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DESCRAMBLE Project: Gas Logging While Drilling the Venelle_2 Geothermal Well (Larderello, Italy)

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ABSTRACT

We present the first application of a mud logging service specifically dedicated to gas analysis in the Larderello geothermal area. In the frame of UE-funded project DESCRAMBLE (Drilling in dEep, Super-CRitical AMBient of continentaL Europe), continuous gas logging techniques were applied while deepening down to 2909 m b.g.l. the Venelle_2 well, a non-productive well located in the southern part of the currently exploited geothermal field. Peaks of major (CO_2 and H_2S) and hydrocarbon gases were detected during the drilling. The presence of a deep crustal component was inferred on the basis of a maximum $^3He/^4He$ value of 1.5 Ra. Overall, gas data suggested that no major fracture systems were intersected during the drilling, able to drain fluids from rock volumes possibly acting as reservoirs for supercritical fluids. The gas logging of the Venelle_2 well emerged as an operationally simple and relatively inexpensive technique to obtain important information on the composition of formation gases, and to possibly predict the occurrence of absorption/permeable zones during drilling.

1. INTRODUCTION

Exploiting supercritical geothermal resources represents a frontier for the next generation of geothermal research projects. Geothermal research is targeting supercritical geothermal resources because the heat capacity of supercritical fluids is much higher than fluids at subcritical conditions. It is expected that any possible utilization of these resources could have a positive impact in terms of (i) increase of the output per well, and (ii) extension of the reservoir operating life.

Supercritical geothermal systems are very high temperature systems where reservoir fluids are expected to be in the supercritical state (e.g., Fournier, 1991). Supercritical conditions have been found at the roots of a number of geothermal fields in the USA (The Geysers and Salton Sea), Japan (Kakkonda), Italy (Larderello), Iceland (Krafla), and Mexico (Los Humeros), but no potentially exploitable resources were encountered until now.

Aimed at developing novel drilling technologies for a proof-of-concept test of tapping unconventional supercritical geothermal resources, the 3-years UE-funded DESCRAMBLE project was completed on April 2018 with the deepening (on late 2017) of the Venelle 2 well from 2200 m down to the depth of 2909 m b.g.l. An extremely high temperature value of more than 500°C was estimated at bottom hole, associated with a leak-off pressure of about 300 bar, though the existence of an exploitable reservoir was not proven (Bertani et al., 2018).

Real-time drill mud gas logging for scientific purposes was performed earlier in the framework of the San Andreas Fault Observatory at Depth program (SAFOD; Erzinger et al., 2004), of the German Continental Deep Drilling Program (Erzinger et al., 2004, 2006), of the monitoring of the Mt.Unzen volcanic area, Japan (Tretner et al., 2008), and of the Chinese Continental Scientific Drilling project (CCSD; Zheng et al, 2015, and references therein).

Few studies exist in the literature that present data on mud drilling gases. Among these, Aquilina and Brach (1995) applied a geochemical monitoring system during the deepening the GPK-1 borehole in Soultz-sous-Forêts, France, to investigate possible variations in the chemistry of fluids drained during the deepening of the well. Aquilina et al. (1998) compared data from drilling mud gas with gas released from drill core leaching experiments from the Balazuc-1 borehole in France. Rowe and Muehlenbachs (1999), and later Tilley and Muehlenbachs (2006), used instead drilling mud gas samples to investigate hydrocarbon migration and mixing in the Western Canada Sedimentary Basin. All the aforementioned studies are based on samples provided by commercial mud logging companies.

Almost all these studies have evidenced the inherent geochemical complexity of the interactions between the different matrices interacting during the deepening of wells under high-temperature conditions. In particular, a number of ill-defined reactions are expected to occur due to the presence of drilling additives that may enhance reactions among water, casing and/or drill bit steel, and host rocks. A large amount of so-called "artificial gases" are typically detected under these conditions (e.g., Whiticar, 1994).

These complexities do not affect noble gases that are chemically inert, and, in some case (e.g., He and Ar) significantly enriched in natural deep fluids compared to atmosphere. Accordingly, noble gases were measured in the gas discharges of Venelle_2 well to detect/trace the contribution of fluids coming from different crustal environments, such as shear zones, open fractures and, more generally, rock volumes with enhanced permeability.

2. GEOLOGICAL SETTING

The Larderello geothermal field, located in the Neogene Tuscan-Tyrrhenian extensional area (Fig. 1), is one of the few vapor dominated geothermal systems in the world. It is considered as a single, large hydrothermal system recharged by meteoric waters and heated from deep magmatic intrusions into a thinned continental crust.

Young (Pliocene to Quaternary) granite plutons have been identified as the primary heat source in the southern Tuscan geothermal areas including Larderello–Travale and Monte Amiata (Brogi 2008; Gianelli et al. 1997, 1988). These acidic intrusive bodies belong to the Tuscan Magmatic Province and can be linked to the extensional tectonic setting in the region (Brogi 2008). They are non-uniformly distributed and emplaced at various depths, leading to rather large differences in surface heat flow (100–1000 mW m^{-2}; Bellani et al. 2004) all over the Tuscan geothermal area.

Deep crustal seismic reflection profiles revealed the crust structure underlying the Tuscany, that consists in (Fig. 1): (i) a complex and structured upper part, (ii) an intermediate less (or poorly) reflective part and (iii) a highly reflective mid-lower portion, often bottomed by a laminated Moho discontinuity at 22-24 km depth (Accaino et al., 2005). The bottom of the uppermost reflective part is marked by a discontinuous high amplitude reflector, named K-horizon, locally marked by bright spot features. The K-horizon reaches minimum depths of about 3 to 6 km in correspondence of the geothermal areas, whereas it deepens to greater depths moving outwards (Cameli et al., 1993).

A second, deeper and more continuous reflector (K-2), though weaker than the above K-horizon, was imaged at about 7-9 km depth on the basis of AVO (Amplitude versus Offset) analysis of the seismic data (Tinivella et al., 2005). Possible fluid overpressure characterizes specific portions of both horizons. The nature of K horizons is still matter of debate. Two different interpretations were proposed in the literature: (i) the upper K-horizon could be the top of the brittle-ductile transition, and over-pressured fluids could be associated with this transition (Cameli et al., 1993); (b) K-horizons could top permeable reservoirs containing high pressure supercritical fluids (Accaino et al., 2005).

A correlation between the depth of the heat source, the presence of geothermal fluids enriched in mantle-derived ^3He and the K-horizon depth was hypothesized, among others, by Hooker et al. (1985), Magro et al. (2003, 2009), Bellani et al. (2004, 2005).

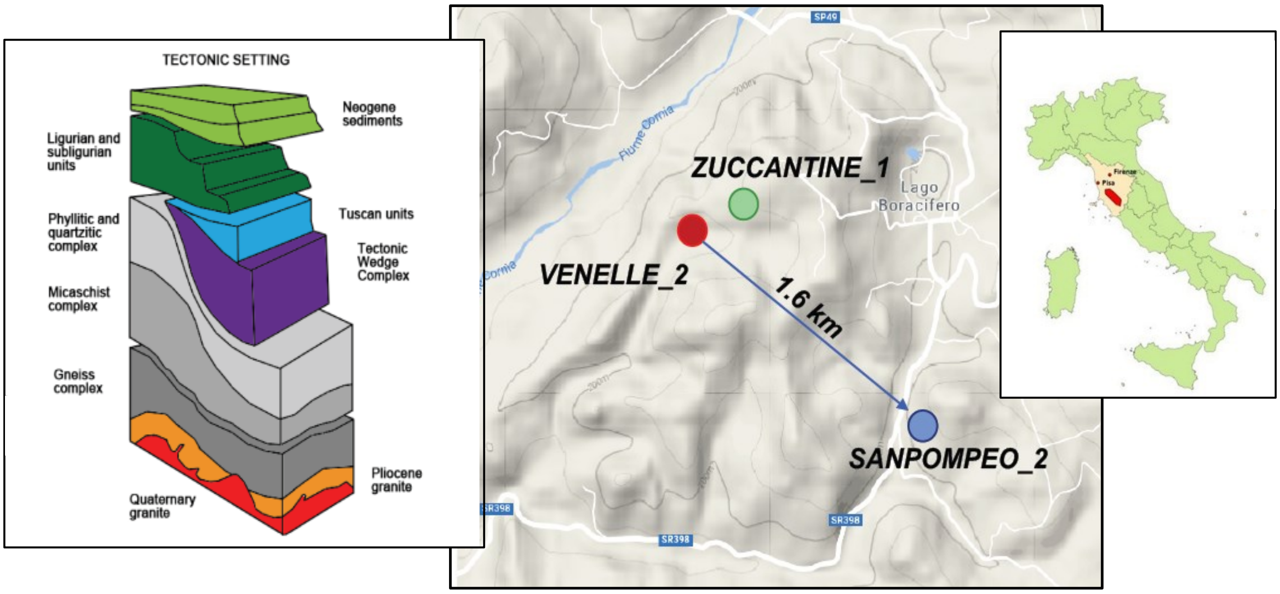

Figure 1: Location of the Venelle_2 well, Larderello, Tuscany, Italy and a schematic tectono-stratigraphic column of the study area (modified after Ebigbo et al., 2016): from up to down Pliocene (including Quaternary and Neogene) sediments (light and dark green); Ligurian and Subligurian units, which consist of remnants of the oceanic crust and its marine to pelagic sedimentary cover; (light blue, dark blue); Tuscan Nappe units, which are represented by continental margin deposits (Triassic to Miocene) of the Adria paleomargin, Carbonate and pelagic–turbidite successions (Tuscan units above Burano"); the Burano formation, which forms the basal unit of the Tuscan Nappe successions and consists mainly of anhydrite and carbonates; the deeper Tuscan metamorphic complex, referred to as the Farma formation (light and dark grey); Quaternary and Pliocene granites (red and orange) (Batini et al., 2003, and references therein).

The Venelle_2 well features were considered favorable for testing and optimizing the scientific, technical and economic efforts of deep drilling operations under harsh temperature conditions. In particular, extremely high temperature and pressure (supercritical) conditions were expected below about 3 km depth, considered that a temperature of 350 °C at about 2.2 km depth was registered at the bottom of this existing dry well.

Further to this, the Venelle_2 well is located in an area of the Larderello geothermal field where a thick pack of major seismic reflections was highlighted by geophysical methods, and the so-called K-horizon was supposed to culminate at shallow depth (up to

3 km deep). In this area, the presence of ^3He-enriched deep mantle derived fluids in geothermal fluids was witnessed by $^3He/^4He$ ratios up to 3.2 Ra (with Ra = $^3He/^4He$ reference value for the air; Hooker et al.,1985, Magro et al., 2003), indicating the upper mantle as the main active source for the crust thermal and ^3He anomalies

The Venelle_2 well is close to San Pompeo_2 well, a well drilled in 1979 and blowed-out before reaching the K-horizon due to high-pressure fluids unexpectedly encountered during its deepening to about 2.9 km depth. The erupted rock material assemblage consisted of tourmaline-quartz breccia and vein fragments, similar to a number of rock specimens collected from other magmatic-hydrothermal systems developed at the top of granite intrusions in Tuscany.

3. METHODS

3.1 Real-time gas logging

The technique of measuring standard drilling and gas parameters in the geothermal exploration drilling is relatively new. With the more extensive implementation of mud logging techniques in geothermal wells, and the development of new surface logging equipment, a number of specific tools for the geothermal exploration have been recently deployed by adapting pre-existing oil and gas drilling/monitoring techniques (e.g., Carcione et al., 2017; Regan et al., 2018).

In the recently deepened Venelle_2 well, a modern mud logging unit was installed and equipped with sensors for the detection of CO_2, H_2S, H_2, He and C_1-C_5 hydrocarbons extracted from the drilling fluids, along with electromagnetic flow meters to early detect possible absorption/permeable zones.

In particular, a dual FID gas system detector able to measure and quantify the presence of hydrocarbon gases from methane (C1) to normal-pentane (nC5), a total hydrocarbons detector and a microGC (equipped with a thermal conductivity detector) able to measure non-hydrocarbon gas concentrations of compounds like helium, hydrogen and carbon dioxide (Fig. 2), were installed. All gas sensors were connected to a constant volume mud gas extractor (CVD) which allowed for an efficient mechanical extraction of the gases from the drilling fluid. The gases continuously extracted by the CVD were sent through a gas line connected to a gas distribution system (GDS) for the analysis. A specific device allowed to collect additional gas samples for stable isotope analyses in the laboratory.

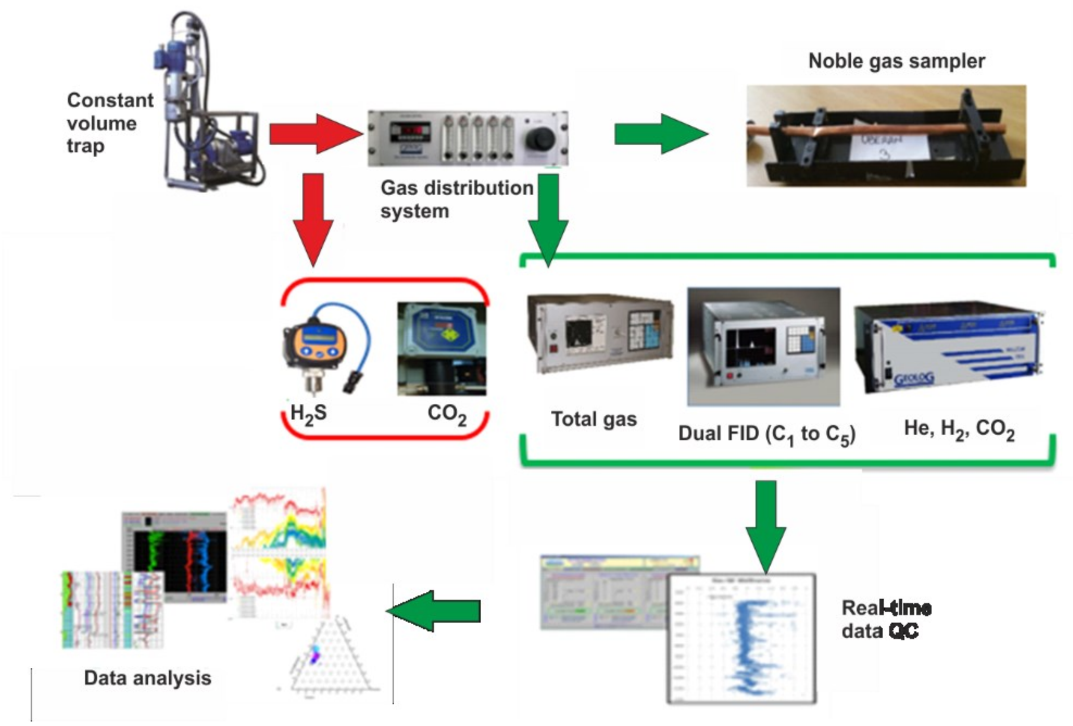

Figure 2: Gas sampling/logging chain deployed in Venelle_2 well.

3.2 Electro-Magnetic flow meters (EMFO/EMFI)

In addition to the gas monitoring system, a number of electromagnetic flow meters were installed to monitor real time losses and gains of perforation fluids during the drilling. The use of high-resolution electromagnetic flowmeters is a very effective method to detect and characterize conductive fractures and/or high-permeability zones, that relies on an accurate and continuous recording of fluids loss from/entry into the borehole environment. By this method, any possible influx of formation fluids is sensitively detected by real time monitoring of flow variations (Fig. 3).

Figure 3: Electromagnetic flow meters installed in the Venelle_2 well.

Figure 4 shows the total losses event at 2333m MD and the dynamic losses behavior starting from 30 to 35 m^3 hr^{-1}, until the full returns was established by reducing the mud flow in rate. In the Venelle_2 well, the correct management of mud losses helped in minimizing borehole stability issues, and, consequently, in reducing non-productive time (NPT) and in effectively performing wireline logs, casing runs and cementing job.

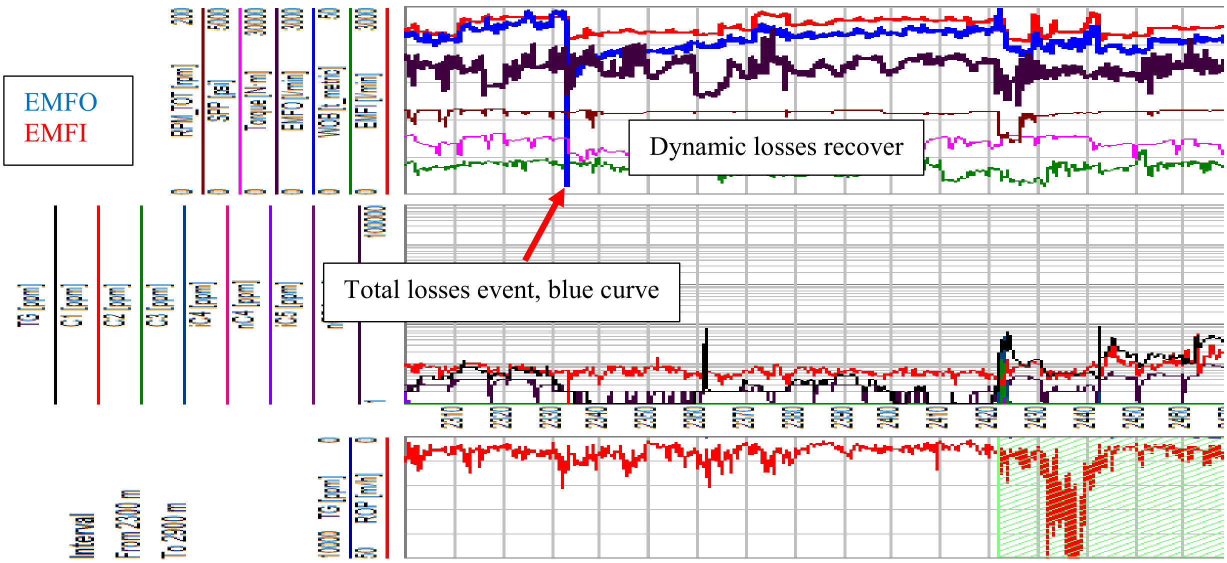

Figure 4: Total losses event recorded by EM flowmeter Out (EMFO).

3.3 Offline sampling

Noble gas aliquots were extracted from perforation fluids (mud or water, depending on the depth) after mechanical degassing at the surface. The degasser was installed in the mud pit above the shaker screens directly at the outlet of the mud flow line, to guarantee an efficient degassing of the drill mud immediately before the extraction of the gas. Commercial gas-water separators, optimized for standardized, repeatable results, were used. In such separators, the gas was extracted from the drilling mud (or water) by mechanical stirring and stripping with air.

During the drilling of the Venelle_2 well, the type of perforation fluid was changed: (i) mud during the first stage of the drilling (i.e. down to about 2700 m), (ii) below this depth, waste geothermal water, pumped from tanks, after re-equilibration with air at near-ambient temperature. An atmospheric component was thus always present in drilling fluids, considered that both mud and water tanks were open to air. Helium concentrations were measured in parallel by gas chromatography (continuous gas log) and by mass-spectrometry (spot samples), allowing for an efficient cross-testing of the different instrumental detection limits. Discrete noble gas samples were analyzed in the IGG Rare Gas Lab of Pisa, Italy, for He, Ne, Kr, and Xe abundances, and for their isotopic composition, in 14 samples collected in concomitance with the occurrence of positive anomalies in total gas concentrations, as detected by gas chromatography during the continuous gas log.

3.4 Magnetic and quadrupole Noble Gas Mass Spectrometry

The samples for noble gases analysis were processed on a stainless steel high-vacuum line equipped with cold (active charcoal at liquid N_2 temperature) and hot traps (Ti getter) to separate noble gases from reactive gases (Magro and Pennisi, 1991). Noble gases are then separated each other by means of traps cooled at variable temperatures by a cryostat pump.

The extraction line is connected both to a magnetic mass spectrometer (MMS=MAP 215-50) and a quadrupole mass spectrometer (QMS=Spectralab 200, VG-Micromass). The amount of He + Ne is checked via QMS before being introduced into the MMS. ^3He and ^4He are determined by peak jumping and detected on an ion counting and faraday cup device, respectively. Resolution for ^3He was close to 600 AMU for HD-^3He at 5% of the peak. Ne, Kr and Xe were determined by peak jumping and detected on faraday cup device. A standard volume of air at different pressures (from 1013 to 10.13 mbar) was introduced into the extraction line and treated in the same way as the samples to check measurement reproducibility (Magro et al., 2003). The air $^3He/^4He$ ratios exhibited a reproducibility better than 10%. The mass ratios (4)/(20) measured on air standards by MMS and QMS showed a reproducibility better than 10%.

4. RESULTS AND DISCUSSION

4.1 Reactive gases

Reactive gases showed the following concentration peaks (Fig. 5): (i) at 1400-1500 m depth, CO_2 and minor amounts of H_2 were detected, with a maximum value in correspondence with a minor circulation loss at 1500 m depth; (ii) at about 2600 m depth, another concentration peak of CO_2 and H_2 was observed, while other gases were still almost absent; (iii) below 2700 m depth, CH_4 increased up to 14% v/v, H_2 peaked at 4% v/v, while CO_2 dropped to few ppm in correspondence with a supposed seismic reflector identifiable as H and/or K horizon, during a drilling break. Also low hydrocarbons (C_{2+} compounds) were detected, though in low amounts; (iv) at bottom hole (2909 m depth), CO_2 increased again, while H_2S was detected in considerable amount for the first time (up to 200 ppm).

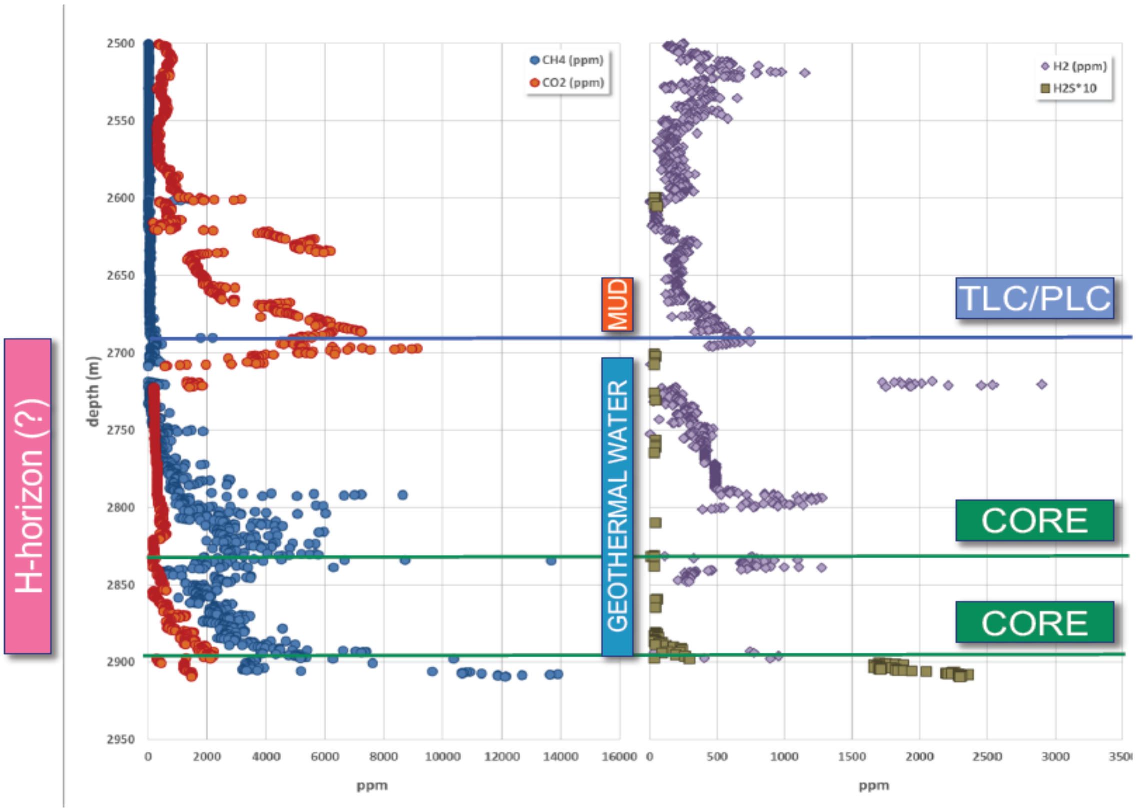

Figure 5: Real time logs of CO_2, CH_4, H_2 and H_2S concentration, along with indication of the circulation fluid using during the drilling (mud vs geothermal water). TLC/PLC = total/partial loss of circulation. CORE = coring depth.

No positive correlations were observed between gas concentration, rock porosity and the amount of rock crushed in time, as typically reported for oil and geothermal drilling exploration. On the contrary, a negative correlation among these parameters was observed, along with a series of anomalous increase patterns in CH_4, CO_2 and H_2 concentration (see arrows of Fig. 6). Further to this, the chemical signature of Venelle_2 C-bearing gases appeared markedly different from the gases collected at similar depths, from the same lithology (phyllites), in the productive sectors of the Larderello geothermal field (e.g., Gherardi et al., 2005). Overall, these features were interpreted as an indication of an artificial origin of these gases. Thermal cracking induced by the mechanical action of the drill bit on borehole rocks was one of the possible generation mechanisms hypothesized to explain these observations.

The same mechanism, possibly coupled with a contamination effect related to the inflow of organic and inorganic additives at the surface, was also invoked to explain the occurrence of detectable amounts of C_{2+} hydrocarbons in 3 sections, i.e., in concomitance with: (i) the conditioning of a new in hole mud system at 2697-2700 m depth, (ii) wireline log and coring activities at 2800-2830 m depth, (iii), bottom-hole coring between 2900 and 2909 m depth. This conclusion was further supported by the fact that C_{2+} components did not show any direct correlation with variations in CH_4 concentration. On the contrary, the existence of a constant positive correlation between H_2, CO_2 and CH_4 concentrations further supported the hypothesis of an artificial origin of all the reactive gases detected during the deepening of theVenelle_2 well.

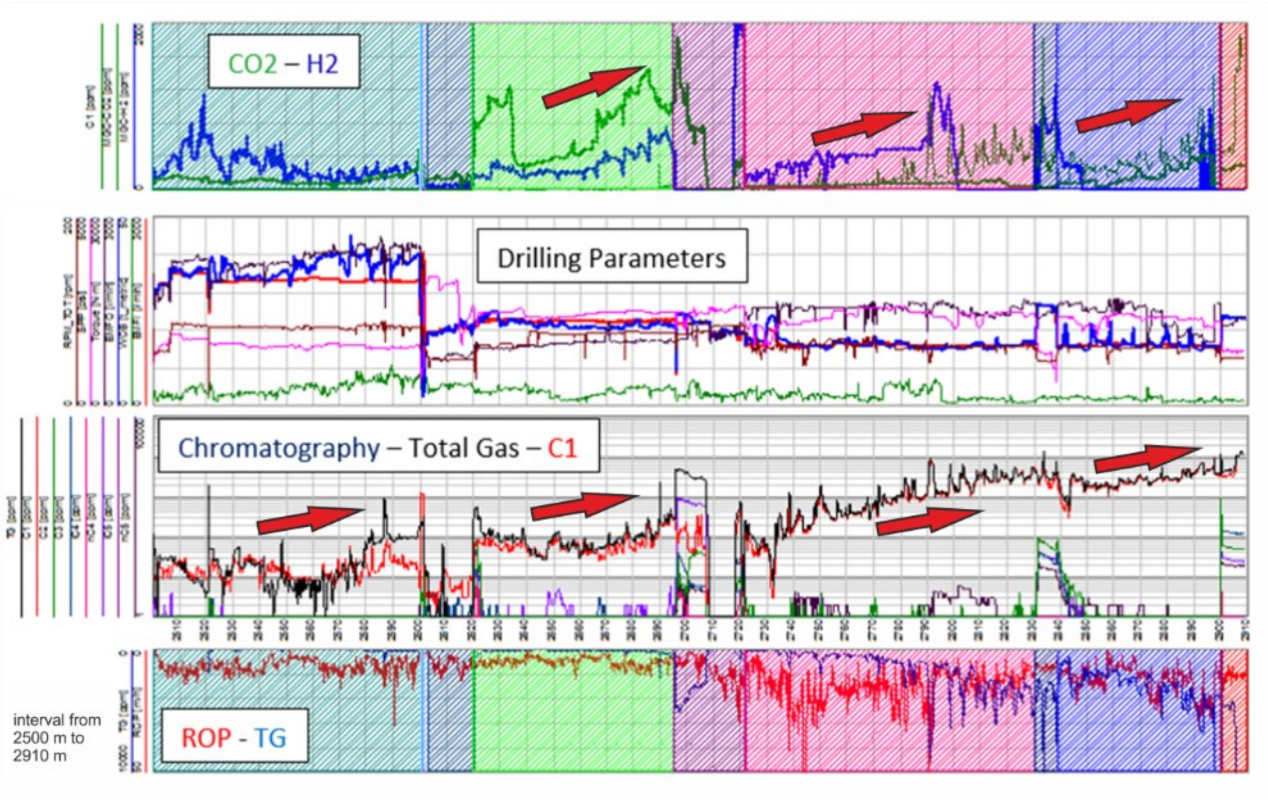

Figure 6: Composite log of drilling parameters and gas chromatographic concentrations of CO_2, H_2 and CH_4. Zonation colors represent single bit runs.

4.2 Noble gases

All gas samples extracted from drilling fluids contained low, but measurable amounts of He, as detected by spectrometric techniques. Helium concentration were generally below the air typical value of 5.24 ppm, whereas $^4He/^{20}Ne$ ratios spanned the range 0.253 to 0.318, typical of air saturated water (between 0.253 to 0.280, for air-saturated water equilibrated at 10°C and 30°C, respectively) and/or air (0.318). Notably, the gas chromatographic detector used during real time drilling monitoring failed to detect He in most of the samples successfully analyzed by mass spectrometry. This was not surprising, considered the significantly different sensitivity of the two methods (mass spectrometric techniques have a markedly higher sensitivity).

The $^4He/^{20}Ne$ ratios clearly indicated that the noble gas atmospheric component derived from the mixing of air and air-saturated water end members (Fig. 7). This mixing was further confirmed by the behavior of Kr (Fig. 7) and Xe, two sensitive noble gas tracers of atmospheric contamination. A relevant feature of this figure is the shift from values closer to the air end-member, typical of the early drilling phase operated with mud as circulation fluid (samples from C1 to C4), towards values closer to the air-saturated water end-member, typical of the late drilling phase operated with waste geothermal water as circulation fluid (samples C6 to C21).

Despite the low He abundance and the atmospheric signature of $^4He/^{20}Ne$ ratio, the presence of deep-seated He likely derived from a ^3He-enriched source in all the samples was unequivocally indicated by $^3He/^4He$ values between 1 to 1.59 Ra. The severe air contamination intrinsically associated with gas extraction device did not allow for the correction of measured R/Ra values with standard formulas (e.g., Craig, 1978). This is because the helium correction is very sensitive to the $^4He/^{20}Ne$ ratio assumed for the atmospheric component. Accordingly, the highest measured $^3He/^4He$ ratio of 1.59 Ra should to be considered as a sort of minimum reference value for the "real" R/Ra value effectively associated with fluids drained during the perforation of Venelle_2 well.

Noble gases from Venelle_2 well did not show any significant trend with depth. It is worth noting that in one of the wells preliminary sampled in the surroundings of the perforation area, $^3He/^4He$ values significantly higher than in the Venelle_2 well were measured (2.54 Ra instead of 1.59 Ra). Further to this, the highest $^3He/^4He$ value found in Larderello (3.2 Ra; Hooker et al., 1985), was measured in the San Pompeo 2 well, before its blow-out, not far from Venelle_2.

The absence of spikes with deep He isotopic signature (i.e., markedly enriched in ^3He) suggested that during the deepening of well, no major fracture systems were intersected, able to drain fluids from the deepest sectors of the currently productive metamorphic geothermal reservoir, or from other rock volumes possibly acting as reservoirs for supercritical fluids. Overall, these features were interpreted as an evidence about the highly impermeable nature of the rock volume (and/or of its external envelope) crossed by the perforation.

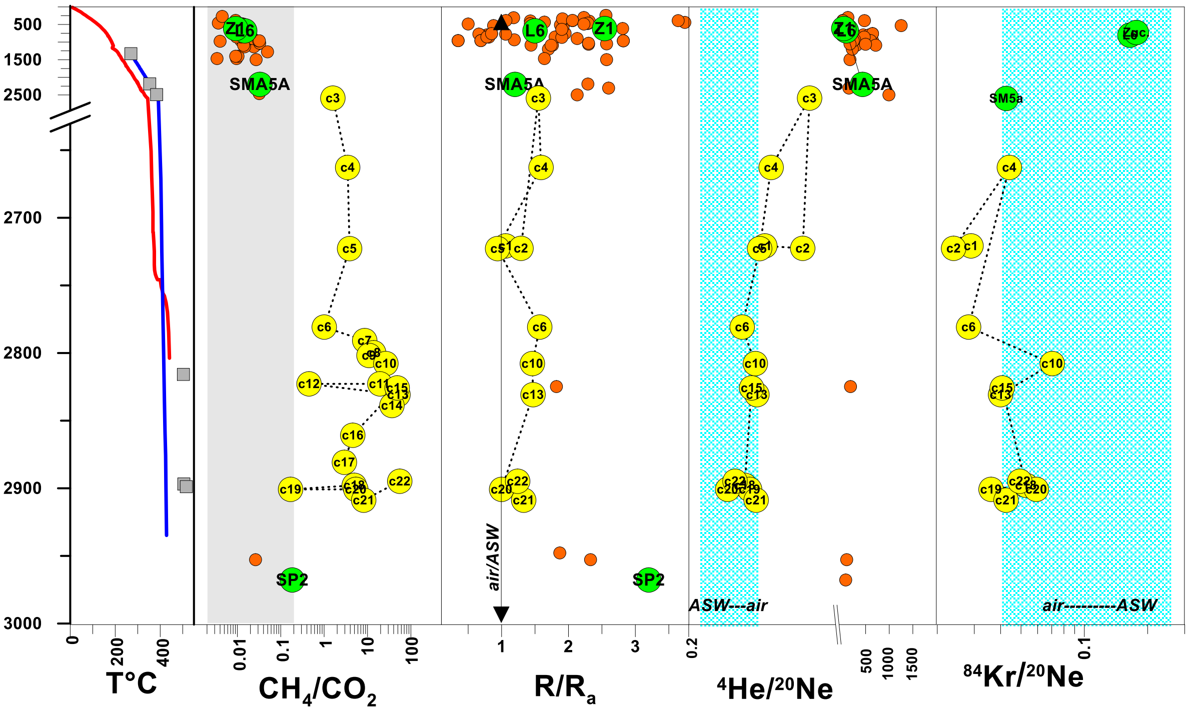

Figure 7: Temperature, and CO$_2$/CH$_4$, $^3He/^4He$ (R/Ra), $^4He/^{20}Ne$, $^{84}Kr/^{20}Ne$ ratios depth profiles in the Venelle_2 well.

5. CONCLUSIONS

Gas logging during the deepening of the Venelle_2 well emerged as a valuable tool for detecting absorption/permeable zones, that provided important information on the gas composition of formation fluids. This technique is operationally simple and relatively inexpensive. It helps in taking decisions about drilling strategies, and is a valuable mean to ensure safe drilling conditions. The larger the number of gas species analyzed, the more information is obtained to help understanding deep processes. For geothermal applications, CH_4, He, CO_2, H_2 and H_2S represent a minimum set of components to be analyzed. However, a number of interferences that depend on site-specific drilling conditions may affect the representativeness of the chemical composition of reactive gases.

In particular, under the harsh conditions of the Venelle_2 borehole drilling (elevated P,T conditions, circulation of fluids contaminated with unknown amounts of inorganic and organic additives), reactive gases showed anomalous spikes likely related to the mechanical action of the drill bit on borehole rocks. This was interpreted as an evidence of the predominant “artificial nature” of the aforementioned reactive gas compounds. Although the thermal cracking of the additives circulating in the borehole environment during the drilling was supposed to be a major process of gas formation, more specific investigation on the chemistry of the lubricant and of the different drilling fluids used are needed to unequivocally decipher the origin of CH_4, CO_2, and H_2.

Conversely, due to their inertness, noble gases turned up as a reliable geochemical parameter to constrain the origin of crustal fluids drained by the Venelle 2 well. Despite the low He abundance and the atmospheric signature of $^4He/^{20}Ne$ ratio, the presence of deep-seated He likely derived from a ^3He-enriched source in all the samples was unequivocally indicated by $^3He/^4He$ values between 1 to 1.59 Ra. Notably, noble gases features did not show any trend with depth, coherently with the lithological homogeneity of the geological formations (phyllites) crossed during the drilling. Even the crossing of the so-called H/K seismic reflectors was not mirrored by any change in the noble gases signature.

The fact that no relevant changes in the $^3He/^4He$ composition were recorded in concomitance with the crossing of the H/K local seismic reflector raises additional questions about the geothermal, geochemical and hydrological significance of this type of seismic reflectors, starting from their significance as possible targets for drilling and industrial exploitation of supercritical fluids.

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