Understanding supercritical resources in continental crust

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ABSTRACT

The DESCRAMBLE project, which developed a proof-of-concept test of reaching deep geothermal supercritical resources, has been an occasion to improve knowledge of deep chemical-physical conditions for predicting and controlling future drilling activities. The test site has been an existing dry well in Larderello, Italy, already drilled to a depth of 2.1 km and temperature of 350 °C, which was deepened to intersect a seismic marker at almost 3 km depth. Down at the final depth of 2.9 km, in the middle of the seismic reflections, an unexpected extremely high temperature was measured (507- 517°C at 2.9 km). This value, associated with the geological conditions of the rocks, with a leak off pressure of about 30 MPa (300 bar), can pave the way for a further utilization of this well for an EGS system, producing supercritical fluids from reinjected water.

1. INTRODUCTION

The DESCRAMBLE project, running from May 2015 to April 2018, was aimed at drilling and testing geothermal resources at extremely high temperature in continental-crust condition for demonstrating novel drilling techniques and the control of gas emissions. The project targeted also at improving knowledge of deep chemical-physical conditions for predicting and controlling any drilling conditions.

The first-in-the-world intra-continental, mid-crustal borehole in very high temperature condition has been our test site, using an existing dry well in Larderello, Italy, already drilled to a depth of 2.2 km and temperature of 350 °C, which was deepened to 3 km depth. Larderello, the birthplace of geothermal power production, has been extensively explored and investigated for many decades. 2D and 3D seismic survey data highlighted an important deep seismic marker named “K-horizon” culminating below the currently exploited, vapour- dominated, reservoirs and recognizable throughout southern Tuscany (Figure 1). The high seismic impedance of this seismic marker, even resembling a bright-spot in some areas, was interpreted as due to magmatic/metamorphic fluids, possibly in super-critical conditions. Evidence strengthening this interpretation was provided by the exploratory well San Pompeo 2, drilled on 1979 to cross K-horizon. Before reaching the K-horizon, high-pressure fluids were unexpectedly encountered, and induced well blow-out and the eruption of a large amount of tourmaline-quartz breccia and vein fragments, which are typical of high temperature, magmatic hydrothermal systems occurring at the top of many granite intrusions in Tuscany. The chosen well, Venelle-2, is close to San Pompeo 2 well, and the drilling target, i.e. the pack of seismic reflections corresponding to the K-horizon, is particularly thick and shallow in this area (Figure 1).

The site was considered perfect for such an experiment, as it is representative of deep crustal levels in Europe, is cost effective (since drilling for reaching the target is reduced to a minimum), and is practical due to the high probability of encountering extremely high temperature and pressures (supercritical condition). DESCRAMBLE explores the possibility of reaching extremely high productivity per well, up to ten times the standard productivity, with a closed loop, zero emission, and reduced land use.

Specific Objectives were:

- Demonstrating safe drilling of a deep geothermal well and extremely high temperature and pressures (supercritical condition).

- Reducing the technical and financial risks of drilling and exploiting deep geothermal wells by improving knowledge of the physical and chemical conditions in deep geothermal formations.

- Reducing pre-drilling uncertainty in the exploration of deep geothermal wells.

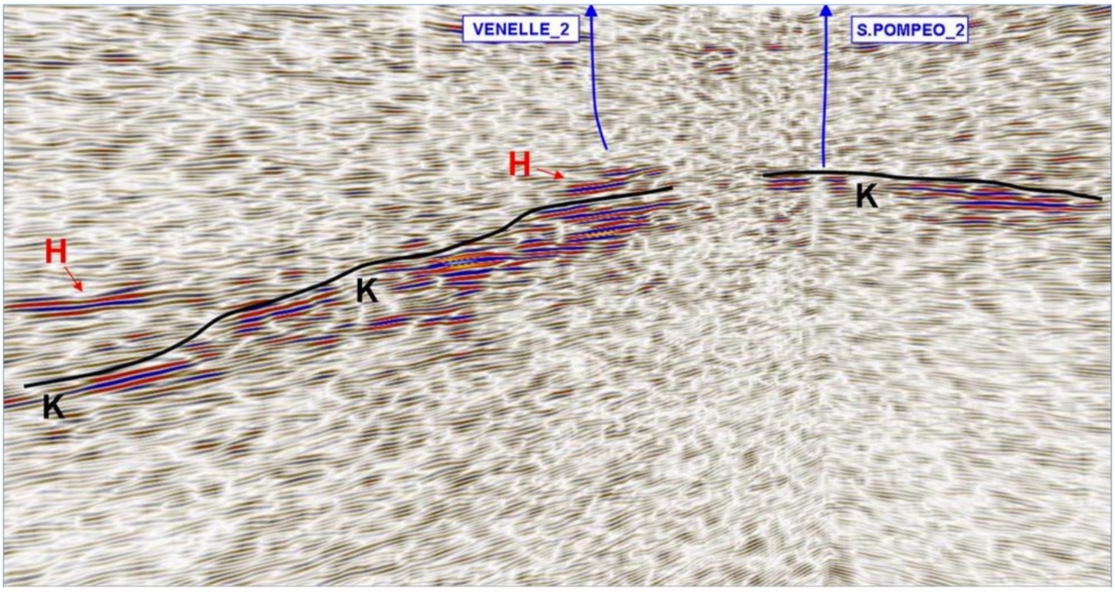

Figure 1: Random-line from 3D seismic in the area of Lago (Larderello) showing existing wells (Venelle 2 and San Pompeo 2), the main seismic markers (K and H) and target interpretation (black line).

- Improve in-situ characterization by developing a special tool for extremely high temperature and pressure measurements and by analysing fluid and rocks samples of deep, supercritical conditions

- Investigating the economic potential of exploiting chemicals and minerals by analysing fluid samples for valuable raw materials.

The present paper describes the project organization, with each technical WP leader as responsible for its specific chapter. Of course, the content of the paper and the amazing results achieved are the result of a common effort of all the team.

2. DRILLING HISTORY & TECHNICAL SOLUTIONS

Drilling operations in extreme conditions were carried out 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.

The performance of the new materials identified to perform the operations were very good, although drilling conditions in some intervals were even more extreme than expected, especially in terms of temperature. In consideration of the extreme temperature (450°C) and pressure (45 MPa) expected at bottom hole, the drilling would have been completely out of standard drilling conditions, and required a careful selection of materials and procedures for safety drilling conditions, as detailed later. A special cement and other material solutions (rock bit, casing), never used by Enel Green Power before, were designed or selected among commercial, high performance products.

Drilling activities started on 28th April 2017. After plugging the existing open hole, deviation started with drilling in sliding and rotary mode (Kick Off Point at 1054 m), by the use of a 12 1⁄4" rock bit. The aim was to keep an inclination lower than 10° (pseudo vertical well). Starting from 1180 m depth, some little losses (0-7 m^3/h) occurred while drilling with water as drilling fluid. Directional drilling continued down to 2275 m of depth, where some problems of torsion occurred. Drilling continued encountering a total loss of circulation at 2334 m, afterwards reduced to 25 m^3/h losses. Drilling continued down to 2470 m, where it was stopped to set the 9 5/8” liner (casing shoe at 2468 m). Drilling continued afterwards with a 8 1⁄2” BHA down to 2500 m of depth, where a temperature log and a Leak Off Test were performed. From 2600 m to 2601 m coring operations were performed, but due to some top drive troubles coring operations were interrupted. Afterwards a new leak off test was performed, using an 8 1⁄2” open hole swellable packer set at 2585 m.

Taking into account the results of the LOT, it was decided to stop deepening and proceeding to set the 7” casing, divided in three sections. The deep liner was placed with shoe at 2601 m and hanger at 2299 m, and it has been completely cemented using Thermalock^{TM} slurry. After WOC and milling of the cement above the hanger, the intermediate liner was placed with the tie-back at 2299 m and the hanger at 949 m. During this cement job, a large fire occurred in the area around the rig site, forcing to increase significantly the mud circulation time at bottom hole before starting with the cementation. At the end of the cement job the insulation valves failed, and consequently for pressure balance the slurry entered in the casing.

Logs were performed in order to verify the cement quality, revealing a large interval where cement was not present or only partially present. In order to ensure the integrity of the column and its mechanical resistance, it was decided to remove part of the liner. The not cemented section was extracted after a casing cut (at 1205 m of depth), while the section only partially cemented was milled (from 1205 to 1409 m). Once arrived at 1409 m the column was reintegrated up to the surface. Drilling continued with a 6” BHA, that was used also to drill a short section of open hole. At 2616 m a new LOT was realized and at 2620 m it was registered a static log (temperature build up). At this stage, the MPD equipment was installed and water was substituted with sepiolite mud.

Because of thermal expansion in case of circulation stop and consequent thermal recovery, the mud, whose density was particularly high (1.5 kg/l), caused an important rise in well head pressure when circulation was stopped and the well was shut in. Consequently, many problems were encountered in the application of the standard well control procedure by means of the Driller’s Method. However, drilling continued with the same mud density, with return of circulation, using a 6” Full Stinger Bit, obtaining a high ROP value down to 2695 m of depth, when the first stuck pipe for differential pressure was experienced.

Since it was not possible to release the BHA by jarring and pulling up, the density was decreased down to 1.35 kg/l and a special additive able to break the mud panel was pumped. As soon as the drilling started again, at 2708 m, the well went into TLC, stabilized as small absorption and at 2709 m there was a second stuck pipe. In order to decrease the differential pressure between the well and the formation, the mud present into the well was fully displaced by pumping water to decrease the hydrostatic pressure, leading to no losses. This situation forced to review the well control procedures, because of the lower fluid density. When the BHA was free, the drilling continued with water up to 2721 m with total return of circulation. Pressure tests were performed in order to estimate the absorption increasing the WH pressure.

In order to increase the formation resistance and reduce the risk of losses, various squeezes of clogging materials and barite were performed, with the purpose of clogging the absorbent zone, but after each job, the pressurization tests gave negative results. Drilling started again with water and controlled parameters, and reached the final depth of 2900 m. At 2830 m of depth a core was performed (9 m), and then a series of static temperature logs, using Enel Green Power’s Kusters and synthetic fluid inclusion measurements by CNR. At 2900 m of depth a further core (9 m) and a static temperature log were achieved. With the purpose to realize a new LOT, a 6” swellable packer was run in hole and set at 2898 m, but the attempt to set the tool failed, and the packer was pulled out. A last static temperature log was performed using the tool designed for the project (see chapter 4). At this point, it was decided to proceed with a temporary abandonment of the well.

3. DRILLING MODELLING

The drilling campaign anticipated drilling into an impermeable layer, which together with the planned casing could create a situation where drilling fluid was returned to surface. This is somewhat unusual in the area, where wells are typically drilled with complete loss to the formation. However, it is the normal mode of operation when drilling oil and gas wells, where the rate of the return flow is an important diagnostic variable, indicative of both gas kicks and fractures. The SINTEF Flow Model (Petersen et. al 2006) is a simulation tool for the flow of drilling and formation fluids during drilling of oil and gas wells. This simulator was modified for the DESCRAMBLE project and simulations were carried out to determine if the DESCRAMBLE drilling crew could use the return flow to detect influx from the formation and boiling of the drilling fluid.

In oil and gas well drilling, return fluid is collected in a "mud pit" before being pumped down into the well again. An increase in fluid level in the pit indicates that more fluid is exiting the well than entering and is therefore used as an indication of gas or fluid influx into the well. Flowmeters may provide the same information with a higher accuracy. We investigated if this method could be applied in the Venelle-2 case.

Water expands when heated and as is often observed, a well already full of water will expel some of it as it heats. This observation can be erroneously interpreted as boiling or gas influx. We first ran a simulation to quantify the magnitude of this mundane effect. Our simulation starts with the Venelle-2 well being drilled to 2100m, with drill bit on bottom, static temperature conditions and an applied choke pressure of 2.5 MPa to avoid boiling. We start circulating 1000 litres per minute through the drillstring for 600 minutes. The overall temperature of the wellbore fluid drops and we find that the volume in our virtual pit drops, rapidly at first, before leveling out at a deficit of 14 cubic metres. In oil-well drilling, a difference of as little as 9 cubic metres is often enough to sound an alarm. Stopping the pump and allowing the water in the well to heat up, we see a similar pit volume increase. As the density of the water decreases during heating, we observe a pressure drop of about 1 MPa at the bottom.

We then proceeded to simulating boiling. The pump is stopped after circulating and the water in the well is allowed to heat up, with choke pressure being kept at 1.5 MPa. We soon observe boiling at the bottom of the well, resulting in a drop in bottom hole pressure, due to a decreased hydrostatic column. The pit volume rises significantly more sharply than for thermal expansion and can be clearly distinguished from the slower rise in volume due to thermal expansion.

In summary: If pit volume is used as an indicator in the drilling operation, benign thermal expansion and contraction will have a strong signal. However, it will still be possible to visually distinguish it from the more rapid change caused by boiling. As thermal expansion will play out in much the same way from one pump stop to another, it is furthermore possible to subtract this signal from the measurements, simplifying the monitoring.

4. PRODUCTION MODELLING

Production from a supercritical well put strong requirements on equipment such as casing and choke valve. As input to the well design process, the likely pressures, temperatures and flow rates from a supercritical production well was calculated. The calculations were carried out using a modified version of LedaFlow, a commercial multiphase flow pipeline simulator initially developed for the oil and gas industry.

The simulations uncovered surprisingly strong pressure and temperature fluctuations in the well during opening and closing of the choke valve. The magnitude of the transient effects can be explained by the well's state being close to water's critical point. This means that phase-changes are easily induced in the well, in turn causing larger pressure and temperature fluctuations than expected from ordinary geothermal wells.

A multiphase simulation with a simplified representation of the Venelle-2 well and extrapolated temperature profile was constructed. Simulations were run for different bottom hole pressures and choices of well-head pressure, corresponding to a choice of choke opening. With the bottom hole pressure fixed, a low well-head pressure implies high flow-rates. There is therefore a lower limit for technically feasible well-head pressures.

Our steady-state multi-phase simulations showed that with a bottom hole temperature around 400 °C and a bottom hole pressure above about 35 MPa, we will see condensation at the top of the well and the fluid being produced as a two-phase mixture. As wellhead pressure is decreased, the mass flow-rate will increase but its percentage of liquid water will also increase.

We then extended the multi-phase simulation to transient flows, seen during opening and closing of the production valve. These simulations are more sensitive to details of equipment design and transient modelling is more technically challenging. For a "warm" start- up, where the temperatures of the surrounding rock formations are still at steady-state temperatures, we observe oscillations in the flow- rate. This can be explained by numerical instabilities in the model further down in the well, where conditions are just above the critical point and the fluid is very sensitive to changes in pressure and temperature. The density can vary from 300 kg/m^3 to 600 kg/m^3 over the span of a few bars. This is numerically challenging, but also illustrates that the flow rate is highly sensitive to downhole conditions in the transient phase. Predictions of the flow rate will therefore be uncertain and we cannot rule out that oscillations or erratic changes will occur in real-world scenarios too. In the simulation, we also find pressure oscillations corresponding to the flow oscillations. Supercritical wells are unknown territory and such transient oscillations may be a feature for some well designs.

In the simulation, we also find that the well-head pressure needed to start the well differs significantly between a cold start with just 13.3 MPa under the well head, to 28 MPa in the warm case. The practical consequence is that a warm start offers the possibility of starting the well at a pressure high enough to keep the flow single-phase from the start.

5. MEASURING TEMPERATURE IN SUPER-HOT CONDITION

Temperature and pressure profiles of the well are important parameters for evaluating the formation properties, inspection of the well completion and for optimizing production. Reliable logging of such extreme temperatures (T > ca. 350°C) is currently not possible using commercially available P&T logging tools.

The Venelle-2 first drilling took place in the 2006, from 08/15/2006 to 11/20/2006. During the drilling activities two temperature extrapolations were conducted: on 11/14/2006 at 1334m depth and about 270°C; on 11/16/2006 at 2212m depth and about 360°C (Figure 2). A very high temperature gradient (0.1°C/m) was measured, similar, however, to temperature profile already found in other wells located near the Venelle-2 well. In the final drilling phase new temperature data were collected.

A temperature extrapolation was conducted on 9 and 07/10/2017 at the depth of 2490 m. A mechanical Kuster was lowered to 2490 m in the well, in the 8”1/2 borehole, and the log lasted 15 hours. During that time, the tool registered the temperature build up transient which started from a temperature altered by the drilling mud circulation. The extrapolated value at 2490m is 386°C. This temperature is in line with the thermal gradient measured during the first drilling of the Venelle-2 well.

A temperature data was measured on 11/17/2017 at the depth of 2815 m. A mechanical Kuster was lowered to 2815 m in the well, in the 6” borehole (Figure 2). Probably, the measured temperature is not representative of the static temperature of the formation for two reasons: the complete heat return did not take place and the measured data was at full scale of the tool. In conclusion, from that log it was possible to assert that the static temperature formation at 2815m is greater than or equal to 504°C.

A further temperature measurement was executed on 11/24/2017 at the depth of 2894 m. A specific tool, provided by the CNR (synthetic fluid inclusions), was located at the bottom of the drilling string and it was pull down. The temperature calculated through this method is 507-517°C (Figure 2). In the same occasion, also some thermosensitive paints were used to estimate the formation temperature range, which resulted 480°C/610°C. The measured temperature does not represent the stationary formation temperature since the tool was lowered into the well after less than 2 days from the stop of injection.

Due to a lack of logging tools that can withstand the extreme temperatures expected, DESCRAMBLE developed a new logging tool that measures P&T (pressure and temperature) with a minimum of 6 hours operation at 450°C. The tool is named SINTEF PT tool (see Bertani et al., 2018 for more details). The tool has been tested in an offline well at lower temperature (250°C) and in two logging runs in Venelle-2 up to ca. 450°C.

The main objective for the last logging run in the Venelle-2 well using the SINTEF PT tool was to continuously measure the temperature of the well down, as close as possible, to its target depth of 2900 m. The target depth of this run was set to 2810 m, the same depth as they recorded more than 500°C with the Kuster KTG tool, stay there for 5 minutes, and return to top. Friday 1st of December 2017 the logging operation was performed. The maximum temperature measured at 2810 m depth was 443.6°C (Figure 2). The maximum internal temperature (recorded by internal temperature sensor) was 34.7°C.

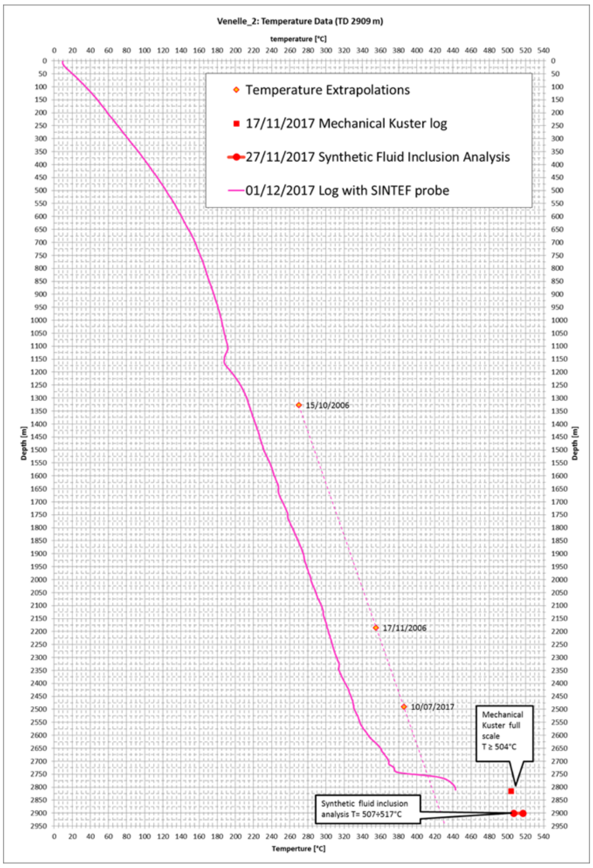

Figure 2: Temperature data collected in the Venelle-2 well during first drilling and DESCRAMBLE project. Note the sudden change of the thermal gradient at about 2750m and the consistency with independent measurements at the bottom hole.

The temperature profile obtained by the SINTEF PT tool is not representative of the stationary formation temperature because of the thermal disturb induced by the drilling fluid circulation. On the other hand, the variation in the thermal gradient at about 2750m, registered by the tool, can be related to the natural thermal gradient variation indicated by all the previous measurements.

The Figure 2 shows the overall temperature log. In conclusion, according to the temperature data collected during the first drilling and the DESCRAMBLE project, the temperature profile of the Venelle-2 well shows a sudden increase of the thermal gradient at the bottom hole. The data are not sufficient to determine the exact depth at which the thermal gradient variation occurs; nevertheless, the temperature log registered by the SINTEF PT tool allow to locate it at about 2750m, in correspondence with the beginning of the seismic reflection zone.

6. RESERVOIR CHARACTERIZATION

Characterization 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. In any case, an entire work-package was dedicated to the reservoir characterization within the DESCRAMBLE Project. The objective of reservoir characterization was to achieve a comprehensive understanding of the geological structure and physical conditions of the supercritical reservoir, which was needed in three stages of the project: a) before drilling in order for defining the model and constraining the framework in geothermal reservoir modelling and prediction; b) during the drilling phase to improve ahead drill prediction and operational steering; c) after drilling for assessing the agreement of prediction and findings and for deriving conclusions for a general guidance for identifying deep supercritical conditions. To achieve these results, an investigation strategy was followed that included three main approaches: 1) conceptual; 2) indirect and 3) direct.

The conceptual approach needs some explanatory notes. It was based on the large wealth of knowledge we have on the architecture of the Tuscan continental crust and the explored portion of the Larderello geothermal field. 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 both magmatic and meteoric water. Extension and magmatism progressively migrated from west (e.g. Elba Island; 8.5-5.9 Ma) to east (e.g. Larderello; 3.8 Ma-Present). We adopted the following conceptual model: the magmatic system responsible for the present-day thermal anomaly in Larderello is assumed to be similar to the "fossil" magmatic-hydrothermal systems cropping out in the eastern area (Elba Island, Campiglia, Giglio Island, Gavorrano, etc.). All these 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 surrounded by a contact metamorphic aureole, hosting a large variety of sub- vertical and sub-horizontal veins and breccia bodies cemented by tourmaline, quartz and sulphides (Dini et al., 2008). All the isotopic and geochemical data produced on these high temperature veins are coherent with a derivation from fluids issued by the granite magma. 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, paleo-reservoirs could represent a proxy for the supercritical reservoir possibly occurring in correspondence of K-horizon seismic marker. Similar high temperature, boron-rich magmatic hydrothermal systems were active around the old granite plutons in Larderello (3.8-1.3 Ma; Dini et al., 2005; Farina et al., 2018) as indicated by the occurrence of tourmaline-quartz-sulfide veins hosted by contact metamorphic rocks above the granite intrusions (cored in several geothermal wells). The Tuscan magmatic hydrothermal systems have peculiar geochemical and isotopic signatures (high B content, low δ^{11}B, radiogenic Sr isotope ratios, noble gas contents and isotope ratios, temperature, salinity, etc.) that can be traced in rock samples from the Larderello fossil systems as well as in fluids coming from the potentially active supercritical reservoir at depth.

The indirect approach involved acquisition of new seismic data (VSP, Piggy back experiment) and use of existing three-dimensional (3D) and two-dimensional (2D) seismic data set to provide high-resolution seismic images of the K-horizon.

The direct approach, i.e. the investigation of rock and fluid samples sampled inside the reservoir, was obviously linked to the possibility to physically reach the reservoir by drilling and performing a proper sampling activity. Fluids and rocks from the deep reservoir were not collected.

Core samples of the relatively old hydrothermal veins as well as samples of their contact metamorphic host rocks and granite intrusions have been selected for the DESCRAMBLE Project. Multiple petrographic, geochemical, isotopic (Sr, Nd, B, Hf, O, H), geochronologic (^{40}Ar-^{39}Ar, U-Pb), and fluid inclusion analyses have been performed by CNR in order to determine physical-chemical parameters useful for reservoir characterization at the K-horizon level. Petrological modelling of these data provided important constraints on processes and sources that played in the lower-middle crust during the formation and transfer of the granite magma. Petrological characters of hydrothermal tourmaline are indicative of their formation from high temperature fluids issued by granite intrusions and contact metamorphic reactions. P-T estimates provided by fluid inclusion data (P: 70-82 MPa, T: 495-510°C) suggest that P was slightly above present-day lithostatic P, suggesting lithostatic conditions in the paleo-K-horizon (Figure 3). The depth of formation of such inclusions was higher than the present-day depth of the core-sample. The U-Pb ages of zircons from granites indicate that magma emplacement, crystallization, fluid exsolution and contact metamorphism follow a cyclical evolution with at least 4 main stages (3.7, 3.1, 2.6 and 1.6 Ma; Farina et al., 2018). Geochemical and isotopic features of granite and basement rocks indicate that temperature of partial melting at source level (lower crust) did not exceed 900°C. Partial melts were sequentially transferred into a large magma chamber in the middle crust before the final emplacement at shallow crustal levels (4000-6000 m). All these parameters have been integrated in thermal models.

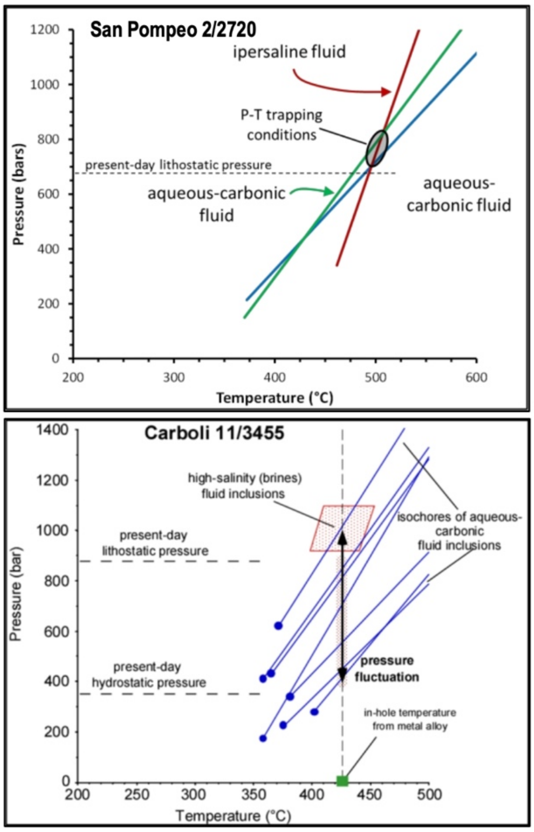

Figure 3: P-T trapping condition estimated from isochores intersection for examined samples. Isochores have been computed by using micro-thermometric data.

Core samples of metamorphic rocks have been also selected for laboratory measurement of multiple petrophysical parameters conducted at RWTH (conductivity, specific heat capacity, porosity). Thermal conductivity measurements were performed for dried and re-saturated state of the core samples. Average bulk thermal conductivity in dried condition is 2.76 W m^{-1} K^{-1} ± 0.084 W m^{-1} K^{-1}. After saturation, thermal conductivity was re-assessed, yielding significantly higher thermal conductivity values, with an average of 3.6 W m^{-1} K^{-1} ± 0.08 W m^{-1} K^{-1}. Specific heat capacities of rock samples were measured at ambient pressures in a temperature sweep from 40°C to 290 °C. Anisotropy factors of thermal conductivities were assessed by measuring thermal conductivities parallel and perpendicular to the foliation. Porosities range between 2 % and 4 %, with matrix densities of around 2789 kg/m^3. Measured bulk thermal conductivities of re-saturated samples and measured porosities were used for assessing an average matrix thermal conductivity, using the geometric mean. The obtained calibrated relations between specific heat capacities and temperature were averaged and used for reservoir simulations, as all samples resemble the same Unit "metamorphic basement" in the geological models built in reservoir modelling (next chapter). Petrophysical measurements at simulated in-situ conditions were performed on 11 rock samples (CAU). High-pressure (100 to 150 MPa at room temperature) and high-temperature (up to 600°C) were conducted using a multi-anvil press. The laboratory measurements are in good agreement with the seismic velocity-depth function derived from field measurements. However, they show that the rocks are highly anisotropic. These petrophysical findings have implications for the depth determination of the K-horizon and its uncertainty. The analysis shows that the positioning uncertainty induced by unrecognized seismic anisotropy is of the order of 200 m in both horizontal and vertical directions. The petrophysical results are then applied for determining the seismic reflection structure of the K-horizon by Monte Carlo inversion.

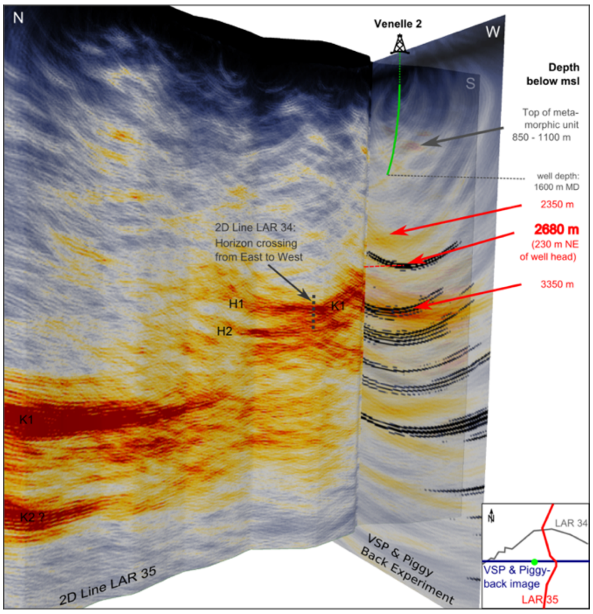

Figure 4: Comparison of imaged horizon revealed within 2D LAR seismic data (N-S-slice) and VSP & Piggyback experiment (W-E-slice): The reflectors imaged within the VSP survey are overlain (dark reflectors) and do not represent the actual lateral shape. The integration of different data reveals a more precise depth estimate at 2680 m below msl.

The resulting models suggest that the K-horizon is not a single reflection but an interference pattern of reflections from layers with alternating high and low seismic velocities, which may be identified with thin tight and hydraulically conducting layers. Of particular importance is unrecognized seismic anisotropy, which can introduce systematic bias into the velocity analysis, which may be of the same order of magnitude as the random uncertainties caused by random velocity fluctuations and methodical limitations.

Acquisition of new seismic data (VSP, Piggy back experiment) and use of existing three-dimensional (3D) and two-dimensional (2D) seismic data set revealed high-resolution seismic images of the K-horizon (Figure 4). The Fresnel Volume Migration (FVM) approach carried out in this study has overcome the limitation of the standard time domain imaging technique to reveal the K-horizon structure below the geothermal field. From the structural interpretation, we determined that the K-horizon below the geothermal field forms an anticlinal structure with the apex at around 900 m to the east of the Venelle-2 well position. At the top of the anticlinal structure, the K-horizon might be found as shallow as approximately 2650 m BMSL. The anticlinal structure seems to be dipping mainly to the north-east (NE) direction from the well. Based on the results of this work, we estimate that the K-horizon below the well might be reached at approximately 3100–3200 m BMSL.

Unfortunately, no representative fluid samples were available during the drilling of the Venelle-2 well. This was principally due to the lack of substantial fluid entrance in the borehole during the deepening of the well, i.e. to the lack of steam/fluid lock up in the rock matrix crossed by the well perforation. However, the fluid geochemistry team produced sampling protocols and geochemical analyses of fluids/gases collected during the Venelle-2 well perforation, as well as on fluid samples collected from three wells (Lago-5, Zuccantine-1, and San Martino-5A) located in the surroundings of the Venelle-2 well, before its deepening (δ^2H, $\delta^{18}O$, $\delta^{11}B$, $\delta^{34}S$ noble gases, concentrations of Cl, SO_4, Si and F). The aim of this work was to (i) test the efficiency/reliability of different sampling methods, and (ii) to obtain representative samples for "standard" fluids/gases coming from the producing metamorphic reservoir, likely drained by the Venelle-2 well before reaching the deepest, supercritical horizons, and/or from limestones/anhydrites present in the local stratigraphic column. All gas samples extracted from drilling fluids contain low, but measurable amounts of He, as detected by spectrometric techniques. The new $^3He/^4He$ data collected complement a pre-existing, quite large dataset based on samples from Larderello productive geothermal wells (Magro et al., 2003). All the samples are characterised by a significant oxygen-shift, indicative of enhanced meteoric water-rock exchange at high temperature. The boron isotopic compositions indicate the occurrence of boron-rich/low $\delta^{11}B$ fluids in the San Martino-5A well (magmatic signature);

conversely, the boron isotopic signature of fluids from the Lago-6 and Zuccantine-1 wells, is in agreement with an anhydride /dolomitic limestone reservoir and also gives evidence for a contribution from fluid generated by reinjection processes.

7. RESERVOIR MODELLING

A three-dimensional geological model was built using available geological and geophysical data. This model forms the basis for subsequent simulation of heat and mass transfer in the geothermal reservoir system. Geological data comprise structural contours (Gola et al., 2017), borehole stratigraphy, and geological maps. Processed and interpreted three-dimensional seismic data forms the geophysical data source. The geological model focuses on a best representation of the geometry of the K-horizon, and comprises six different units, divided into two main complexes: the sedimentary and the metamorphic complexes (see e.g. Batini et al., 2003). The tectonic situation in the study area is a direct result of the Apennine orogeny. A detailed interpretation of the structural geology in the study area can be found in Batini et al. (2003) and Dini (2005).

Figure 5 shows the top of the K-horizon as interpreted from seismic data and maps of structural contours. Based on the geological model, we created reservoir models at three different scales for simulating the geothermal reservoir system evolution. On a regional scale, a three-dimensional reservoir model covering an area of 14 km × 14 km provides information about large-scale reservoir behavior. For a more detailed assessment in the vicinity of the borehole Venelle-2, a three-dimensional local-scale model centered around the borehole covers an area of 2 km × 2 km. Finally, a one-dimensional model along the borehole trace was used for simulating phase changes at the borehole scale. A part of the modelling was performed by CNR using a commercial version of TOUGH 2 – EOS2 with Petrasim interface, also creating a TOUGH2 Equation of State (EOS) able to handle supercritical water, but is not discussed here.

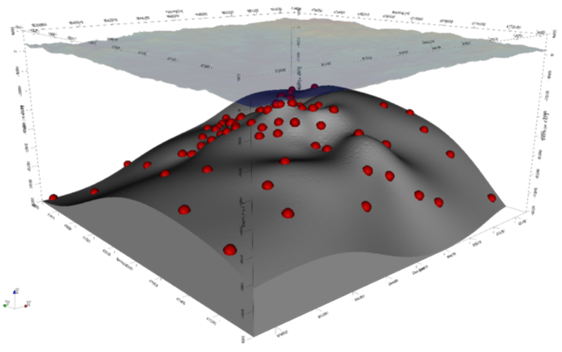

Figure 5: Three-dimensional model (view from SW) showing the top of the K-horizon as indicated by data (red spheres) and as a model unit (grey body). Topography is shown as transparent layer at the top.

Conductivity Model - Well test data acquired in December 2017 suggests that the heat transport in the vicinity of Venelle-2 is predominately conductive. Hence, we simulated single-phase conductive heat transport in the local model and compared it to temperatures recorded in the borehole. The local model consists of a hexahedral, rectilinear grid comprising 131,200 cells in total (40 × 40 × 82 in x-, y-, and z-direction, respectively). It covers an area of 2 km × 2 km centered around the well Venelle-2. Input parameters for the different units in the model are reported in Bertani et al. (2018).

In this model, porosity and matrix thermal conductivity are the controlling parameters as we consider merely conductive heat transport. We apply Neumann and Dirichlet boundary conditions at the model boundaries: no-flow Neumann conditions at the lateral boundaries, and Dirichlet conditions at the top and bottom boundaries. At the bottom boundary, we apply a temperature of 450 °C, as the K-horizon is assumed to represent an isothermal surface of that temperature (Ebigbo et al., 2016; Romagnoli et al., 2010; Batini et al., 2003). At the top boundary temperature is set according to the average annual surface temperature in Tuscany as a function of altitude (Ebigbo et al., 2016). We simulate a steady-state model, i.e. the simulation result represents "equilibrium conditions". This assumption may be questioned, as it is unclear whether the emplacement of a young granite may have disturbed the thermal equilibrium, with the system re-equilibrating since, but not yet having reached a steady state.

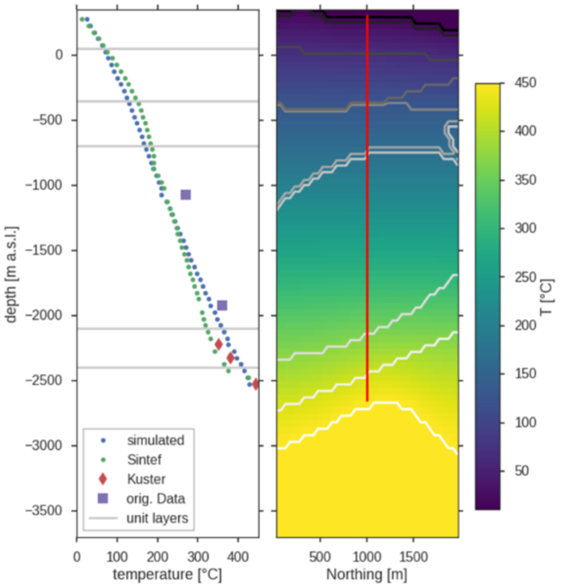

Figure 6: (Left) simulated temperature profile in Venelle-2 (blue dots), compared to measurements from the high-pT logging tool (green dots), Kuster data (red diamonds), and previous BHT (purple squares). (Right) N–S cross-section through the local model; gray lines: boundaries of lithological units.

Figure 6 shows a temperature profile of the simulated Venelle-2 well. The simulated temperature profile (blue dots), generally agree well with measured data. This supports the conclusion drawn from pressure tests, that the local heat transport is dominated mainly by conduction. Green data points were measured with the high-PT logging tool developed and built during DESCRAMBLE. However, it should be noted that the data acquired by this logging-tool most likely do not represent original rock temperatures, as indicated by a strong increase in temperature at a depth of about 2 500 m below sea level.

They are likely too low as they were measured during or shortly after drilling. Different BHT temperatures (purple squares) also suggest that equilibrium temperatures may be higher than those indicated by the logging tool. This supports the hypothesis, that emplacement of a young granite or a different heat source caused recent temperatures in the system to be higher than a steady-state simulation suggests. Thus, the resulting temperature distribution by a conductive steady-state simulation should be interpreted as a lower bound for temperatures in the local vicinity of Venelle-2.

Nonetheless, the generally good fit of simulated and measured temperatures suggests, that a single-phase conductive model can roughly approximate the thermal environment of Venelle-2. However, a multi-phase approach is necessary for better understanding the geothermal system, since production data of the geothermal field as well as simulated temperatures and pressures suggest a multi-phase geothermal system consisting of a mixture of steam and liquid water. Accordingly, we developed a pressure-enthalpy formulation for simulating a two-phase, single-component system, such as a steam dominated geothermal reservoir, enhancing the simulation code SHEMAT-Suite (not detailed here).

Two-Phase Water/Steam Model - Simulation around the Venelle-2 well poses some challenges due to the nature of the subsurface geothermal system. Temperature is high, with values of 500 °C and above. Below the Ligurian Units, a steam cap is formed with water and steam in the pore system. Finally, regions with low permeability alternate with high permeability regions. Initial simulations with a Dirichlet boundary condition at the surface (temperature of 15 °C and atmospheric pressure) resulted in bad convergence. Therefore, we start our simulations below the Ligurian Units and use a fixed temperature of 219.5 °C and a pressure of 1.5549 MPa as top boundary conditions. The bottom boundary condition is defined by the K-horizon with a constant temperature of 450 °C and a pressure of 28 MPa. The lateral boundaries are assumed as impermeable. Initial conditions use the known temperature and pressure values and interpolate them linearly. The discretization is the same as for the conductive model.

Figure 7 shows the final temperature distribution around Venelle-2. The K-horizon (here with an assumed temperature of 450 °C) provides heat to the model.

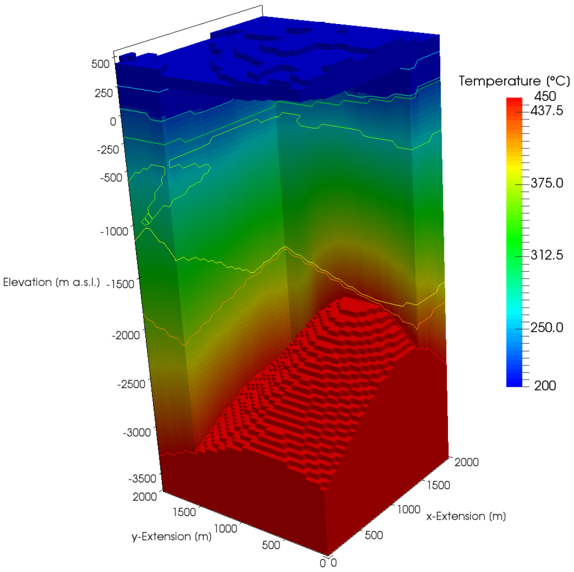

Figure 7: Final temperature distribution derived from the Two Phase Water/Steam model.

3. CONCLUSIONS

Drilling operations on the Venelle-2 represented the most important aspect of DESCRAMBLE. Despite several problems encountered during the well constructions, mainly due to the very high temperature and the unexpected behavior of drilling mud, the drilling was able to collect valuable information from the high pressure and temperature system that will be useful to analyze possible future uses of the well. On 20 October at depth of 2.7 km, it has been identified a loss of circulation zone, with temperature over 400°C and pressure of about 30 MPa. It was a first evidence of the existence of supercritical conditions in our deep system.

Down at the final depth of 2.9 km, in the middle of the seismic reflections, an unexpected extremely high temperature was measured (507-517°C at 2.9 km). This value, associated with the geological conditions of the rocks, with a leakoff pressure of about 30 MPa, can pave the way for a further utilization of this well for an EGS system, producing supercritical fluids from reinjected water.

The activity on the well has been terminated at 2.9 km, concluding the data acquisition and leaving the well in safety condition through a temporary cement plug. At bottom home temperature exceeding 500°C was above the design value for the entire project, and it was impossible to cement the absorbing zone for further drilling in safety conditions.

Up to now, the drilling did not prove the existence of a reservoir and fluids. However, the thick pack of reflectors has been only partially investigated. From a technical point of view, the obtained results are a major outcome of the project, and according to the expected thermodynamical and geological forecasting down to further depth, the associated costs and risks from the extra data we gathered do not justify additional drilling. However, a more detailed analysis is ongoing. In the figure 8 the Map of the amplitude anomalies clearly shows that what we have found in the Venelle-2 well is not an isolated "hot spot", but it can be an important drilling target for future development.

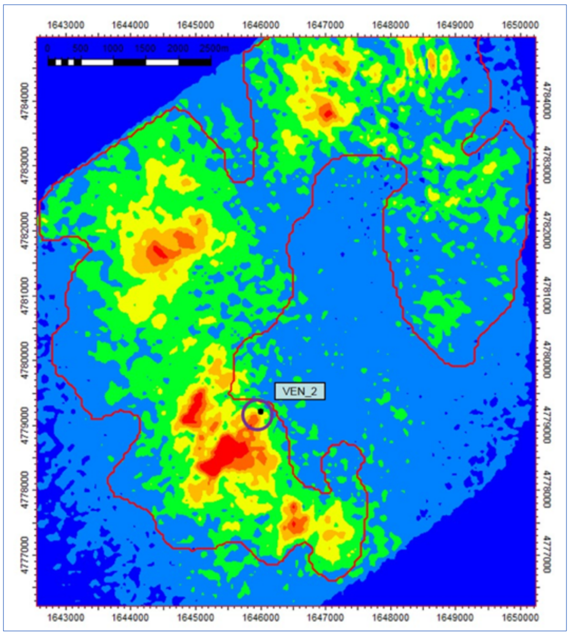

Figure 8: Map of the amplitude anomalies RMS calculated within the volume included between top and bottom of the K-horizon. In the purple circle the target for the deepening of the Venelle-2 (VEN_2).

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