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The New Well to Obtain Hot Water and the Drilling Problems in Very Fractured Granitic Massif in Unhais da Serra Spa - Portugal

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ABSTRACT

A study is presented in this paper with the objective to drill a geothermal well with a depth of 1000 m to be applied in urban spaces, bathing waters, and at *Unhais da Serra* Medical Spa in Portugal. Drilling took three years to complete and was not completely successful in terms of the initial goals due to some very peculiar geologic and structural characteristics of the drilling site. The many occurrences of alternate semi-vertical fractures with resistant granite reaching great depths were especially abnormal.

Several aspects of the construction of this drilling, the techniques applied to this perforation, lithological classification, drilling speed, material recovery, rock quality (RQD), and the explanation of the events that led up to the decision of drilling are presented in this article. Negative geological characteristics led to frequent collapsing of the perforation walls, necessitating frequent injections with cement to stabilize them. The techniques of deviation are also discussed. Finally, the production capacity of the new well producing mineral water at 38ºC and considerations about the energetic potential of this resource are presented.

1. INTRODUCTION

The construction of the new well US1 is predicted to solve, or at least to be a valuable contribute to, the energetic fulfillment of the new hotel and thermal complex, which has been completed (STUS, 2009). This complex had a global cost of €15,000,000. The initial goal of drilling the well was to achieve 1000 m depth and obtain mineral water at 60ºC. Particularly because of the drilling problems, the goal was only partially achieved. The present study was conducted in Portugal, a country in south-western (SW) Europe, and had the idiosyncrasy of a geological fault called the Vilariça Fault located in the work zone. A geological map of the region is displayed in Figure 1. The Vilariça Fault stretches over two-hundred kilometers across northeastern Portugal, reaches depths of several hundred meters, and in the Torre area crosses Serra da Estrela, the highest mountain in Continental Portugal (2000 m). The drilling site is located 688.2 m above sea level above highly fractured granite rocks and within fairly close range of the schistose rocks that are theoretically located west of Vilariça Fault.

Theoretically, because of work performed that led to evidence of a system of parallel faults closely orientated to the global direction NE-SW, US1 probing is in that area. It is impossible to determine the exact position of this fracture system *in situ*, because there are almost 30 meters of glaciofluvial deposits that rest over granitic rocks in the well and Spa areas.

Some characteristics of the mineral water system in Unhais da Serra have been presented (Ferreira Gomes and Machado Saraiva 1997), as well as specific information about the new US1 well (Ferreira Gomes et al. 2007a). In hydrogeological terms, there is essentially one semi-confined aquifer of hot mineral water in the granite rocks. In the first 130 m below the surface, there are fractured, almost completely saturated rocks with small alteration signs; below this, the hot mineral water only circulates locally, and the majority of the area is completely dry due to the occurrence of a complex system of fractures with a dominant clay filling isolating the productive area completely. A glaciofluvial covering with big round blocks of granite and a gravel-clay matrix on top of the granite make it very difficult to flush the area of the mineral water.

There are several *water points* that are worthy of mentioning here: the old springs, the *Banho* and the *Cortiço,* have water with a maximum temperature of 28ºC; the wells ACP1 and AC2, built in the 1990's, have hot mineral water at 37ºC; and the wells AC1 and AC3 from around the same time present no interest in mineral water terms. Some aspects of these *water points* are presented in Table 1. The water of mineral aquifers, usually designated as sulfuric water, is more formally called "sodium bicarbonated, carbonated, fluoreted and sulfidrated" water. Before the new drilling, the exploration plan allowed for the retrieval of 4 l/s for use in a small bathing place, which was demolished in the meanwhile.

2. WELL PROJECT MOTIVATION

There were several motivating factors for this project: the need for an increase of mineral water, the construction of a well that gave guarantees of retrieving mineral water in a more stable fashion, and a fundamental need to obtain hotter water so the ambient, sanitary waters and playing pools in the new complex could be heated.

On other hand, there was the notion that this area contained geothermal anomalies. The temperature of the mineral water in the Cortiço spring is 28ºC and in the ACP1 Well is 37ºC at depths of only 65.5 m.

So, if a geothermal gradient of 0.033ºC/m is assumed according to average approximation, it would be necessary to drill to a 1000 m depth to obtain 61ºC water (IGM 1998). The local estimated gradient obtained near the ACP1 Well of 0.14ºC/m is much higher than the average, and if the gradient extends to 1000 m, the fluid obtained would theoretically be at 168ºC. Another point worthy of emphasis is near the Manteigas Medical Spa (shown in Figure 1) in the extreme of Serra da Estrela mountain, north of Torre, and in association at the same Vilariça Fault, is a well with 100m depth and geothermal fluid at 48ºC.

Applied geothermometers based on the solubility of silica (57.8 mg/l, DGGM, 1992) that, after calculation, either using geothermometer-quartz in adiabatic situation (ΔH =0), or isentropic situation (ΔH = S) (Aires de Barros 1979), indicated water temperatures of 109 ºC in the reservoir offer further motivation. All of these factors motivated the plan for a new drilling with intentions of reaching 1000 m and a predicted fluid temperature of at least 60ºC.

All available geological structural elements were analyzed rigorously and drilling was programmed according to the model shown in Figure 2. The drilling direction was changed to NE, making its course 1.5 degrees with the vertical axis so that it would intersect almost perpendicularly (in horizontal plane) the WNE-ESSE fractures that were predicted to be productive in hot mineral water. This model achieved complete success in the Carvalhal Medical Spa, where water was obtained at 69.5ºC in the bottom of a 600 m well (Ferreira Gomes et al., 2007b)

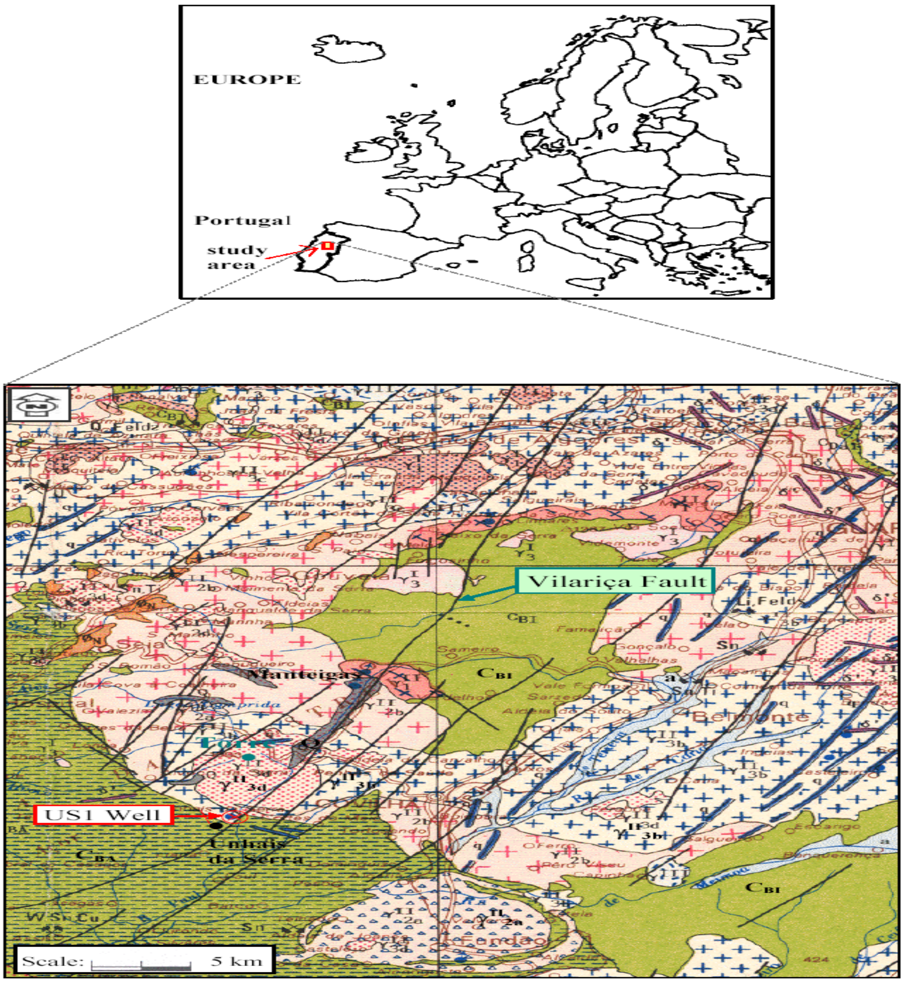


Figure 1: Locations of Unhais da Serra's Medical Spa (Portugal) and the US1 well implanted in a geological map of the inside region of Portugal.from SGP (1992). C_{BA}, C_{BI}: ante-ordovicic schistose rocks; Υ - granitic rocks (≈250-280 millions of years): Υ_{II3b} - porphyritic granite; Υ_{II3d} – non porphyritic granite; Q- glaciofluvial deposits (Quaternary); a – recent alluvium.

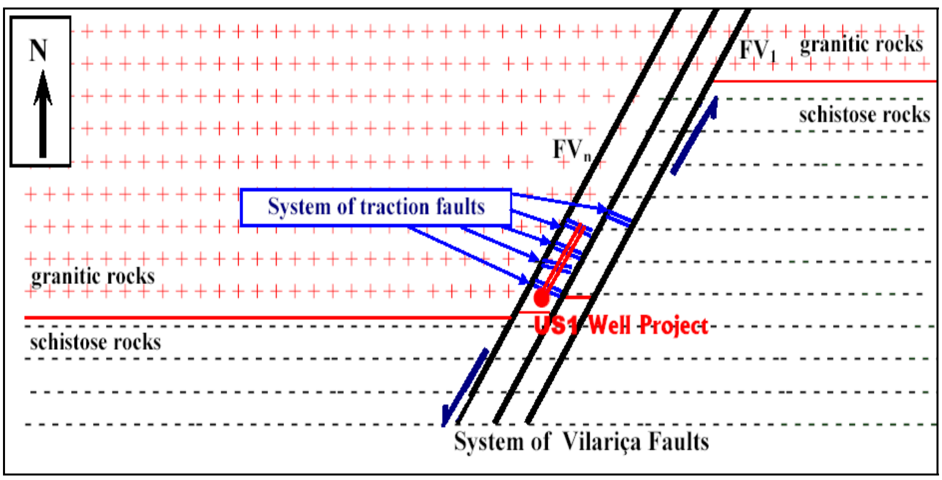


Figure 2: Conceptual model of new drilling location, in relation with the Vilariça fault system (FV1…FVn) in the area of Unhais da Serra Medical Spa (UBI, 2004).

Table 1: Geometric situation of the several water points in the area surrounding Unhais da Serra Medical Spa.

Water point	US1	ACP1	AC1	AC2	AC3	Cortiço	Banho
Distance US1	0	24	38	10	117	10	24
Terrain height (above of the sea level)	688.2	689.9	689.2	688.2	693.8	689	689.4
Static level height	690.5	690.5	689.5	690.5	691.5	688.4	688
Static level depth	-2.3	-0.6	-0.3	-2.3	2.3	0.6	1.4

Note 1: the negative sign means that level is above terrain height, that is, there's a artesian spring; in the points with positive values (in AC3, Banho and Cortiço), the depth to reach water level corresponds those values. Note 2: the AC3 well produces normal water; all others produce sulfuric water.

3. EXECUTED WORK AND RESULTS

The beginning of the well drilling was recorded at 01/07/2005 and its end at 20/12/2008. The pump test was recorded on the same day, but perforation works ended in August 2008. The long global period of 3 years and 6 months was due to some stops in the process and the geological complexity of the location, with occurrences of singularities that increased the difficulty of the situation and decreased the possibility of having a positive outcome. Disregarding the dead time due to malfunction, the construction of the well took 2 years and 2 weeks, or 24.43 months.

The aforementioned geological singularities were mostly of two types:

i) Immediately after the onset of perforation, glaciofluvial deposits were intersected, as shown in Figure 3. This led to many cementing and perforation repetitions. In addition to the long period of time spent on this phase, a constraint had to be made for the hole geometry to have a different position from that ideally predicted. The particularity of the occurrence of stones and very resistant blocks with very even and round surfaces forced the deviation of the hole

ii) At depths greater than 150 m, there were intersections with completely decomposed granite, similar to loose soils, associated to thick fault boxes, as seen in Figure 4. It was necessary to perform several cementations to overcome these terrains in a way that the drill zone could be resistant and somewhat consistent in toughness. This was a particularly poor situation because it was predicted that the perforation would be performed continuous drill core rotation in tough rock with no need for cementing. In some fault box zones (e.g. between 148.7 and 152 m) the perforation was executed without finding any apparent solid elements. That is, only stirred water was found as a result of the desegregation of clay and water that occurred in thick, semi-vertical faults. These singularities caused the walls of the hole to collapse. Since the crown and of all the drilling tools were at great depths, it sometimes took over one week of maneuvers only to retrieve the rods at the bottom.

Work was frequently performed in an abnormal regime, as difficulties in the perforation of the glaciofluvial deposits were not foreseen, and the granites were expected to be robust enough to permit continuous perforation by the rotation drill core, as was customary in this region.

This situation forced the first use of the Guided Perforation technique in this kind of work in Portugal. It should be noted that this merely helped to minimize the situation, which was far from ideal because of the alternation of very resilient granites with sand and clayish terrains, which added more difficulties and caused consecutive collapses. Cementing was necessary to overcome these situations and progress in depth.

i) *Route 0* (R0), from 0 to 126m, drilled in rotopercussion;
ii) *Route 1* (R1), from 126 to 326 mb performed with continuous drill core rotation;
iii) *Route 2* (R2), between 141.2 and 532.4 m, performed with guided perforation and continuous drill core rotation;
iv) *Route 3* (R3), between 47.2 and 132 m, performed with guided perforation and continuous drill core rotation.

The location of the various US1 probing routes are presented with a local geological-structural map in Figure 5. The original predicted orientation of probing is also shown. Sketches of the various routes and some aspects of the perforation are displayed in Figure 6. The main technical characteristics of the various routes, including achieved depths, diameters, tubing, time of operation, costs, and aspects of the pumping tests are presented in Table 2. Pictures of the various perforation techniques used are presented in Figure 7.

Figure 3: Images of the glaciofluvial deposits in the area of Unhais da Serra Medical Spa.

Guided perforation was also employed in the drilling of R2 in order to impose a spatial development to the Northwest to intersect the initially intended area but once again resulted in a dry route. The guided perforation was replaced with perforation with continuous rotation of the drill core whenever the probing achieved the projected position. This route did not intersected mineral water, leading to the belief that it rises only in a very specific area, most likely at the intersection of two fractures. In the development of a singular semi-vertical alignment that evolved gradually in the course of the drilling from West to North and then Northeast, it was postulated that the drilling route circled around the area of rising mineral water. Some theories of this situation are presented in UBI (2008a). In that phase of the process (at 532.4 m), the perforation did not progress in depth due to the fact that the probe did not have many chances to intersect mineral water upon reaching this depth, so there was a need to change its course. Despite the theoretical possibility of this, putting it into practice would seriously aggravate the problems of ruptured beams and screws when using the continuous drill core rotation because the position of several curves would present a very peculiar situation. Thus, it was decided in this stage to commit to a plan that would obtain a positive outcome despite a large increase in expenses over the initially predicted amount.

The drilling of R3 was executed after some intermediate actions and finally led to positive results and the completion of drilling. Several expediting pumping tests were performed in this stage that led to the discovery of an excellent water flow with a temperature of 38ºC.

The well had a total perforated length of 802 m in the virgin massif. In order to reach this length, several tasks including a great deal of cementing had to be performed. This led to new perforations in cement after drying with a total length of 937.8 m. Therefore, the total length of perforation was 1739.8 m.

It should be noted that this stage of cementing operations exhausted 50.71m^3 of syrup (cement grout), corresponding to a total of 45,685 kg of cement, as shown in Table 2. Images of the manual preparation of syrup and the pump used in these operations are presented in Figure 9. A sodium chloride additive was used at times to facilitate the drying time of the syrup due to the fact that the groundwater was sulfuric. The waiting time for the syrup to dry and cement was 709.7 hours, and the unitary cost of this was €120, resulted in unproductive task of €85.140. Other details including the global cost of well US1 of €599,381.10, can be observed in Table 2.

It is important to note that a 30 m thick superficial formation of glaciofluvial deposits was discovered in the zone near well US1 over a granitic massif.

At depths less than 150 m, the granitic massif consisted mainly of medium grain granite. Below 150 m, the probe intersected regularly fractured porphyritic granite with faults and thick clay boxes.

Material recovered in some of the core stick samples presented a new granitic aspect: when in contact with vibrations, they deconstructed easily into tiny grains, becoming a sort of small-grained gravel. (See Figure 4d.) This situation is probably due to the tectonic stresses of the active area, in which the rock decompressed and became friable when being pulled towards the surface. This new variable should be especially noted in future projects of this kind to eliminate uncertainty.

To better illustrate some of the massif characteristics and some consequent difficulties as exemplified in Fig.10, with the detailed cut perspective in routes 0 and 1, with evidences of the lithological alternation, cementing extensions (grouting), as well as the length of each effective perforation operation in virgin massif and their progress speed. As can bee seen in the figure, 57 distinct groutings were verified in these routes with the particularity that none of them occurred at 25-63 m, 126-144 m, or 239- 326 m. In the rotopercussion stages, there were times that collapses occurred after the first cementing so that there was a need to cement second time at the same depth with a maximum of 14m initiated at 52-66 m in the continuous operation. The best advance in the continuous drill core rotation stage of the operation was 6m, initiating at 105 m. It was verified that the rate of advancement was 14 m/day during the rotopercussion stage and 6 m/h during the continuous drill core rotation stage.

(a) (b) (c) (d)

Figure 4: Images of the granitic massif extracted from over 150 m depths, in a typical situation of many times sandy materials (a), other times with clayish faults (b,c) besides of intercalation with apparently very resilient granite, that turned out to be fragile and prone to fracture (c), in probing US1 of Unhais da Serra Medical Spa, Portugal.

Analysis of the core stick samples to determine the degree of alteration and fractures required the indexing of several parameters in order to have a relative idea of the internationally used classifications (ISRM,1978, 1981). These parameters included:

- RR, or recovery rate (0-100%), calculated as the ratio of the length of the sample collected from manipulation to the drilling length;

- RQD, or Rock Quality Designation (0-100%), calculated as the ratio between the sum of the length of core sticks more than 100 mm long and the total length of drill run; the quality classification of RQD values are:

RQD (%)	Quality classification
0 – 25	1 - Very poor
25 – 50	2 - Poor
50 – 75	3 - Fair
75 – 90	4 - Good
90 – 100	5 - Excellent

- F, or joint spacing, which being *s* from spacing, the following designations are obtained:

F5, if $s < 0.06$ m;
F4, if $0.06 < s < 0.2$ m;
F3, if $0.2 < s < 0.6$ m;
F2, if $0.6 < s < 2$ m; and
F1, if $s > 2$ m.

- W, or weathering, corresponds to the various alteration degrees based on the macroscopic observation of hitting with the geologist's hammer and comparing the experience. This ranges from W1 for rocks with no alteration signs to W5 on the other extremity. For rocks with high alteration degrees, S is also considered whenever the material has soil features.

In the shallowest areas of granite,(30-150 m), where continuous drill core rotation was performed, a RR of 100% was observed. Joint spacings of F3 and F4 frequently occurred between fractures in these areas. In the majority of situations, the RQD indicated Fair Quality, followed in frequency by the Poor and Good situations, respectively. The degree of alteration in this area of superficial granites was frequently of the W3/W2 type.

The RR value in the granite zone below 150 m was below 100% in many situations, sometimes reaching 0% when crossing the fault. In these areas, the joint spacing was frequently logged as F5 and F4. The observed RQD values led to the frequent labeling of the massif as very poor to poor. Rarely did the value indicate fair or better quality. Good quality was only observed in the terminal zone (500-532 m). The degree of alteration was frequently observed to be W5 and W4. Material that segregated at the touch of the hand was classified as S corresponding to sandy terrains, sometimes clayish or even pure clay.

A pumping test was implemented from December 19-20, 2008 to determine the potential of hot mineral water. Submersible pumps were applied in wells US1 and ACP1 at around 18 m depths. In an arrest situation, the aquifer level tended to stay 2.3 m above the surface of the terrain in US1.

In the initial phase, pumping was in US1 over various steps of constant water flow during a predetermined period of time, all the while measuring the levels in both wells, as shown in Fig.11a.

After analyzing the results of the first phase (Fig.11b), both wells were pumped simultaneously with water flows of 13.2 l/s in US1 and 5.0 l/s in ACP1. The evolution of the levels to 8 m of relatively stabilized drawdown showed a potential water flow of 18 l/s.

A physiochemical analysis verified that both wells had similar resources: sulfuric water reaching a maximum temperature of 38ºC, which was also similar to the mineral water that served the medical spa for a few hundred years.

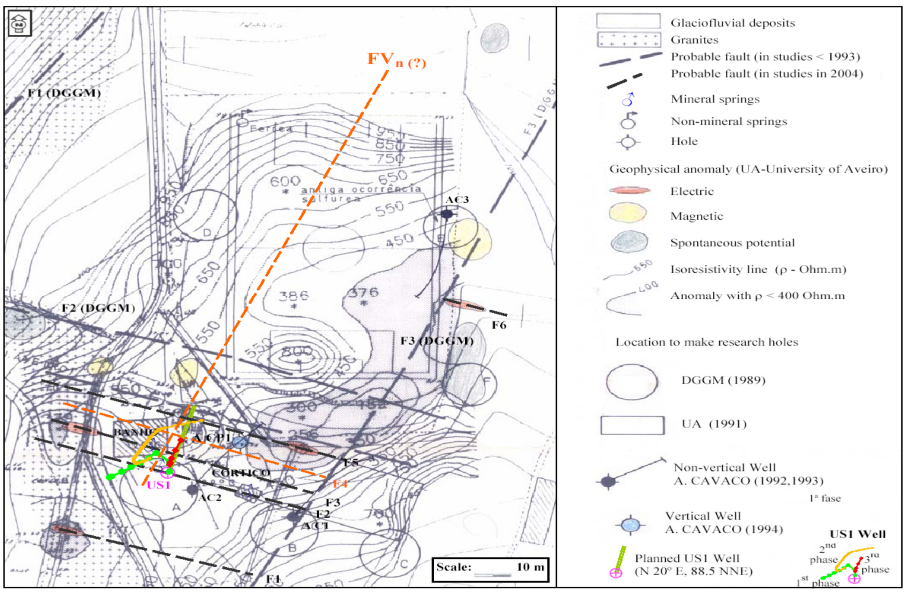


Figure 5: Deployment of US1 with its several phases and its position in relation to that initially planned in the Unhais da Serra Medical Spa area in Portugal.

Table 2: Main characteristics and other elements associated with the perforation of US1 Well in the Unhais da Serra Spa area.

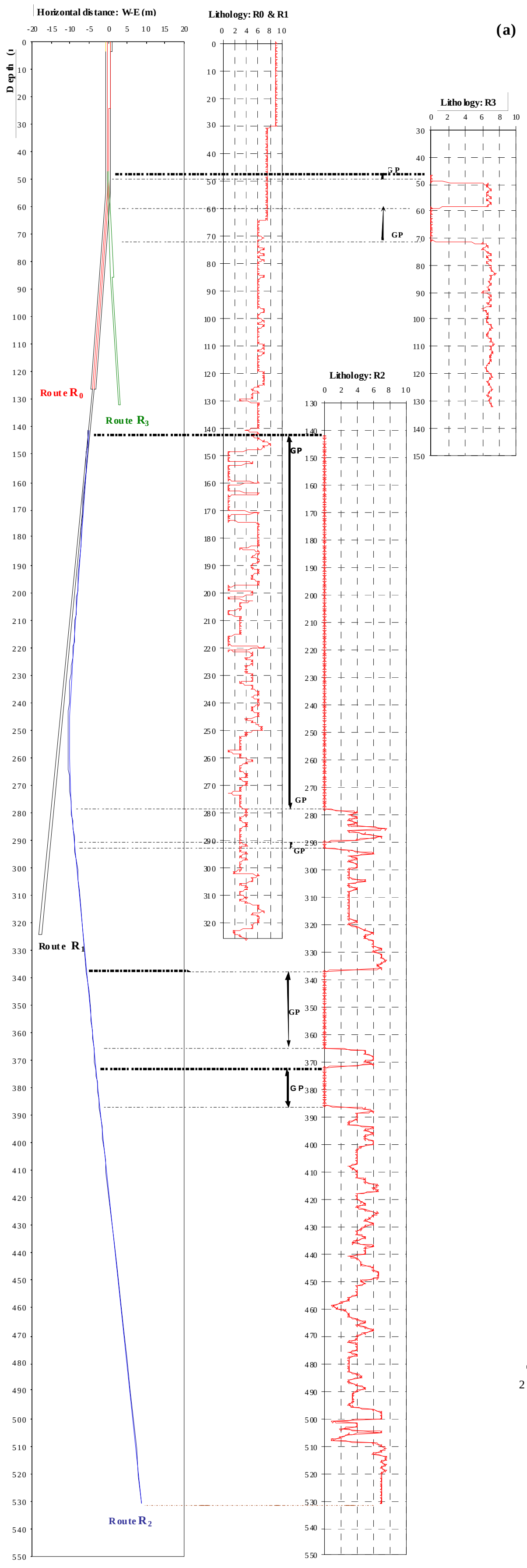
Parameter	Characteristics	Unit cost (€)	Route R_0	Route R_1	Route R_2	Route R_3	Final phase	Total
Depth (m)		-	0-126	126-326	141,2-532,4	47,2 – 132,0	-	802,0
Preparation and Transport		30.000	1	-	-	-	-	-
Assembly and disassembly		5.000	1	1	-	-	-	-
Period	Beginning	-	01.07.2005	29.03.2006	27.11.2006	12.11.2007	17.12.2008	01.07.2005
	End	-	06.01.2006	08.09.2006	09.11.2007	30.05.2008	20.12.2008	20.12.2008
	Months - total	-	6,2	5,3	9,4	6,6	0,13	27,63
	Effective months (*)	-	6,2	5,0	7,7	5,4	0,13	24,43
Drilling in the natural massif (m)	Mechanical digger	-	4,0	-	-		-	4,0
	Rotopercussion ∅ = $12^{1/4}$" (311,2mm)	150	122,0	-	-		-	122,0
	Rotation drill core PQ (122 mm)	130	-	200,0	-		-	200,0
	Rotation drill core HQ (96mm)	140	-	-	205,9	23,4	-	229,3
	Rotation drill core NQ (76mm)	130	-	-	-	46,4	-	46,4
	Guided Perforation GP (∅ ≅ HQ)	140	-	-	163,8	100,7	-	264,5
Drilling in the cement (***) (m)	Rotary	(***)	210,9	-	-	-	-	210,9
	PQ/HQ	(***)	-	165,0	539,1 (**)	22,8	-	726,9
Intubation (m)	Normal steel (0-4m) ∅ = 18" (457,2 mm)	150	4,0	-	-	-	-	4,0
	AISI 316L (0-24m) ∅ = 8" (204mm)	195	24,0	-	-	-	-	24,0
	AISI 316L (24-126 m) ∅= $6^{1/2}$" (168,3mm)	185	102,0	-	-	-	-	102,0
Concrete	(m^3)	113,85	10,0	-	-		-	10,0
Cement (syrup)	(m^3)	160	37,12	4,00	8,18	1,41	-	50,71
Sodium chloride	(kg)	0	495				-	495
Time of special operations	(h) cementing/perforation cement/…	150	281	208	840	330	-	1.659
Waiting time	(h) for the cement to dry	120	381	54,5	206	68	-	709,5
Number of cementing operations	in perforation	-	45	12	36	7	-	100
	In tubing - anular	-	10	-	-	-	-	
Deviations	(even 5º)	14.500		-	1	1	-	2
Attitude measurement	Nº	150		9	13	8	-	30
Expeditious pumping tests	1 h	150	2,5	-			-	2,5
Final pumping tests	-	13.650	-	-			1	1
Report	-	5.000	1	1	1	1	1	5
Cost	Partial (Euro)		177.772,7	75.730	225.236,8	101.991,6	18.650	-
	Accumulated (Euro)		177.772,7	253.502,7	478.739,5	580.731,1	599.381,1	-

(*)the considered effective time is the result of global time with the subtraction of the malfunction days, fisheries, maintenance and other kinds that didn't contribute in real time for the advancement of labors (1 month was considered equal to 30 days).

(**)this value includes 24.4 m that corresponds to perforation in deviation of 141.2 to 162.6m, counting as cement perforation, but that gradually included granite in the drilling diameter cross section.

(***) these operations are not counted in costs, because they are considered in working hours consigned to special operations.

Note: the rotation drill core always a used wire-line system to collect the samples

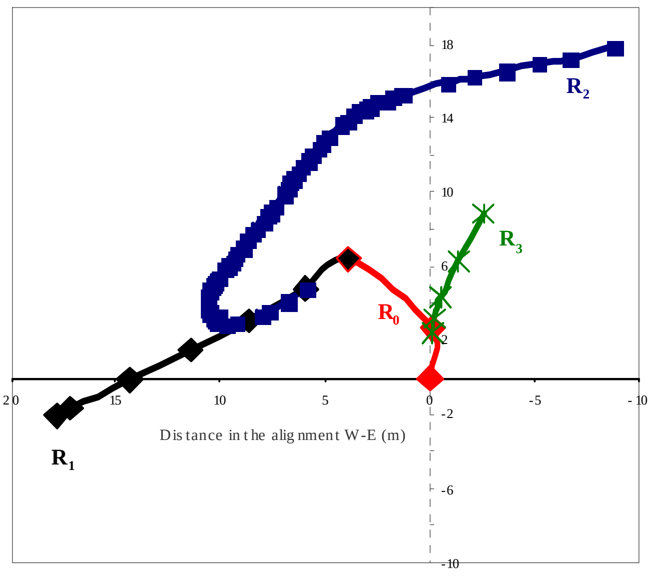


Legend in the lithological column

Lithology – alteration degree	N° in lithological column
Glaciofluvial Deposits	9
Granite - W1	8
Granite – W2	7
Granite - W3	6
Granite - W4	5
Granite - W5	4
Granitic soil (sandy)	3
Clay -sandy soil	2
Clay (box fault)	1

Note: the zero value correspond the uncertainty because it happened Guided Perforation (GP)

Route	R_0	R_1	R_2	R_3	total
Depth (m)	0 – 126	126 - 326	141,2 –532,4	47,2 – 132	-
Length (m)	126	200	391,2	84,8	802
Tubing	AISI 316L	open hole	open hole	open hole	-
Final diameter	∅ = 8”: 0 - 24 m; ∅ = 6”: 24 - 47,2 m Neutralize: 47,2-126 m	neutralized	neutralized	∅ = 3.8”: 47,2-85,6 m; ∅= 3”: 85,6 - 132m	-
Drilling type	0-126 m: Roto-percussion (RP)	126-326 m: Rotation drill core PQ (96mm)	141,2-532,4m: alternated in Guided Perforation (GP)(96mm) and Rotation drill core (PQ)	47,2 – 85,6m: alternated in Guided Perforation (GP) and PQ; 85,6- 132m: Rotation drill core NQ (76mm)	several: RP, PD, PQ, NQ



(b)

Figure 6: Sketch of the spatial position of the US1 Well with its various routes in vertical cross section according to direction W-E (a) and in the horizontal plane (b) along with some of the characteristics of the Unhais da Serra medical Spa area

Figure 7: Images of the perforation techniques used in the construction of US1 probing, by rotopercussion system (a, b, c), by system of rotation with continuous rotation of the drill core (e, f, g) and with guided perforation system (g, h, i, j, k), in Unhais da Serra, Portugal. Note: the system of guided perforation adapts to the continuous rotation of the drill core, with the detail of substituting the classic head and gauge for a hollow bar (i) in association to a piece with a gentle curve before the bit (h); bit rotation is triggered by an iron rod of helical shape in the interior of the hollow bar so that receiving injected water at high pressure (g) causes the rotation of the bit; thus, because the only things moving are the interior of the equipment and bit, it is possible to control the deviation curve position in the interior of the hole. Also note the fact that in the classic continuous rotation of the drill core, the head spins in harmony with the rods and with the head of rotation on the surface.

Figure 8: Images of the spatial probing positioning measurements performed with a "Reflex Instruments- EZ-SHOT" device in US1, Unhais da Serra.

Figure 9: Images of manual preparation of syrup (cement grout) in recipient and of pump for injection in the interior of the drill US1, in Unhais da Serra

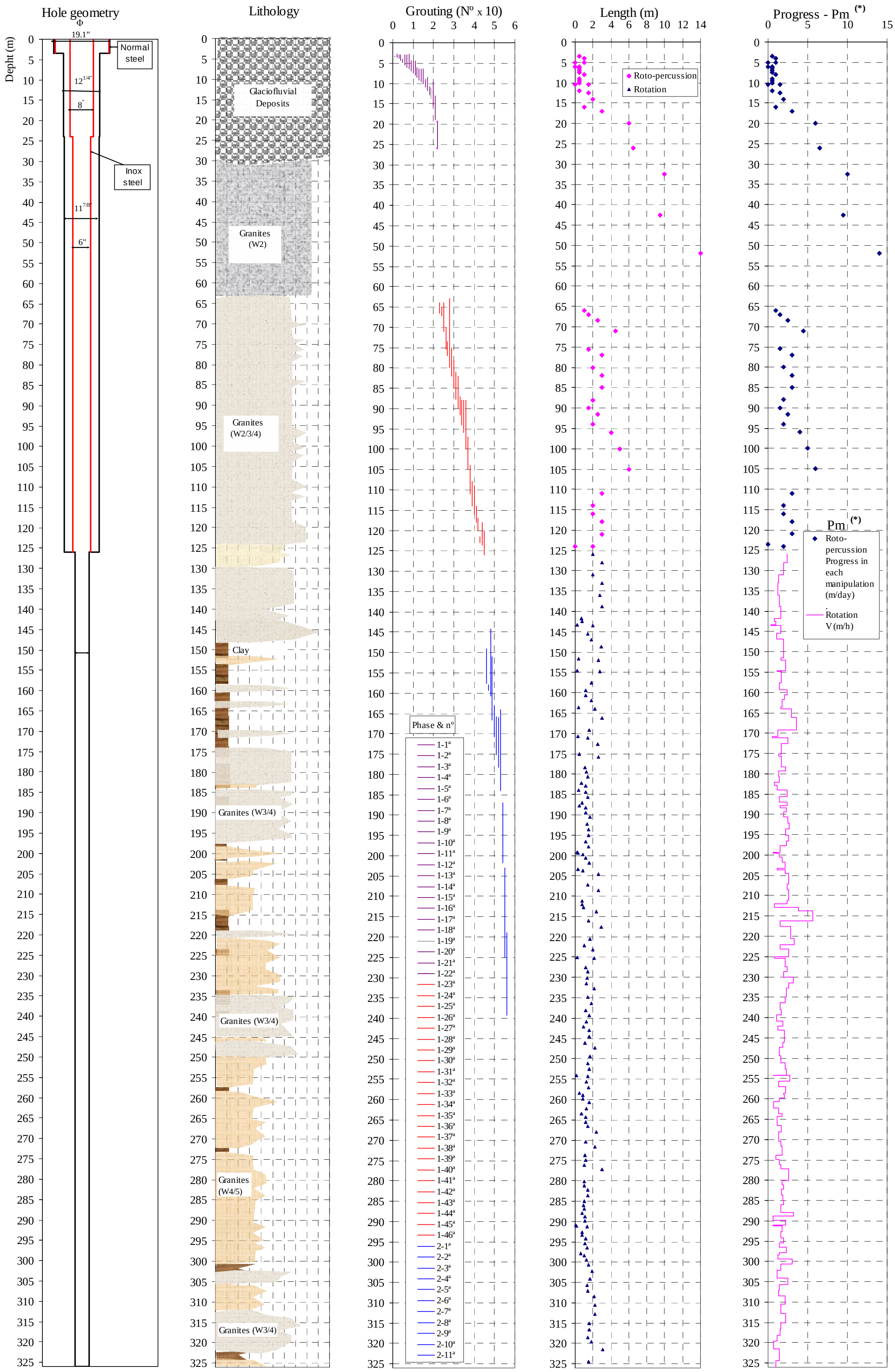


Figure 10: Elements of Routes 0 and 1 related to the evolution of lithology with depth, number of cementing (grouting) and respective extensions, length of each advancement manoeuvre, and the speed of perforation (progress), in probing US1 in Unhais da Serra, Portugal (Ferreira Gomes et al., 2007b).

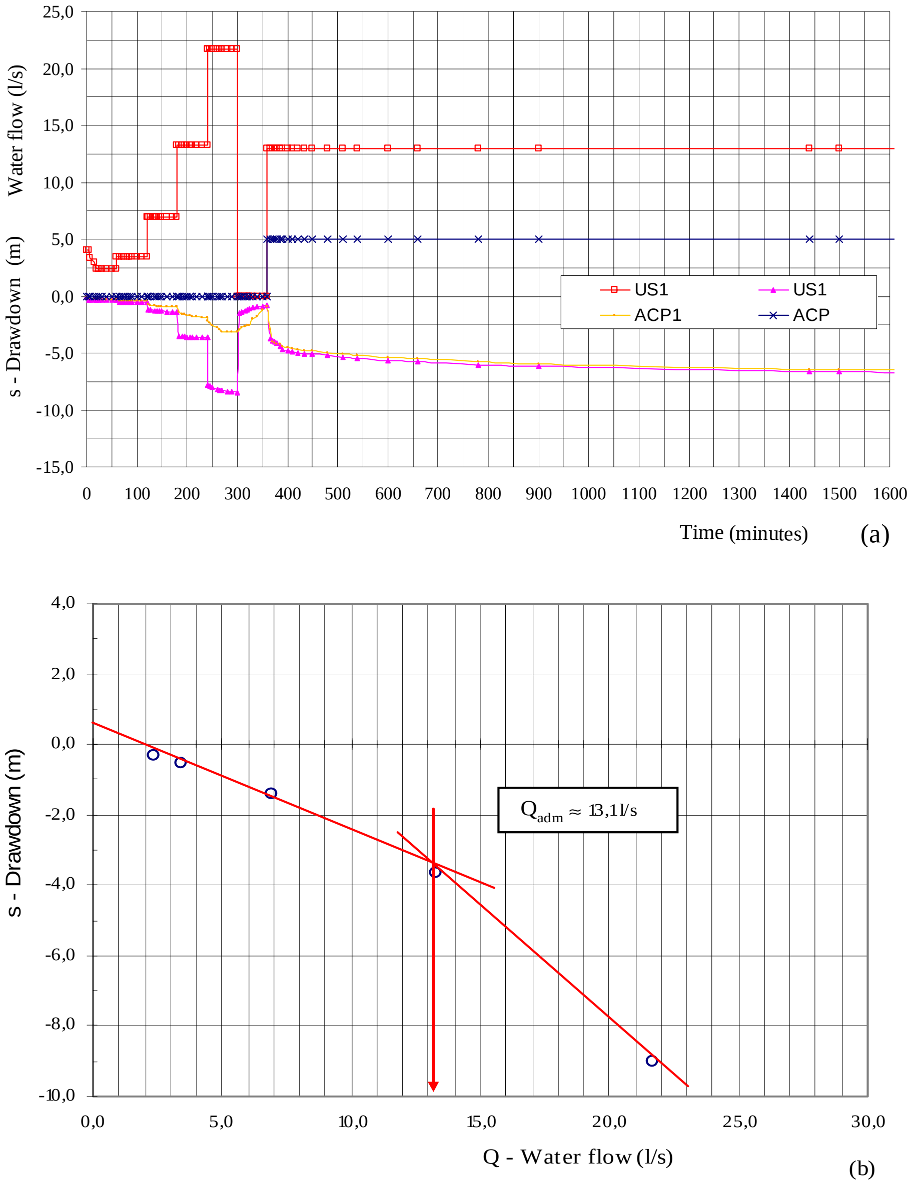


Figure 11: Results of the pumping tests in the 1st stage of pumping only in well US1 and in a second stage, pumping in US1 and ACP1 simultaneously (a) and characteristic curve of US1 (b) in Unhais da Serra medical spa, Portugal

4. GEOTHERMIC POTENTIAL AND ECONOMIC AND ENVIRONMENTAL ASPECTS

It is emphasized that in geothermic terms, the initial objective of reaching at least 60ºC water was not met, but it is now evident that this is possible in a future phase. The elements of this phase allowed for the refinement of the geohydraulic model and the collection of elements that allowed the planning of a new probing in the area with more adequate techniques and without so many geological surprises. Advancement wasn't possible in this stage because of the depletion of the predicted budget and the fact that the Portuguese government isn't prone to prioritize this type of energy.

However, the attained results will save in the owners of this complex money in energy bills and minimize the cost of ambient heating of the sanitary waters of the Hotel with 90 bedrooms, the Medical spa, and the play spaces including the pool waters. Still, the mineral water in the majority of the applications in the medical spa does not have to be heated.

Then, considering the basic water flow of 18 l/s at 38ºC, admitting that the removed energy corresponds to a downgrade of 38ºC to 15ºC, and allowing for the fact that it is necessary to heat the swimming pool water and all other applications, the theoretical available thermal energy will be:

$$E \approx (18\ kg/s)_*(38-15)_*1kcal/kg = 414\ kcal/s = 0{,}4814kWh/s = 15_*10^6\ kWh/year$$

according to the fundamental heat equation (Monteiro 2001). If it is possible to establish a well devised plan of exploration to utilize all this energy, it would substitute the same amount of energy supplied in electricity by EDP (Portuguese public company of energy supply). This would allow for savings up to 1,500,000 €/year when considering the 0.10 €/kWh amount.

Another probable possibility in Portugal is the supplying of that energy to supplement a propane gas boiler with a heat potential (PCI) of 12.9 kWh/kg (GDP 1998). Assuming a burning efficiency of 90%, this would replace 1,292,000 kg/year of propane. At a propane cost of 0.58 €/kg, this corresponds to 749,360 €/year.

For the previous numbers, it is obvious that existing a necessity of that energy if it wasn't supplied by geothermal source, it would be supplied by the gas source, due to the inferior cost, when compared to electricity. This would lead to an environmental burden because 1 kWh of energy supplied by the burning of propane gas corresponds to the emission of 257.9 g of CO_2 into the atmosphere (Ferreira Gomes, 2007). Thus if the total amount of energy was to be supplied with propane gas, a total of 3,868.5 tons/year of CO_2 would be released into the atmosphere.

These values of economical and environmental aspects demonstrate the major importance of the results attained at the US1 well.

5. CONCLUSIONS

The initial goal of drilling a 1000 m well to obtain mineral water at 60ºC near the Unhais da Serra Medical Spa was not achieved. The hydrogeological indicators point to the impossibility of such a situation. The geological singularities of the area (the occurrence of glaciofluvial deposits in the first 30 m and a highly fractured granitic massif with semi-vertical faults oriented in such a way that the semi-vertical probing would intersect hard rock alternated with soft clay at depths greater than 150 m) led to a different probing course than was initially projected. The technical limits of performing deviations from the original spatial position without losing diameter led to the first use of the guided probing technology in Portugal. The lack of experience in guided perforation in terrains with alternating materials of very diverse toughness necessitated the cementing and consecutive new perforations in the weaker layers. This also contributed to the original objective not being totally met. The objective was constrained due to the elevated cost of probing stemming from the cementing and other frequent special operations (including syrup injection, waiting for the syrup to dry, and new cement perforation).

During this work, 802 m of virgin rock were perforated, leading to an unusual geometry probing, as is presented in Figure 6. This was constituted by a central route (R0), and three other routes (R1, R2, and R3). The maximum reached depth was about 530 m.

Despite all this, the pumping tests shown in Figure11 indicated a sulfuric mineral water flow of 18 l/s (13 l/s in US1 and 5 l/s in ACP1) similar to that used at "Unhais da Serra" with a 38ºC temperature.

In a theoretical exercise that considers the use of 18 l/s of geothermal water at 38ºC with a rejection temperature of 15ºC, the sum of energy available would about $15*10^6$ kWh/year. If ideally harnessed, this would save up to 749.360€/year in propane gas expenditures (at a cost of 0.58€/kg), and consequently avoid the release of 3,868.5 tons/year of CO_2 into the atmosphere.

At last, these works allowed for a better knowledge of the geohydraulic conditions of the Unhais da Serra, and this will lead to a better probability of goal achievement in future probing. Most of all, it is expected that this paper can be used to make the Portuguese government and the European Union aware that geothermal funding should be made available to this small country as to others alternative sources of energy, as Portugal has immense geothermal potential stemming from "hot rocks" of granitic origin.

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REFERENCES

Aires de Barros, L. (1979). Termometria geoquímica – Princípios gerais, aplicações geotérmicas a casos portugueses. *Com. Serv. Geo. Portugal*. T. LXIV. Lisboa. pp.103-132. (in Portuguese).

DGGM (1992). Termas e águas engarrafadas em Portugal. *Ed. DGGM.*. Lisboa. (in Portuguese).

Ferreira Gomes, L. M. (2007). Aproveitamento Geotérmico em Cascata em São Pedro do Sul. *Boletim de Minas, 42 (1).* DGEG - Direcção Geral de Energia e Geologia. ISSN 00008 5935. Lisboa. pp.5-17.(in Portuguese).

Ferreira Gomes, L. M. and Machado Saraiva, C. M. (1997). Protection areas of Unhais da Serra Spa. *Proceedings* of the Int. Symp.on Eng. Geology and the Environment. Athens, 23-27 June 1997. Ed. Marinos, et al.; Rotterdam. Balkema. Vol.2; pp.1851-1855.

Ferreira Gomes, L. M; Andrade Pais, L.; and Mendes, E.; Marques Martins, T.F. (2007a.). Elements promoting the knowledge of the mechanical behaviour of granitic massifs on the border soil-rock to great depths. *Proceedings* of the First International Conference on Soil & Rock Engineering. Ed.Kulatilake & Associates. Colombo. Abstracts, p.22; paper 2940, 10p. in CD.

Ferreira Gomes, L.M.; Andrade Pais, L. and Mendes, E. (2007b). Contribution for the knowledge of the fracturing and hydraulic characterization of the granitic pluton of Castro Daire region - Viseu (Portugal). *Proceedings* of the 11th Cong. of the International Society for Rock Mechanics. Ed. Ribeiro e Sousa, Olalla & Grossmann. © Taylor y Francis Group. ISBN 978-0-415-45084-3. London. Vol.1. pp.207-210.

GDP (1998). Unidades de energia e estrutura do tarifário do Gás Natural. Gás de Portugal, SGPS, AS. *Rev. Energia* nº1. pp. 32 a 36. (in Portuguese).

IGM (1998). Recursos geotérmicos em Portugal Continental. Baixa Entalpia. *Boletim*. Ed. Instituto Geológico e Mineiro, Direcção de Serviços de Gestão e Recursos Geológicos, Divisão de Recursos Hidrogeológicos e Geotérmicos. Lisboa. 23p.

ISRM (1978.). Suggested methods for the quantitative description of discontinuities in rock masses. *Int. Jour.. Rock Mech. Min.* Sci. & Geomech. Vol. 15, pp.319-368.

ISRM (1981). Basic geotechnical description of rock masses. *Int. Jour.. Rock Mech. Min*. Sci. & Geomech. Vol. 18, pp.85-110.

Monteiro, V. (2001). Novas Técnicas de Refrigeração Comercial em Hoteleira. Vol. I. Lidel – *Edições Técnicas, Lda.*. 243p. (in Portuguese).

SGP (1992). Carta Geológica de Portugal. Escala 1/500 000. *Serviços Geológicos de Portugal*. Lisboa. STUS (2009. H_2OTEL Congress & Medical SPA; AQUADOME, The Mountain SPA.; AQUATERMAS, The medical SPA. Site: www.h2otel.com.pt. *Sociedade Termal de Unhais da Serra*. Covilhã.

UBI (2004). Memória Justificativa e Ante-Projecto de uma Sondagem de Pesquisa de Água Mineral para Aproveitamentos Geotérmicos em Cascata. Termas de

Unhais da Serra. Covilhã. C.M.C. *Relatório Interno.* UBI. 20p. (in Portuguese).

UBI (2005). Acompanhamento da Sondagem de Pesquisa e Captação de Água Mineral Termal Quente. Relatório sobre evolução de Trabalhos nº1 – Perfuração à Roto-Percussão. Projecto sobre Aproveitamentos Geotérmicos nas Termas de Unhais da Serra, para Sociedade Termal de Unhais da Serra, S.A.. Covilhã. *Relatório Interno.* UBI. 22p. (in Portuguese).

UBI (2007). Acompanhamento da Sondagem de Pesquisa e Captação de Água Mineral Termal Quente. Relatório sobre evolução de Trabalhos nº2 – Perfuração à Rotação – Troço Experimental Projecto sobre Aproveitamentos Geotérmicos nas Termas de Unhais da Serra, para Sociedade Termal de Unhais da Serra, S.A.. Covilhã. *Relatório Interno.* UBI. 16p. (in Portuguese).

UBI (2008a). Acompanhamento da Sondagem de Pesquisa e Captação de Água Mineral Termal Quente. Relatório sobre evolução de Trabalhos nº3 – Perfuração à Rotação Dirigida & Carotagem. Projecto sobre Aproveitamentos Geotérmicos nas Termas de Unhais da Serra, para Sociedade Termal de Unhais da Serra, S.A.. Covilhã. *Relatório Interno.* UBI. 17p. (in Portuguese).

UBI (2008b). Acompanhamento da Sondagem de Pesquisa e Captação de Água Mineral Termal Quente. Relatório sobre evolução de Trabalhos nº4 – Trabalhos Finais. Projecto sobre Aproveitamentos Geotérmicos nas Termas de Unhais da Serra, para Sociedade Termal de Unhais da Serra, S.A.. Covilhã. *Relatório Interno.* UBI. 10p. (in Portuguese).

UBI (2008c). Sondagem de Pesquisa e Captação de Água Mineral Termal Quente. Relatório Final. Furo US1 – Captação Definitiva. Projecto sobre Aproveitamentos Geotérmicos nas Termas de Unhais da Serra, para Sociedade Termal de Unhais da Serra, S.A.. Covilhã. *Relatório Interno.* UBI. 20p. 6 Anexos. (in Portuguese).