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Co-operators: Serena Botteghi and Eugenio Trumpy (CNR)	
Abstract: This report describes the Final Conference of the DESCRAMBLE project and organize its Proceedings, as activity of WP6	
Keywords: Dissemination	Reviewed by:

1 Contents

Executive Summary

The DESCRAMBLE Final Conference took place in Pisa, Italy, on March 2018, and has been the occasion to learn about the project result and to exchange ideas and hints with international colleagues. The conference brought together EU and national representatives from industry and research to explore and discuss opportunities and strengths related to **drilling in superhot condition for producing heat and electrical power**.

The conference was organized in 4 blocks of presentations.

The **opening session** provided an overview of actual geothermal perspectives in the topics related to the DESCRAMBLE project. Following the welcome notes from the Host (CNR), the EU support to geothermal energy was presented F. Gagliardi, EU Commision Officer. A series of presentations then addressed drilling technologies and European activities in this field. E. Huenges (GFZ) presented the activity of the Working Group on Drilling of the ETIP-DG, and debated the status of drilling technologies and innovation frontiers. His presentation was followed by the presentation of two European running Projects strictly linked to the topics of reference of DESCRAMBLE: I. Thorbjornsson (ÍSOR) and A. Ragnarsson (ÍSOR) described the DEEPEGS and GEOWELL European Projects, respectively. Another important international project, which was originally mentioned in DESCRAMBLE proposal for coordinated efforts, is JBBO Project in Japan: since Prof. Asamura could not attend or organize a presentation, R. Bertani (DESCRAMBLE’s Coordinator), who was recently invited in Japan, reported about the status of pre-feasibility studies carried on in Japan. Bertani also presented, on behalf of P. Romagnoli of Enel Green Power (EGP), the genesis of DESCRAMBLE’s proposal.

After the opening, three technical sessions describing the DESCRAMBLE project results run for the rest of the day. The presenters of the opening session were kindly available for chairing and moderating all the sessions of the day.

Session 1 covered the description of **Pre-drilling assessment activities**. Active seismic data were discussed by S. Ciuffi (EGP) in relation to VSP data, and W. Rabbel (Christian-Albrechts-University at Kiel - CAU), who described seismic data processing, while M. Casini (EGP) described the definition of drilling target based on seismic data, underlining the differences between what was expected and what was retrieved during the drilling. R. Spinelli (EGP) introduced to the Seismicity Monitoring in the DESCRAMBLE’s study area. A. Dini (CNR) made an overview of Pre-drilling resource assessment, focusing on granite, hydrothermal vein and metamorphic basement petrology, and explaining how samples and studies from other areas provided information to forecast deep drilling and crustal conditions.

Lessons learnt in drilling DESCRAMBLE’s super-hot well was the base of D. Pallotta (EGP): new material for cement and drilling fluid, drillbit, BOP and drilling procedures were described in detail and have been a main topic of discussion during the networking moments of the conference. The modelling of drilling and production conditions in a supercritical well completed the session, and was presented by M. Hjelstuen from SINTEF on behalf of researchers of SINTEF who could not join the conference.

After lunch, Session 2 and 3 focused on the **activities performed during and after the drilling**.

M. Hjelstuen (SINTEF) described the prototype developed in DESCRAMBLE for measuring temperature and pressure in very harsh well condition. The prototype was also on show in the Hall of the Conference area. H. Büsing from RWTH Aachen University and G. Montegrossi from CNR described the reservoir modelling performed in the Larderello area, pinpointing the advancements achieved in software development and interpretation results.

G. Giudetti from Enel Green Power and F. Gherardi from CNR described the Gas logging results and discussed their preliminary interpretation, explaining the insights they provided on deep crustal condition and potential chemical reactions of drilling fluids at bottom-depth.

J. Niederau and R. Pechnig from RWTH Aachen University and H. B. Motra from CAU discussed the petrophysical properties at high temperature and pressure condition of core samples retrieved during the DESCRAMBLE drilling, whereas R. Pechnig from Geophysica LtD discussed the logging results. Eventually, G. Ruggieri (CNR) presented the petrographic characterization of core samples and described the synthetic fluid inclusions experiment performed in the DESCRAMBLE well and M. Cei (EGP) pinpointed how the DESCRAMBLE drilling activities helped in constraining resource characterization.

The project coordinator, R. Bertani (EGP) concluded the conference, narrating how, as in other moments of the production history of Larderello, the innovative drilling has provided unprecedented information of deep resource condition, and opened new technological perspectives for further deployment of geothermal resources. Although the drilling proceeded in very harsh condition, with temperature above 500 °C and pressure exceeding 300 bar, drilling procedures proved totally safe.

The 24 posters constituting the Poster Session were ideal for learning in more detail the technical advances achieved during the DESCRAMBLE project, and also a place for showing results from other projects and activities.

Proceedings

DESCRAMBLE

Drilling in dEep, Super-CRitical AMBient of continentaL Europe

DESCRAMBLE Project FINAL CONFERENCE

PROCEEDINGS

28 March 2018 CNR

AUDITORIUM

Via G. Moruzzi, 1 - 56124 PISA (Italy)

Consiglio Nazionale delle Ricerche

DESCRAMBLE project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under grant agreement №640573.

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Oral Presentations (by order of presentation)

VSP and drilling target definition

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Keywords: K seismic horizon, VSP, geothermal target

Abstract

The target of the deepening of the Venelle_2 well is the seismic K horizon, present in the whole LarderelloTravale geothermal area. In the Lago area, where the Venelle_2 well is located, this reflector reaches its shallowest elevation ranging between 3000 and 3500m.

This horizon has been reconstructed through the interpretation of the more than 50 2D seismic lines and 6 3D seismic surveys processed in time.

The interpretation of the seismic data in correspondence of the Venelle_2 well, identified two deep seismic horizons, named H and K. The first one shallower and associated with good confidence to our mining targets, the second and deeper one, of unknown meaning because no well has ever reached and crossed it.

The precision of the in depth conversion strongly depends on the accuracy of the velocity model used for the in-depth migration during the processing of the seismic data, but also for the in depth conversion of the surface reconstructed in the time domain.

The well seismic surveys (VSP) provide the velocity functions along the well and a seismic image around the well to be correlated with the seismic data. In the framework of the DESCRAMBLE project a VSP survey has been carried out on November 2015, before the deepening of the well. Due to an obstruction in the well, only the first 1600 m have been investigated. The conditions encountered in the Venelle_2 well during the drilling did not allow to carry out further VSP surveys, leaving a certain degree of uncertainty in the determination of the velocity field in the deeper part of the data and then of the target depth.

Different approaches to decrease the degree of uncertainty in the target depth definition have been attempted. One approach consisted in the use of the velocity model obtained by the processing of the 3D seismic survey, updated with the VSP data, to convert in depth the surface in time corresponding to the interpreted K horizon. The second approach consisted in the use of formation velocities for the estimation of the depth/time relationship to convert in time the well data.

Both approaches have led to similar results with estimated depth of 3150-3200 m true vertical depth (TVD) for the K horizon and 2750-2800 m TVD for the H horizon.

The Venelle_2 well reached the final measured depth of 2909m. On the base of the previous considerations, we can confidently assert that we have reached and crossed the whole package of the shallower reflections connected to the H horizon, while it is likely that the K horizon has not been reached.

Seismic data processing

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Abstract

The best possible seismic characterization of the super-critical region associated with the K-horizon was the goal of major seismic processing and data acquisition efforts undertaken by the DESCRAMBLE team. To achieve this goal the latest seismic processing, imaging and interpretation technology was applied to 2D and 3D seismic reflection data and the results were calibrated and evaluated using borehole data and petrophysical data of rock samples. The results of the joint efforts are:

1. 3D images of the K-horizon and geological structure of the hanging wall at highest possible resolution gained from both careful classical reprocessing and innovative 3D prestack Fresnel volume and coherency migration algorithms.
2. A seismic velocity-depth model integrating results from first-arrival travel-time-tomography and reflection-tomography at shallow depth levels, vertical seismic profiling, and reflection travel-time analysis based on normal-moveout and migration velocity studies
3. Based on reflection imaging and velocity model a regional map of the K-horizon could be determined.
4. Special emphasis was put on estimating uncertainty bounds for seismic velocity model and related target depth. The uncertainty analysis considers random velocity fluctuation resulting from subsurface heterogeneity, systematic deviations associated with seismic anisotropy, and calibration points obtained from borehole seismics.
5. The structure of the K-horizon as such was investigated using seismic amplitudes and waveforms. Amplitude-versus-offset analysis shows distinct differences between the target reflections and reflections of the hanging wall. Waveform modelling and inversion shows that the K-horizon is most probably composed of thin alternating layers of low and high seismic velocity that could be associated with fractured and sealing rock sheets, respectively.

Seismicity Monitoring

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Abstract

The high resolution microseismic monitoring of the Venelle 2 area is focused at improving the resolution and quality of the monitoring of the natural microseismicity of the area, in order to:

- reduce environmental seismic risk,
- to enforce drilling operation's safety,
- to check any possible correlation of seismic events with drilling operations

In compliance to the mentioned goals, and with the aim of improving the Larderello Travale Seismic Network (LTSN) detection capability for the Venelle 2 area, four Additional Temporary Seismic Stations (ATSS) from 1.5 to 2 km distance from the Venelle 2 well were installed.

Three of the ATSS were equipped with Trillium Compact Posthole 3C seismometer, placed in a shallow well at depth of 10 m, and one with a downhole high resolution broad band seismometer was placed into the nearby (not in use) Castiglioni 1 geothermal well at 136m depth. The fourth ATSS with 16 Seismic Stations (SS) of the LTSN, were set up to compose a dedicate Venelle 2 High Resolution Microseismic Network (V2HRMN). This network ensures detection of microseismic events over a wide magnitude range, and robust hypocentral localization error reduction in an area of 10 km radius around the drilling site Venelle 2. All SS and ATSS are real time connected to the Larderello seismological datacenter. Here, the signals coming from the stations are scanned thru the automatic acquisition system. When an event is detected, it is automatically processed, and in a few seconds the hypocentral determination and magnitude are provided. Whenever an earthquake with magnitude greater than 1.5 occurs in a radius of 2 km from Venelle 2 well, an alert is being sent to the seismologist and to the drilling plant operators.

The V2HRMN started operations in the first days of 2016. The two years period of observation covers: 15 months before the start of Venelle 2 drilling operation (blank measurement), the entire drilling period from April 28, 2017 to November 12, 2017, up to the end of the 2017.

In the observation period, 373 events with magnitude ranging from -1.04 to 1.92 occurred. Seismic activity is present more or less throughout the entire area (Figure 1), but in certain areas there is a greater concentration. These areas are: the Terme del Bagnolo and Lustignano clusters and the clear NW-SE alignment that from Lagoni Rossi thru the well Venelle 2, Lago Boracifero goes down to Poggio al Lupo.

The projection of the foci on the vertical cross-sections A-A' and B-B' (Figure 2) running in NW-SE direction demonstrates that earthquakes take place almost entirely within 6 km depth, and predominantly at 3-5 km. At any rate, it is noteworthy that the hypocenters are located above the k horizon, with depth ranging from

1.5 to 3.5 km. Only in the south eastern quadrant of the studied area, the foci are deepening down to 3.5 to

4.5 km. The deeper earthquakes form SW- NE direction alignment in correspondence of a strong discontinuity of the K horizon (lack in the continuity of k horizon seismic signal) and seem to act as clear-cut boundaries for the seismically active zone.

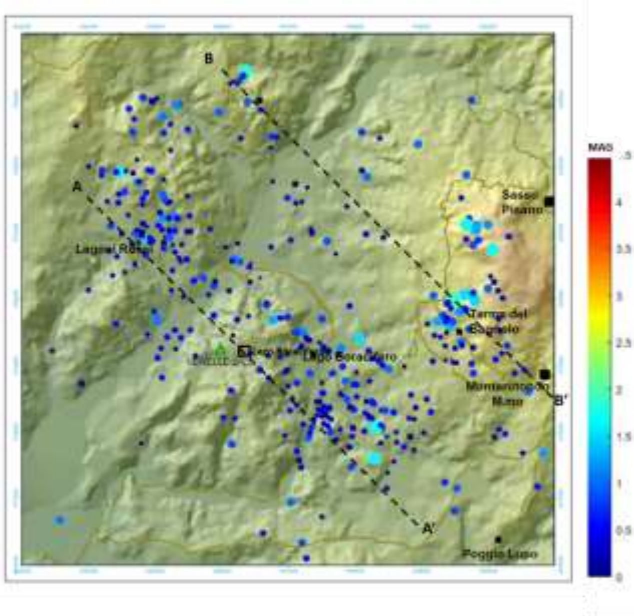

Figure 1. Epicenters map of Venelle 2 area from January 2016 to December 31, 2017. Dots are the epicenters and their color is the Magnitude (MAG color code bar).

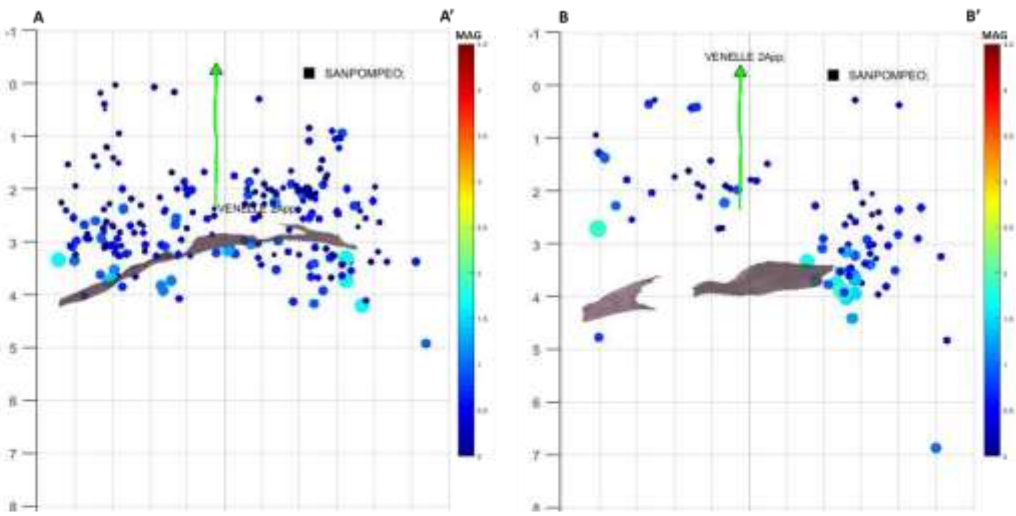

Figure 2. Hypocenter depth distribution of the foci on the two cross-sections A-A' and B-B' the events showed in Figure 2 projected on a vertical plane. Envelope of the K horizon picked seismic signal is shown in gray. Dots are the epicenters and their color is the Magnitude (MAG color code bar).

Comparison between seismic activity and drilling operation, such as partial or total loss of circulation (PLC and TLC) and Leak-Off Tests (LOT), allow to evaluate the occurrence of potentially induced or triggered seismic phenomena.

Spatial and temporal relationship between PLC, TLC and LOT operation and seismicity occurred in a close volume around the well (Figure 3 Figure 4) demonstrates that no increase in seismic activity was verified during Venelle2 drilling, and no temporal and spatial correlation seems to exist between the seismicity and drilling operation.

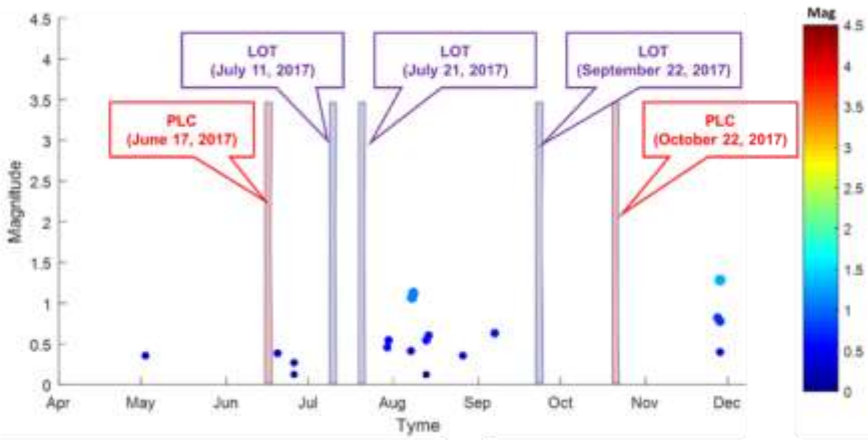

Figure 3. Temporal relationship between seismicity occurred during Venelle 2 drilling (from April 28, 2017 to November 12, 2017), in a volume with dimension of 2x2 km (latitude x longitude) and 6 km in depth centered on well and PLC (Red bars) and LOT (Violet Bars) operation. Dots are the events and their color is the Magnitude (MAG color code bar).

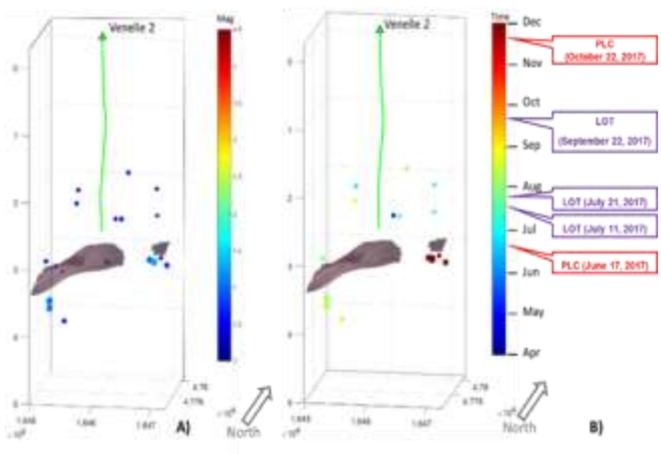

Figure 4. Spatial and temporal relationship between seismicity during Venelle 2 drilling in a volume of 2x2 km (latitude x longitude) and 6 km in depth centered on the well. In Figure 4A) Dots are the events and their color is the Magnitude (MAG color code bar), and the envelope of the K horizon picked seismic signal is shown in gray. In Figure 4B) Dots are the events and their color is the time in days from April 1, 2017 (Time color code bar) K horizon is shown in gray.

Pre-drilling resource assessment: insights from granite, hydrothermal vein and metamorphic basement petrology

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Keywords: Magmatic-hydrothermal system, granite, tourmaline, metamorphic rocks

Abstract

Pre-drilling resource assessment of a geothermal reservoir that has not yet been reached and/or explored by extensive drilling is a very challenging task. Addressing this issue for a potentially supercritical system, characterized by extremely high T and P, is an even more demanding but, at the same time, stimulating task. The aim of the DESCRAMBLE pre-drilling reservoir characterization was to achieve a comprehensive understanding of the geological structure and physical-chemical conditions of the supercritical reservoir by studying older geological analogues of the ongoing magmatic-hydrothermal system in the deep zone of the Larderello geothermal field. We faced this challenge through the petrological study of granites, hydrothermal veins and metamorphic rocks cored in exploratory wells from the geothermal area around the Venelle 2 well.

The Tuscan crust, from Elba Island to Larderello, experienced a common tectono-magmatic evolution since Middle Miocene. Post-orogenic extensional tectonics triggered thinning of continental crust, production of peraluminous, boron-rich magmas in the lower crust, their subsequent emplacement at shallow crustal levels (granite plutons and laccoliths) and activation of hydrothermal systems involving magmatic, metamorphic and meteoric water. Magmatic-hydrothermal systems progressively migrated from west to east: from Elba Island (8.5-5.9 Ma), to Campiglia (5.5-4.3 Ma), to Larderello (3.8 Ma-Present). We adopted this conceptual model: the magmatic system responsible for the present-day thermal anomaly in Larderello was assumed to be similar to the "fossil", exhumed magmatic-hydrothermal systems cropping out in the eastern area (e.g. Elba Island). All these boron-rich granite intrusions produced contact aureoles that were sequentially invaded by magmatic fluids (boron-rich) released by the crystallizing magma. The net result was a granite pluton province surrounded by contact metamorphic aureoles, hosting a large variety of sub-vertical and subhorizontal veins and breccia bodies cemented by tourmaline, quartz and sulphides. Such hydrothermal reservoirs behaved as closed systems, confined into the contact metamorphic shell, with no apparent connections to the overlying shallow meteoric circuits. These confined, dominantly magmatic-metamorphic,

paleo-reservoirs could represent a proxy for the supercritical reservoir possibly occurring in correspondence of the K-horizon seismic marker at Larderello.

Multiple petrographic, geochemical, isotopic (Sr, Nd, B, Hf, O, H), geochronological (^{40}Ar-^{39}Ar, U-Pb), and fluid inclusion analyses have been performed on granites, hydrothermal veins and metamorphic rocks from Larderello. The DESCRAMBLE Team produced a large petrological data set that integrated previous studies providing important constraints at depth. High-precision U-Pb zircon dating of granites are coherent with ^{40}Ar-^{39}Ar ages and indicate that Larderello is a multi-pulse magmatic system including five main stages (3.83.6 Ma; 3.3-3.1 Ma; 2.7-2.5 Ma, 1.9-1.6 Ma, and present day). Geochemical-isotopic study of granites and basement metamorphic rocks indicate that granite magmas formed by partial melting of a fertile lower crust made by interlayered metasediments and amphibolites. Temperature in the lower crust (23-16 km depth) did not exceed 900°C due to the buffering effect of partial melting and the efficient dissipation in such a thin crust (< 23 km). Petrographic-geochemical features and intrasample U-Pb zircon ages indicate that granite melts accumulated in the middle crust (15-10 km depth) forming large reservoirs (several hundred km^3) that acted as magma chambers for the relatively smaller intrusions (few tens to hundred km^3) we studied in the shallow crust (above 8-6 km depth). Distribution of metamorphic assemblages in host rocks at the top of Larderello intrusions are consistent with the transient formation of multiple, ductile contact aureoles characterised by strong thermal gradients and maximum temperatures of 650°C. During the waning stage, the concomitant fluid exsolution from the crystallising intrusions, and the switch back to brittle conditions in the aureole favoured the formation of tourmaline-bearing veins and breccias. Geochemical and isotope data (B, O, H, Sr) coupled with fluid inclusion data indicate that these veins crystallised from high temperature fluids (450-550°C; P≈400-800 bars) of dominantly magmatic-metamorphic origin. These fluids are the best candidates for what we expect to find at the K-marker level. All these data provide a new architectural frame for the Larderello magmatic-hydrothermal system from its root in the lower crust to the K-marker target, that takes into account the transient thermal state of the whole crustal section below the geothermal system.

Drilling Activities and Lessons Learnt – DESCRAMBLE project

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Keywords: Drilling, Special materials, High temperature and pressure, Experimental procedures.

Abstract

Drilling activities started with the plugging of the lower part of the original well with inert material and cement. A new branch of 12 ¼" bore size was created from the kick off point at 1054 m in open hole, and continued with vertical path down to 2470 m. At this depth the 9 5/8" casing was set. Due to the presence of a total loss of circulation, the cementing job was not completely successful and the hanger head resulted not cemented. For that reason the column was not set in an unique solution with continuity, but the surface casing's shoe was set at 985 m, about 8 m upper than the hanger head of the liner.

During the well deepening a crucial aspect was represented by the knowledge of the formation fracture gradient at various depth, information required in order to set the 7" liner shoe in the right position. This fundamental information was acquired by the execution of Leak Off Tests, first of which has been performed at 2500 m using RTTS packer near the casing shoe with no good results. The drilling activities were started again until 2600 m when was taken a formation sample with coring operations. Afterwards a new LOT was performed with an innovative swallable packer for open hole in HT environment.

Taking into account the good results of the LOT, was decided to stop deepening and proceeding to install the 7"casing with shoe at 2600 m (7" deep Liner liner in steel grade T95; 7" intermediate liner and surface tie back in steel grade TN125SS).

Logs were performed in order to verify the cement quality, revealing an interval where cement was not present or only partially present due to the failure of the one way valves of collars and shoe. Was decided to partially cut and pulled out, where possible, the casing not cemented, and where not possible milled the resting casing reaching the part that was completely cemented. Afterwards was reintegrated and cemented the casing extracted in order to ensure the integrity of the column. On surface, a wellhead API 10k with sour service layers was mounted. Over were installed a complete BOP stack 10k and the Managed Pressure Drilling System. This innovative system allows to mitigate the risks related to uncertainties on pore and fracture gradient and about the drilling fluid density behaviour at such high temperature.

Drilling continued with sepiolitic mud of 1.5 kg/l density (FW-HT-Microdense™), with total return of circulation, using a 6" Full Stinger Bit down to 2695 m of depth. From this depth a lot of stuck pipe problem

were incurred due to decantation tendency of the Microdense™ during the connection time at such temperature. The problem was solved reducing the weight of the mud in first step, and, at the end, switching to drilling water. At 2708 m a temporary total loss of circulation occurred. From this moment the stuck pipe problems increased due to differential pressure between hydrostatic and fracture/formation pressure. This situation forced to review the drilling procedures, because of the low fluid density that was not guaranteeing the first barriers for blow out prevention as standard well control procedures. In order to try to increase the formation resistance and reduce the risk of losses, various squeeze jobs with clogging inert material were performed, with the purpose to plug the absorbent zone with negative results.

Drilling started again with water and controlled parameters, with the purpose of reach the final depth of 2900 m. At 2830 m and 2900 of depth two cores were performed of about 9 m each one.

The prosecution of the drilling activities was not possible because of the impossibility to guarantee safety margin of the operation due to the presence of this absorbent zone. If in the prosecution the over-pressured zone could be encountered with an open hole with lower fracture gradient, the risk of an uncontrolled underground blowout was high. For that reason it was decided to proceed with a temporary closure and abandon of the well.

To achieve this result, innovative geothermal technologies, equipment and materials specifically designed for extreme conditions, in terms of high temperature and pressure, have been used and specific drilling procedures have been implemented, representing a significant learning opportunity for the geothermal drilling industry.

Modelling of drilling and production conditions in a supercritical well

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Keywords: Drilling, supercritical, modelling

Abstract

We present work done on computer models of the DESCRAMBLE drilling campaign and production scenario. For the drilling campaign we modelled the likely response of the well during heating of drilling fluids, determining the top-side signature of both benign and unwanted effects. For the production scenario we modelled pressure, temperature and flow-rates for the supercritical well, with top-side choke control. In particular, we identified transient pressure and temperature effects during closing and opening of the well, which has consequences for production planning and well design.

A novel high temperature wireline logging tool for measuring temperature and pressure in supercritical geothermal wells

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Keywords: Logging tool, wireline, memory tool, high temperature, high pressure, dewar, supercritical, geothermal

Abstract

Exploitation of super-critical water from deep geothermal resources can potentially give a 5-10 fold increase in the power output per well. Such an improvement represents a significant reduction in investment costs for deep geothermal energy projects, thus improving their competiveness. The ongoing European Horizon2020 DESCRAMBLE (Drilling in dEep, Super-CRitical AMBients of continental Europe) project will demonstrate the drilling of a deep geothermal well with super-critical conditions (>374°C, >220 bar) by extending an existing geothermal well to a depth of 3km. State-of-the-art electronic logging tools does not operate reliably at these conditions. In the DESCRAMBLE project, SINTEF has developed a novel pressure and temperature (PT) logging tool for monitoring these supercritical conditions.

The logging tool components (Figure 1); high temperature electronics, sensors and batteries are shielded from the environment by a heat shield (Dewar). A pressure vessel with special seals, envelops the dewar enabling the tool of 6 hours logging operation at 450°C/450 bar. Such dwell time is necessary in order to log a 3km deep well with peak temperature of 450°C. A high performance heat and pressure shield protect the electronics platform that can operate and store data up to a minimum of 200°C, with some key components targeting as high as 300°C. Having the thermal performance to be able to operate for 6 hours at 450°C also means that the tool can operate with even longer dwell time in other applications where temperature is

lower. Alternatively, it can operate at the same dwell time with a lower internal temperature resulting in more available electronic components that can be used.

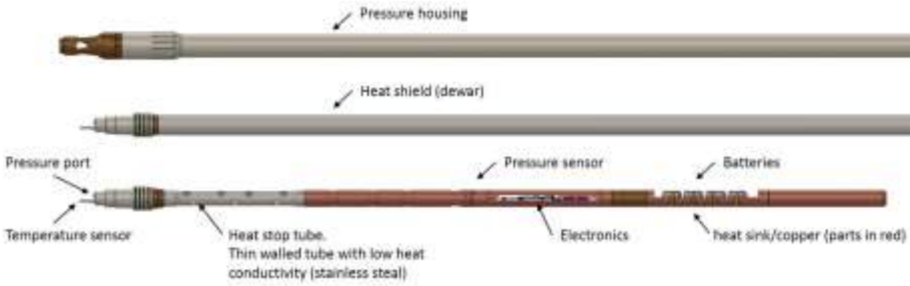

Figure 1. Top: The complete tool with pressure housing. Temperature sensor and pressure port to the left and connection for the slickline wire to the right. Middle: Pressure shield and nose protector removed. Picture show the nose of the tool and the heat shield. Bottom: Heat shield removed. Picture show the inner parts of the tool. Electronics located in the middle of the tool.

A field-test of the tool was performed in an off-line geothermal well (Lumiera) at Enel Green Power's facilities in Larderello, Italy in February 2017. The performance of the tool was compared with the Kuster K10 tool – the current state-of-the-art high temperature geothermal logging tool commercially available (Kuster, 2015). The SINTEF tool measured the same pressure and temperature profile of the well compared with Kuster K10 and had in addition a much lower internal temperature gradient.

Two successful logging runs was performed with the SINTEF tool in the Venelle 2 well being drilled in the DESCRAMBLE project. First run was performed in late September down to 2610m with measured max temperature 372.9°C (Figure 2). The second run was performed in start of December down to 2810m with measured max temperature 443.6°C (Figure 3).

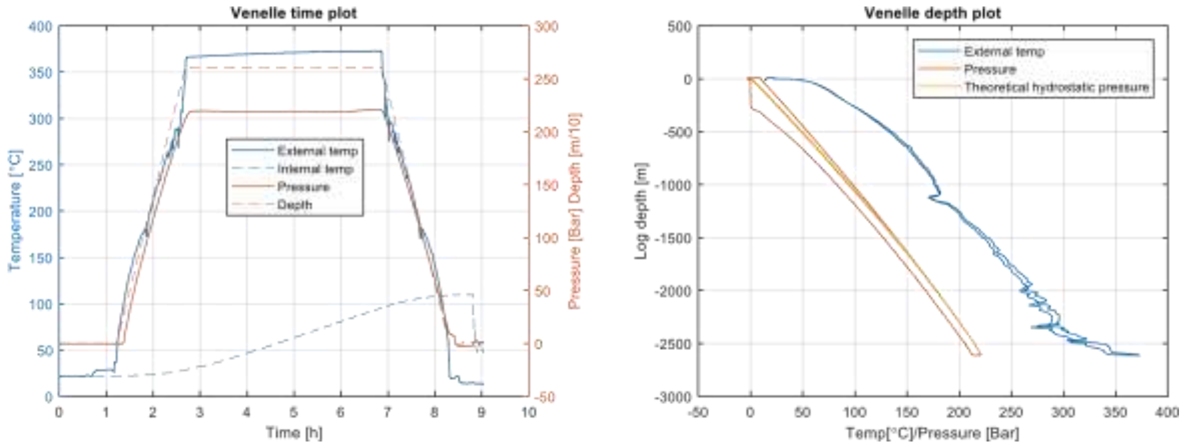

Figure 2. Measurements performed in Venelle 2 – run 1. Depth measurements from the Kuster depth box.

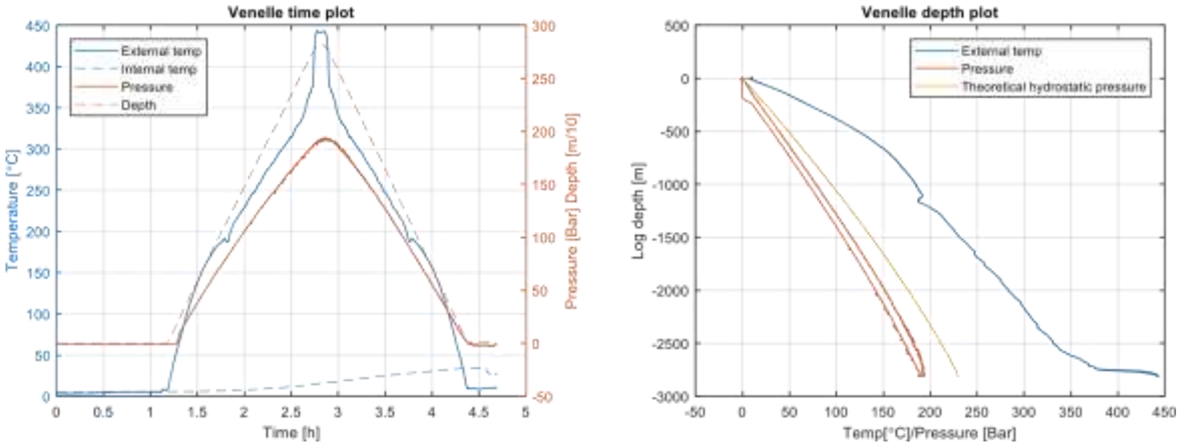

Figure 3. Measurements performed in Venelle 2 – run 2. Depth measurements from the Kuster depth box.

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INTEGRATED NUMERICAL MODELLING OF THE MULTI-PHASE SUPERCRITICAL GEOTHERMAL RESERVOIR SYSTEM AROUND VENELLE-2

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Abstract

The simulation of the geothermal system around the Venelle-2 borehole is a challenging task due to the peculiar nature of the subsurface. High temperatures (> 450 °C) and pressures (> 35 MPa) require accurate description of fluid properties in the supercritical range. In addition, the occurrence of steam, and thus multiphase behaviour, further complicates the simulation task. Our approach addresses these challenges with a range of model sizes, physical descriptions and adapted dimensionalities. We move from simpler models (steady state, single-phase, one-dimensional) to complex models (transient, multi-phase, threedimensional). This allows to choose the right model for the question to be answered. We show simulation results for the regional and local surroundings of the Venelle-2 borehole and quantify the influence of uncertain reservoir parameters.

TOUGH2 MODELLING FROM EOS FOR SUPERCRITICAL FLUIDS TO VENELLE 2 REGIONAL AND LOCAL MODELS

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Abstract

The Equation Of State formulation for high T,P mixture of water, CO_2, NaCl was implemented in a working codes that could be compiled with different computational options. The compiled code for windows have a partial compatibility with the petrasim graphical interface, being able to use the computational grid obtained by the petrasim graphical interface and to show the results in the main windows after importing the "SAVE" file. The present code is also part of a collaboration with GNS (Institute of Geological and Nuclear Sciences, New Zealand) in the "Geothermal supermodels programme".

The modelling strategy started from the numerical model of Venelle 2 area (regional model), with an extension of 17.0x17.75x5 km to define the condition of the system above the K-horizon up to 350°C, using the standard version of TOUGH2-EOS2; this model was calibrated with the temperature measurements of 8 deep wells surrounding Venelle 2.

The second step was a local model of the Venelle 2 well, in which we used the conditions obtained from the regional model as boundary conditions for the shallower part of the local model. The aim of the Venelle 2 local model is to reconstruct the measured temperature and pressure behaviour of the deeper part, providing an insight on the temperature distribution and the bottom thermal boundary.

Finally, the obtained boundary conditions at depth were used to have a numerical model of the Venelle 2 area that include the temperature distribution below the K-horizon. It is worthy to point out that the only existing data are from the new Venelle 2 well, nevertheless the forecast provided in the updated regional model are very important for the future investigations of the supercritical system below the K-horizon.

CO_2, CH_4, H_2S, H_2 logging while drilling: first results on geothermal applications

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Keywords: Mud Logging, gas determination, seismic horizon

Abstract

Mud logging (ML) service is normally used in Oil and Gas drilling aiming at the identification of the potentially productive hydrocarbon-bearing formations. For the first time ML was used in the geothermal area of Larderello during the Venelle_2 well. Its utilization was both for safety and fluid characterization reasons.

The targeted fluid was supposed in High Pressure (450 bar) high Temperature (450°C) conditions, much higher than those present in the exploited metamorphic basement of Larderello (30-50 bar and 300°C). Previous drilling at SANPOMPEO_2 well (the drilling ended at 2937m with reconstructed temperature and pressure of 450°C and 240 bar) evidenced gas mixt different from usual average of Larderello system, with increased content of CH_4, up to 12% v/v, and H_2 up to 20 % v/v, while CO_2 was as low as 65 % v/v.

Given this composition as reference for deep seating gas, ML was aimed at obtaining first indications about potential high pressure gas kick that could impact on drilling crew safety, and deep gas composition in real time that could support drilling operations.

The Mud logging unit, working 24/24h, utilizes a gas extractor (CVD, constant volume degasser) to agitate recirculated drilling fluid in order to release the gas contained in it. The amount of gas is influenced only by the downhole conditions, regardless from the drilling fluid flow rate and the variations in the mud level.

The CVD has been coupled to both a DualFID chromatography and a TCD-MicroGC, ensuring a real time (24/24h) gas analysis. The DualFID provides determination of hydrocarbons from C1 (methane) to C5 (n- and iso-pentane) with a guaranteed resolution of 1 ppm and an accuracy of 1%; the Micro GC provides an accurate analysis of H_2, H_2S, CO_2, He, N_2 and O_2.

Since the mud/drilling fluid was stored in open pits, N_2 and O_2 gases concentrations reflect air composition. He content was already corrected for air contribution.

In the first 1400 m only CO_2, and minor amounts of H_2, are detected. The two gases show alternating peaks with a maximum value in correspondence of a minor circulation loss (few cubic meters) at 1500m depth. Up to 2600m, almost no gas was measured, with only small amount of CO_2.

CO_2 and H_2 peak again at about 2600 m depth, while other gases are still almost absent.

From 2700 m, in correspondence with supposed depth of a seismic reflection identifiable as H and/or K horizon and a drilling break, CH_4 gas increased dramatically up to 14% v/v and H_2 also peaked at 4% v/v, while CO_2 dropped to few ppm. Also other heavier hydrocarbons appeared, although in low amounts. Reaching the bottom hole depth (2909m) CO_2 increased again, while H_2S was detected in considerable amount for the first time (up to 200 ppm).

To explain the abrupt increase in CH_4 concentration two hypotheses are suggested:

a) a C1-C5 bearing horizon was intercepted; high seismic reflectivity and fragile rocks characteristics (as testified by drilling break, i.e. high rate of penetration) is due to gas entrapped into primary porosity;

b) the Fisher-Tropsch process is supposed to occur; the reaction between H_2 and CO_2, in presence of a catalyst, leads to the formation of alkanes CnH2n+2; in fact, an increase of methane and hydrocarbons occurs while CO_2 is consumed. The open hole (about 500°C and pressure 430 bar) acts as a reactor vessel speeding up the process.

As a final result gas logging during drilling is a useful tool for potentially detecting absorption zones and derive chemical characteristics of gas present in geothermal environment. The larger the gas species analyzed the more information is obtained to help understanding deep processes in HTHP conditions.

Real-time mud logging of Venelle 2 well: insights from noble gases

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Keywords: Helium isotopes, heavy noble gases, mud logging

Abstract

The DESCRAMBLE project represents a unique opportunity to test the real-time monitoring response of noble gases, He in particular, as tracers of fluids of different origin under high-temperature geothermal conditions. Few studies exist in the literature that present data on real-time drill mud gas logging for scientific purposes. Almost all these studies have evidenced the inherent geochemical complexity of the interactions between the different matrices interacting during the deepening of wells under high-temperature conditions. These complexities do not affect noble gases that are chemically inert, and, in some cases (e.g. He and Ar) significantly enriched in natural deep fluids compared to atmosphere.

Noble gas aliquots have been extracted from perforation fluids (mud or water, depending on the depth) after mechanical degassing at the surface. During the drilling of Venelle 2 well, He concentrations were measured in parallel by gas chromatography (continuous gas log) and mass-spectrometry (spot samples). Discrete noble gas samples were analysed for He, Ne, Kr, Xe abundances, and for their isotopic composition at IGG-Rare gases Lab by magnetic (MAP 215-50) and quadrupole (Spectralab200) mass spectrometry.

All gas samples extracted from drilling fluids contain low, but measurable amounts of He ranging from 4.03 to 6 ppm, generally close to the air typical value of 5.24 ppm. Notably, the GC-detector used during real time drilling monitoring failed to detect He in most of the samples. $^{4}He/^{20}Ne$ ratios span the range 0.41 to 0.29, close to air/asw values, indicating that the noble gas atmospheric component derives from the mixing between air and air-saturated water end members. This mixing trend is further confirmed by the behaviour of heavier noble gases, Kr and Xe.

Despite the low He abundance and the atmospheric signature of $^{4}He/^{20}Ne$ ratio, the presence of deep-seated He likely derived from a ^{3}He-enriched source in almost all the samples is unequivocally indicated by $^{3}He/^{4}He$ values between 1 to 1.59 Ra (with Ra = $^{3}He/^{4}He$ reference value for the air). The severe air contamination intrinsically associated with gas extraction device does not allow for the correction of these measured R/Ra values. Although not correctable for air contamination, $^{3}He/^{4}He$ values measured in Venelle 2 well fall into the range of R/Ra values (1.2 to 2.5) measured on fluids collected from three productive wells (Lago 6, Zuccantine 1, and San Martino 5A) located in the surroundings of the Venelle 2 well. It is worth of mention that Venelle 2 well is located in the area of the highest R/Ra values of the Larderello geothermal field, where the so-called K-horizon culminates (Magro et al., 2003, 2009; Gherardi et al., 2005).

Summing up, noble gases data suggest that the perforation of the Venelle 2 well did not intersect any major fracture system draining fluids from the deepest sectors of the local metamorphic geothermal reservoir, as well as from other deeper rock volumes possibly acting as reservoirs for supercritical fluids. The fact that no relevant changes in the $^3He/^4He$ composition were recorded in concomitance with the crossing of the H/K local seismic reflector raises additional questions about the geothermal, geochemical and hydrological significance of this type of seismic reflectors, starting from their significance as possible targets for drilling and industrial exploitation of supercritical fluids.

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Petrophysical properties of core samples from wells around Venelle2

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Abstract

For characterizing the geothermal system around Venelle 2, several measurement campaigns were conducted on multiple core samples from Venelle 2 and neighboring wells. In total, the measurement material comprises over 13 cores from neighboring wells (from depths between 1700 m and 3600 m), and several cores from Venelle 2 (from a depth of around 2800 m). At RWTH Aachen, different petrophysical properties of the core material were assessed at ambient conditions. The assessed properties are crucial for characterizing heat transport in a geothermal system, and comprise: Porosity (ϕ), thermal conductivity (λ), specific heat capacity (c_p), and density (bulk and matrix). Repeated measurements yield average parameter values with associated uncertainty, which are used for calibrating numerical models of the geothermal system around Venelle 2. We calibrated published equations relating specific heat capacity to temperature were calibrated with collected measurement data. Further, we estimated anisotropy values of thermal conductivity for samples with strong schistosity, for subsequent implementation in the numerical models. As the majority of measurement techniques at RWTH Aachen are non-destructive, samples were sent to the Christian-Albrechts-University of Kiel (CAU), after measurements at RWTH Aachen were conducted.

At CAU, a detailed study of seismic properties (P and S wave velocity, anisotropy and shear wave splitting) as well as additional petrophysical properties such as density, stress-strain behavior, Poisson's ratio, and elastic moduli has been carried out. We selected three representative core samples from Venelle 2 for the petrophysical measurements. Measurements were done on sample cubes of dry rocks in a multi-anvil apparatus under in-situ boundary conditions (up to 100 MPa and 450 °C). Rising of pressure yields a velocity increase, closely related to progressive closure of microcracks. Seismic velocities of the Venelle 2 samples show a slight nonlinear sensitivity to the in-situ pressure (<100 MPa). At 30 MPa and 100 MPa constant pressure, the increase in temperature causes the velocities to decrease slowly with linear slopes. P wave velocities show a strong anisotropy, with velocities perpendicular to foliation almost half of the P wave velocity parallel to the sample foliation. Based on assessed wave velocities we derived the petrophysical properties mentioned before (e.g. density, Poisson's ratio, volumetric strain, and elastic moduli) at different pressure and temperature conditions. These results contribute to the reliable estimate of petrophyscial properties of rocks, as well as to reliable and realistic velocity models of the subsurface around Venelle 2.

Petrophysical Characteristics of Basement Rocks – Results of Log and Core Data Interpretation

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Keywords: Log Interpretation, Petrophysics, Reservoir Characterization

Log Interpretation – Venelle 2

A suite of logging data has been recorded in the open hole section of Venelle 2 well down to 1600 m depth. The operation included standard physical tools such spectral gamma, induction resistivity and sonic as well as special tools such as an ultrasonic borehole wall imager and a geochemical tool. Due to safety reasons no tools with radioactive sources (density and neutron) were used in the well.

Based on the methods which have been developed within other wells in Tuscany (Ebigbo et al. 2016), log interpretation has been performed for the basement rocks. In a first step, a simple rock component profile has been generated by using the spectral gamma logs, while porosity curves have been generated from the sonic log. Thermal conductivity (matrix and water filled formation) has been then deduced from rock component and porosity logs. The result of this simple two-component rock assumption has been checked in a next working stage by a multi-mineral approach. Input data for the multi-mineral approach are spectral gamma ray, sonic log and chemical element logs which have been measured by the FLeX tool in the Venelle well. Chemical data curves are available for the elements Si, Fe, Al, Ca, Mg, Ti, C, S from FLeX tool plus K, Th and U from spectral gamma tool. By iterative procedures, different mineral assemblages and different combination of input logs were tested for prognosis. Multi-mineral approach finally based on K, Th, U, Si, Ca, Mg and the sonic traveltime DT for predicting water filled porosity and a multi-mineral assemblage. Mineral prediction resulted in following mean values for the phyllitic basement rocks investigated: quartz (41 %), muscovite (19 %), biotite (15 %), chlorite (14 %), plagioclase (3 %) and calcite (6 %). Graphite and/or pyrite were added in optional modes and predicted with less than 1 %. The mineral prediction reveals a slight increase of quartz and a significant decrease of chlorite with depth. Muscovite and biotite show relative constant values down to ~ 1500 m. Below this depth muscovite dominates over biotite and chlorite.

Comparison of total quartz-feldspar-matrix volumes from multi-mineral and standard approach reveals good agreements over larger sections (Figure 1). Differences occur at depth sections where silicon and potassium is not negatively correlated as it is normally the case for the phyllites. Here, the standard approach of a linear relationship between potassium content, respectively gamma ray activity and phyllosilicate volume fails. This seems to be especially the case in zones of strong sericitic alteration (below 1500 m).

Prediction of Petrophysical Parameter

Multi-mineral results were finally used to calculate a suite of physical properties: porosity, bulk density, grain density and thermal conductivity. In general, porosity is low with a mean of 2.2 %. Bulk density is predicted with a mean of 2.74 g cm^{-3} and grain density with ~ 2.77 g cm^{-3} for the entire phyllite section. Thermal conductivity mean value of the saturated formation is 4.02 W m^{-1} K^{-1}. The incorporation of graphite does not produce a significant increase in thermal conductivity and can therefore be neglected. Sonic logs data were investigated for their quality and their information content regarding formation structures and overlay effects with rock matrix. Due to low quality of shear wave records in the deeper part, a synthetic shear wave log has been produced from rock composition logs by the approach of Greenberg & Castagna 1992. Based on this, mechanical modules and Poisson ratio were calculated. Sonic curves and it's derivates and resistivity logs indicate two zones of increased fracturing (1030 m -1090 m, 1400 m – 1420 m). They show low Vp and Vs data, high Vp/Vs and Poisson ration and low resistivity values. Four other levels are highlighted by increased Vp/Vs ratio and are interpreted as slightly damaged or altered rocks.

Integration of log and laboratory data

Finally core and log data were integrated and results were compared. Here, also log data and interpretation results from the neighbouring SanPompeo wells were included. Several core pieces from Larderello wells have been investigated at Aachen University for thermo-physical properties and later on at Kiel University for acoustic properties under increased temperature and pressure. In parallel a similar rock collection has been investigated for mineralogy and petrography by CNR, Pisa.

Core-log integration concentrates on phyllites, gneisses and micashists, as being the main rock types occurring in the logged depth sections. Unfortunately, no direct comparison of log and core data is possible; because all core pieces are from wells or depth sections without logging data. So, comparison only allow for analogies and general trends. Surprisingly, mean values and standard deviations of thermal conductivity of core pieces (only six samples of phyllites and gneisses) are in an excellent agreement with the log results from the phyllites of Venelle and SanPompeo wells. A guiding value of 4.0 ± 0.6 W m^{-1} K^{-1} can be attributed to the Phyllite Group under saturated conditions. Matrix densities of cores and logs are also in very good agreement with a mean value of about 2.78 g cm^{-3}. ´

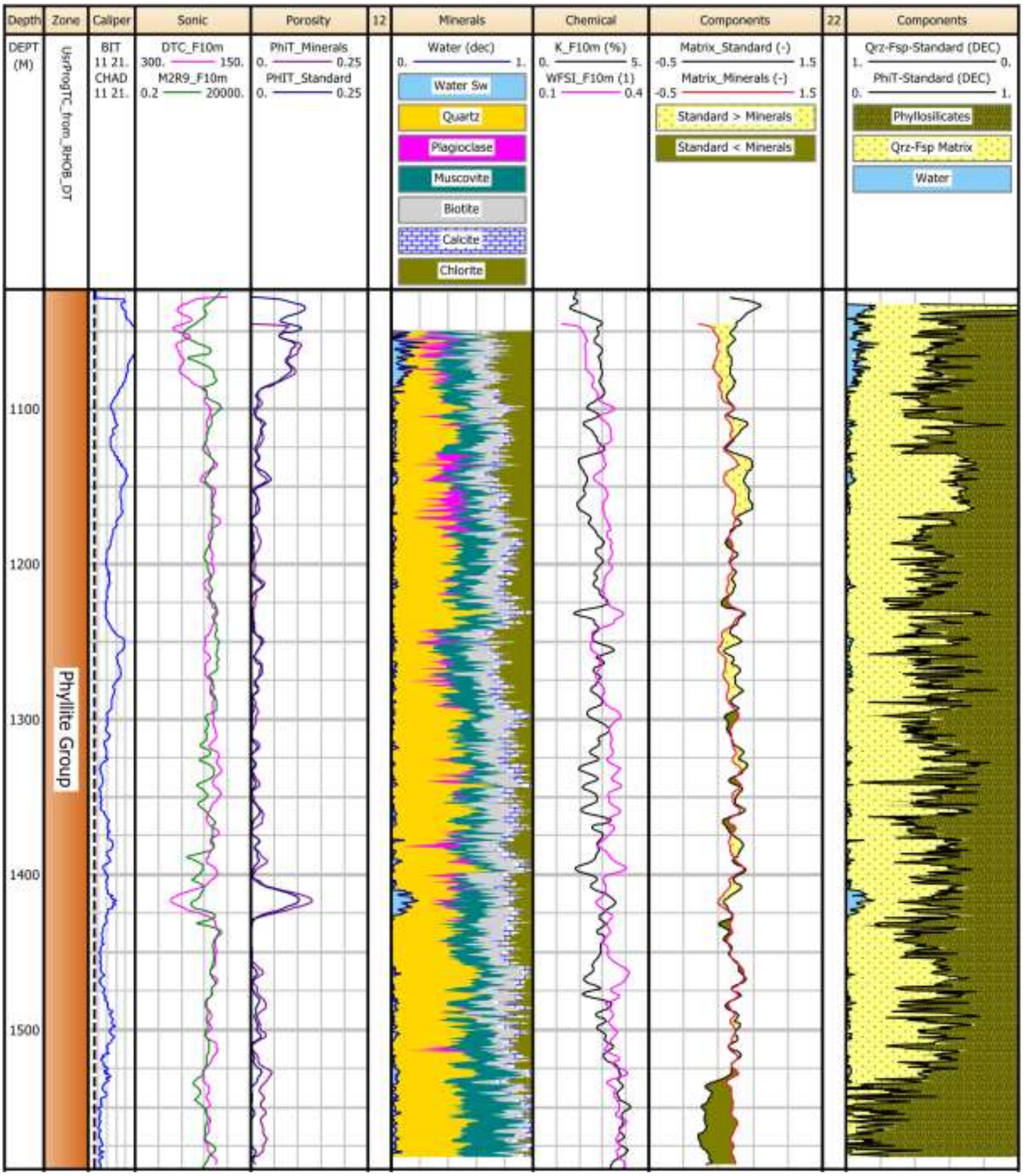

Figure 5: Lithology results of multi mineral and standard approach. Comparison of porosity prediction (track 5) and quartzfeldspar-matrix volume (track 9) from standard and mineral analysis. Porosity of both approaches is in good agreement beside within the deepest section of strong overestimate of phyllosilicates by standard method. Matrix predictions are in good agreement in zones of negative correlation between K and Si. (Logs are displayed as averaged over 10 m sliding window)

The integration of acoustic data from cores can be summarized as follows. Laboratory Vp mean values range from 4.78 km s-1 to 5.87 km s-1, mean Vs values vary between 2.70 km s-1 and 3.63 km s-1. A clear relationship between rock type and Vp and Vs value range is not visible. All rock samples show anisotropies of shear and compressional wave velocities regarding propagation in spatial directions. Anisotropy is correlated with the grade of foliation and shistosity. Low anisotropy is documented for the quarz-feldspar rock samples with no visible shistosity; highest values are measured for narrow foliated amphibolites. All samples show an increase of velocity with pressure at which “pressure anisotropy” is correlated with spatial anisotropy and grade of foliation, respectively. Pressure dependence also strongly effect velocity-density relationship, especially in the lower pressure stages.

For comparison with acoustic core data, sonic data were selected from undamaged/undisturbed depth intervals to avoid data mismatch. Unfortunately, no phyllites have been investigated at Kiel University, so only gneisses and micashists laboratory values are available to compare with. Mean Vp values from undisturbed formation (Venelle and SanPompeo) do not exceed 5.0 km s-1 and thus they are slightly lower than the mean laboratory data of gneisses and micashists. This is also the case for the mean Vs values, which are lower than 3.0 km s-1. Heterogeneity of Vp log data over the entire measured interval is in a similar range than spatial anisotropy measured for the core data, while Vs log heterogeneity is significantly higher. The latter one might be caused by log quality/processing effects.

Core and log data were finally used to define a velocity-density relationship. Established empirical conversions for density prediction have been tested versus measured density log data and a modified Gardner law of Rho = 0.326 Vp0.25 has been found as most reliable for the phyllitic basement. Here, it is to note, that densities which have been calculated from multi-mineral analysis based on chemical logs fit very good with the modified Gardner prediction. This also supports the robustness of the formula.

In general it can be stated that core and log data are in good agreement regarding the thermophysical and acoustic properties. Anyhow, the small number of core samples investigated does not allow for general conclusions regarding the relations between log and core data. Here, further data sets should be integrated, also in order to cover other rock types than gneisses/phyllites in a representative way.

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Post-drilling characterization of pressuretemperature conditions in the Venelle 2 well from petrographic studies and synthetic fluid inclusion analyses

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Keywords: synthetic fluid inclusions, pressure, temperature.

Abstract

Pressure and temperature measurement in the deepest parts of the Venelle 2 geothermal well (i.e. 28002900 m below the ground level, b.g.l.) was a major challenge of the DESCRAMBLE EU project (H2020), since very high temperature and aggressive fluids occurring at such depths hinder the use of conventional logging methods. IGG-CNR has faced this challenge by analyzing synthetic fluid inclusions formed within two different equipment lowered to the well bottom (i.e. 2900 m b.g.l.). Moreover, minero-petrographic studies of three samples cored in the Venelle 2 well also provided information on the thermal regime to which the cored rocks were subjected.

Synthetic fluid inclusions production consists in the trapping of fluid within fractures of quartz crystals free of natural fluid inclusions. To this purpose, pre-fractured quartz chips were placed in a gold capsule, together with a saline-alkaline aqueous solution and silica powder. During the permanence of the capsule at the established depth in the well, aqueous solution entered in quartz fractures, which were sealed, due to the silica oversaturation of the solution. Two methods based on the synthesis of fluid inclusions were used. The first consists in the production of synthetic fluid inclusions in gold capsules placed in direct contact with the environment of the well. Pressure-temperature conditions at 2900 m b.g.l. caused fluid immiscibility since very high-salinity liquid coexists with a low-salinity vapor, as disclosed by fluid inclusions. The highest homogenization temperature of synthetic fluid inclusions indicates temperatures of 510±10 °C, which corresponds to a pressure of 42±3 MPa.

In the second method the gold capsules were placed inside a micro-reactor containing a volume of de-ionised water such that the density of water in the micro-reactor has a critical value. In this case, only temperature can be estimated by synthetic fluid inclusions. This was computed by the intersections between the isochores calculated by microthermometric measurements of synthetic fluid inclusions and the critical isochore of water; this method gives maximum temperatures of 509±8 °C.

Synthetic fluid inclusions indicate temperature of about 510±10 °C at the bottom of the Venelle 2 well; such value appears in agreement with the thermal gradient measured by SINTEF PT tool in the deepest parts of the well. On the other hand, the maximum estimated pressure by synthetic fluid inclusions methods (42±3 MPa) is notably higher than that estimated at 2700 m b.g.l. (30 MPa) by Enel Green Power, thus suggesting that the pressure regime in the deepest part of the well is supra-hydrostatic.

Minero-petrographic studies of the three cores drilled between 2600 and 2900m b.g.l. reveal that they are entirely composed by metapelitic rocks, reasonably belonging to the Monticiano–Roccastrada tectonostratigraphic Unit. This unit, composed mainly of quartz-phyllites and phyllites, is considered to be of pre-Hercynian age, and lie above the Paleozoic Micaschist Group and the deeper Gneiss Complex (Brogi et al., 2005). Phyllitic rocks from the Venelle 2 cores appear affected by poly-metamorphism, evidenced by two deformational stages, and show mineral assemblages typical of low-grade greenschist facies metapelites (quartz, muscovite, biotite, plagioclase, chlorite) with the presence of graphitic matter, sometimes very abundant. Peculiar features occurring in these rocks, such as static porphyroblasthesis of muscovite + biotite, Ca-plagioclase + biotite enriched levels and transversal veins filled by quartz + plagioclase + muscovite + biotite + epidote, could be related to the thermal effects of a supposed underneath pluton. All these last aspects need further in-depth analyses to assess if they can be related to the recent activity of the granite intrusion or if they represent inherited features from previous thermal events.

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Resource characterization post-drilling

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Keywords: Supercritical conditions, thermal gradient, pore pressure, loss of circulation

Abstract

The "Drilling in dEep, Super-CRitical AMBient of continentaL Europe" (DESCRAMBLE) project proposed to drill in continental-crust, looking for super-critical geothermal conditions. An existing well in Larderello (Tuscany, Italy), Venelle 2, was deepened from its previous depth of 2.2 km down to 3.0 km. The targeted fluid was supposed in high pressure (450 bar) and high temperature (450°C) conditions, much higher than those present in the exploited metamorphic basement of Larderello (30-50 bar and 300°C).

The thermodynamics characterization of the geothermal resource was conducted during and post drilling activity by using some specific tests for both temperature and pressure. No prolonged total loss of circulation was encountered during drilling of Venelle_2, so it was not possible to finalize a fluid-dynamic characterization of the formation around the well, although at the moment it is possible to state that a significant permeable formation has not been encountered in Venelle_2.

In the first drilling of Venelle_2 (2006) a very high static temperature was evaluated (gradient 0.1°C/m) by two temperature extrapolations conducted at different depths: about 270°C at 1334m and 360°C at 2212m. During the drilling activities of the DESCRAMBLE project new temperature data were collected:

- At 2490 m a temperature of 386°C was extrapolated by a temperature build-up acquired with a mechanical Kuster. This temperature is in line with the thermal gradient measured during the first drilling of the Venelle_2 well (0.1°C/m).
- At 2815 m temperature greater than 504°C (full-scale of the instrument) was measured. Probably, this temperature is not representative of the static temperature of the formation due to no complete heat return and full scale of the tool. However, a static temperature greater than 504°C at 2815 m could be hypothesized. This value gives a higher temperature gradient (>0.3°C/m) for the deeper part of the well.
- At 2894 m an indirect temperature measurement at 2894m by means of synthetic fluid inclusions was conducted, with a result of 507-517°C.
- At the end of the drilling activity (bottom hole of 3000 m) a temperature and pressure log was conducted by using the SINTEF tool. The temperature profile obtained confirmed the probable abrupt increase of thermal gradient below 2750 m.

During the drilling activities of the DESCRAMBLE project the hydraulic resistance of the rock formation was tested several times by some leak off tests, with a maximum fracturing pressure of 580bar with a total depth

of 2603 m. At 2708 m a partial loss of circulation of about $65m^3$ was encountered. The drilling stopped and no pressure was detected at the wellhead. After, during an injection test, a limited partial fluid loss of about $20m^3/h$ with wellhead pressure of 70bar was observed. A second injection test was conducted at a depth of 2721 m (reached without loss of circulation during drilling). The wellhead was pressurized at 140bar and absorption was about $28m^3/h$. From this test no quantitative estimation of the rock permeability was possible but, on the other hand, it was deduced that the real permeability value could be hardly higher than 1mD and that the pore pressure of the formation could be less than 400 bar.

At 2909m a small loss of circulation happened, about 300-400l/h. A swellable packer was set at 2898m and a leak off test was conducted. Reached 90bar the packer lost its hydraulic seal. Nevertheless it was possible to verify that the rock fracturing at that depth takes place at pressure higher than 350bar. That means the Venelle_2 encountered only a partial fluid loss at a depth of 2700-2900 m, characterized by a very low permeability.

However, even if no permeability was encountered, the temperature and pressure measured in Venelle_2 confirm supercritical conditions at depths of about 3000 m, with temperature much higher than the expected one.

Posters (by alphabetical order of first author)

Heat Flow and Helium Isotopes in the Geothermal Areas of Tuscany (Central Italy)

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Keywords: Heat flow, Helium isotopes, Deep seismic profiles, Geothermal fields, Tuscany

Abstract

A wide part of Tuscany is affected by a large heat-flow anomaly, with maxima corresponding to the geothermal fields of Larderello-Travale and Mt. Amiata. Anomalous heat flow is very often related to the presence of ^{3}He-enriched fluids. The comparison of R/Ra, He/Ne ratios and heat flow through Tuscany along three deep seismic profiles, shows no straightforward correlation among these parameters. A phased correlation exists at Larderello-Travale (Fig. 1), where maxima are almost coincident, while they appear decoupled at Mt. Amiata. Different heat and He transport mechanisms through the crust are the most likely explanation. At Larderello-Travale, the almost constant value of R/Ra in fluids issuing at surface indicates that the contribution of hot ^{3}He-enriched fluids must have occurred through deeply rooted faults. The decoupling of the heat and He anomalies in the Mt. Amiata area is then related not only to a lower degree of fracturing and/or a different depth of the faults roots, but also to infiltration of meteoric water in shallow aquifers.

The cross-correlation between physical parameters (heat flow) and geochemical parameters (isotopic composition of helium) emerges as a powerful tool to investigate potential geothermal areas and allows to improve and complement the interpretation of seismic profiles.

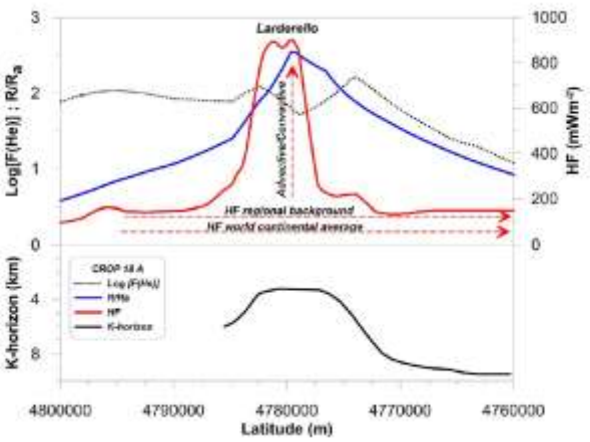

Figure 6: HF, R/Ra, F(He) trends and depth to the K-horizon along the CROP 18A seismic profile.

Numerical Aspects of the Simulation of a Supercritical Water/Steam Geothermal Reservoir in Tuscany, Italy

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Abstract

In high enthalpy geothermal systems, such as the study area in DESCRAMBLE, the state of water can reach from liquid over vaporous to supercritical. Hence, numerical codes for simulating the geothermal system need to consider these multiple phases. We implemented a water-pressure enthalpy formulation for the simulation of supercritical water/steam geothermal reservoirs into SHEMAT-Suite. This formulation uses the same primary variables, pressure and enthalpy, across all phase states, namely liquid, gas and supercritical. The implementation is based on PETSc (the Portable Extensible Toolkit for Scientific computation) and allows the efficient solution of the occurring non-linear systems on laptops as wells as super-computers. We showed weak scaling of our method on JUQUEEN, the parallel high-performance computer from Jülich, with system sizes of 25 million cells and up to 1,024 compute cores. For this, high-performance linear solvers relying on algebraic multigrid are used. Finally, we show simulation results from the surroundings of the borehole Venelle-2.

Synthetic Seismic Reflection Modelling of the CROP18A: An Image of the K-horizon in the Larderello Geothermal Field

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Keywords: Synthetic seismic modelling, CROP-18A, K-horizon, physically perturbed layer

Abstract

Exploration strategies of geothermal reservoirs may significantly benefit from the development of synthetic seismic reflection modelling by analyzing prospective features on acquired seismic reflection data. The synthetic seismic reflection modelling represents an important instrument to better calibrate geologicalgeophysical interpretation and model reconstruction. To be elaborated a synthetic seismic reflection profile requires a conceptual geological model of the subsurface structure and a hypothesis on the physical properties.

The K-horizon, probably drilled by the San Pompeo 2 well (Gianelli et al., 1997), has been widely observed in several seismic lines and it is characterized by a strong amplitude reflective signal (Batini et al., 1978, Accaino et al., 2005). In this study, geological and geophysical available data have been integrated to develop a 3D geological-geophysical model of the portion of the Larderello geothermal field drilled by the San Pompeo 2 well. A 2-D model has been then extrapolated from the 3D geological-geophysical model along the CROP18A seismic reflection line acquired within the CROP project (Scrocca et al., 2003).

The geological surfaces modelled by means of well data, published geological information, and subsurface geological maps are the Neogene deposits, the Ligurian Complex, the Tuscan Nappe plus TWC, and the Metamorphic Unit. The velocity ranges defined for the aforementioned units derive from previous literature data (Batini et al., 1978, Accaino et al., 2005). Due to its geological-geophysical complexity, the attribution of P seismic velocity to the unit below the K-horizon is one of the main issues for this study and for the seismic exploration in the Larderello geothermal field in general.

The synthetic seismic modelling of the line CROP-18A has been generated using the exploding reflector seismo-acoustic approach (Loewenthal et al., 1976) which has been developed in Matlab by the CREWES consortium and partly modified by us in this application.

Besides an acceptable calibration of the line CROP-18A with homogeneous units, 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 an asymmetric randomized velocity distribution simulating a rock physics model with fluid inclusions corresponding to the K-horizon.

The responses with the PPL model indicate that:

- A PPL could explain the reflectivity features and pattern of seismic horizons with a strong amplitude reflective signal observed in the Tuscan geothermal area;
- Asymmetric velocity distribution (a general decrease in velocity within the PPL) generates a pseudo-layer which exhibits reflection events both at the top and at the bottom of the PPL (sometime observed as typical pattern of reflectivity);
- In the case of thin layer (about 100 m) the wedge and PPL exhibit a response similar to a homogeneous layer but characterized by a diffuse reflectivity;
- A PPL between 100 m and up to 500 m in thicknesses generally shows, below the K-horizon, responses characterized by an increase of the diffuse reflectivity pattern similar to the one observed in the original data stacked section.

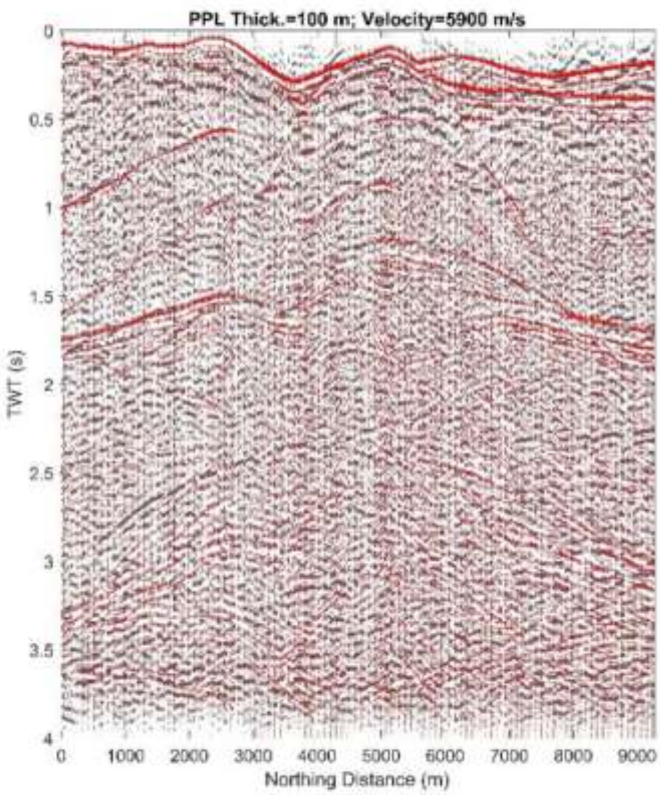

Figure 1: Synthetic stacked profile with a PPL of 100m in thickness and a P velocity of the unit below the K-horizon of 5900 m/s. The synthetic seismic response, plotted in positive variable area in red, is superimposed on the processed stacked data, plotted in gray.

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Isotopic constraints on crustal partial melting in the roots of Larderello geothermal field

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Keywords: granite, amphibolite, metapelite, partial melting

Abstract

Peraluminous S-type granites with high SiO_2 and K_2O/Na_2O typically derive from water undersaturated magmas produced mainly by fluid-absent partial melting of metasedimentary continental crust. They are characterised by high $^{87}Sr/^{86}Sr$ (>0.710) and $d^{18}O$ (+10/+16 ‰) coupled with low neodymium (<0.5122) and hafnium (ε_{Hf} < ca. -6) isotopic compositions: a peculiar isotopic signature that is inherited by their metasedimentary crustal sources. However, many S-type granites contain an excess of CaO, FeO, MgO and TiO2 that is not consistent with experimental partial melts of metasedimentary protoliths. In the past, such mafic excess was mainly attributed to mantle-derived magmas mixed-mingled with crustal melts and/or to restitic phases inherited from partially melted crustal protoliths. Recent advances in granite petrology indicate that, in many cases, the observed geochemical and isotopic trends can be explained by the variable entrainment and subsequent dissolution of peritectic phases (ortho- and clino-pyroxenes, garnet, ilmenite) internally produced in the crustal melting zone (Stevens et al., 2007; Farina et al. 2012). In particular cases (e.g. Elba Island monzogranites, Tuscan Magmatic Province; Farina et al., 2012; 2014), the positive correlation between Ca and Fe+Mg coupled with Sr-Nd isotopic variations indicate that amphibolites participated in the anatexis of a crustal source, for the most part made of metasedimentary rocks. Latter results are controversial because a high degree of partial melting in amphibolites requires temperatures well above 900°C; a limit possibly imposed by the buffering effect of endothermic melting reactions in the crust. The study of anatectic terrains (migmatites) indicate that crust volumes experiencing partial melting, independently on the pressure, rarely reached temperature higher than 900°C. UHT metamorphic conditions (T>900°C) can be obtained only in terranes that previously experienced multiple thermal events and melt loss, thus in crustal sectors that are not anymore fertile. Moreover, dehydration melting of amphiboleplagioclase-rich rocks produce melts of granodioritic-tonalitic composition, that are in contrast with the usual high K/Na character of many peraluminous granites. Available melting experiments conducted on interlayered pelite-amphibolite, may help to descramble the paradox. In fact, diffusional effects at incipient melting interfaces enhance melt production in the metasedimentary rocks – also in relatively feldspar-poor lithologies – providing amphibolite-like components without having to reach extremely high temperatures. Thus, melt productivity in the continental crust may be larger than expected, because interactions among different lithologies are likely to be common in nature.

Interlayered amphibolite-micaschist formations have been frequently intersected in the deepest part of the Larderello geothermal field. In the frame of DESCRAMBLE Project we selected several samples of pre-Triassic metamorphic basement cored at depth by geothermal exploratory wells in Larderello. Sr-Nd isotope data and geochemical-isotope modelling are here provided supporting the origin of some of the S-type peraluminous granites from Tuscan Magmatic Province by partial melting of interlayered pelite-amphibolite protoliths. Such sequences represent a quite common feature of the metamorphic basements all along the Alpine and Apennine-Maghrebide chains, a character inherited by their common pre-Mesozoic/pre-Variscan derivation from the northern Gondwana paleo-margin.

This conclusion put new insights on the thermal state of the middle-lower crust under the Larderello-Travale geothermal field. Partial melting of an interlayered metasedimentary-amphibolite crust provides enough melts for feeding plutons in the shallow crust without having to reach temperatures larger than 900°C.

UNRAVELLING THE THERMAL EVOLUTION OF THE LARDERELLO GEOTHERMAL FIELD BY AN INTEGRATED MULTIDISCIPLINARY APPROACH

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Abstract

In the western sector of the Larderello-Travale geothermal field the occurrence of high temperature-high pressure fluids hosted in the metamorphic basement below the currently exploited hydrothermal systems has been discovered in the early 1980s during drilling of the San Pompeo-2 well. Nowadays, in the area referred as Lago Boracifero, the deepening down to 2900 m of the pre-existing Venelle-2 well confirmed the presence of a remarkable thermal anomaly characterized by temperatures beyond 500°C near the bottom hole. This thermal anomaly should be framed in the overall regional heat flow anomaly affecting the Southern Tuscany and linked to the evolution of the Tuscan Magmatic Province. Shallow plutonic bodies have been intersected by deep drilling both in the western and in the eastern part of the geothermal field. Isotopic ages (U-Pb, ^{40}Ar-^{39}Ar and K/Ar) of magmatic minerals indicate that the studied intrusions emplaced as multiple pulses at ca. 3.8-3.6 Ma, 3.3-3.1 Ma, 2.7-2.5 Ma and 1.9-1.6 Ma. Although many boreholes do not intersected intrusions, most of them reached the contact metamorphic rocks whose micas give isotopic ages that roughly fall within the range outlined by granites. Nevertheless, the present-day high temperature anomaly is not compatible with heat contribution from these relatively old intrusions. In order to forecast the present-day temperature distribution, our numerical strategy is mainly based on the history matching of the detected past thermal climax controlled by the Pliocene-Pleistocene magma inputs. We hypothesized a very recent magmatic intrusion but similar in size, emplacement temperature and other physical characteristics at a depth of the order of 3-5 km. We set-up a 3-D thermal model that numerically simulates the temperature variations in a layered crust, induced by the emplacement of intrusive bodies over a time span of ca 4.0 Ma. The in-hole temperature patterns measured in the San Pompeo-2 and Venelle-2 wells, whose bottom-hole reached yet contact metamorphic rocks, were used as thermal constraints to validate the numerical results at the present-time. Instead, the fossil thermal evolution was constrained by the petrological information coming from the San Pompeo-2 well. In the sector of the Lago Boracifero, the available thermal, geochemical and petrological data seem to be compatible with the waxing stage of a thermal wave triggered by a recently emplaced intrusion. The numerical result constrained this thermal event to approximatively 40-50 ka ago.

A novel high temperature wireline logging tool for measuring temperature and pressure in supercritical geothermal wells

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Keywords: Logging tool, wireline, memory tool, high temperature, high pressure, dewar, supercritical, geothermal

Abstract

Exploitation of super-critical water from deep geothermal resources can potentially give a 5-10 fold increase in the power output per well. Such an improvement represents a significant reduction in investment costs for deep geothermal energy projects, thus improving their competiveness. The ongoing European Horizon2020 DESCRAMBLE (Drilling in dEep, Super-CRitical AMBients of continental Europe) project will demonstrate the drilling of a deep geothermal well with super-critical conditions (>374°C, >220 bar) by extending an existing geothermal well to a depth of 3km. State-of-the-art electronic logging tools does not operate reliably at these conditions. In the DESCRAMBLE project, SINTEF has developed a novel pressure and temperature logging tool for monitoring these supercritical conditions.

The logging tool components; high temperature electronics, sensors and batteries are shielded from the environment by a heat shield (Dewar). A pressure vessel with special seals, envelops the dewar making the target specification for the tool 6 hours of logging operation time at 450°C/450 bar. Such dwell time is necessary in order to log a 3km deep well with peak temperature of 450°C. A high performance heat and pressure shield protect the electronics platform that can operate and store data up to a minimum of 200°C, with some key components targeting as high as 300°C. Having the thermal performance to be able to operate for 6 hours at 450°C also means that the tool can operate with even longer dwell time in other applications

where temperature is lower. Alternatively, it can operate at the same dwell time with a lower internal temperature resulting in more available electronic components that can be used.

A field-test of the tool was performed in an off-line geothermal well (Lumiera) at Enel Green Power's facilities in Larderello, Italy in February 2017. The performance of the tool was compared with the Kuster K10 tool – the current state-of-the-art high temperature geothermal logging tool commercially available. The SINTEF tool measured the same pressure and temperature profile of the well compared as Kuster K10 and had in addition a much lower internal temperature gradient.

Two successful logging runs was performed with the SINTEF tool in the Venelle 2 well being drilled in the DESCRAMBLE project. First run was performed in late September down to 2610m with measured max temperature 372.9°C. The second run was performed in start of December down to 2810m with measured max temperature 443.6°C.

Advanced seismic imaging of the K-Horizon below a geothermal field in Southern Tuscany

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Abstract

We applied Fresnel Volume Migration imaging technique on a three-dimensional seismic data set to successfully image the K-Horizon below a geothermal field in Southern Tuscany, Italy. The challenge in imaging the K-Horizon below this region were the presence of strong wavefield scattering and low signal-tonoise ratio in the seismic data records. The migration velocity model was carefully constructed using firstarrivals traveltime tomography, taking into account the velocity function from a zero-offset vertical seismic profiling measurement in the area. Prior to the imaging, the data was carefully preprocessed in the time domain. The key in the data preprocessing was the implementation of tomostatics, as well as statistical trace muting to prevent degradation of the stackpower due to severely incoherent noise in the seismic data. Our imaging approach has resulted in a clear and reliable structural image of the K-Horizon, as well as provided the basis for a successful exploration and characterization of the potential geothermal reservoir.

Quality Evaluation of Optical Fiber DAS and Geophones Applying to Geothermal resources

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Keywords: DAS, earthquake observation

Abstract

Geothermal sources with porous rocks containing vapors or hot water could have seismic properties distinct from surroundings and the geothermal reservoir might be boiling and generating seismic tremors. Through the time-lapse study of oil and gas reservoirs, we carried out seismic imaging of the temporal change using backpropagation of the residual waveforms, in which receivers behave as a source array. We apply this method to the geothermal exploration. Distributed Acoustic Sensor (DAS) can give seismic records at a few meters interval along the optical fiber elongation as a dense receiver (or pseudo source) array. DAS uses backscattering of input laser and sense the strain at any location, while a magnet-coil geophone measures the particle velocity. To examine the discrepancy of two measurements, we carried out a field test using the Schlumberger hDVS system and geophones.

Three 100-m-long optical fibers were buried at 20 cm depth below the ground surface. 4.5 Hz vertical geophones with 1 m spacing and eighteen 3C geophones with natural frequencies of 1 or 0.2 Hz were placed along the fibers. The hDVS measures the strain rate (Hartog, 2017). To compare the records of geophones and DAS, we calculated stain rates using the 3C geophone records, where we took the difference between horizontal waveforms of two adjacent geophones and divide by the distance and then all the strain rate for the nearest pairs were averaged. We observed two natural earthquakes whose epicentral distances were both ~100 km.

The DAS records for M3.1 Ibaraki earthquake features array seismic records in 100 m line. Three fibers located nearly the same positions show similar waveforms except subtle differences. Comparing the strain rate calculated by geophone records and the DAS records for the earthquake, surprisingly two waveforms seem almost identical although amplitude variations show some difference. For another M4.2 earthquake which occurred near Izu Oshima, we obtained similar waveform resemblance.

We compared DAS and geophone records in strain rate domain to show extremely nice fitting. However, geophones placed on the ground and fibers buried in the ground can be affected by the local ground condition in a different way. The records obtained by three fibers show some differences, while the

discrepancy among two geophones at the same location is smaller. This could be due to variation of the sensitivity and/or coupling to ground. For the measurements in the borehole or at the ocean floor, we might consider to get the same coupling to the ground.

This project was funded by The Mechanical Social Systems Foundation. The CRIEPI institute provided the test field. The experiment was done by using Schlumberger hDVS and we express our thanks to Mr. Kimura for his great efforts to the operation of hDVS.

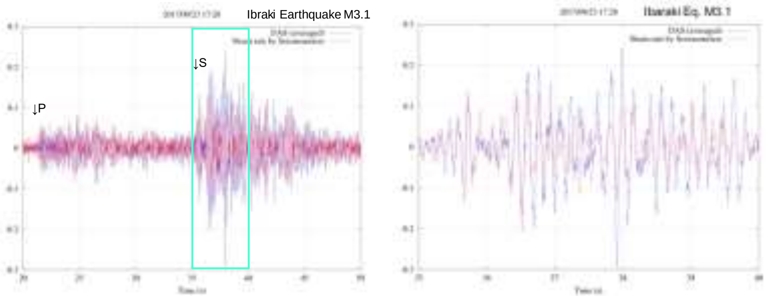

Figure 7: The DAS records (blue) and calculated strain rate using geophone records (red) for M3.1 Ibaraki earthquake. The right panel shows enlarged version of rectangle box in the left. Amplitudes are normalized.

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Imaging of Supercritical Geothermal Reservoir Using Full Waveform Inversion Method

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Keywords: supercritical water, geothermal, full waveform inversion, time lapse

Abstract

The supercritical water is attracting world geothermal people as a future important renewable energy. The critical point of pure water is 373.95°C and 22.064 MPa. In Kakkonda geothermal field in Japan, a scientific drilling showed the temperature was >500°C at 3,800 m depth. There are several leading countries such as Iceland, USA, Mexico, Italy and Japan for this supercritical energy source. In Japan, NEDO is promoting the supercritical geothermal source.

We have used backpropagation technique of residual waveforms to image the temporal changing reservoirs (Kasahara and Hasada, 2016). In recent geophysical exploration, the full waveform inversion (FWI) technique has been applied to the imaging of subsurface. To estimate the physical properties at the supercritical zone, we applied the FWI method by Tromp et al (2005). The sensitivity kernels for compressibility, rigidity and density can be obtained by the adjoint method using backpropagation. Because the waveforms at receivers are considered to be new seismic sources by the reciprocity principle of Green's function, we assume to use fiber optical DAS receivers along the borehole. We carried out a simulation with a seismic source placed in the downhole at 2 km depth. In the simulation, we tested three different locations of source, 5, 3 and 1 km from the drilling borehole and reconstructed the image. We assumed 1 km long x 200 m thick supercritical reservoir at 4 km depth with the physical property change of ΔVp=5% ΔVs=5% and $\Delta\rho$ =2.5%. The results show satisfactory retrieval of the assumed zone. The source at 3 km gave the best results. After several iterations in the inversion, the Vp, Vs and density were retrieved as 4%, 4% and 2% at the almost exact location and thickness, respectively. The satisfactory results suggest that the proposed technique is very promising for the supercritical heat energy investigation.

The quality of DAS data has been tested in field, and it can be comparable to seismometers. The DAS can be used at high temperature circumstances as ~500°C. The current simulation does not include noise test. If we use ACROSS (Accurately Controlled and Routinely Operated Signal System) described in Kasahara and Hasada (2016), background noise can be separated from source signal using spectral comb method. In addition, stacking of data for long duration enhances the S/N drastically. We could use several weeks data for imaging. In the true situation, distribution of supercritical zone or low-velocity zone might cause the scattering of seismic waves.

This presentation is based on results obtained from a project commissioned by the New Energy and Industrial Technology Development Organization (NEDO). We express our great thank to NEDO and officers in NEDO.

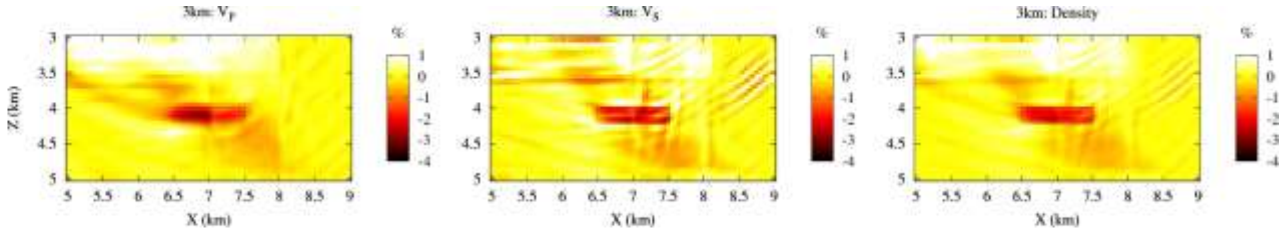

Figure 8: Simulation results for P-wave velocity, S-wave velocity and density (left to right). A single source at (X, Z) = (3, 2) and receivers at surface, in two boreholes and horizontal well at the depth 5 km are assumed. The input temporal changes (5% in velocities and -2% in density) are reasonably recovered.

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An Overview of the EGS Collab Project – Fracture Stimulation and Flow Experiments for Coupled Process Model Validation at the Sanford Underground Research Facility

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Keywords: EGS, field fracture stimulation and flow experiments, coupled process modeling

Abstract

The objective of the EGS Collab project is to establish a suite of intermediate-scale (~10-20 m) field test beds coupled with stimulation and interwell flow tests to provide a basis to better understand fracture stimulation methods, resulting fracture geometries, and processes that control heat transfer between rock and stimulated fractures. We have already developed the first experimental test bed for conducting these experiments at the Sanford Underground Research Facility (SURF), located in Lead, SD. Our experimental site is located on the 4850 level (1478 m below the surface) of SURF, a former gold mine, in the Precambrian Poorman Formation phyllite. The test bed consists of a stimulation/injection borehole, a production borehole, and six monitoring boreholes (Fig. 1). The borehole layout was designed so that the axes of the injection and production boreholes are parallel to S_{hmin}, which will cause hydraulic fractures to be generated perpendicular to the boreholes. In this initial test bed, we will perform well-controlled, in situ experiments focused on creating a series of hydrofractures that connect the injection and production boreholes, and these fractures will be used to evaluate fluid flow and heat transfer. The testing and evaluation of models are key goals of the EGS Collab experiments. The development of Enhanced Geothermal Systems (EGS) as sustainable and commercially viable resources will require an ability to accurately predict the flow rates and changes in temperature of fluids produced from production wells over time. Complex heterogeneous fracture pathways can lead to channeling, short-circuiting, and premature thermal breakthrough, thus complicating EGS. These experiments will provide a means of testing tools, codes, and concepts that could later be employed under

geothermal reservoir conditions at the Frontier Observatory for Research in Geothermal Energy (FORGE) and in EGS. Pre- and post-test modeling of each test will allow for improved experimental and monitoring design, model prediction and validation. The comprehensive suite of instrumentation consists of continuous activesource seismic monitoring (CASSM), passive microseismic (MEQ), acoustic emissions (AE), electrical resistivity tomography (ERT), borehole pressure monitoring, in situ borehole deformation monitoring using the SIMFIP tool, and continuous distributed monitoring of temperature, seismicity, and strain using fiber optic cables; this suite of sensors will be used to collect high-quality, high-resolution geophysical and fracture characterization and fluid flow data. These data will be analyzed and compared with models and field observations to further elucidate the basic relationships between stress, induced seismicity, and permeability enhancement. We will observe and quantify other key governing parameters that impact permeability, and will attempt to understand how these parameters might change throughout the development and operation of an EGS project with the goal of enabling commercial viability of EGS.

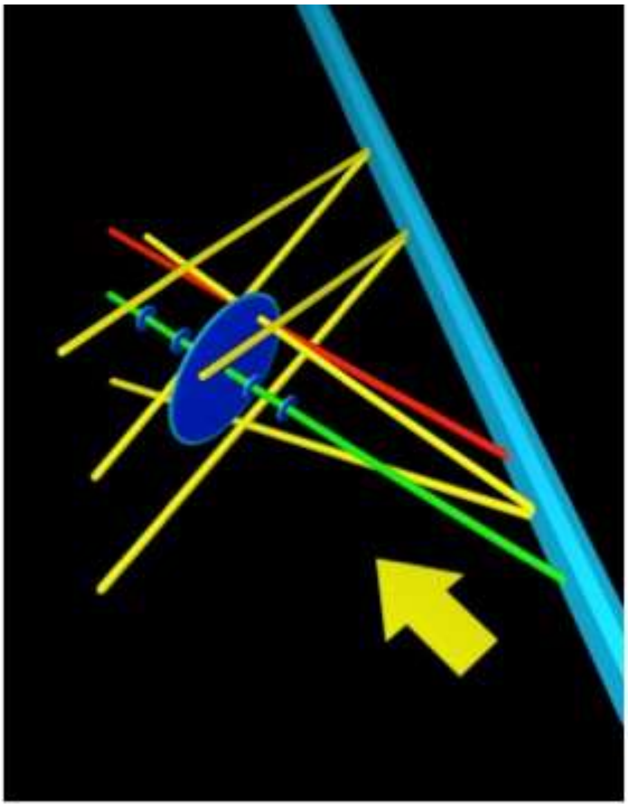

Figure 9: Layout of the EGS Collab borehole test bed developed on the 4850 level (1478 m below ground surface) for fracture stimulation and flow experiments. Boreholes are ~60m in length. The green borehole is the stimulation/injection borehole, the red borehole is the production borehole, and the yellow boreholes will contain an array of sensors to monitor the experiments. The yellow arrow indicates north. The blue discs represent zones in the stimulation well that were notched to facilitate hydrofracturing in the design direction, which is perpendicular to S_{hmin}; the larger blue disc is a conceptual fracture trajectory from a notched section of the borehole.

Acknowledgements

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Effects of seismic anisotropy on target depth determination in geothermal exploration

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Abstract

The characterization of geothermal reservoirs is primarily based on seismic imaging techniques. In most cases the underlying physics of seismic wave propagation relies on an isotropic acoustic or elastic approximation. In this study we investigate the effect of elastic anisotropy on the depth estimation of geothermal target horizons in seismic images. Realistic values for Tilted Transverse Isotropy (TTI) anisotropic elastic models are estimated from in-situ HP/HT laboratory ultrasonic measurements of rock samples from the Larderello area. Seismic imaging by anisotropic Reverse Time Migration of numerical scattering experiments and reflection seismic data from the study area reveal a vertical displacement of up to 500 m for geothermal target layers compared to the isotropic elastic case.

Seismic reflection structure of a high-temperature geothermal reservoir from Monte Carlo inversion

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Abstract

The K-Horizon is a well-known seismic reflection structure of regional extent in the Larderello area. The geological nature of the K-Horizon is unknown though. It is supposed to be a geothermal reservoir where supercritical conditions could to be possible (~450°C temperature). Investigation of the structure and geothermal potential of the K-Horizon is one of the main objectives of the collaborative DESCRAMBLE project of the European Union Horizon 2020 program.

Petrophysical laboratory data and geologic field observations suggest that the K-Horizon consists of alternating layers of fractured, fluid-containing (low seismic velocity) and unfractured rocks (high seismic velocity) that may seal a reservoir of superhot fluids. Indications on the low- and high velocity ranges are available from borehole samples from the area. We used this information as a starting point for modeling the seismic signature of the K-Horizon and for estimating its spatially variable structure from high-quality field seismograms from a 3D-seismic survey. For the seismic inversion we applied a Monte Carlo approach:

In order to verify, whether such a layered system would produce the dominating reflectors in the way they are observed throughout the 3D-seimic survey we composed random models of alternating high- and lowvelocity layers. The velocities were allowed to vary around a mean within a Gaussian distribution. The layer thicknesses were drawn from a Frechet distribution with a mode of 80 m and shape such that a minimum thickness of 20 m was ensured. This lower boundary corresponds to the theoretical resolution capacities of the survey instrumentation. Vertical incidence seismograms were produced by convolving the source signal (a vibro-sweep) with the reflectivity series and then correlated with the real time-migrated data. We computed more than one million models. For each input trace the models yielding the ten highest correlation coefficients were averaged to obtain a representative time-velocity model.

Adjacent traces show very consistent results in terms of layer thickness and velocity. Thus, the observed seismic time sections are very well represented by these time-velocity model traces. It turns out that the KHorizon is well defined by at least one pair of thin high- (10-25% against background) and low- (-10-25%) velocity layers. Moreover, the variation between all contributing models of a trace is lowest around the KHorizon. Together with the enormous velocity contrasts, this strongly supports the idea of the alternating layer model. In addition, the large number of considered models enables a careful uncertainty analysis.

Chemical characterization of circulation fluids during drilling of the Venelle-2

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Keywords: Venelle-2, circulation fluids, water chemistry

Abstract

During drilling at the Venelle-2 well an attempt to characterize the circulation fluid exposed to supercritical conditions was done. The aim was to identify potential inputs from geothermal fluids, thus gaining information on possible productive zones, and/or investigate water/rock interaction at high P & T (HPHT) conditions, comparing the content of selected dissolved compounds in circulation fluid. Drilling fluid was sampled before and after its circulation in the well.

Drilling operation have implied the use of chemical additives in order to manage properly the drilling. In particular, at Venelle-2 the well-known physical and chemical low resistance of commercial sludge at supercritical conditions have forced the development of a special experimental mud, which was tested in laboratory and then during the drilling. The test was stopped on October 23th, 2017 at the depth of 2708 m, because the developed mud drilling gave negative results in terms of physico-chemical stability, impeding the prosecution of the drilling activity. Therefore, the drilling was continued using available geothermal water as drilling fluid, down to the depth of 2910 meters.

Collected water samples during this last stage, all look dark and have some suspended material and show oily substances at the surface. Accordingly, samples were filtered first at 0.45 µm and then at 0.2 µm, and finally diluted 50 times, before being analysed.

The concentrations of Cl, SO_4, SiO_2 and F were determined, which were considered potential constituents of a geothermal fluid. Anions species were determined by means of the Metrohm883 Basic IC Plus ion chromatograph (IC). The IC instrument was equipped with a column Metrosep A Sup4 (250/40), since it is particularly suitable for separation of anion species in complex matrix. However, despite the samples pretreatment done before analyses, the "hard" matrix of these samples did not allow the whole set of analyses to be analyzed and completed. In particular, the IC column was compromise and analyses thus stopped.

In the analyzed samples, the chloride content appears quite homogenous, whereas sulphate shows a wider compositional range. Fluoride data also show a wide range of variation.

A mixture of all used additives is expected to be provided from the borehole. These additives are composed by inorganic and organic compounds, also containing Mg, Ca, Ti, SiO_2 and others chemical elements, making difficult the identification and the interpretation of the significant variations of dissolved chemical compounds in circulation water. In addition, taking into account that geothermal water was used as drilling fluid after the use of mud (which experimented gelling problem), the mix of all used additives + mud is expected inside the borehole, as well as the sum of their contributions to the chemistry of the circulation water extracted by the Venelle-2 well.

Assuming the geothermal fluid is enriched in Cl, the constant concentration of Cl can be easily explained with the hypothesis that no formation fluid was encountered. The variations in SO_4 and F could be ascribed to chemicals added or, less probably, to water/rock interaction. Given the P & T measured, the drilling water underwent supercritical conditions even for prolonged days when the bit remains inside the casing (at 2600 m of total vertical depth) during drilling pauses or log registrations. However, taking into account the large uncertainties posed by the use of different kinds of chemical additives and geothermal waters it was no possible to propose hypothesis regarding the geochemical processes affecting the water circulated inside the Venelle-2 well. Probably, this issue represents one of the main problem which limit the overall interpretation of mud/fluid logging data in geothermal exploration at least in HPHT conditions.

Special effort should be addressed to develop specific procedure in order to reduce the uncertainties for sampling and sample treatment before analyses.

NE-trending shear zone affecting the Larderello Geothermal Area (southern Tuscany, Italy): kinematic data and comparison with local focal mechanisms

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Keywords: transfer zone, kinematics, stress field, Larderello geothermal area

Abstract

We refined the structural setting and faults kinematics of structures affecting the Larderello geothermal field. We present a new structural and geological map integrated with public boreholes and geophysical data (by ENEL GreenPower), highlighting a NE-trending shear zone passing through the whole geothermal area. 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. The study shear zone interrupts the lateral extension of the NW-trending normal faults delimiting the Pliocene-Pleistocene structural depressions (Pomarance and Anqua Basins, Bossio et al., 1993), the latter filled up by marine to continental sediments. Contrastingly, in other cases, the NW-trending faults dissect the NE-trending segments, thus suggesting a contemporaneous activity of 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 contemporaneously ot the development of the Tuscan basins (Martini and Sagri, 1993; Liotta et al., 1998; Brogi et al., 2005). 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 (as indicated by geophysical data), in correspondence of the structural depression that developed within such a shear zone, accounts for the possible control exerted by the NE-trending shear zone on the magma emplacement and, consequently, on the location of the local heat flow anomaly (up to 1000 mW/m^2. 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.

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Performance of Special Material & Equipments

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Keywords: Drilling materials, Innovative technology

Abstract

During DESCRAMBLE project, drilling operations in extreme conditions were carried out in the well Venelle_2 safely and can be considered a significant success of the project. To achieve this result, innovative geothermal technologies, equipment and materials specifically designed for extreme temperature and pressure conditions and specific drilling procedures have been used, representing a significant learning opportunity for the geothermal drilling industry.

In consideration of the extreme temperature (450°C) and pressure (450 bar) expected conditions at bottom hole, EGP decided to implemented the standard technologies by some special equipment projected for this specific well, in order to minimize safety risk and increase the performance.

During the planning phase of the well, the focus has been on the well materials (casing, cement and wellhead). A specific laboratory study was performed to choose the best cement for the application, comparing different types of high temperatures blends, as well as a detailed casing design study, considering the presence of H_2S, to avoid sulphide stress corrosion phenomena or failures due to the high compressive load. With the aim of increasing the well control while drilling, different innovative solutions for geothermal drilling were adopted with the intention of improving the monitoring systems (mud logging), mud properties (both the type of fluid and the cooling system), rate of penetration and durability in hard temperature hard rock (bit) and real time pressure control (managed pressure drilling). Materials and other solutions were designed or selected among high performance products available on the market. A particular attention was also addressed to acquire information on the fracture gradient at different depths, including sections of open hole isolated by using an innovative sweallable packer suitable for high temperature.

After completion of drilling activities, we can say that the performance of the new materials and equipment identified to be used during the operations were in line or ever exceeded the expectations, although drilling conditions in some intervals were even more extreme than expected, especially in terms of measured temperature.

Geochemical activities on geothermal and drilling fluids during the DESCRAMBLE project

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Keywords: Geochemical activity, Geothermal fluids, Real-time drilling samples, Isotopes.

Abstract

We report on geochemical activities (task 4.6) conducted in the frame of the Work Package 4 (WP4) “Reservoir characterization”. The objective of WP4 is to achieve a comprehensive understanding of the geological structure and the physical conditions of the supercritical reservoir. The aim is to obtain a geochemical characterization of fluids drained during the deepening of the Venelle_2 well. The focus is both on fluids produced from currently exploited layers and from deeper layers, possibly associated with major local seismic reflectors (H- and/or K-horizon) under T, P supercritical conditions (referred to water).

Lab / Team	Matrix	Type of analysis
CNR Rare Gases Lab	Gas phase	He, Ne, Ar, Kr, Xe
CNR Stable Isotope Lab	Condensed vapor	d^2H, $d^{18}O$
CNR Stable Isotope Lab	Gas phase	$d^{13}C$-CO_2, $d^{13}C$-CH_4
CNR TIMS Lab	Condensed vapor	$d^{11}B$, $d^{34}S$, B
CNR-Chemical Lab	Circulation water	Cl F, SO_4

We discuss sampling and analytical methods, along with results obtained for the representative samples – when available – collected during the perforation of the Venelle_2 well.

We also show chemical and isotope data on fluid samples collected from three wells (Lago_6, Zuccantine_1, and San Martino _5A) located in the surroundings of the Venelle_2 well. The aim of this additional work was to (i) test the efficiency/reliability of different sampling methods, and (ii) to obtain representative samples for fluids, likely drained by the Venelle_2 well before reaching the deepest, supercritical horizons.

We outline the following main findings:

- Real-time mud/water gas analysis is a valuable and operationally simple way to obtain first qualitative information about the gas contents of the drilled section. Helium concentrations measured in parallel by gas chromatography (continuous gas log) and Helium isotopic composition by mass-spectrometry (spot samples) has important application in determining possible fluid origin and mixing processes.
- The geochemical characteristics of boron in fluid from well San Martino 5A encourage further investigation aimed at magmatic-type fluids.
- The geochemical characterization of circulation water before and after circulation at supercritical conditions is done for the first time during DESCRAMBLE project. Nevertheless, the large uncertainties posed by the use of different chemical additives do not allow to postulate hypothesis regarding the geochemical processes affecting the Venelle_2 well.

We advance the following key recommendations:

- The gas extraction system needs to be improved to ensure high extraction efficiency in combination with lower air contamination, to guarantee a better performance of the noble gases “tool”.
- The use of geothermal water as drilling fluid could significantly reduce -or set to zero - the sensitivity of boron as a useful tracer to investigate the water/rock interaction process and/or to evidence geothermal fluid entrance in the borehole during drilling.

The Deep Roots of the Larderello Geothermal Field (Italy) from Heat Flux and ^{3}He anomalies

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Keywords: Helium isotopes, heat flux, seismic reflectors, Larderello geothermal field

Abstract

Deep roots dynamics of the Larderello geothermal field has been investigated since longtime with various methodological approaches. A significant contribution came from the comparison of the surface distribution of helium isotopes from geothermal wells and gas manifestations of the Larderello and neighboring areas in Tuscany, with surface heat flux data and deep seismic images of the crustal structures. The conceptual model elaborated by Magro et al. (2009) highlighted some specific features of mantle-crust interactions beneath the Tuscan geothermal area (fig.1).

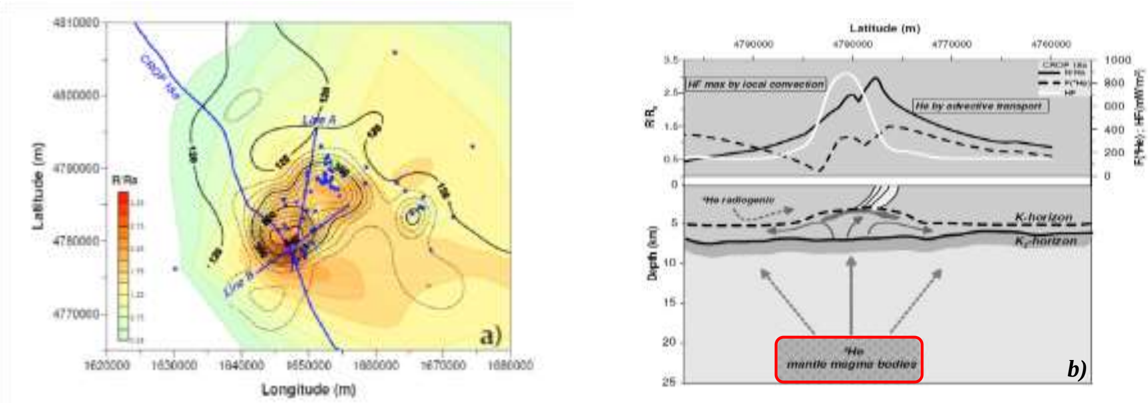

Figure 10: a) Contour maps of HF (black curves), and R/Ra (color scale filled contours). Blue lines: tracks of seismic profiles. Blue squares: gas sampling locations. b) Distribution of HF, R/R$_a$ and ^{4}He along the Crop 18A seismic profile (modified after Accaino et al.,2005). The K and K-2 horizons, the reservoirs with overpressured fluids (dark grey areas below K-horizons), and the main fault systems (black curves in light grey area) are shown.

The almost coincident presence of K-horizon culminations, HF and R/R$_a$ (^{3}He/^{4}He ratio normalized to air value) maxima indicates that hot ^{3}He-enriched fluids issue at surface mainly by advective transport, which is the most efficient mechanism of transfer of ^{3}He enriched fluids to the surface. Short-wavelength thermal perturbations appear likely related to the increase of ^{4}He radiogenic fraction derived from long-term waterrock interaction, whereas long-wavelength thermal perturbations are related to ^{3}He enriched fluid rising from the mantle and reaching the surface along preferential channels, as evidenced by the seismic image of the deep structures. The presence of coherent thermal and $_{3}$He anomalies indicates that both energy and mass fluxes pass through the crust and issue at surface, after being homogenized and stored in the reservoirs below and above the K-horizons.

The He isotopic composition in the Tuscan area is strongly dependent on the crustal fluid dilution and homogenization at the K-horizons, and is highly influenced by the drainage depth of the feeding channels. The presence of fluid-homogenizing reservoirs, densely spread at various depths below the Tuscan geothermal areas, introduces an important constraint for the extrapolation of the primitive signature of the mantle beneath central Italy

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Geological Modelling and Petrophysical Parameter Characterization for the Geothermal System around Venelle-2

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Abstract

Basis for numerical reservoir models of the geothermal system around Venelle-2 are a geological structure and a parameter range for this structure. The geological structure directly results from a geological model, based on multiple different data sources, such as seismics, stratigraphic borehole logs, or geological maps. We integrated all available data in a geological model covering an area of 14 km × 14 km centered around Venelle-2, and extending down to a depth of 8 km below sea level. The model comprises two major geological complexes in the area, a sedimentary complex overlying a metamorphic complex. Additionally, the model includes the probable shape of the K Horizon, based on combining seismic interpretations from associates in DESCRAMBLE and data from the European IMAGE Project. The discretized geological model is used as a geometry for numerical reservoir simulations.

For assessing the petrophysical parameters of geological units included in the aforementioned model, we conducted several measurement campaigns on multiple core samples from Venelle-2 and neighboring wells. In total, the measurement material comprises over 13 cores from neighboring wells (from depths between 1700 m and 3600 m), and several cores from Venelle-2 (from a depth of around 2800 m). As heat transport in the vicinity of Venelle-2 is assumed to be primarily conductive, we focus on petrophysical parameters important for conductive heat transport. Such parameters comprise: Porosity, thermal conductivity, specific heat capacity, and density (bulk and matrix). Statistical analysis of measurements results yield average parameter values with associated uncertainty for geological units in the metamorphic complex. As such, measurement results provide reasonable parameter variances used for calibrating our numerical models. Further, we estimated anisotropy values of thermal conductivity for samples with strong schistosity, for subsequent implementation in the numerical models.

Boron isotopes in geothermal fluids: analytical advances (Neptune Plus), results from the Venelle-2 area and database compilation during the DESCRAMBLE project

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Keywords: Venelle-2, boron isotopes, geothermal fluids, isotope database

Abstract

Boron is a very mobile element that strongly partitions into aqueous phase during water-rock interaction. The large atomic mass difference between its two stable isotopes makes the B-11/B-10 ratio a sensitive tool in geothermal environments. At the Larderello geothermal field, boron isotopes were used to trace the origin of geothermal fluids and to monitor the environmental effects associated to their exploitation, with special attention on the drinking water supply (Pennisi et al., 2001; Pennisi et al., 2006).

In the DESCRAMBLE project, boron, O, H, C, and noble gases were selected as multi-isotopic toolbox to characterize the supercritical geothermal fluids expected during the Venelle drilling. However, given that these fluids were not intercepted, the planned activities were redirected to: a) advance the analytical techniques for the analysis of boron isotopes in geothermal fluids; b) characterize fluids located in the surroundings of the Venelle; c) building a new database of boron isotopic composition of geothermal fluids.

Analytical advances on the isotopic analysis of boron in geothermal fluid. During the DESCRAMBLE project the Thermal Ionization Mass Spectrometry (TIMS) laboratory of the IGG-CNR (Pisa) was upgraded with the addition of an High-Resolution Multicollector Inductively-Coupled Mass Spectrometer (HR-MC-ICP-MS; Thermo-Fisher Neptune Plus). In the second half of 2017, the IGG-CNR Neptune team implemented a new analytical routine for the analyses of boron isotopes by MC-ICP-MC using international standards provided by the inter-calibration exercise promoted by IGG and IAEA (Gonfiantini et al., 2001).

Samples collected during the DESCRAMBLE project from the Venelle area (San Martino #5, Lago #6 and Zuccantine #1 wells) were analyzed using the new methodology at the IGG-CNR, and replicate analyses were also performed at an external laboratory (ALS, Luleå). These independent results are in good agreement and indicate that fluids from the San Martino#5A well are boron-rich and show a “close to” magmatic boron isotopic signature, whereas the isotopic composition of fluids sampled from the Lago#6 and Zuccantine#1 indicates their interaction with an anhydrite/dolomitic limestone reservoir and mixing with reinjected fluids.

The ISOBORDAT database. From 1986, boron isotope data in natural substances has increased significantly in scientific publications. Analytical difficulties derived from complex geochemical matrices have been faced, and results of inter-laboratory calibrations reported in the boron literature.

ISOBORDAT, an interactive database of boron isotope composition and content of natural waters was presented in 2011 by IGG-CNR to the community of boron isotope users (Pennisi et al., 2011). From the ISOBORDAT website data can be downloaded as .xls files. During the DESCRAMBLE project, ISOBORDAT has been implemented with the new category “Geothermal Fluids”. The data inserted in the database are derived from geothermal wells, thermal and geothermal springs, geysers, hot volcanic mud and fumaroles. The analysis of this dataset showed an extreme variability of the boron isotopic composition (**d**11B) of geothermal fluids, ranging from - 16.57‰ in fluids from the Lhasa block and the Tethyan Himalayans (Tibet, China) to + 54.90‰ in hot springs from Hamme Mazor (Dead Sea, Israel).

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Characterization of metamorphic rocks from Larderello deep wells (DESCRAMBLE project)

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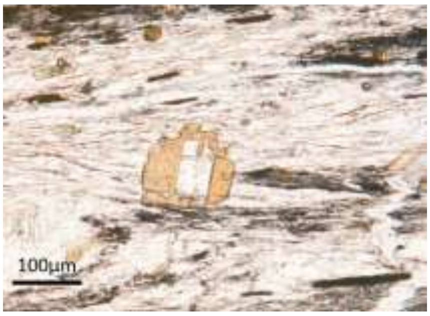
Keywords: core samples, metamorphism, ^{40}Ar-^{39}Ar dating

Abstract

We report petrographic and petrologic characterization of metamorphic rocks selected from cores drilled at different depth (between 1485 m and 3657 m) in wells surrounding the site of the Venelle 2 well, in the framework of Task 4.7 (WP4). These samples were studied with several techniques (Scanning Electron Microscopy, Electron MicroProbe Analysis, X-ray Fluorescence, X-ray Powder Diffraction) in order to provide information on the rocks that presumably would have been encountered during the deepening of the Venelle 2 well. The analyses done on this first group of rocks indicated the presence of many different lithologies (phyllites, micaschists, gneisses and amphibolites) in a narrow area, and confirmed the difficulty to draw, as initially planned, straight correlations and distinctions among them. In some case, rocks are affected by contact metamorphism (occurrence of andalusite and cordierite). Data obtained were useful in further calculations of other research groups within the project, such as phase volumes estimates, petrophysical modeling, chemical composition quantifications.

In the last months, during the drilling of the Venelle 2 well, three new cores were recovered at 2600, 2830 and 2900m, crosscutting the first seismic reflector placed at nearly 2680 m. A temperature of about 510 °C was measured at the well bottom. Detailed analyses on these recently acquired rock samples are still ongoing. However, the cores from the Venelle 2 well are entirely composed by metapelitic rocks, of very similar aspect and substantially classifiable as phyllites. In particular, these poly-metamorphosed metapelites, comparable only to analogous rocks from San Pompeo 2 well, show mineral assemblages typical of low-grade greenschist facies phyllites (Qtz, Ms, Bt, Pl, Chl) with the presence of graphitic matter, sometimes very abundant. The effects of a supposed underneath pluton could be recognized in particular features such as static porphyroblasthesis of muscovite+biotite (in figure), Ca-plagioclase+biotite enriched levels and transversal veins filled by Qtz+Pl+Ms+Bt+Ep. All these last aspects need further in-depth analyses to assess if they can be related to the recent activity of the granite intrusion or if they represent inherited features from previous thermal events.



Over the years, several samples from drilling were made available, some of them with suitable characteristics for dating. Unfortunately, there are no chronological data in the same well on (contact metamorphosed) wall rocks and granites. Anyway, age data reported for thermo-metamorphic micas from the deepest core samples roughly fall within the range outlined by granites, making the dating of these micas useful when drillings do not reach intrusions. Noteworthy, deep core samples from the area around Venelle 2, where the top of the K-horizon is shallower, record the youngest ages of the entire geothermal field, of the order of about 1.5 ÷ 1.6 Ma. The study of Venelle cores is still ongoing, but one of the samples should contain micas in size and amounts suitable for dating. The use of amphibole has proved to be more problematic: a hornblende from Puntone 4B amphibolite (-3290 m b.g.l.) displays a complex age spectrum, where it is difficult to decouple the last thermal event from earlier geological events, analogously to what previously observed on an amphibole from another area of the Larderello geothermal field.

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

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Keywords: 3D DERT, electrical resistivity, geothermal site.

Abstract

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 inhole 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 dataloger 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 final data were inverted by a 3D code and a 3D electrical resistivity image was highlighted (figure 1).

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.

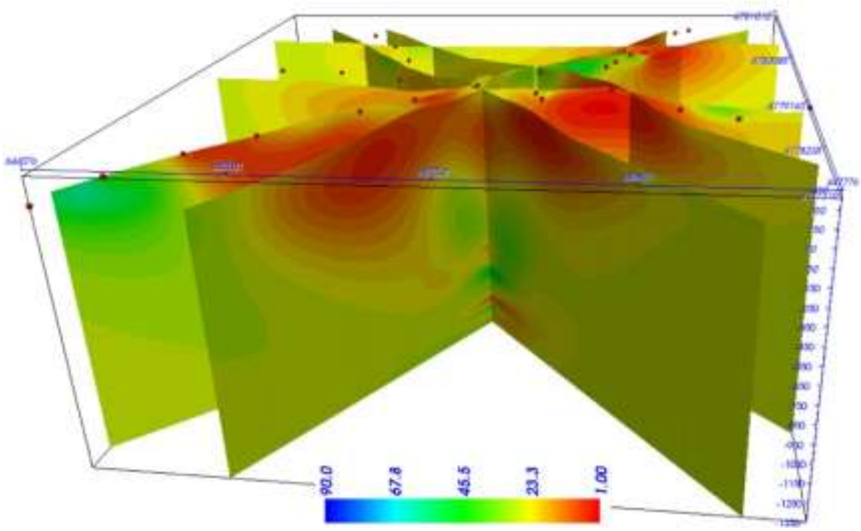

Figure 11: The 3D geoelectrical model

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Predictive characterization of pressure-temperature condition of the K-horizon from fluid inclusion studies on quartz-tourmaline veins from the Larderello geothermal system

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Keywords: fluid inclusions, pressure, temperature.

Abstract

Since the Larderello geothermal field has been subject to exhumation and uplifting, rocks which are currently at a given depth and temperature in the past had to be at a greater depth and temperature. Thus, these rocks may contain fluid inclusions recording the physical-chemical conditions of an older exhumed super-hot reservoir present at the level of a paleo K-horizons. Quartz-tourmaline veins found in deep core samples in the Larderello geothermal field were interpreted to represent a paleo-hydrothermal system similar to that likely present at the level and/or below the current K-horizon. The aim of fluid inclusion study in quartztourmaline veins was to provide information on the conditions that should be present at the level and/or below the K-horizon.

Fluid inclusions have been analyzed in two-core samples (Carboli 11 - 3455 and San Pompeo 2 - 2270) characterized by quartz-tourmaline mineral assemblage. Quartz in both samples contains two main inclusion types related to an early high-temperature fluid circulation: aqueous-carbonic and hypersaline inclusions. Fluid inclusions in tourmaline were not observed. In the Pompeo 2 - 2270 sample, hypersaline inclusions, consisting of liquid + vapor + halite + one or two solids, are usually associated to two-phase aqueous-carbonic inclusions. In Carboli 11 - 3455 core sample two-phase aqueous-carbonic inclusions in quartz sometimes coexists with hypersaline inclusions, containing halite and sporadically one additional mineral. In other cases, aqueous-carbonic inclusions appear to be trapped at a later stage. In addition, rare two-phase high-salinity aqueous inclusions were observed in this sample.

Microthermometric analyses showed that in all aqueous-carbonic inclusions clathrate formed at low temperature. In some of these inclusions it was also possible to measure the melting temperature of the carbonic phase, between -57.4 and -56.9°C, close to the triple point of CO_2, suggesting that the volatile phase is mostly constituted by this gas. In general, aqueous-carbonic inclusions are characterized by relatively lowsalinity. On the other hand, multi-phase inclusions are hypersaline, as their salinity (computed from the melting temperature of halite) is up to 34 wt.% NaCl equiv. Two-phase high-salinity inclusions in Carboli 11 - 3455 sample are characterized by very low ice melting temperature (between -29.5 and -26.7°C). Both

hypersaline and high salinity inclusions showed very low eutectic temperature (between -66 and -84°C) indicating the occurrence of LiCl (and possibly $FeCl_2$ and $CaCl_2$) in addition to NaCl in the fluid. Total homogenization temperatures are from 339 and 385°C for aqueous-carbonic inclusions, and between 349 and 462°C for hypersaline and saline inclusions. According to previous fluid inclusions studies of Larderello samples, aqueous-carbonic inclusions are interpreted to record fluids issued during contact-metamorphism, whereas high-salinity and hypersaline inclusions trapped fluid of magmatic origin (Cathelineau et al., 1994; Boiron et al., 2007).

Textural relationships suggest that in San Pompeo 2 -2270 sample aqueous-carbonic fluid inclusions multiphase inclusions are almost co-genetic. This implies that such inclusions were trapped nearly at the same PT conditions. Thus, P-T conditions (700-820 bars, 495-510°C) were computed from isochores intersection of the two inclusion types. Trapping pressure is slightly above present-day lithostatic pressure, suggesting lithostatic conditions in the paleo-K horizon. The same method for P-T estimate can be applied for the Carboli 11 - 3455 fluid inclusions. However, as in this sample aqueous-carbonic and multi-phase inclusions rarely coexist only some inclusions these two fluids were trapped at identical P-T conditions. In particular, aqueouscarbonic fluid inclusions with relatively high density were likely trapped with high-salinity fluids at high pressure (900-1100 bars) under lithostatic regime. Whereas, isochores position of lower density aqueouscarbonic inclusions indicates that they were trapped at lower pressure (down to 350 bars), suggesting a pressure drop or pressure fluctuation between lithostatic and hydrostatic conditions. Trapping temperature of fluid inclusions in Carboli 11 - 3455 sample (400-450°C, i.e. around the present T indicated by metal alloy at that depth) was lower than those San Pompeo 2 -2270.

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Characterization of seismic reflections of a geothermal reservoir in Southern Tuscany

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Abstract

Advanced seismic imaging methods are proven to provide a clear and focused image of geothermal reservoirs. As a result we achieved a high quality structural interpretation comprising a precise depth estimate of the seismic horizons of a potential geothermal reservoir as well as high resolution images of the 3D structure.

In order to explain the reflection strength and the cause of the reflection we developed a reflection analysis workflow using the newly acquired VSP and Piggy Back data. The benefit of this work is that the reflector does not need to be penetrated for estimating reflection coefficients and modeling of the seismic response. The challenge within this work is to separate the upgoing from the downgoing wavefield carefully in order to prevent the reflection amplitude and to design a robust VSP deconvolution operator for removing the influence of the seismic source signal from the data.

We obtained seismic reflection coefficients at near vertical incidence which provide a basis for explaining the reflection strength of the top layer of the potential reservoir. A representative waveform of the seismic reflection is extracted and used for modeling of the internal structure of the uppermost seismic horizon.

Integrative seismic data analysis for geothermal reservoir characterization within project DESCRAMBLE

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Abstract

We present a workflow for the structural characterization of seismic horizons by integration of different seismic data sets. Our approach is split in three steps: 1. migration velocity model building in order to compensate the effects of strong topography and lateral varying geology, 2. structural interpretation of the so-called K-Horizon and 3. quantitative seismic interpretation and modelling of the K-Horizon.

Velocity model building comprises first arrival traveltime tomography and the incorporation of several well velocities. We performed an advanced three-dimensional (3D) seismic depth imaging approach using Kirchhoff Prestack Depth Migration (KPSDM) and Fresnel Volume Migration (FVM) techniques. With this approach, our seismic studies have revealed seismic images of the K-Horizon with good quality. Our structural interpretation is a reliable basis for geothermal rock characterization as well as for steering of the first well in the geothermal field to penetrate the seismic horizons.

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