balance equations of a 2D THM model of the Soultz-sous-Forêts reservoir in order to invert both the temperature and stress profiles with depth. The brine properties are assumed to depend on the fluid pressure and the temperature as in Magnenet et al. (2014). A sensitive parameter is the viscosity of the brine that is assumed to depend exponentially with temperature. The rock matrix is homogenized at large scale assuming the representative elementary volume of the fractured medium to be 100m large with a little influence of the details of the local fault network. We introduced four main geological units (two for the sedimentary cover and two for the granitic basement) to adjust the rock physic parameters at large scale: thermal conductivity, permeability, radioactive source production rate, elastic and Biot parameters. We obtain a new family of solutions with a large hydro-thermal convection for which the cover-basement transition has a weak influence leading to a significant hydro-thermal flow close to the surface and a significant lateral variability. Interestingly, the geothermal gradient in the sedimentary layer is weakly influenced by the radioactive production rate in the upper altered granite. Our study provides new insights on the origin of the heat anomaly in Soultz-sous-Forêts with a strong geothermal gradient close to the surface related to a thermal boundary layer.

Magnenet V., Fond C., Genter A. and Schmittbuhl J.: two-dimensional THM modelling of the large-scale natural hydrothermal circulation at Soultz-sous-Forêts, *Geothermal Energy*, (2014), 2, 1-17.

Novel noise based seismic acquisition and processing techniques, de-risking geothermal exploration and monitoring

Vincent Vandeweyer¹, Arie Verdel¹, Stefan Carpentier¹, Dirk van Haeringen², Sjeef Meekes¹, Bob Paap¹

¹TNO, Utrecht, The Netherlands

²Utrecht University, Utrecht, The Netherlands

The objective of this study was to build, test and validate the capability of ambient noise seismic interferometry (ANSI) to contribute to image resolution in a sedimentary environment. This can be of use in, but is not limited to, both geothermal exploration and monitoring. Currently seismic exploration typically makes use of signals originating from carefully designed and constructed seismic sources. If comparable results can be accomplished without the requirement of complex man-made sources, but rather by relying on (ambient) seismic noise from the earth, pre-drill risks can be lowered at significantly reduced costs. But also if the resolution of a seismic image can be increased by combining active seismic with processed ambient noise recordings, promising opportunities for applying passive seismic recording occur.

During this study auto-correlations of ambient seismic noise are used to image deep reflecting layers by producing a zero-offset seismic reflection profile. The resulting reflectors have been successfully linked to vintage active seismic data. The ambient seismic noise data is also combined with recently shot (basic hammer blow) active data in order to study the spectral properties of the combination.

Also, near-surface shear wave velocity profiles have been created from ambient seismic noise. This involved cross-correlation of ambient seismic noise to create virtual source gathers. Dispersion curves were generated from surface waves present in these virtual source gathers and inverted using a neighbourhood algorithm. The resulting shear wave velocity-depth profiles were then successfully linked to formation transition depths from borehole data.

During this study we have been successful in finding efficient methods for imaging both deep reflecting layers and determining near-surface shear wave velocity profiles, solely from ambient seismic noise recorded with a single seismic geophone array and by combining ANSI with conventional active seismic data.

The research leading to these results has received funding from the European Community's Seventh Framework Programme under grant agreement No. 608553 (Project IMAGE).

Passive seismic reflection interferometry at Reykjanes peninsula, SW Iceland

Arie Verdel¹, Harry Wedemeijer¹, Bob Paap¹, Vincent Vandeweijer¹, Joana Esteves Martins¹, Cornelis Weemstra², Philippe Jousset³, Steven Franke³, Hanna Blanck⁴, Kristján Ágústsson⁴, Gylfi Páll Hersir⁴

¹TNO, Utrecht, The Netherlands

²Delft University of Technology, Delft, The Netherlands

³GFZ, Potsdam, Germany

⁴ÍSOR, Reykjavik, Iceland

We present results from the application of seismic interferometry to passive data recorded on Iceland's Reykjanes peninsula. Specifically, ambient noise seismic interferometry (ANSI) is applied to recover reflectivities in the subsurface for the purpose of imaging geothermal reservoirs. The objective of this study is the retrieval of reflected body waves (P-waves) that provide velocity-versus-depth as well as subsurface structural information.

We show, for a subset of the onshore seismometers, that reflection information is present in the frequency bandwidth 3-8 Hz. We have observed both time-lapse variations where we expect them and time-invariant results where we expect to see no temporal changes.

As we lacked availability of active seismic reflection and sonic logging data that could serve as reference, we discovered, in our search to find a truly independent means for checking the reflection information quality of our ANSI results, that the coda of a global seismic P-wave, that is created by scattering in the crust, shows quite good correspondence with the 40-days ANSI results, whereas random noise correlation results, using the same amount of data as the coda response, shows less resemblance. But then, the ANSI-derived reflectivity estimates in turn suggest that P-wave crustal scattering information from global seismic waves is present in the frequency-range of 3–8 Hz, which is extremely high for global seismic waves. The latter aspect may open up a large range of opportunities for detailed crustal research at any location on the globe where broadband, and even short-period, seismometers are installed.

The research leading to these results has received funding from the European Community's Seventh Framework Programme under grant agreement No. 608553 (Project IMAGE).

Imaging and structural analysis of the Geysir field, Iceland, from underwater and drone based photogrammetry

Thomas R. Walter¹, Philippe Jousset¹, Massoud Allahbakshi¹, Tanja Witt¹, Magnus T. Gudmundsson², Gylfi Pall Hersir³

¹GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany

²University of Iceland, Reykjavík, Iceland

³ÍSOR- Iceland GeoSurvey, Reykjavík, Iceland

The effects of the geological structure on geysers are of importance for understanding their distribution, appearance and activity. To better understand the tectonic coupling and hydrothermal activity at the Geysir geothermal field, a detailed analysis of the spatial distribution of the thermal expressions, and their relationship to the tectonic framework was carried out. By use of high resolution unmanned aerial vehicle (UAV) based optical and radiometric infrared cameras, we are able to identify 364 distinct thermal spots distributed over the area. Close analysis of their arrangement yields a clustered appearance, following a preferred direction that is found to be consistent with the assumed tectonic trend in the area. Furthermore by using underwater cameras we are able to obtain for the first time detailed images from the two largest geysers at depths exceeding 20 m. Near to the surface, the conduit of the geysers are near circular, but at a depth of 9-12 m the shape changes into a crack-like elongated fissure. The elongation direction of these deep cracks is consistent with the identified thermal expression at the surface, highlighting a structural or even tectonic control at the Geysir geothermal field, which may also explain the susceptibility for seismically triggered activity changes.

Continuous MT monitoring: Resistivity variations related to the large March 9, 1998 eruption at La Fournaise Volcano

Pierre Wawrzyniak¹, Jacques Zlotnicki², Pascal Sailhac³, Guy Marquis⁴

¹Bureau des Recherches Géologiques et Minières, 3 av ; Claude Guillemin, BP 36009, 45060 Orléans 7 Cedex2, France

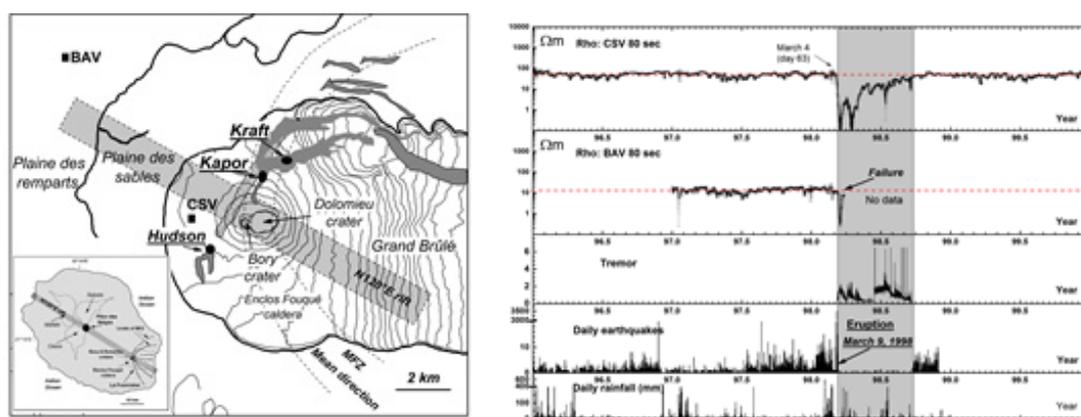
²CNRS, UMR6524-OPGC-UPB, avenue des Landais, BP80026, 63177 Aubière Cedex

³GEOPS, CNRS-UMR 8148, Université Paris Sud, Orsay, France

⁴France IPGS, CNRS-UMR7516, Université de Strasbourg, France

This work has not been performed in the framework of the IMAGE project but concerns important monitoring issue that could be transferred to Geothermal monitoring topics. The 2645 m-high La Fournaise volcano, located in the Southwest of Réunion Island (Indian Ocean), is a shield basaltic volcano where effusive eruptions generally occur along long fissures starting from the summit, alongside major fractures that characterize the eruptions' dynamism and effusivity. Between 1992 and 1998, the volcano underwent a quiet period during which few earthquakes were recorded. Minor seismic activity returned after 1997 and picked up in March 1998 during the 35 hours preceding the March 9 eruption. From 1996, two autonomous stations (CSV and BAV) were installed on the volcano. CSV was located inside the Enclos Fouqué caldera while BAV was positioned 8.2 km NW of the volcano summit. Horizontal components of the electric and magnetic fields were sampled every 20seconds. Continuous time-series were available from 1996 to 1999 at CSV, and from 1997 to March 1998 at BAV.

Data have been processed using both single-station and remote-reference processing. Both results show apparent resistivity variations synchronous to the eruption. Time-lapse impedance estimates are computed on overlapping time windows of about two days at both stations. They show that the only time interval between 1996 and 1999 undergoing a decrease of the observed impedance coincides with the March 1998 eruption. At CSV, the resistivity started to drop about five days before the eruption, reached several local minima until April, and then slowly increased as the volcanic crisis reduced in activity. After the end of the crisis in September 1998, the apparent resistivity recovered its pre-crisis value. The time-lapse results also show variability in directionality: sharp and elongated phase tensor ellipse residuals also appear during the eruption with a N105° orientation, suggesting the emergence of an almost NS-striking dyke. A simple 1D reference model built from MT soundings performed during the quiet period (1996 to February 1998) and including a 3D NS-striking dyke shows a good agreement with the spatial distribution of the resistivity variations observed during the eruption.



Left Figure: Sketch of La Fournaise volcano. BAV and CSV are the electromagnetic stations. Lava flows emitted by Krafft, Kapor, and Hudson cones are in dark grey color. Dash lines represent the Main Fracture Zone along which most of fissure eruptions occur. The grey rectangle illustrates the regional N120°E volcanic and fissural axis. Grey cross-pattern corresponds to the trace of main earthquakes associated with the March 9, 1998 crisis. **Right Figure:** From top to bottom. Determinant of the resistivity values at CSV and BAV for the 80 second period computed by single MT method between 1996 and the end of 1999. Tremor activity and daily number of earthquakes. Daily rainfall.

MT and CSEM data robust processing techniques. New developments

WAWRZYNIAK Pierre, SMAI Farid, COPPO Nicolas, DARNET Mathieu, BRETAUDEAU François

BRGM, France

A Python based library for MT and CSEM robust processing has been developed at the BRGM. It is named Razorback and is planned to be distributed as open source. In the framework of the IMAGE project, we tested some of razorback robust processing techniques such as weighted least square, M-estimator and bounded influence processing on CSEM data acquired on the eastern side of Strasbourg city (France) during WP8.2 exploration campaign. We discuss the improvement observed on CSEM data quality when processed with robust methods.

Multiple Remote Reference MT bounded influence processing has also been performed using distant (>30km away) and close (<5 km) reference stations. Razorback allows comparing processing results associated to any possible combination of a set of reference station. In addition, during a two day long MT sounding, a CSEM source has been activated for current injection tests, contaminating the data set with a controlled anthropic source. We will show how the robust processing deals with this noise.

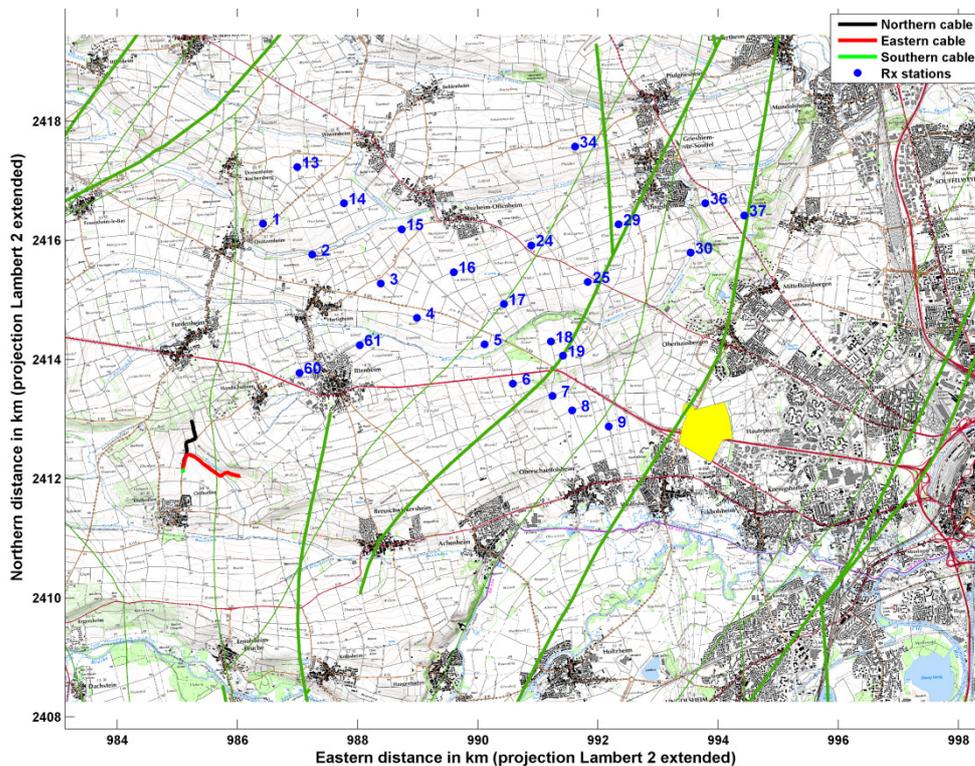


Figure: Map of the Strasbourg Region survey. Large green lines show the major accidents of the region. The yellow area represents Fonroche prospect area for the building of a geothermal doublet. The source cables for Tx dipoles are shown in black red and green. Receiver positions are blue points.

Validation of the Influence of Cation-exchange Capacity on Resistivity Logs within Hydrothermal Systems

Tobias Björn Weisenberger, Heimir Ingimarsson, Gylfi Páll Hersir and Ólafur G. Flóvenz

Iceland GeoSurvey (ÍSOR), Grensásvegur 9, 108 Reykjavik, Iceland

E-mail: tobias.b.weisenberger@isor.is

This research study describes measurements of the effect of the cation-exchange capacity (CEC) on resistivity of rocks in geothermal systems. Four wells in high-temperature geothermal fields in Iceland have been selected for this study, well KJ-18 (Figure 1) in the Krafla geothermal field (NE-Iceland), wells HE-42 and HE-46 in the Hellisheiði geothermal field (SW-Iceland), and well RN-15 in the Reykjanes geothermal field (SW-Iceland). Results of CEC measurements of cutting samples in all four wells show that the low resistivity in the electrical resistivity logs coincide with high CEC values (> 5 meq/100 g). At the facies boundary between the mixed-layer clay and epidote-chlorite zone the CEC drops below ~ 5 meq/100 g and decreases slowly with increasing depth. The facies boundary overlaps with the transition where resistivity logs shows an increase in resistivity. In addition, CEC was also measured in 7 core samples from different alteration zones that had previously been studied in details with respect to petrophysical and conductivity properties. The results show that the sample conductivity does not show a simple relationship with the measured CEC. However, there is a clear correlation between CEC and the iso-electrical point which describes the value of the pore fluid conductivity where transition from surface conductivity to pore fluid conductivity occurs.

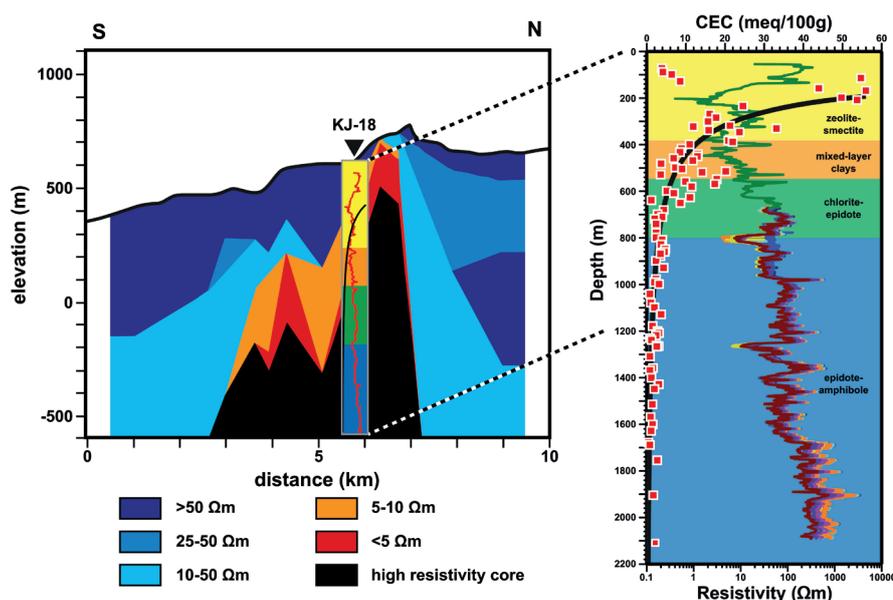


Figure 1. North-south profile of the subsurface resistivity structure of the Krafla high-temperature geothermal system, NE-Iceland (left figure). The location of well KJ-18 is given including the resistivity logs and the trendline for the CEC results. The more detailed log profile of well KJ-18 is given to the right.

The research leading to these results has received funding from the European Community's Seventh Framework Programme under grant agreement No. 608553 (Project IMAGE).

Crustal Stress Pattern of Iceland

Moritz Ziegler^{1,2}, Mojtaba Rajabi³, Oliver Heidbach¹, Gylfi Páll Hersir⁴, Kristján Ágústsson⁴, Sigurveig Árnadóttir⁴ and Arno Zang^{1,2}

¹Helmholtz Centre Potsdam, German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany

²University of Potsdam, Institute of Earth and Environmental Science, Karl-Liebknecht-Str. 24-25, 14476 Potsdam-Golm, Germany

³Australian School of Petroleum, The University of Adelaide, Adelaide, SA 5005, Australia

⁴Iceland GeoSurvey (ÍSOR), Grensásvegur 9, 108 Reykjavík, Iceland

Iceland is one of the few places on earth where an active spreading can be observed onshore, yet the contemporary crustal stress state has not been investigated intensively. We compiled the first comprehensive stress map of Iceland from different stress indicators and analysed data from 57 geothermal boreholes. In total we interpreted approx. 37 km of acoustic image logs for stress indicators, i.e. borehole breakouts and drilling induced tensile fractures. Furthermore, we revised the 38 data records for Iceland from the World Stress Map 2008 and conducted an extensive literature research to compile all available focal mechanism solutions and geological stress indicators.

The new stress compilation consists of 495 data records for the orientation of the maximum horizontal stress (S^{Hmax}) in and around Iceland with 318 data records of A-D qualities according to the World Stress Map quality ranking scheme (Fig. 1). Most of the data records are derived from focal mechanism solutions (35%) and geological fault inversions (26%). Borehole related indicators (breakouts, drilling induced fractures, hydro-fractures) have a share of 20%. Minor contributions to the dataset are provided by the alignment of volcanic vents and fissures and overcoring measurements.

The mean orientation of S^{Hmax} is $17^\circ \pm 39^\circ$ for all A-D quality data. A closer look at subregions reveals four stress provinces with fairly consistent S^{Hmax} orientation. They are in the Capital area and Southern Lowlands (mean $S^{Hmax} = 38^\circ \pm 29^\circ$), the eastern Highlands and Eastfjords (mean $S^{Hmax} = 8^\circ \pm 25^\circ$), the Tjörnes Fracture Zone and Akureyri (mean $S^{Hmax} = 151^\circ \pm 21^\circ$), and the Westfjords (mean $S^{Hmax} = 137^\circ \pm 17^\circ$).

This distribution of S^{Hmax} orientations is in agreement with the prevailing tectonic structure. 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 Iceland's largest earthquakes, S^{Hmax} is at an angle of 20° to 60° to the transform faults which define the plate boundary. In general, a rotation from ridge parallel to intraplate ridge normal S^{Hmax} is expected at some distance from the plate boundary which is observed in the Westfjords, NW-Iceland.

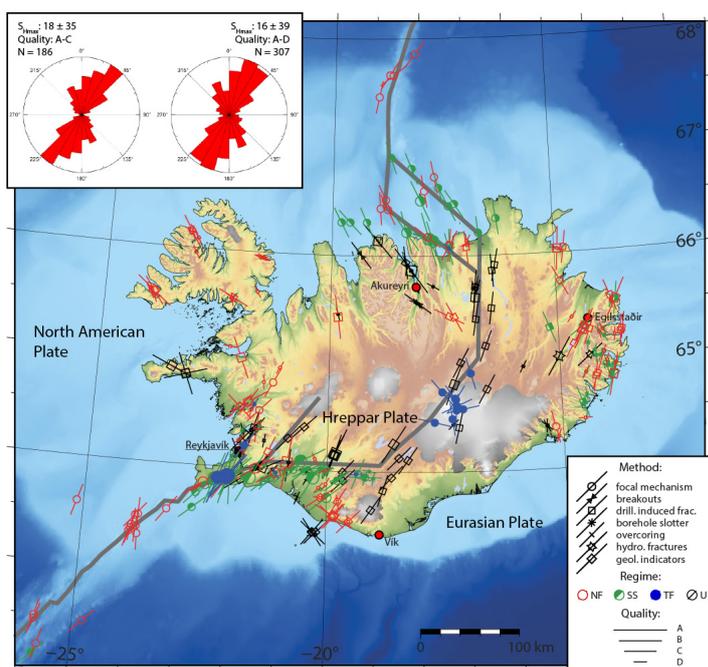


Figure 1: Stress indicator of quality A-D in Iceland. The lines represent the orientation of S^{Hmax} . Major tectonic features are shown.

Fractures and mineralizing fluid paths in the eastern Elba Island exhumed geothermal system (Italy)

Martina Zucchi

Dipartimento di Scienze della Terra e Geoambientali, Università di Bari (Italy)

The circulation and storage of the geothermal fluids in the continental crust is mainly controlled by structures associated to the brittle deformation in the upper crust, particularly during extensional processes accompanied with magmatism. In this framework, a better understanding of the fracture network of rock volumes channelling (i.e. faults) and storing (i.e. reservoirs) geothermal fluids is one of the main targets, to improve our knowledge on the deep geothermal circuits, thus contributing to the reduction of the mining risk. To this goal, the study of analogue, exhumed, geothermal areas has been carried out. These are located in the eastern side of Elba Island, corresponding to an exhumed crustal sector of inner Northern Apennines, triggered by the emplacement of a granitoid at mid-crustal levels (Porto Azzurro monzogranite, 5.9 Ma) and considered the exhumed analogue of the Larderello active geothermal field.

In this view, the research activity has been addressed to the reconstruction of structural (geometry and kinematics of faults, fracture network) and hydraulic parameters (secondary permeability, efficient porosity) and fluids features (temperature and salinity) characterising the palaeo-geothermal system by analysing selected key areas representative of different structural levels and geothermal features. In all areas, detailed structural and kinematic analyses joining to the petrological studies of mineralization and hosting rocks have been performed. Fluid inclusions analyses of quartz and adularia single crystals and/or mineralized veins, have been done in order to get information on the main chemical-physical properties of the parent fluids, and to define the evolution of geothermal fluids in terms of their salinity and temperature.

The structural and kinematic study has been based on the classical approach of structural geology: detailed structural maps (1:100 scale) were performed for each study area. The mineralized veins network, associated with the main structures was reconstructed through scan lines and scan boxes measurements, opportunely located in key sectors of the study outcrops. The palaeo-permeability reconstruction was obtained by means of geometrical parameters (i.e. length, minimum and maximum width and frequency of each mineralized shear veins) measured through the scan box (area 40x40 cm²) methodology. Together with other researchers involved in the Image project, the secondary permeability was computed using a theoretical approach, deriving from the revision of existing algorithms. The main results indicate that the geothermal fluids producing the main mineralization (tourmaline and Fe-ore deposits) were controlled by fracture systems associated to three different faults generations. These latter are characterized by different geometrical and kinematics features but can be reconciled in a common extensional tectonic framework characterising the Elba Island and the northern Tyrrhenian Sea during the Neogene. Secondary permeability (k) values from the analysed areas range from 10-17 m² to 10-12 m², with the majority encompassed between 10-14 and 10-13 m². These values are comparable with those obtained for active geothermal systems in Larderello.

Fluid inclusions analyses highlighted that differences of salinities and temperatures, characterize the geothermal palaeo-fluids in the different areas, representative of the different structural levels. At the deepest level (Cala Stagnone) Th values indicate a range between 250 and 540°C with salinity encompassed between 10 and 47 wt. % NaCl eq. Differently, moving on the shallow structural levels, the Th tends to decrease (<400°C) with a variable salinity that does not exceed 31 wt. % NaCl eq. Furthermore, at Morcone area, evidences of palaeoseismicity have been recognized, enforcing the importance that a continuous tectonic activity is a necessary feature for maintaining an efficient permeability in an active geothermal system.

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

List of Participants

1	Coralie	Aichholzer	EOST	France
2	Masoud	Allahbakhshi	GFZ German Research Center for Geoscience	Germany
3	Massimo	Angelone	ENEA	Italy
4	Alfonso	Aragón-Aguilar	Instituto Nacional de Electricidad y Energías Limpias	Mexico
5	Claudia	Arango-Galvan	Instituto de Geofísica, UNAM	Mexico
6	Antoine	Armandine les Landes	BRGM	France
7	Sigurveig	Árnadóttir	ÍSOR	Iceland
8	Knútur	Árnason	ÍSOR	Iceland
9	Kristian	Bär	TU Darmstadt	Germany
10	Fausto	Batini	Magma Energy	Italy
11	Fred	Beekman	Utrecht University	The Netherlands
12	Stefano	Benato	Cranfield University	UK
13	Ásdís	Benediktsdóttir	ÍSOR	Iceland
14	Ariel	Bennett	Petroleum Geochemistry Inc.	USA
15	Eszter	Békési	Utrecht University	The Netherlands
16	Caterina	Bianco	University of Bari	Italy
17	Adnand	Bitri	BRGM	France
18	Jóna	Bjarnadóttir	Landsvirkjun	Iceland
19	Ingi Þ.	Bjarnason	University of Iceland	Iceland
20	Grímur	Björnsson	Warm Arctic ehf	Iceland
21	Hanna	Blanck	ÍSOR	Iceland
22	Anett	Blischke	ÍSOR	Iceland
23	Damien	Bonté	Utrecht University	The Netherlands
24	Maren	Brehme	GFZ Potsdam	Germany
25	François	Bretaudeau	BRGM	France
26	Andrea	Broggi	University of Bari	Italy
27	Chris	Bromley	GNS Science	New Zealand
28	David	Bruhn	GFZ Potsdam	Germany
29	Philippe	Calcagno	BRGM	France
30	Gerado	Carrasco	Centro de Geociencias-UNAM	Mexico
31	Nataly	Castillo ruiz	Iceland School of Energy	Iceland
32	Cari	Covell	Reykjavik University	Iceland
33	Mathieu	Darnet	BRGM	France
34	Nicholas	Davatzes	Temple University	USA
35	Paromita	Deb	RWTH Aachen	Germany
36	Mickael	Delatre	BRGM	France
37	Chrystel	Dezayes	BRGM	France
38	Heber	Diez	CFE	Mexico
39	Thomas	Driesner	ETH Zurich	Switzerland
40	Vincent	Drouin	Institute of Earth Sciences	Iceland
41	Cécile	Ducrocq	Institute of Earth Sciences	Iceland
42	Guðjón Helgi	Eggertsson	University of Liverpool	UK
43	Kristján	Einarsson	Landsvirkjun	Iceland
44	Rachel	Evans	N/A	UK
45	Steven	Evans	N/A	UK

46	James	Faulds	University of Nevada, Reno; Nevada Bureau of Mines and Geology	USA
47	Matt	Flannery	Petroleum Geochemistry Inc	USA
48	Ólafur	Flóvenz	ÍSOR	Iceland
49	Jessica	Freymark	GFZ Potsdam	Germany
50	Alain	Gadalia	BRGM	France
51	Filippo	Gagliardi	European Commission	Belgium
52	Victor Hugo	Garduño Monroy	UNIVERSIDAD MOCHOACANA DE SAN NICOLAS DE HIDALGO	Mexico
53	Emmanuel	Gaucher	KIT	Germany
54	Bjarni	Gautason	ÍSOR	Iceland
55	Halldór	Geirsson	Institute of Earth Sciences	Iceland
56	Benoit	Gibert	Géosciences Montpellier	France
57	Gianluca	Gola	CNR-IGG	Italy
58	Melchior	Grab	ETH Zurich	Switzerland
59	Randall	Greene	Iceland School of Energy	Iceland
60	Ásgrímur	Guðmundsson	Landsvirkjun	Iceland
61	Luca	Guglielmetti	University of Geneva	Switzerland
62	Ingvi	Gunnarsson	Reykjavík Energy	Iceland
63	Sæunn	Halldórsdóttir	ÍSOR	Iceland
64	Virginie	Harcouet-Menou	VITO NV	Belgium
65	Oliver	Heidbach	VITO NV	Germany
66	Helga Margrét	Helgadóttir	ÍSOR	Iceland
67	Jono	Henry	Reykjavik University	Iceland
68	Matylda	Hermanska	University of Iceland	Iceland
69	Abel	Hernandez	INEEL	Mexico
70	Gylfi Páll	Hersir	ÍSOR	Iceland
71	Jan	Hopman	TNO	The Netherlands
72	Afifa	Imtiaz	BRGM	France
73	Heimir	Ingimarsson	ÍSOR	Iceland
74	Hjalti Páll	Ingólfsson	GEORG	Iceland
75	Georgina	Izquierdo	INEEL	Mexico
76	Anna	Jentsch	Helmholtz-Zentrum Potsdam Deutsches, GFZ	Germany
77	Egbert	Jolie	GFZ Potsdam	Germany
78	Philippe	Jousset	GFZ	Germany
79	Helgi	Jóhannesson	Norðurorka Ltd. - Utility Company	Iceland
80	Brynja	Jónsdóttir	ÍSOR	Iceland
81	Daniel	Juncu	Institute of Earth Sciences	Iceland
82	Egill	Júlíusson	Landsvirkjun	Iceland
83	Junzo	Kasahara	ENAA	Japan
84	Felix	Kästner	GFZ	Germany
85	Katrin	Kieling	GFZ German Research Centre for Geosciences	Germany
86	Wiesław	Kozdrój	Polish Geological Institute - National Research Institute	Poland
87	Thomas	Kretzschmar	CICESE	Mexico
88	Bjarni Reyri	Kristjánsson	Reykjavík Energy	Iceland
89	Juliane	Kummerow	German Research Centre for Geosciences	Germany
90	David	Lagrou	VITO NV	Belgium

91	Marinella Ada	Laurenzi	CNR-Istituto di Geoscienze e Georisorse	Italy
92	Baptiste	Lepillier	TU DELFT	The Netherlands
93	Léa	Lévy	ÍSOR	Iceland
94	Jon	Limberger	Utrecht University	The Netherlands
95	Domenico	Liotta	University of Bari	Italy
96	Simon	Lopez	BRGM	France
97	Aida	Lopez-Hernandez	UMSNH	Mexico
98	Pańczyk	Magdalena	Polish Geological Institute - NRI	Poland
99	Adele	Manzella	CNR	Italy
100	Nicolas	Marino	Géosciences Montpellier	France
101	Sigurður	Markússon	Landsvirkjun	Iceland
102	François	Martin	SIG	Switzerland
103	Joana	Martins	TNO	The Netherlands
104	Hansruedi	Maurer	ETH Zurich	Switzerland
105	John	Millett	VBPR	UK
106	Domenico	Montanari	Institute of Geosciences and Earth Resources, (CNR)	Italy
107	Giordano	Montegrossi	CNR-IGG	Italy
108	Anette	Mortensen	Landsvirkjun	Iceland
109	Andrea	Moscariello	University of Geneva	Switzerland
110	Jiri	Muller	Institute for Energy Technology (IFE)	Norway
111	Leah	Netten	Reykjavik University	Iceland
112	Gregory A.	Newmann	Lawrence Berkeley National Laboratory	USA
113	Franck Laurel	Nono Nguendjio	Pau University _ DMEX	France
114	Gianluca	Norini	CNR	Italy
115	Anne	Obermann	ETH Zurich	Switzerland
116	Andrea	Orlando	CNR- Istituto di Geoscienze e Georisorse, Firenze	Italy
117	Sylvía Kristín	Ólafsdóttir	Landsvirkjun	Iceland
118	Finnbogi	Óskarsson	ÍSOR	Iceland
119	Fleurice	Parat	Geosciences Montpellier	France
120	Mariane	Peter-Borie	BRGM	France
121	Elisabeth	Peters	TNO	The Netherlands
122	Lorenzo	Petracchini	CNR-IGAG	Italy
123	Antonio	Pola	Escuela Nacional de Estudios Superiores - Unidad Morelia. UNAM.	Mexico
124	Flavio	Poletto	OGS	Italy
125	Belinda	Poli	Self	Italy
126	Nolwenn	Portier	IPGS EOST	France
127	Rosa Maria	Prol-Ledesma	Universidad Nacional Autonoma de Mexico	Mexico
128	Ahmad Fauzi	Purwandono	Utrecht University	The Netherlands
129	Siegfried	Raab	GFZ Potsdam	Germany
130	Miguel	Ramírez	CFE	Mexico
131	Mylène	Receveur	University of Iceland	Iceland
132	Fabienne	Reiser	ETH Zurich	Switzerland
133	Valentina	Rimondi	CNR-IGG	Italy
134	Enzo	Rizzo	CNR-IMAA	Italy
135	Christopher	Rochelle	British Geological Survey	UK

136	Baptiste	Rondeleux	CGG	France
137	José	Romo-Jones	CICESE	Mexico
138	Giovanni	Ruggieri	CNR-IGG	Italy
139	Mike	Sandiford	University of Melbourne	Australia
140	Bernard	Sanjuan	BRGM	France
141	Alessandro	Santilano	CNR-IGG	Italy
142	Ingo	Sass	TU Darmstadt	Germany
143	Jean	Schmittbuhl	EOST - CNRS/UNISTRA	France
144	Samuel	Scott	ETH Zurich	Switzerland
145	Davide	Scrocca	CNR-IGAG	Italy
146	Bergur	Sigfússon	Reykjavik Energy	Iceland
147	Freysteinn	Sigmundsson	Nordvulk, Institute of Earth Sciences, University of Iceland	Iceland
148	Kristján	Sigurðsson	HS Orka	Iceland
149	Ómar	Sigurðsson	HS Orka	Iceland
150	Lily	Suherlina	Reykjavik University	Iceland
151	Lukman	Sutrisno	Utrecht University	The Netherlands
152	Ólafur	Sverrisson	Landsvirkjun	Iceland
153	Audrey	Taillefer	Géosciences Montpellier	France
154	Jan	ter Heege	TNO	The Netherlands
155	Tania	Toledo Zambrano	GFZ-Potsdam	Germany
156	Eugenio	Trumpy	CNR-IGG	Italy
157	Lorenz	Ueing	CLEAG	Switzerland
158	Benoît	Valley	Université de Neuchâtel	Switzerland
159	Jan-Diederik	van Wees	TNO	The Netherlands
160	Vincent	Vandeweijer	TNO	The Netherlands
161	Arie	Verdel	TNO	The Netherlands
162	Pascal	Vinard	Geospace Experts LLC	Switzerland
163	Bodo	von Duering	CLEAG	Switzerland
164	Pierre	WAWRZYNIAK	BRGM	France
165	Claudia	Werner	International Geothermal Center Bochum	Germany
166	Leandra	Weydt	TU Darmstadt	Germany
167	Walter H.	Wheeler	Uni Research CIPR	Norway
168	Volker	wittig	International Geothermal Centre HSB / GZB	Germany
169	Alina	Yapparova	ETH Zurich	Switzerland
170	Moritz	Ziegler	GFZ Potsdam	Germany
171	Małgorzata	Ziółkowska-Kozdrój	Polish Geological Institute - National Research Institute	Poland
172	Martina	Zucchi	University of Bari	Italy
173	Unnur	Þorsteinsdóttir	ÍSOR	Iceland
174	Geir	Þórólfsson	HS Oka	Iceland

Document edited for the IMAGE Final Conference

Akureyri, Iceland

ÍSOR- Iceland GeoSurvey, Grensásvegur 9, 108 Reykjavík, Iceland

This project has received funding from the European Union's Seventh Programme for research, technological development and demonstration under grant agreement No 608553.

