PROCEEDINGS, 43rd Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 12-14, 2018
SGP-TR-213

The First Results of the DESCRAMBLE Project

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Keywords: Drilling technology, supercritical resource, logging tools, resource characterization, modelling

ABSTRACT

The DESCRAMBLE project has developed novel drilling technologies for a proof-of-concept test of reaching deep geothermal supercritical resources. In the project, we have drilled and tested the continental-crust condition for demonstrating novel drilling techniques, the control of gas emissions and high temperature/pressure conditions expected from the deep fluids. The project has also improved knowledge of deep chemical-physical conditions for predicting and controlling future drilling conditions. The test site has been 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 reaching supercritical conditions. The productivity and efficiency of the project were ensured by the combination of industrial and research participation and by the recognized expertise of the consortium in geothermal R&D as well as oil and gas drilling, combining excellence in both sectors. DESCRAMBLE's results will be presented in this paper, covering all the main aspects of the project: drilling procedures, material, well control, mud logging, well testing, modelling, geochemical and geophysical surveys and monitoring, petrographic and petrophysical evaluations and very high temperature and pressure logging tool.

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. 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.

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.
- Improve in-situ characterization by developing a special tool for extremely high temperature and pressure measurements and by analyzing fluid and rocks samples of deep, supercritical conditions
- Investigating the economic potential of exploiting chemicals and minerals by analyzing 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.

1. 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 (450 bar) 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 ¼" 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 ½" 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 ½" 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™ 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 sepiolitic 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 Section 2). At this point, it was decided to proceed with a temporary abandonment of the well.

1.1 Materials & Equipment

1.1.1 Well Head

Due to the extremely high temperature expected, the choice of the well head equipment required an important preliminary study in order to consider the de-rating resistance of the materials in such conditions. The choice fell on the best compromise among well head quality/cost and taking into account also safety. The well head equipment has been defined following the API and ASME regulations. Considering all the assumptions explained above and a proper safety factor, it was decided to design the equipment with API 10000 rating. Considering that the purpose of the DESCRAMBLE project was to verify the existence of supercritical fluids with an unknown, potentially corrosive, chemical composition, it was decided to realize the base flange of corrosion high resistance material. At the same time, an overlay of alloy was realized on the parts of the valves and spool exposed to the fluid.

1.1.2 Casings

The casing string was designed following the project assumption of producing a very corrosive fluid, with a high content of H_2S and CO_2fluid, in supercritical condition with a final temperature at well head of 300°C. The stress check string design was realized using a specific software. Casing strength calculations has been based on API Bulletin 5C3. Thermal yield de-rating has been used for load cases at elevated temperatures. The presence of H_2S, potentially in high concentrations, could lead to sulphide stress corrosion phenomena especially during drilling stages in which system temperature cools down due to the mud circulation. To avoid the risk of short term catastrophic failures, material selection for 9 5/8" and 7" casings could be restricted to full sour services grades (L80 or T95). Nevertheless, being the compressive load the "governing load", it was necessary to increase the grade of the steel in the tie-back section. The TN125SS™ material was chosen due to its elastic behavior with the compression load applied during the model running. Although this steel grade was not full sour, it could be safely used in presence of H_2S for environmental temperature higher than of 80°C.

1.1.3 Drilling Fluids

The main objectives of drilling fluids while drilling are to maintain borehole stability, by means of the right fluid properties and drilling parameters, and to guarantee good drilling performance in such environment characterized by critical bottom hole temperature. In our case, the main concerns regarded the possibility to trip in/out of the hole and leave the fluid inside the open hole exposed at high temperatures with the risk of sagging of the weighting agent. At the end of the tests performed to achieve the best drilling fluid for this project, it was decided to proceed with a Water Base Mud weighted up with Ilmenite (Microdense™) and with Sepiolite as suspending agent. The reason was that this fluid had better performance in term of temperature resistance considering that also after a long period the fluid did not present any sagging and could keep the fluid loss under control. This helped the operations, because had not been required a displacement with a heavy brine while tripping. The tested weighting agent was the Ilmenite (Microdense™), which, thanks to its particular particle size distribution (average 5 μm), offers auto suspending properties, helping to prevent sagging and settlement of the weighting agent.

1.1.4 Cement

In order to find a cementing material suitable for high temperature (450 °C) well condition, studies were carried out with the service company Halliburton, comparing some different blends of slurry, in particular Portland and ThermaLock™. ThermaLock™ blend showed good results in tests after high temperature exposure. Once the kind of slurry was selected, the blend composition was slightly modified in order to improve the mechanical and fluid-dynamic properties of the slurry. ThermaLock™ was used in all the cementing jobs of 7" casing and liner and for the temporary plug and abandon job. In each of these activities no problems were encountered related to poor cement quality.

1.1.5 Managed Pressure Drilling

During deepening operations of the Venelle-2, it was expected to encounter an over pressurized reservoir, with a maximum expected pressure of 450 bar. Considering that the inferred reservoir top was hypothesized at 2700÷2750 m of depth, a very high mud density (over than 1.65 kg/l) was required in order to guarantee the primary control of the well. Due to the very high bottom hole temperature (higher than 450°C), working with mud in such conditions presented many difficulties, also because no laboratory tests could be performed before. To mitigate the risk related to uncertainties on pore and fracture gradient and about the drilling fluid behavior at such high temperature, it was necessary to the implement the traditional well control procedures with innovative strategy and equipment. Consequently, Enel Green Power decided to use an innovative system also used by Oil&Gas companies in some circumstances, the Managed Pressure Drilling System (MPD), provided by Weatherford. MPD system is not able to guarantee the well control, in fact it is only a API 2000 device. However, it continuously monitors the bottom hole pressure and the flow rates (in and out from the well) in order to verify in a very short time each minimum variation. The most important parts of MDP system are the RCD (Rotating Circulation Device) and the Coriolis's flow meter. The flow meter can detect all the minimum difference between flow in and flow out, and trough the RCD, MPD's software controls choke valves and regulates the Surface Back Pressure. This action allows keeping the pressure balance at bottom hole, working into the set point range.

1.1.6 Rock bit

In the upper sections of the well it was possible to operate with traditional tricone rock bits because of the important cooling effect of the circulation at the bottom hole. However, in the 6" phase, working with 3 ½ DPs, the circulation flow rate was low, causing a very high working temperature at bottom hole. In such conditions, the risk to damage the elastomer of the bits increased significantly. Therefore, proper studies involving bit manufacturers were developed in order to choose the best solution to drill the 6" section across the target depth. The chosen bit was the PDC Full Stinger type provided by Smith. This type of bit, named StingBlade™ bit, has a Stinger conical diamond element across the bit face, designed to significantly increase footage and ROP in tough-to-drill formations. In particular, this kind of bits have not elastomer inner parts, being only metallic, so they are able to operate with extremely high temperatures while guaranteeing a long working life. Two StingBlade™ 6" bits have been used to drill the bottom hole units, obtaining very good performances both in terms of ROP and durability.

1.1.7 Mud Cooling

Considering the temperature profile expected in the well, it was also decided to increase the mud cooling capability utilizing a Mud Cooling System (MCS) provided by a third party (Halliburton). This system was menant to control and manage the drilling fluid temperatures, maintaining the maximum mud out temperature below 90 °C. In this way, mud boiling was avoided, decreasing also the safety risks for the operators. The mud was cooled in a plate type heat-exchanger by means of a glycol/water mixture which in its turn was cooled down by two radiators with electric driven ventilators. The glycol/water mixture was circulated through the radiators and heat-exchanger by means of an electric driven centrifugal circulation pump. The circulation pump was used to pump the ethylene glycol mixture through the plate heat-exchanger and radiators in a closed circuit system. After an initial phase needed to the system tuning, the mud cooling system was able to reach the set up values of out temperature, also because long circulation periods were necessary during the drilling, contributing to decrease the mud temperature.

1.1.8 Mud logging

The risks deriving from the presence of gases with a composition not fully known and at high pressure required a dedicated services and a continuous monitoring of the drilling parameters and dangerous gases in the air using sensors near tanks, BOP, rig floor and shale shakers.

2. 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 25 bar to avoid boiling. We start circulating 1000 liters 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 10 bars 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 15 bar. 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.

3. 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 350 bars, 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 133 bars under the well head, to 280 bar 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.

4. MEASURING TEMPERATURE IN SUPER-HOT CONDITION

4.1 Introduction

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 is currently not possible using commercially available P&T logging tools. One example is the electronic Quantum Geothermal PT tool from Kuster (Kuster, 2015) which is rated for a maximum of 350°C for 4 hours of operation. This is basically sufficient for the tripping time only. Estimating the well transient response after drilling fluid cooling requires additional time.

Looking beyond what is commercially available, several research projects have addressed the need for instrumentation for high temperature geothermal wells. In the "High Temperature Instruments for supercritical geothermal reservoir characterization & exploitation" (HITI) project they developed instruments capable of logging reservoirs up to pure-water super-critical conditions (T<374°C), (Halladay, et al., 2010), (Ásmundsson, 2014). The U.S. department of Energy has supported several projects that aim at developing a 300°C capable directional drilling system. (Dick, et al., 2013) describes progress in the development of a 300°C directional drilling system for Enhanced Geothermal Systems (EGS). The system requires a Measurement While Drilling (MWD) tool rated to the same temperature. This tool requires electronics rated to 300°C (i.e. telemetry and power source) possibly in combination with actively cooled electronics rated to 200°C (e.g. inertial sensors). (MacGugan, 2013) demonstrates the feasibility of manufacturing a 300°C capable directional drilling module based on electronics rated to 300°C. The module uses custom silicon-on-insulator (SOI) integrated circuits, high temperature co-fired ceramic substrate, high temperature die attach and interconnects. The ZWERG project (Isele & Holbein, Development of a Research Probe for Geothermal Boreholes, 2013), (Isele, Bauer, Dietze, Holbein, & Spatafora, 2015) aims to accelerate development of new instruments for geothermal logging and reduce the associated cost. The project is developing an open source platform of modular tool components currently targeted at geothermal wells up to 200°C.

4.2 Temperature measurements at Venelle-2

The Venelle-2 first drilling took place in the 2006, from 15/08/2006 to 20/11/2006. During the drilling activities two temperature extrapolations were conducted: on 14/11/2006 at 1334m depth and about 270°C; on 16/11/2006 at 2212m depth and about 360°C. 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 10/07/2017 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 17/11/2017 at the depth of 2815 m. A mechanical Kuster was lowered to 2815 m in the well, in the 6" borehole. 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 24/11/2017 at the depth of 2894 m. A specific tool, provided by the CNR, was located at the bottom of the drilling string and it was pull down. The temperature calculated through this method is 507-517°C. 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. The development of the SINTEF PT tool builds on experiences from previous projects by basing the mechanical design on earlier developed high temperature logging tools (Halladay, et al., 2010), (Ásmundsson, 2014), (Halladay, Development of a High Temperature Borehole Fluid Sampler, 1997) and (Halladay & Manning, High Temperature Downhole Tool Development, 1995). The tool has been tested in an offline well at lower temperature (250°C) and two logging runs in Venelle-2.

4.3 Novel logging tool: system Overview

As no electrical wireline cables rated to 450°C are available, the SINTEF PT tool is based on logging to internal memory and powered by high temperature batteries. A pressure housing shields the inner parts from the pressure in the well. Only the nose of the tool is exposed to the well environment. Inside the pressure housing a heat shield (dewar flask) protects the payload (electronics, sensors and batteries) from the extreme outside temperature. A pressure port is placed in the nose together with a temperature sensor. The pressure is transferred to the pressure sensor located inside the heat shield via a thin spiraled tube filled with high temperature grease. The buildup of the tool is shown in **Error! Reference source not found.**.

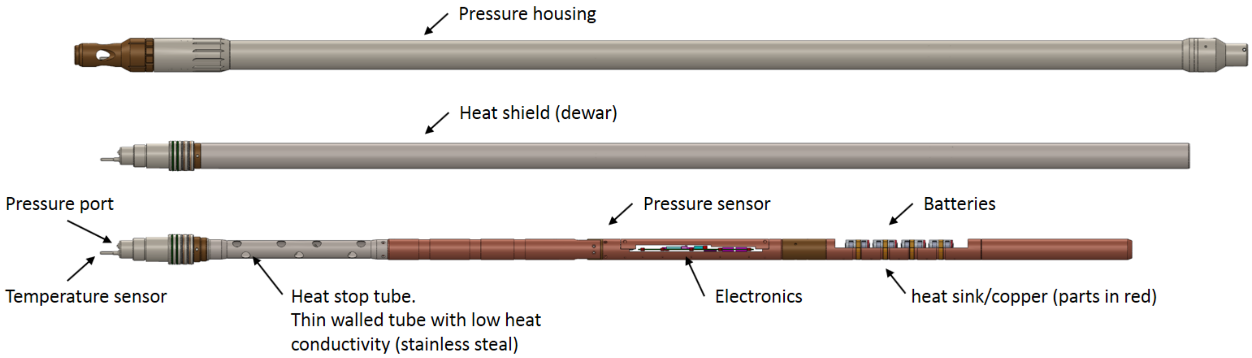

Figure 1: (Top) The complete tool with pressure housing. Temperature sensor and pressure port to the left (nose) and connection for the slickline wire to the right. (Middle) Pressure shield and nose protector removed. Picture show the nose of the tool and the heat shield. (Bottom) Heat shield removed.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

A metal seal rated to 650°C is used to seal the tool. Optionally, a high temperature O-ring can be used in logging operations below 300°C (short operation up to 325°C possible). The heat shield is produced by National K Works. The tool has a total length of 2.6 m, 3" (76.2 mm) diameter, total weight of 50 kg and the pressure shield is rated to 450 bars at 450°C. The max running time continuously at 450°C is 6 hours before the internal temperature reaches 200°C.

The tool has a temperature and pressure measurement accuracy of better than 5°C and 0.5 bars. Sampling rates can be set to 0.1-10 Hz and the tool can store 36000 datapoints x 3 (P,T,t).

4.4 High Temperature Electronics Platform

Except for a few passive components, rated for +200ºC, all components are rated for at least +225ºC. The electronics is assembled on a single 6-layer, dual-sided polyimide PCB, measuring 44 x 260 mm. A simplified block diagram is shown in Figure 1:

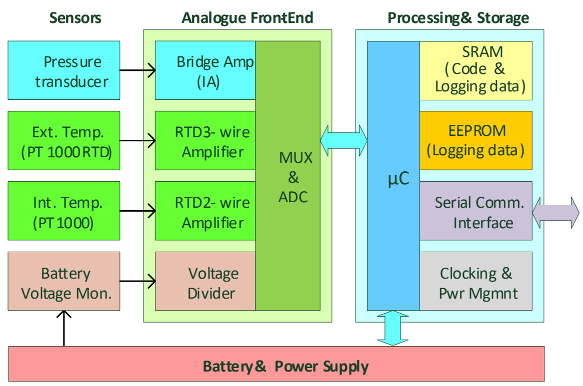

Figure 1: Simplified block diagram.

<u>4.4.1 Microcontroller and memory</u>

The core of the system is an ARM Cortex-M0 microcontroller from RelChip, RC10001. It includes 4 kB of SRAM and a selection of digital peripherals, but no flash or other non-volatile memory. Since the few currently available high temperature, high-capacity non-volatile memory devices are expensive and physically large, static SRAM (RelChip RC2110836) is used both for code, program data, and acquired logging data. A subset of logging data is also backed up to serial EEPROM (Honeywell HTEE25608) to ensure that some data can be retrieved in case of power failure during a logging run. The program must be loaded into memory each time the tool is powered up. This is handled by a hard-coded bootloader in the µC which receives application code over a serial port from an external PC. The RelChip components are remarkable, combining +300ºC rating with higher performance than most alternatives.

4.4.2 Sensors and analog front-end.

Pressure is sensed by a bridge-type transducer from Kulite, connected to a programmable instrumentation amplifier from SGA. Since the transducer cannot withstand the external temperature, it is mounted close to the PCB inside the heat shield. Pressure is transferred from outside by a thin, coiled tube filled with high temperature grease. External temperature is sensed by a PT1000-element mounted at the nose of the tool. Because of relatively long cabling, wiring resistance is partly compensated by a simple three-wire amplifier. A PT1000 element with a similar amplifier is also used for measuring the internal temperature at the PCB. The ADC system consists of a quad analog switch (Honeywell HT1204) used as four-input multiplexer, followed by a 12-bit A/D converter (Honeywell HTADC12). The fourth input on the mux is used for monitoring the battery voltage.

4.4.3 Power Supply

Designing the power supply and power management system was, in many ways, the most challenging task. The main constraint is the high internal resistance in, and corresponding low current available from, the batteries (Electrochem VHT200) at low temperature; only a few mA. The most suitable high temperature low-dropout regulator available, X-Rel XTR70025, may draw close to 3mA in idle, which is too much. A low-power LDO, X-Rel XTR75015, is therefore connected in parallel, and the high-power regulator switched in as needed only. A thermistor is connected to a comparator, switching a microcontroller pin when internal temperature rises above a preset level (70°C) where the battery can deliver sufficient power for normal operation. Then the microcontroller enables the high-power regulator and rest of the electronics as required.

4.4.4 Software challenges

The embedded software design for the tool is basic. Temperature and pressure as well as battery voltage are measured and stored at regular intervals, the intervals are configurable. When the tool is connected, data is transferred serially to a computer program where it is converted, visualized and stored. However, the high temperature hardware design puts constraints on the firmware. The power usage needs to be minimized, particularly when operating at low temperatures due to the battery design. Operation is divided into two modes; low temperature and high temperature. The most demanding mode is low temperature. In this mode, the power usage is minimized, hence the microcontroller is running code from internal RAM at low frequency and all external components including SRAM are in low power mode. For every measurement, the microcontroller is switched to high frequency operation, peripherals are powered and code from external SRAM is executed. Measured data is stored in the external SRAM. The operation is similar in high temperature mode, however every fourth sample from the external SRAM is copied to the external EEPROM as more power is available. In high temperature mode, the sampling frequency is typically much higher than for low temperature mode as this is typically the area of interest.

4.4.5 Power and batteries

Being a slickline tool the electronics need to be powered by on-board batteries. The tool needs to be operational both topside at ambient temperature as well as downhole with elevated temperatures up to 450°C. Even though the batteries do not see the full outside temperature of 450°C, it still represents a large and challenging temperature range of around 200°C. Since no commercially available cell can operate at the full temperature range, the operation domain can be split into two categories:

Medium temperature applications, maximum internal temperature of 165°C. Electrochem PMX165C can be used with operating temperature range of -20°C to 165°C. Critical temperature of these cells, meaning operating temperature (measured on the cell case) where the cells become unstable and over time can vent or explode, is 165-180°C.

High temperature applications, maximum internal temperature of 200°C. Electrochem VHT200C can be used, this is the cell that will be used for logging Venelle-2. The critical temperature of these cells is 210-215°C and they have a specified operational temperature range of 70-200°C. We have characterized these cells below specified operating range (T < 70°C), and the electronics are designed for reduced functionality below 70°C to draw a minimum amount of current. When the internal temperature rises above 70°C the system "wakes up" and full functionality is available.

4.5 Pre-tests of the tool

The tool has been extensively tested during development towards the final testing in the supercritical well Venelle-2.

4.5.1 In-House testing

The thermal performance of the SINTEF PT tool was tested in a large industrial oven at SINTEF, Raufoss Manufacturing branch, in Norway. Here the tool was exposed directly to the estimated 450°C temperature of Venelle-2 and kept there for 3 hours. The internal temperature of the tool during the test is shown in Figure 3 (left plot). Using linear extrapolation, the tool has a dwell time of 6 hours at 450°C before reaching the internal temperature limit of the batteries (200°C).

4.5.2 Field-test

A field-test of the tool was performed in a geothermal well (Lumiera) at Enel Green Power's facilities in Larderello, Italy in February 2017. The test well had a depth of 925 m and a max temperature at bottom of 250°C.

A direct comparison of the internal temperature to the Kuster K10 PT tool, which was used for logging in the same well a week earlier, is shown in Figure 3 (right plot). The SINTEF PT tool has a lower internal temperature gradient than the Kuster K10 tool. Even with a higher starting temperature the SINTEF PT tool also has a lower maximum internal temperature of approx. 64°C at the end of the logging operation.

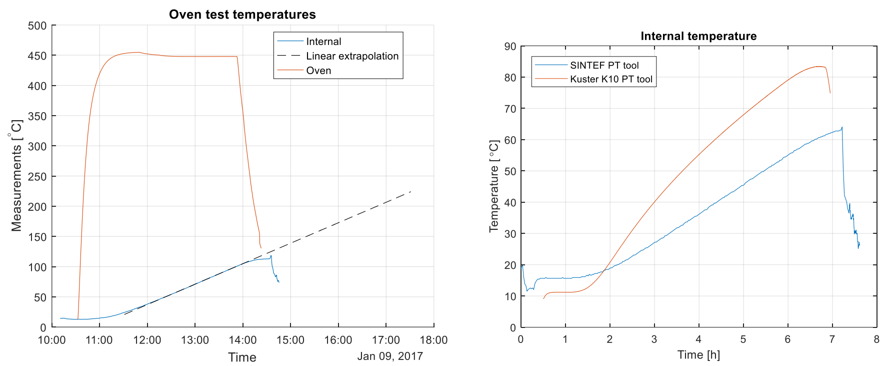

Figure 2: (Left): Internal temperature versus the maximum rated environment temperature (450°C). A linear extrapolation is shown dashed up to an internal temperature of 225°C. (Right): Internal temperature of the SINTEF PT tool and the Kuster K10 PT tool.

A depth plot from the test well comparing both SINTEF PT tool and Kuster K10 PT tool is shown in Figure 4 (right plot). The pressure deviations going down arise from the initial high viscosity at low temperatures of the grease barrier in the pressure tube, while the upwards temperature deviation arise from the internal heat capacity of the tool when leaving the water table at 367m.

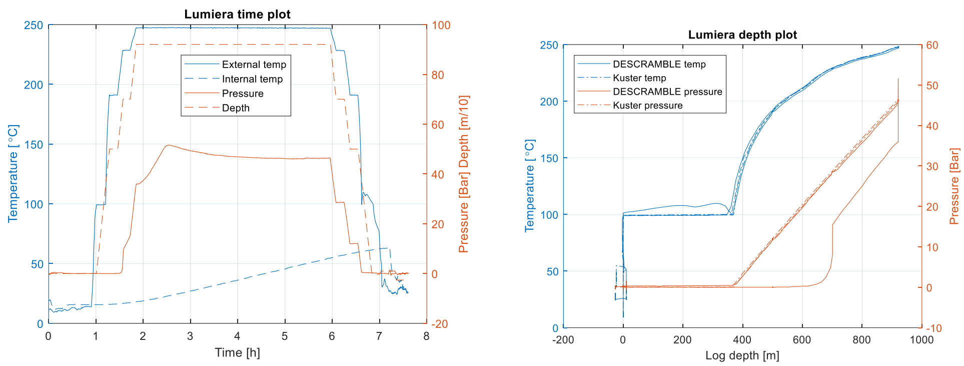

Figure 4: Depth plot of two runs (SINTEF PT tool and Kuster K10) for benchmarking and testing in the Lumiera well.

4.6 Testing in Venelle-2 – run 1

The main objective for the first logging run in the Venelle-2 well using the SINTEF PT tool was to measure the temperature and pressure increase of the well in static conditions 10 m above its current depth of 2620 m. In the days before the logging run Enel Green Power had cemented the 7" casing to 2600 m and then drilled 20 m into the formation.

Monday 25th of September 2017 the logging operation started approximately 12 hours after circulation of the well had stopped. Two logging runs in the well were planned. The first run had a duration of 7 hours (1.5 hours going into the well, 4 hours dwell time at 2610 m and 1.5 hours retrieval time). Figure 5 plots the measurements recorded by the SINTEF PT tool during the logging operation.

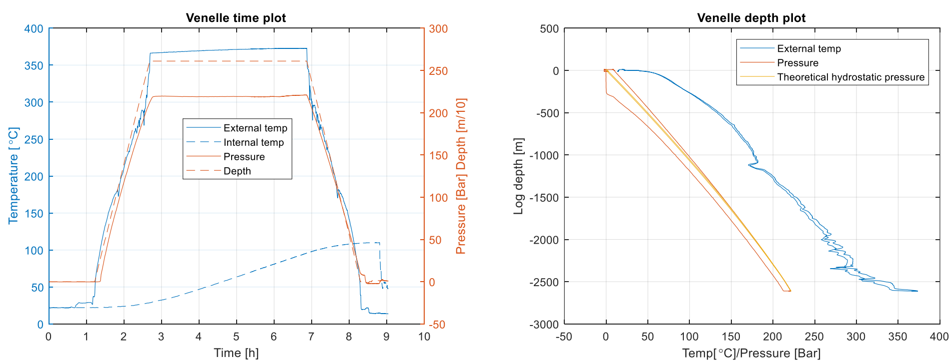

Figure 5: Measurements performed in Venelle-2 – run 1. Depth measurements from the Kuster depth box.

As observed also in the test run in the Lumiera well, there is a pressure delay on the sensed pressure on the way down. This is due to the high viscosity of the grease used in the pressure tube at low temperatures. When the internal parts of the tool are heated (included the grease in the pressure tube), the viscosity will be lower and the tool measures the correct pressure. On its way back to the top of the well the grease is again cooled and the viscosity increases. This can be observed as over-pressure response on its way to the topside. In the pressure readings between 6-7 hours there is a slight pressure increase. This is due to the water level in the well had increased from the wellhead to the top of the risers/lubricator box used to insert the tool in the well.

Key parameters measured in the Venelle-2 were: Maximum temperature: 372.9°C; Maximum pressure (not including the water level increase after 6 hours in the well): 219 bar; Maximum internal temperature recorded by internal temperature sensor: 110.0°C; Recorded internal temperature gradient at 2610 m: 17.1°C/h.

4.6.1 Slickline degradation

During attachment of the SINTEF PT tool to the slickline for the second run, it was observed a notable embrittlement change of the slickline even though the cable was completely new. "Pig tail" break testing of the slickline showed a notable degradation of the cable. Several lengths of the cable were cut off from the slickline drum without noticeable improvement. A second run with the SINTEF PT tool in the well was stopped to not risk losing the tool in the well. A sample of the slickline cable used in the well during the first logging run has been brought to SINTEF for testing and analyzing. Analyses of the cable showed a hydrogen content in the outer layer of 17.2 ppm and in the core a content of 7.45 ppm. A new similar unused cable (Sanicro 28) had in the outer layer 10.83 ppm and in the core 4.0 ppm hydrogen content. This is clearly indicating that the cause of the degradation of the cable is hydrogen embrittlement.

Tension testing has been performed on the slickline sample from the logging run in Venelle-2 at room temperature and the results are shown in Figure 6 (comparison with earlier tests performed at SINTEF). The test shows more than 50% reduction in the break strength of the cable at room temperature. In addition, tests at elevated temperature (400 and 500°C) showed an additional reduction in break strength of 20-30% due to temperature. The margins for performing a safe logging run with a heavy tool in the well was vanishing!

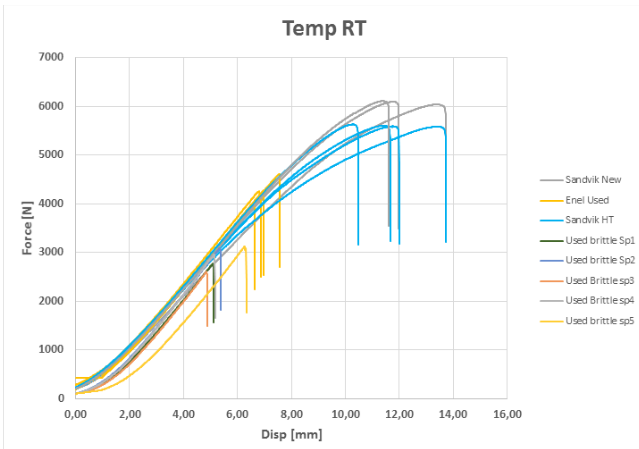

Figure 6: Comparison of break strength of slickline samples from the logging run in Venelle-2 (Sp1 to Sp5) compared with earlier slickline testing performed at SINTEF in DESCRAMBLE.

4.7 Testing in Venelle-2 – run 2

The main objective for the second logging run in the Venelle-2 well using the SINTEF PT tool was to measure the temperature of the well as close as possible to its target depth of 2900 m. Enel Green Power had, before our second run in the well, performed two logging operations in the Venelle-2 well using the Kuster KTG (mechanical tool) to record the temperature at 2810 m depth and a temperature sensitive paint tool to measure the temperature at 2900 m depth. The Kuster KTG tool measured more than 500°C (off-scale), and the paint-tool measured the temperature to be between 490-610°C. The SINTEF PT tool has a rating of 450°C for 6 hours, but can be in higher temperature environments for shorter periods. National-K-Works, which has produced the thermal flask, estimated that the flask can handle up to 550°C for short periods. In addition, the electronics in the tool is set up to measure up to 557°C well temperature and the metal seals are rated up to 650°C. The only components not rated fully to 550°C is the temperature probe which is rated to +500°C and the grease in the pressure tube which is rated to +400°C.

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. In Figure 7, the measurements taken with the SINTEF PT tool during the second logging run in the Venelle-2 are presented.

During this run the internal temperature of the tool only raised to 35°C. This is not high enough temperature for the grease in the pressure tube to become viscous enough to transfer the outer pressure to the pressure sensor located inside the tool. This resulted in a high offset in the pressure sensing.

The maximum temperature measured at 2810 m depth was 443.6°C. The maximum internal temperature (recorded by internal temperature sensor) was 34.7°C. 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.

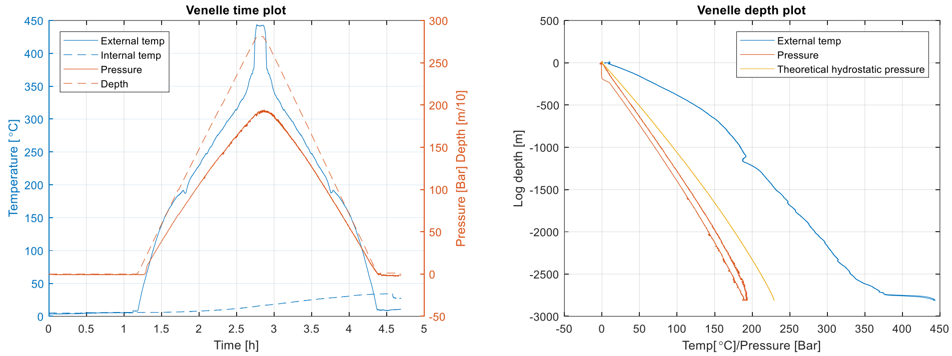

Figure 7: Measurements performed in Venelle-2 using the SINTEF PT tool. Depth measurements from the Kuster depth box.

The Figure 8 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's probe allow to locate it at about 2750m, in correspondence with the beginning of the seismic reflection zone.

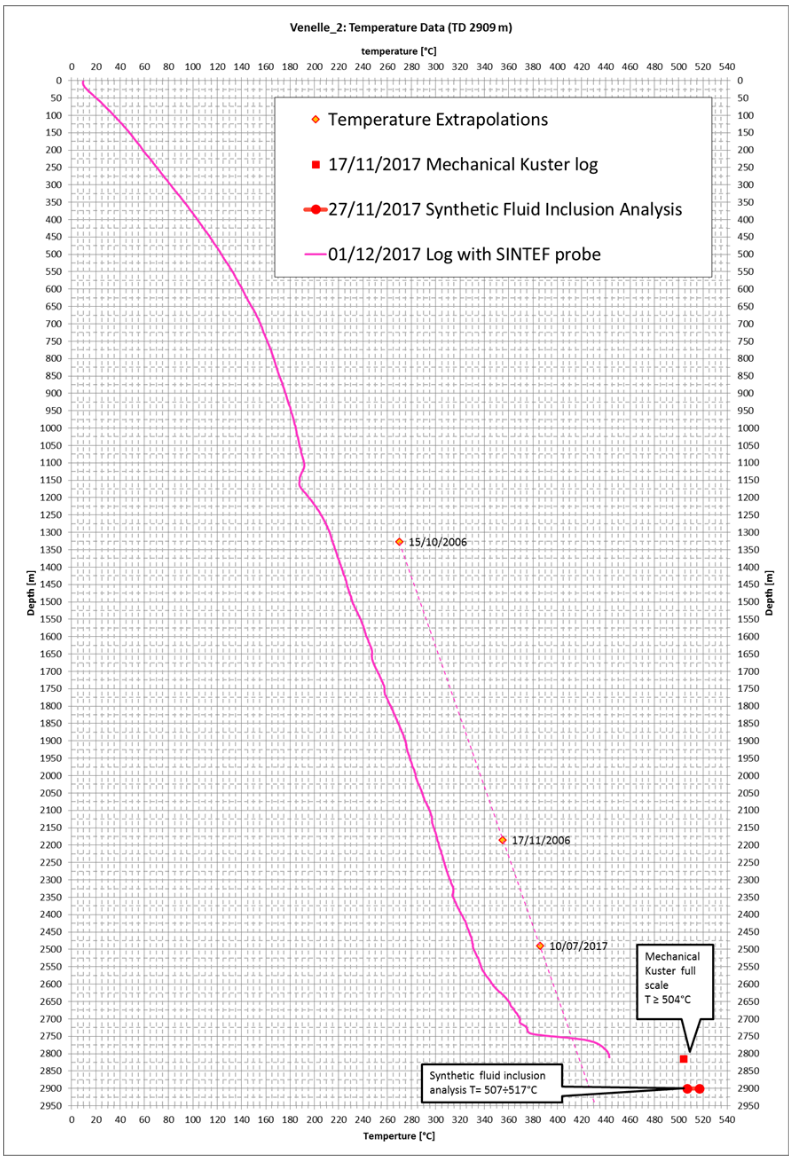

Figure 8: Temperature data collected in the Venelle-2 well during DESCRAMBLE

5. 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) 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 $\delta^{11}B$, 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 (40Ar-39Ar, 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: 700-820 bars, T: 495-510°C) suggest that P was slightly above present-day lithostatic P, suggesting lithostatic conditions in the paleo-K-horizon. 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). 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.

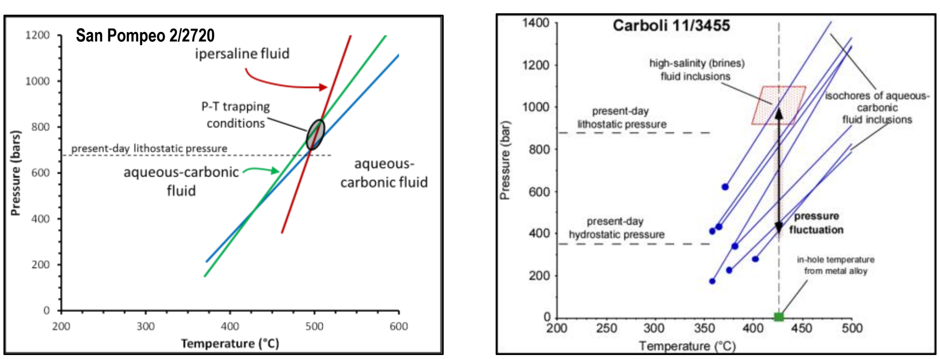

Figure 9: P-T trapping condition estimated from isochores intersection for examined samples. Isochores have been computed by using microthermometric data.

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. 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. 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.

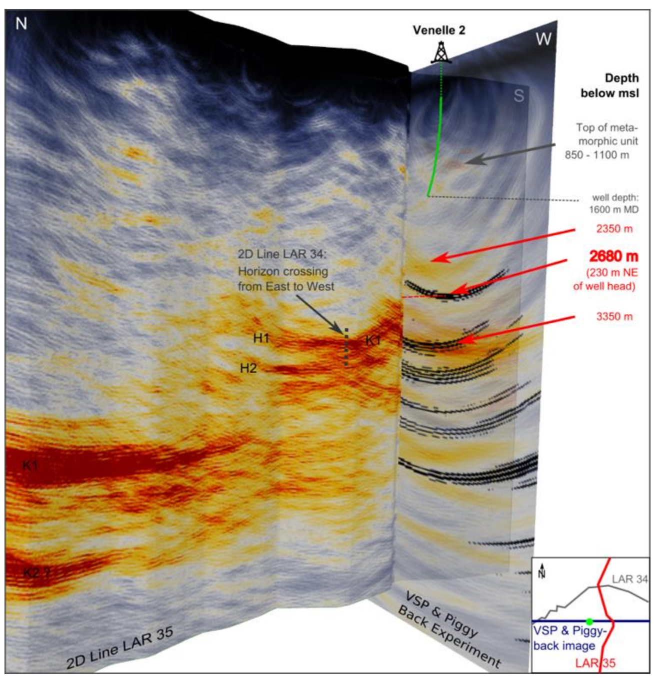

Figure 10: Comparison of imaged horizon revealed within 2D LAR seismic data (N-S-slice) and VSP & Piggyback experiment (W-E-slice): The reflectors imaged within the VSP survey are overlain (dark reflectors) and do not represent the actual lateral shape. The integration of different data reveals a more precise depth estimate at 2680 m below msl.

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 $^{3}He/^{4}He$ 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.

5. RESERVOIR MODELLING

5.1 Geological model

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 tectono-stratigraphic column presented in Figure 11 shows the sedimentary complex (Pliocene sediments, Ligurian Units, Tuscan Units, and Tectonic Wedge) overlying the Metamorphic complex. 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).

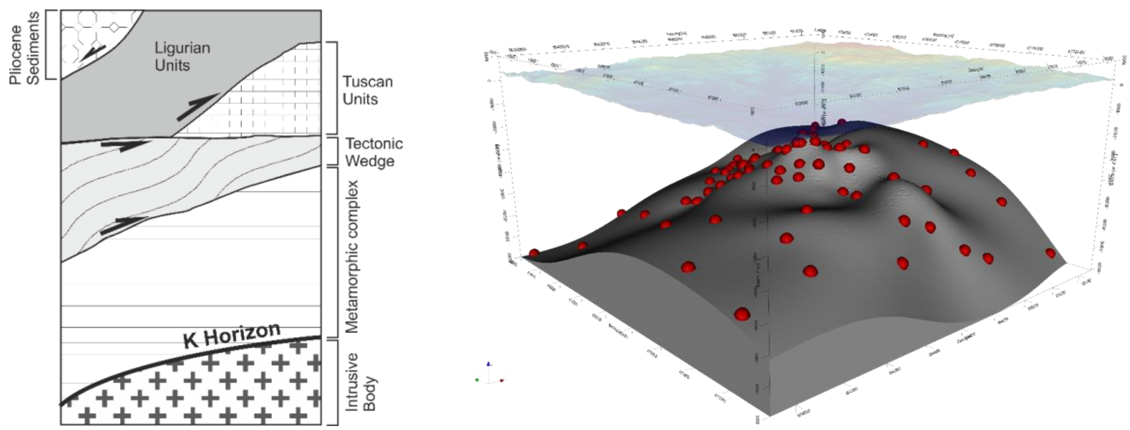

Figure 11: (Left) Schematic tectono-stratigraphic column of the study area (modified from Ebigbo et al., 2016). (Right) Three-dimensional model (view from SW) showing the top of the K-horizon as indicated by data (red spheres) and as a model unit (grey body). Topography is shown as transparent layer at the top.

The unit names presented in Figure 11 (left) are also used for later simulations (Table 1). Figure 11 (right) 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.

5.2 Conductive local 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 listed in table 1.

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.

Table 1: Unit parameters for porosity and thermal conductivity; * estimated values, + averages of data measurement on analogue outcrop samples. The porosity range in the Metamorphic complex represents an assumed fractured interval.

Unit Name	Porosity [-]	Thermal conductivity [W m^{-1} K^{-1}]
Pliocene Sediments	0.04*	1.9*
Ligurian Units	0.04*	2.7*
Tuscan Units	0.04*	2.2*
Tectonic Wedge	0.08^{+}	4.7^{+}
Metamorphic Complex	0.03 – 0.08	3.8
Intrusive Body	0.0001	1000

Figure 12 shows a temperature profile of the simulated Venelle-2 well (left), and a vertical N–S cross-section through the model (right), with unit boundaries indicated. 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.

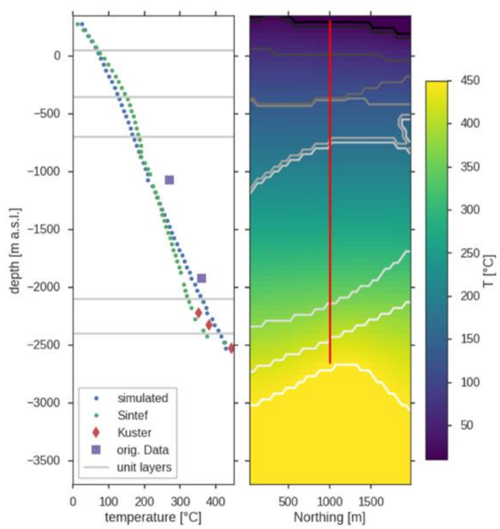

Figure 12: (Left) simulated temperature profile in Venelle-2 (blue dots), compared to measurements from the high-pT logging tool (green dots), Kuster data (red diamonds), and previous BHT (purple squares). (Right) N–S cross-section through the local model; gray lines: boundaries of lithological units.

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).

5.3 Simulation Results of the 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 13 shows the geological layering around Venelle-2 (left) and the final temperature distribution (right). The K-horizon (here with an assumed temperature of 450 °C) provides heat to the model.

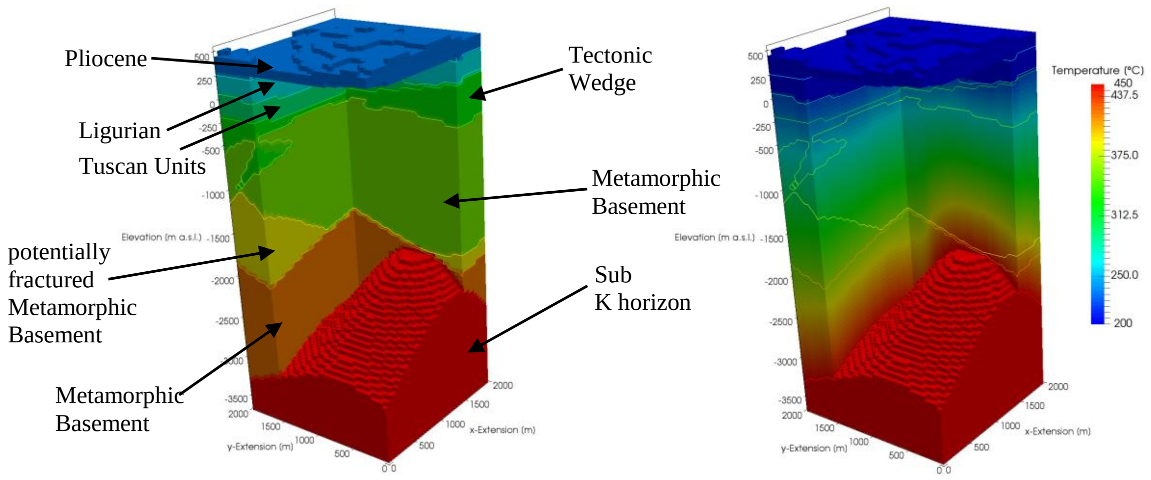

Figure 13: Layering of the local model (left) and temperature distribution (right).

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 300 bar. 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 300 bar, 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 on going.

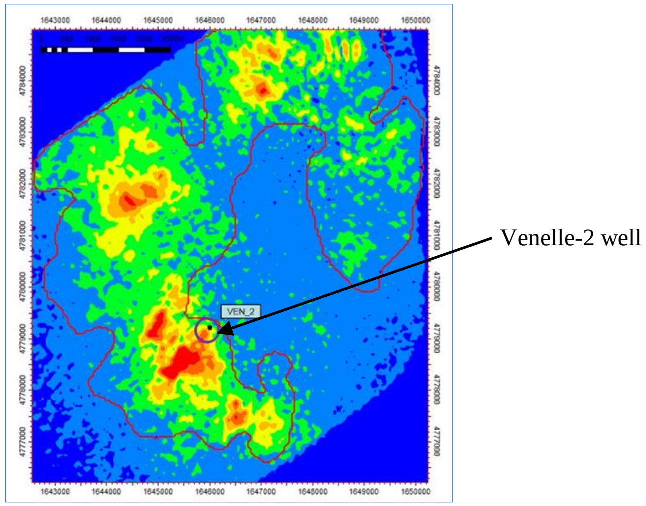

Figure 14: Map of the amplitude anomalies RMS calculated within the volume included between top and bottom of the K-horizon. In the purple circle the target for the deepening of the Venelle-2.

In the figure 14 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.

AKNOWLEDGMENTS

The research leading to these results has received funding from the European Union's Horizon2020 Research and Innovation Program under grant agreement No 640573 (Project DESCRAMBLE).

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