

LOW TEMPERATURE GEOTHERMAL RESERVOIRS IN THE PORTUGUESE HERCYNIAN MASSIF

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ABSTRACT: A number of mineral springs clearly related with deep geological process and neotectonic activity are reported at the Portuguese Hercynian Massif. Twenty seven springs have discharge temperatures between 25°C and 75°C.

Thermal baths are installed over these natural occurrences. In the last fifteen years, almost all classical dug wells or spring arrangements were replaced by drilled wells with depths up to **300m**. Drilling provided considerable new information on the nature of the mineral spring systems. Following these investigations two small low-enthalpy geothermal projects for direct use became operational. Surface consumers in some other sites are adequate for economical direct utilisation of geothermal heat. Chemical geothermometers suggest reservoir temperatures up to 125°C. However, the possibility of electricity production with binary power plants may deplete the resources for traditional thermal (spas) use in some sites.

1. INTRODUCTION

The Portuguese Hercynian Massif, locally called as Hesperian Massif, is composed of granite and metasediments. Because crystalline rocks outcrop over 60,000 km² (about two thirds of the country) an important part of mineral water is delivered largely from granitic, schistose and related fracture aquifers.

The exploitation of these discontinuous fissured aquifers is mainly related with the spa business. Also, the bottled water industry utilizes some hypo-saline waters discharging from quartzite reservoirs. Most of these mineral waters can be considered as geothermal resources where adequate heating demand is present.

According to 1990 Portuguese legislation, geothermal resources are a public domain. Private bodies and municipalities can apply for the right of exploration and exploitation on the basis of a concession granted by the Ministry of Industry.

During the last twenty five years, and particularly after the middle 70s, almost all the classical spring catchworks were replaced by drilled wells in an attempt to increase flows, temperature, and to prevent or remedy pollution and contamination. The former works were mainly dug wells with or without galleries. Some of these works were constructed in the 30s; however a number of them were older, medieval constructions over former Roman spas.

This paper was prepared from the files of the private firm ACavaco that performed most of the studies and drilling. The Instituto Geológico e Mineiro, in charge of the management of mineral water and geothermal resources in Portugal, monitored

operations. Studied springs are considered representative of Portuguese conditions. Field operations were entirely supported by concessionaires (Municipalities and small private companies).

2. HYDROGEOLOGICAL BACKGROUND

According to Ribeiro et al (1979) the Hercynian Massif is separated into three zones: (i) Iberian Central zone, including the Middle Galicia-Trás os Montes domain, (ii) Ossa-Morena zone and (iii) South-Portuguese zone. All three zones are intruded by granite plutons of the Hercynian orogeny. Metasediments are pre and post Hercynian orogeny. Alpine orogeny reactivated main faults. Furthermore, faults with activity in the last two million years could be included in two groups: (i) NE-SW to ENE-WSW reverse faults and (ii) NNE-SSW strike faults associated with grabens and historical seismicity. Faults with neotectonic activity are represented as active faults in fig 1.

Weathering is quite irregular. Average reported depths to bedrock ranges from 0 to 60 m. However, greater depths are known over main active structures. Carvalho (1983) reported a case study, 15 km south of Chaves, fig 1, site 2, where **184 m** of highly weathered granite was drilled: this situation is related to the important NNE-SSW, Régua-Verin fault.

Most Portuguese mineral waters discharge in the Iberian Central zone. Elevations of reported thermal springs range from 10 to 770 m above mean sea level. This concentration may not be a simple inheritance of the provincial tectonic history, as pointed out by Ribeiro and Moitinho (1981). Regional climate and hydrology plays an important role in the productivity and distribution of springs. The recharge conditions are higher in the north-western area of Portugal. According to data of the Comissão Nacional do Ambiente (1987), the average annual rainfall reaches 1811 mm in this area but these figures decrease to less than 600 mm in some eastern and southern regions, the average annual rainfall for the entire country being 917 mm. About 55% of precipitation is lost by evapotranspiration. The infiltration, according to the same source, has values ranging from 20 to 135 mm.

As expected, the occurrence of mineral springs is closely related to tectonics and particularly to active structures. Their distribution is superimposed at fig 1 with tectonic data from Cabral and Ribeiro (1989). It is clear that thermal anomalies follow axis trending NNE, NE and ENE along the main active faults. Ferreira et al (1984) discusses, in detail, the provenance of mineral waters with respect to geochemistry and regional and local tectonics. Some locations, apparently, do not show a sharp correlation to main tectonic axis. Natural discharge from pre-1970 spring catchment systems ranges from a few m³/d to 800 m³/d. In general, with new drilled wells, it has been possible to increase the former production. Portuguese thermal

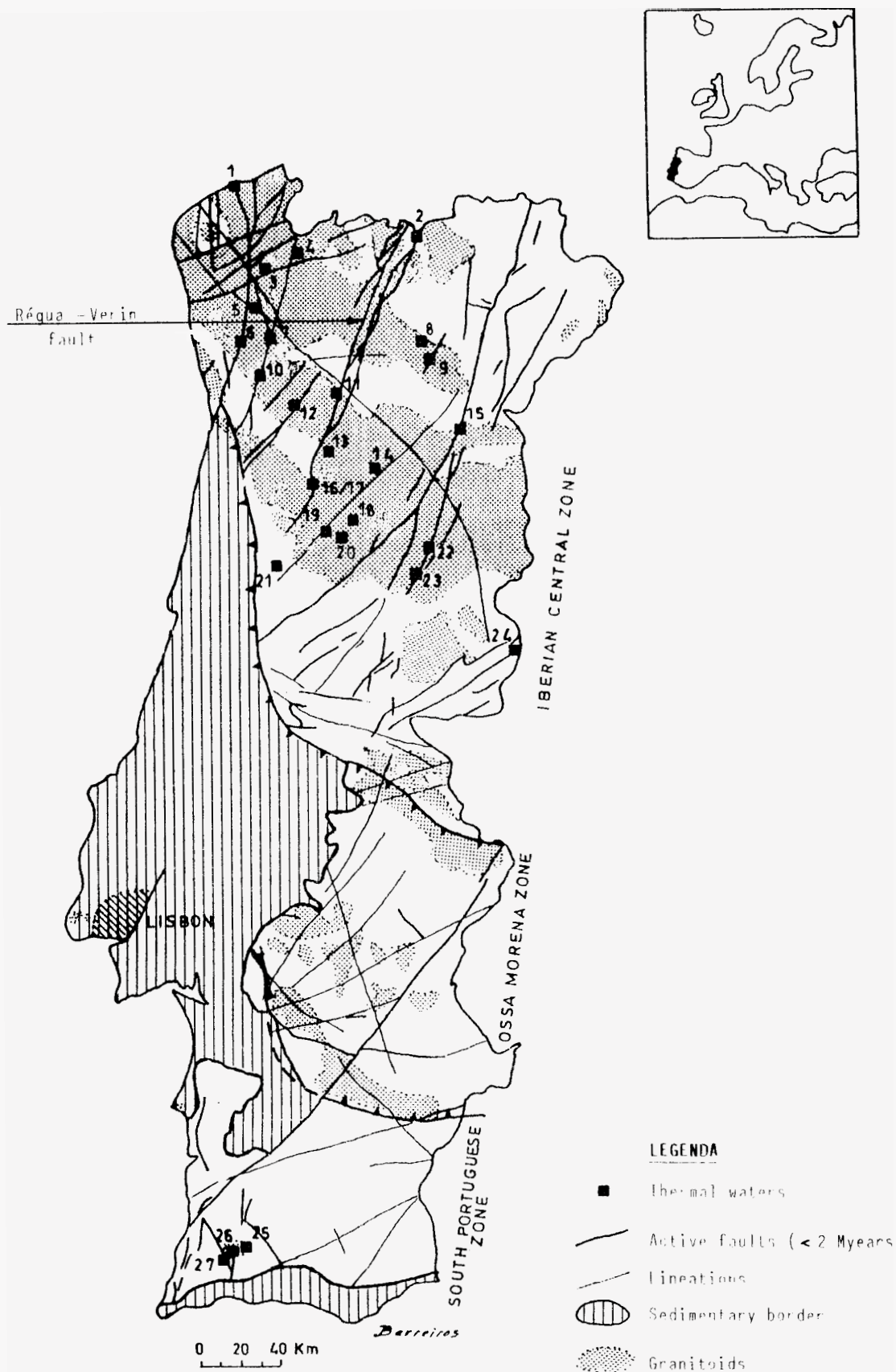


FIG. 1 - PORTUGAL - HESPERIAN MASSIF THERMAL WATERS ($T > 25^{\circ}\text{C}$)

waters (Table I and fig 1) discharge from granitic rocks, except site 2, Chaves (schists), site 11, Moledo (skams) and the Monchique group (sites 25, 26 and 27) related to syenite of the Alpine orogeny. Temperatures of mineral waters range from 15 to 75°C. Distribution of high temperature springs seems related to active faulting, as described above. However, typical cold mineral waters in a geological sense, are sometimes present a few kilometres away over the same structure. An example is the Régua-Verin fault where cold and hot mineral waters (15 to 75°C) of the same chemical composition are colocated within 10 km distances.

The Hesperian Massif has three types of water: (i) hypo saline waters with TDS less than 150 mg/l circulating mainly inside quartzite reservoirs with temperatures up to 28°C, (ii) sulphurous waters with up to 1,000 mg/l and temperatures up to 62°C, and (iii) carbonated waters with TDS up to 2,500 mg/l and temperatures up to 75°C. Reported thermal waters present TDS ranging from 40 to 2,508 mg/l and pH from 5.4 to 9.5.

3. METHODOLOGY OF THE INVESTIGATIONS

The philosophy for resource development has been a classical step by step approach matching investment with resource potential and exploration maturity. The studies generally included: (i) evaluation of medium-long term consumption, (ii) geological mapping to scale 1/10,000, with particular areas at 1/1,000 or even more detailed scales to understand the controlling traps (structure, contacts, lithology, faulting, jointing, veins, weathering), (iii) surface and ground water inventory including location, hydrodynamic data, and chemical analysis, (iv) air photo interpretation at scales 1/25,000 and/or 1/15,000, (v) geophysical surveys (mainly resistivity profiling), (vi) drilling of diamond cored wells for structural, lithological and, if possible, hydrodynamic control, (vii) evaluation-production wells by down-the-hole-hammer and, in early days, with cable tool rigs, (viii) tentative recharge evaluation, and (ix) environmental constraints, including inventory of pollution sources and design of protection areas. Studied areas ranges, in area, from 2 to 30 km².

This integrated exploration achieved good results. The success rate, judged by wells producing at least 1.5 l/s, is about 85 %.

3.1 Location of wells

It is necessary to understand the role of structures on the hydromineral (and non mineral) circulation. Aerial photographs have limited use because anthropogenic features tend to cover or obscure important structures and geomorphology related to mineral spring occurrence.

However, geoelectric resistivity surveys are particularly useful when sitting wells for mineralised waters (higher than 400 mg/l) in granitic environment. In this case, the method displays low resistivity anomalies superimposed on a resistant background. Generally, a Schlumberger profiling array (rectangle with AB=400 m, MN=10 m) is used. In some cases, emission lines up to a maximum of 2,400 m are used with success. General reconnaissance surveys with five penetrations up to AB=180 m combining profiling and light vertical electrical soundings are in use. All these techniques must be carried out with several lengths of emission lines. This approach takes into account the location of surface springs in order to detect the dip of the circulated structures and to conceptualise models on the ground water flow. Other geophysical methods (SP, VLF, seismic, magnetic) have very restricted utilisation.

Generally, vertical or angled wells are designed to intercept the hydrogeological structures at 50 to 80 m depth. However, circulated hydromineral aquifers were intercepted at depths up to 300 m. Generally speaking it seems advisable not to drill vertical wells directly over low resistivity anomalies. In some cases, these anomalies correspond to highly weathered bands with low hydraulic diffusivity. In schistose environment circulated discontinuities are not revealed by electrical profiling even with waters up to 2000 mg/l. In these cases, resistant bands indicate, as a rule, quartz veins and/or quartzite layers and are the real targets to be drilled. Accurate interpretation of lithology is the key for success. Significant case histories of these kind of problems are discussed at Carvalho (1983 and 1988).

3.2 Design of wells and pumping tests

Evaluation-production wells normally are drilled with down-the-hole-hammer and air-rotary. Design generally includes drilling with diameter 8 1/2 in, till depths of 50 m, continuing afterwards with 6 1/2 in up to about 150 m deep. Current drilling problems include caving in upper layers or upper overburden. This is generally overcome by grouting or installing provisional surface casings. With highly incompetent rock mud-rotary drilling must be employed. These last procedures are generally not welcome because hydrogeological control is masked.

Hydrogeological control includes: (i) lithology every two meters, (ii) fluid analysis (conductivity, temperature, pH, total iron and sulphide, depending on the type of water), (iii) periodic measurement of static levels and/or artesian flow, which is quite common in Portuguese mineral waters, and (iv) regularly spaced pumping tests with air lift or surface or submersible pumps. Electrical logging is carried out quite often. The most useful within this peculiar environment are the sonic and caliper logs. However a good approach is generally obtained with a routine package including, additionally, resistivity, gamma ray, temperature and temperature gradient and salinometry.

Considering that exploitation yields are generally lower than 3 l/s, the 5x3" casing programme includes slotted screens, whose open area is considered sufficient according to current design principles. Artificial gravel packing with 3-5 mm and 5-7 mm siliceous material is used to stabilise casing rather than to control fines in the formation which is generally competent bedrock. In some situations, production section is kept open-hole.

Well and reservoir evaluation include step drawdown tests and long term extraction up to 72 hr. During these pumping tests, nearby waterworks, piezometers and classical spring arrangements are monitored both from the chemical and hydrodynamic point of view.

In many difficult situations with sub-vertical structures, angled diamond cored holes are drilled. Drilling diameters are 98 and 76 mm. Experience shows that the choice between this last methodology and the immediate option for the faster down-the-hole drilling is quite controversial. In fact, core recovery is generally superb with diamond drilled wells but hydrodynamic data is difficult to obtain in non flowing wells.

As the main goal is to produce water without pollution and contamination it is normal practice to grout overburden with cement.

Table I - Hercynian Massif Geothermal Ressources

Site	TDS (mg/l)	pH	Temp (°C)	Depth (m)	Available yield (l/s)	Measured yield (l/s)	Available resources(toe)	Measured resources(toe)	Heating needs(toe)
1-Monção	559	7.8	45	50	10.0	44.0	467	2053	100
2-Chaves	2508	6.9	75	155	15.0	40.0	1400	3732	3000
3-Caldelas	136	8.3	34	169	8.0	10.0	236	295	230
4-Gerês	288	9.1	47	Spring	1.5	1.5	75	75	230
5-Taipas	256	8.2	32	150	2.5	10.0	66	264	100
6-Saude	595	8.9	32	106	4.0	11.0	106	291	100
7-Vizela	345	9.3	61	123	2.0	11.0	143	787	230
8-Carlão	434	8.2	30	Spring	0.5	0.5	12	12	5
9-S.Lourenço	305	7.8	30	Spring					2
10-Canaveses	290	9.4	30	Spring	0.6	0.6	14	14	50
11-Moledo	247	9.4	44	112	8.0	25.0	361	1128	80
12-Aregos	300	8.9	63	65	13.0	20.0	970	1493	130
13-Carvalho	300	9.3	42	50	3.0	3.5	126	147	120
14-Cavaca	360	8.3	29	Spring	1.1	1.1	24	24	80
15-Longroiva	497	8.7	34	Spring					2
16-S.P.Sul	341	8.9	69	Spring	10.0	10.0	840	840	350
17-S.P.Sul (Vau)	359	8.8	67	216	10.0	40.0	809	3235	20
18-Alcafache	360	8.4	51	Spring	3.0	3.0	168	168	150
19-Sangemil	469	8.4	50	54	4.0	10.5	218	572	130
20-Felgueira	414	8.4	34	300	5.0	12.0	148	355	170
21-Luso	40	5.4	27	150	6.0	25.0	112	467	120
22-Manteigas	185	9.2	47	90	4.0	10.0	199	498	200
23-Unhais	256	8.5	40	100	4.0	40.0	156	1555	150
24-Monfortinho	49	5.7	26	53	12.0	20.0	205	342	200
25-Alferce	607	8.6	27	Spring					2
26-M. Quente	341	7.8	29	Spring	3.0	3.0	65	65	2
27-Monchique	341	9.5	32	Spring	10.0	10.0	264	264	100
Notes:					TOTAL		7183	18675	6053

Available yield: Total recommended yield for the existing exploitation systems in a sustained basis.

Measured yield: The higher yield extracted at former exploration works.

Available resources: Energy that can be substituted for heating considering the available yield and existing temperature, an annual utilisation period of 4,320 hours and a reference temperature of 15°C.

Measured resources: Energy that can be substituted for heating considering the measured yield and existing temperature, an annual utilisation period of 4,320 hours and a reference temperature of 15°C.

Heating needs: Existing or envisaged heating needs replaceable by geothermal resources in a short-medium term.

toe (Tons of oil equivalent): Energy produced by the total combustion of 1 ton of oil. 1 toe = 10,000 th = 11.628 Mwh

Normally, the artesian flow are not higher than 1 or 2 l/s. However, artesian discharges of 18 Us are known. Potentiometric heads up to +35 m above the ground level were registered. This situation occurs at narrow valleys when recharge areas are located over the surrounding mountainous areas. Air lift discharge, measured when drilling with down-the-hole-hammer or air rotary, can reach as much as 40 l/s. Most common figures are 4 to 7 l/s. Normal exploitation yields are limited to 2 to 3 l/s with a maximum of 10 l/s per well. For geothermal resource evaluation purposes, exploitation yields are described as available resources in table I.

In a general way these aquifers could be considered as confined. Quite surprisingly, flux to wells is reasonably reproduced with the Theis model. However, it is necessary to pump for a long period of time to detect fracture dewatering barriers and take in account the effects of anisotropy and double porosity. The interpretation of 40 pumping tests for 35

wells considered the aquifers as confined. The Cooper-Jacob logarithmic approach as well as the Theis recovery method, gives transmissivities (T) from 12 to 200 m²/d. Fifty per cent of these transmissivities fall within the 40 to 100 m²/d interval. At a number of sites, a lower 2nd order transmissivity (revT) could be computed. These transmissivities (from 2 to 70 m²/day) control the performance of wells for long-term extraction. When piezometers were available, or reliable observation measurements could be carried out at the existing water catchworks, storativity (S) could be determined. Standard values fall within the interval 0.0006-0.00004. This storativity seems higher (0.005) in places as Chaves (site 2) and Monção (site 1), fig 1. Probably, they correspond to semi-confined aquifer sectors, close to rivers with alluvial deposits having hydraulic continuity with fissured thermal traps. Also, at these sites, exceptionally high transmissivities near 700 to 800 m²/d were determined.

For a given location, transmissivities are generally higher a few meters away from the major structural control generally mapped following low resistivity anomalies. At Unhais da Serra (site 23), for instance, a well located over the main fault has an artesian flow of 0.6 l/s; thirty meters away, another well, over a secondary fault, delivers 7 l/s. Also, the location of a number of thermal springs suggests a conspicuous preference for the west flank of the main NNE faulting. This could be related to priority recharge areas possibly located westwards. It seems that main faults act as barriers to ground water flow thus forcing discharge through secondary associated structures.

An important question is the determination of the exploitation yield of the well or wells inside a given hydromineral location considering the maintenance and improvement of the chemical and bacteriological water quality. This deals with factors as: (i) recharge conditions, generally approached with hydrometeorological methods, (ii) reservoir hydrodynamics evaluation and (iii) environmental prevailing conditions. Generally, a decision is taken to reduce drawdown as much as possible. This implies the abandonment of the practice of pumping high yields, even though for a short period of time. In fact, hydromineral circulation is not hydraulically isolated at the sites of emergence. It coexists both with shallow aquifers generally with high vulnerability to pollution and in depth with other non mineral waters. Fortunately, in most systems, hydraulic head is higher in hydromineral waters when compared with non mineral ones. This enables an exploitation strategy trying to maintain dynamic levels higher than "normal waters" potentiometric surface or water table. In some sites shallow normal waters are systematically dewatered with horizontal drains.

The Final recommendations for exploitation are based upon: (i) extrapolation of drawdown curve for a given discharge until the time where a recharge period could be considered as probable, (ii) to maintain dynamic levels above well screens, (iii) to maintain laminar flux to wells, and (iv) influence of yield, and pumping distribution versus time, in water quality and temperature of thermal water.

4. GEOTHERMAL RESOURCES

As previously pointed out, geothermal fluids in the Hesperian Massif are strongly related to neotectonics. From a medium-term perspective it is envisaged that these resources will only be used as low-enthalpy resource, even though data provided by geothermometers, suggest reservoir temperatures higher than 100°C at several locations (Aires-Barros 1978, 1979 and 1981; Almeida 1979 and 1982; Johnston 1980). Ribeiro (1981) using Portuguese thermal waters found the correlation $T = 0.61t + 81.84$ between temperature (t) and reservoir temperature (T).

Several constraints for direct-use geothermal are: (i) it seems clear that the available water for recharge does not allow the extraction of amounts of water much higher than the present exploitation systems without incurring severe environmental damage, (ii) low heating load and demand do not justify large investments and (iii) thermal bath towns are quite aware of its status and opinion makers claim that geothermy could be a danger for the future of the tourism and spa industries.

Nevertheless, a few small geothermal operations are already in activity. The most promising sites are located over the Regua-Verin fault, namely Chaves (site 2) and S. Pedro do Sul (site 16/17), fig 1. Carvalho and Silva, (1988) and Carvalho, (1991) summarised and evaluated geothermal resource potential by following a modified Muffler and Cataldi (1978) approach. This methodology considers geothermal resources mainly

dependent of the rate of ground water recharge to the hydrothermal circuits. Table I presents some data on geothermal conditions in the Hesperian Massif for heating purposes. Resources are presented in tons of oil equivalent per year (toe).

At Chaves, (site 2, Fig 1) a rhomb-shape graben, with an area of 18 km², Cabral and Ribeiro (1988), and with a basin-fill of at least 450 m, according to Carvalho and Silva (1988), the municipal swimming pool geothermal project has been in normal operation since 1982, including space heating and hot tap water production. The geothermal fluid is pumped from a 150 m deep well at a temperature of 75°C. TDS is about 2,500 mg/l. This well, positioned about 200 m from the known thermal spring was located and drilled in Silurian metasediments crossed by hydrothermal quartz veins. Other well was drilled for balneotherapy. During drilling with down-the-hole-hammer, air-lift yield reached 40 l/s. After completion, at a final 72 hr pumping test, specific capacity, at apparently steady state, was 11.3 l/s/m. Thermometric logs to 150 m deep do not reveal an abnormal temperature gradient. Furthermore, a gradient inversion was found from 50 m to final depth. This work is expected to be followed by an operation, already partially financed by the Demonstrations Projects of the European Community. This project will include two new evaluation-producing hole up to 650 m in order to provide geothermal fluids to an hospital, some hotels and several public buildings in the town centre. At present, energetic savings are about 100 toe; the new operation will allow as much as 3000 toe with an estimated pay-back of 3 years. It must be remembered that Chaves is a small town with 15,000 inhabitants where the heating season reaches 7 months. Difficulties on funding are delaying the proposed extension. Meanwhile, a research project supported also by the European Community (Joule I Project) aiming to improve the conceptual model of the entire geothermal field is said to be about complete. Partial interpretation of data was recently available (Andrade Afonso et al 1994a,b, Monteiro Santos et al 1994, Aires-Barros et al 1994). The meteoric origin for geothermal fluid seems confirmed as well as a recharge zone located on the eastern border of the graben. For the approved industrial multi-use cascade operation it is clear, by economical and technical reasons, that additional wells must be drilled where heat consumers are located, Carvalho and Silva (1988).

S. Pedro do Sul (nº 16/17, Fig 1) is another interesting site, Carvalho (1994). The site is located over the referred Régua-Verin fault and the classical, archaic, spring arrangement discharges 10 l/s at 68 °C water from fractures in granite. TDS of the geothermal water is about 390 mg/l. This bath (Termas) is the most important in the country with about 15,000 registrations in 1992. There are several hotels which could be reasonable heat consumers. One km southwards, over the same fault, a small thermal spring (Vau) suggested that the geothermal field could be larger. Studies and works carried out over 5 Km² around the existing thermal springs included: (i) geological mapping at 1:15,000 scale, and (ii) gravimetry and radiometry measurements each 100 m. These investigations, carried out in 1991, fully pictured the tectonic blocks in the area. In a later stage, tactical prospecting at three selected areas (Vau, Termas and Várzea) included: (i) geological mapping at the scale 1:1,000, (ii) soil radon measurements (emanometry), (iii) Very Low Frequency measurements and (iv) resistivity profiling and vertical electrical soundings up to AB=2400 m. These surveys fully delineated the Vau and Termas poles and suggested evidence of hydrothermal circulation at Várzea, 1 km northwards of Termas. Two angle 200 m cored wells were drilled in granites at Vau, in order to

investigate low resistivity anomalies related to transversal faulting. The results were quite encouraging. The artesian flow reaches 3 l/s with temperature of 69°C; at final pumping tests, 10 l/s were pumped with 5.2 m drawdown. Calculated transmissivity and storage are 107 m²/d and 0.00004 according to Cooper-Jacob method. A 2 ha greenhouse, producing tropical fruits (mainly pineapple and banana), is installed on this site. Another angle well, 236 m length, drilled at Varzea was unsuccessful. Following these investigations, a multi-use cascade project including district heating and further applications in agriculture and fish-farming was included in the European Community 1994 Thermie program. Because of the mild climate the first stage geothermal district heating operation will not exceed 150 toe. However, estimated pay-back is 5 years considering savings only on the district heating operation.

In 1989 at Carlão in north-western Portugal (site 8, fig 1) a small thermal spring (30°C and 0.5 l/s) was employed to heat a 1,000 m² greenhouse that produces hors-season vegetables and melons for the local market. A three year payback was estimated by the owner. However the operation stop running last year as the concessionaire was more interested on the spa business.

5. CONCLUSIONS

Development of geothermal resources at the Portuguese Hercynian Massif is limited by: (i) subsurface hydrogeology, (ii) heating demand (iii) utilisation conflicts with spa and tourism industries, and (iv) financial problems. However, the reported operations fully demonstrate that geothermal resources of the Hercynian Massif could be technically and economically developed for direct use, enhancing local and regional economies at a number of sites. Total energy savings could reach approximately 6000 toe on a short-medium term basis and are compatible with demonstrated resources (Table 1). Considering recharge and reservoir characteristics, electricity production with binary power plants is not clearly conceivable in a medium term perspective. Further investigations (possibly combined with a hot-dry-rock program !!) could be advisable for a long term project. Low natural recharge for possible electricity production wells and scarce surface water resources for injection are major drawbacks for such programs.

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