EVALUATION OF GEOTHERMAL RESOURCES IN THE CHAVES REGION (NORTH PORTUGAL)

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ABSTRACT

Geological, geochemical and geophysical surveys were performed in the Chaves area to built up the hydrothermal model associated with the Chaves hot springs.
The geomorphology of the survey area is dominated by the Chaves Depression, which is a graben whose axis is oriented NNE-SSW. Two major geological structural features have been considered in the area: the so called Chaves fault and the N70º-80ºE faulted system, crossing the above mentioned Depression close to Faiões and Chaves town.
The integrated interpretation of the geological, geochemical and geophysical data, suggests a meteoric origin for Chaves thermal waters which infiltrate in the northeast zone of the Chaves Depression or farther areas, percolate at great depth and ascend at Chaves Depression, probably due to the cross line zones of the existing fault systems. In fact, in the above mentioned zones, low resistivity values were measured, which are probably associated with the hydrothermal circulation.

1. INTRODUCTION

The low temperature geothermal system of Chaves is an elemental unit of a broad hydrothermal province located in northern Portugal, whose hydrochemistry is rather uniform. A lot of hot springs with temperatures ranging from 35° to 78° C occur on or close to one of the major NNE-SSW trending faults. Figure 1 shows the location of the main hot and mineral springs known in the region and the schematic geological map of the Chaves geothermal area.

All the above mentioned waters are chemically similar. So the temperatures observed, suggest different pathways in depth. The regional geological structure, favoring the deep circulation towards the Chaves Depression of the infiltrated meteoric waters in the Mairos-Bolideira region, would play, an important role in the existence of the Chaves geothermal field. The existing strain field with NW-SE to NNW-SSE maximal strain , in connection with the fault systems crossing the Chaves Depression (fig.1), favors the existence of decompression zones and could be responsible for the ascending hydrothermal fluids.

2. METHODS AND TECHNIQUES

2.1. Geophysical surveys

Resistivity

The arrays used were the vertical electrical soundings (30), dipole-dipole lines (4), pole-dipole lines (5) and rectangular arrays (4). The automatic inversion of the resistivity data was achieved:
-Vertical electrical soundings was performed assuming a horizontally stratified earth, by a least square adjustment (Johansen, 1977).
-Dipole-dipole and pole-dipole lines were carried out assuming a two dimensional approach to the geoelectric structures;
a) By a trial and error procedure using the finite element method (Rijo, 1977);

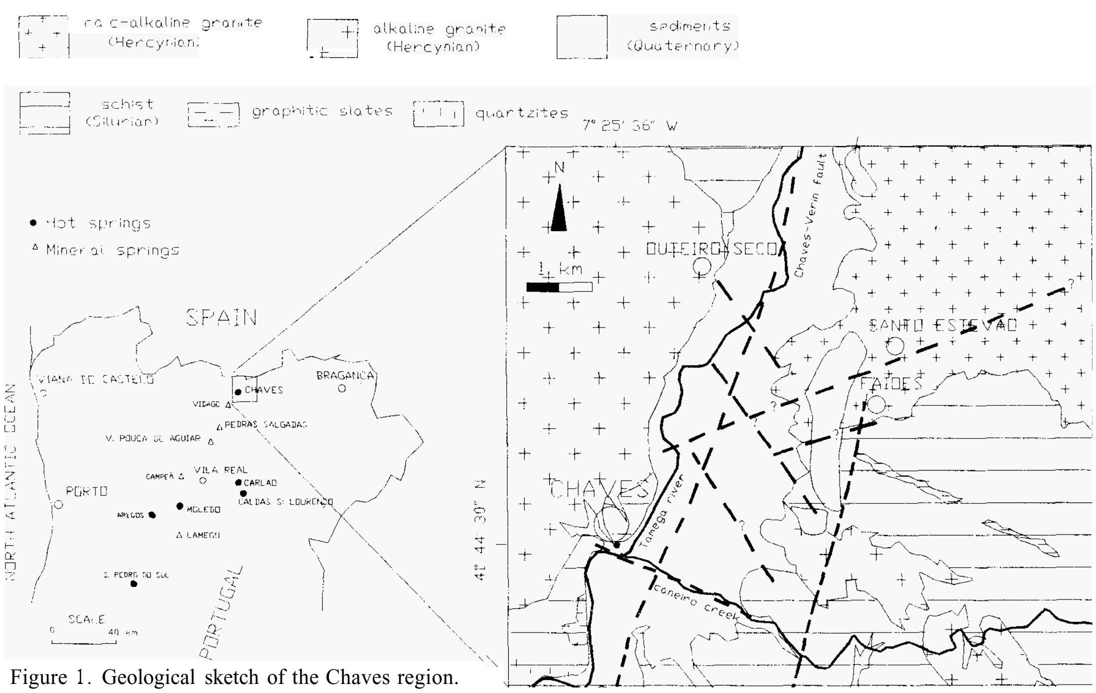

Figure 1. Geological sketch of the Chaves region.

b) Using a non linear smoothness-constrained least square method (Sasaki, 1989);
Nevertheless, the Chaves Depression is crossed by a dense net of faults, favoring fluid circulation, and as a consequence, changing the electrical macroanisotropy coefficient. A three dimensional integrated resistivity data processing, using the dipole-dipole, rectangle and vertical electrical soundings data, provided a fine resistivity pattern in the central area of the graben.

Audiomagnetotellurics

The automatic inversion of the AMT soundings data (120), whose frequency range was 2300-4.1 Hz, was carried out:
-1D inversion performed by a least square adjustment, assuming an horizontally stratified earth;
-2D inversion using the above mentioned non linear smoothness-constrained method (Sasaki, 1989).

Maenetotellurics

The MT data processing and interpretation including:
- Maps of polar diagrams(Z_{xx} and Z_{xy}) and for several frequencies;
  - Principal direction of the impedance tensor (Swift, 1967);
  - Regional and local strikes (Zhang, 1989);
  - 1D interpretation of the apparent resistivity and phase curves of the invariant (Z_{det});
  - 2D interpretation of the apparent resistivity and phase curves (TE mode) of some soundings in the Chaves graben.

2.2. Geochemistry

Physical, chemical and isotopic data have been collected from periodic and seasonal field work campaigns. Temperature, pH, redox potential, conductivity and dissolved oxygen were measured ***"in situ".*** Chemical analyses of sampled waters were also performed, at laboratory. Ca, Mg and Mn were determined by atomic absorption spectrometry; emission spectrometry for Na, **K,** Li, Rb and **Cs;** colorimetric methods for silica, **Al** and Fe_{total} ; ionic chromatography for SO, and Cl; potentiometric methods for alkalinity and HCO,. TDS was determined evaporating a measured volume of water at 180°C. Isotopic analyses (oxygen-18, deuterium and tritium) of waters were performed at the ICEN Environmental Isotopes Laboratory (Portugal). Besides these values we have assembled analytical data from the International Atomic Energy Agency.

3. RESULTS

3.1. Geological surveys

The Chaves region is characterized by two major faulted systems: The Chaves faulted system in the lineament of Luarca, Verin, Chaves and **S.** Pedro do Sul, and the N70°-80°E one, crossing the area in the neighbourhood of Faiões and Chaves.
The geomorphology of the area under research is dominated by the above mentioned Depression (with 7km length and 3km wide and altitude of about 350m a.s.l.) which is a graben whose axis is oriented NNE-SSW. The eastern boundary of the ***"Chaves Graben"*** is very well expressed by the fault escarpment of Padrela Mountain with a 400m rough jump in altitude and maximum elevation of about 1000m (a.s.l.). The western margin (not so pronounced as the Eastern one) shows a ***"staired tectonic configuration"*** being composed by successive blocks coming from the Heights of Barroso (with altitude of about 900m a.s.l.) and which tend to subside going eastwards to the Chaves Basin. The depression, with the central zone marked by the development of the Tâmega River alluvial plain, continues through the North to the Verin Basin (Spain) which is similar to the Chaves one. The granitic massif of S.ta Bárbara closes the Chaves Basin at the southern border.
The most recent Chaves formations are Miocene-Pleistocene sedimentary series. These formations, showing variable thickness, have their maxima expression along the central axis of the depression. The oldest formations (Ante-Ordovician) consisting of metamorphic schistose rocks are represented by the schisto-graywacke complex. At Ordovician and Silurian times, quartzites and schists were formed, being metamorphised at the end of the Paleozoic by the contact of the Hercynian granitic intrusion. Later on, these rocks suffered the Alpine Orogeny; the corresponding extensive tectonic activities were responsible for the formation of the several hydrothermal poles.

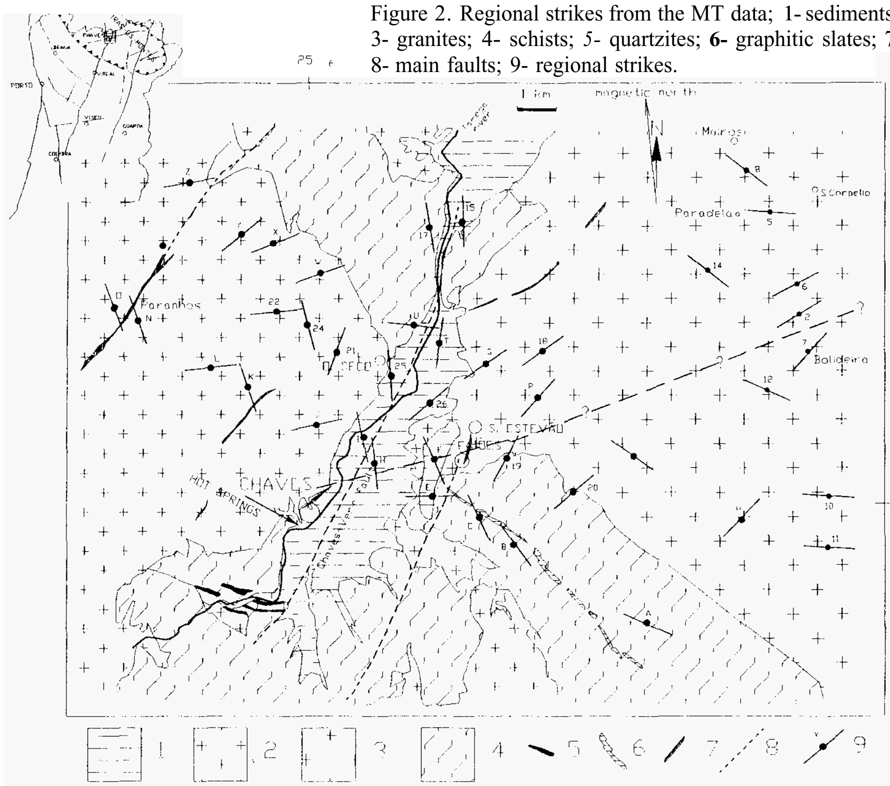

Figure 2. Regional strikes from the MT data; 1- sediments; 2- and 3- granites; 4- schists; 5- quartzites; **6-** graphitic slates; 7-dykes; 8- main faults; 9- regional strikes.

3.2. Geophysical surveys

The polar diagrams of the elements of the impedance tensors for the frequency of 10 Hz shows that the Zxy polar diagrams are strongly influenced by the shallow structures and mainly by the Chaves fault. However, the general pattern suggests a 2D structure with a strike close to N35°E for the Chaves graben. The tensor decomposition has been performed, assuming that the regional and local strikes are two dimensional structures with different strikes (Zhang, 1989). Two regional strikes were defined: N-S inside the Chaves graben and N65±10°E between Faiões and S. Cornélio (Fig.2). The first one is correlated to the Chaves fault and the second one with the fractures originating from the D3 phase of the tardi-hercynian episode. A more uniform distribution for the local strikes is observed and an average strike (N35-45°E) can be defined. At Mairos-Bolideira zone, the local strike is close to N-S. The 1D models for the N-S profile Mairos-Bolideira (Fig. 3) were built, using a trial and error procedure. The most interesting feature of the models is a conductive zone in the median crust, that could be related to altered watered geological formations.

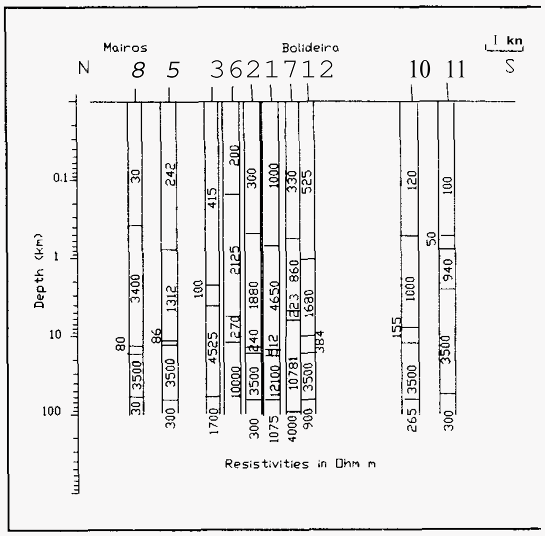

Figure 3. 1D interpretation from the MT (Z_{det}) data.

Besides the different strikes inside and outside the graben, a "two dimensional" model was built to get some information in the graben area. In the model, a low resistivity zone *(5* Ohm.m), can be seen, extending downwards to a depth greater than 12 km.
In the resistivity method, all the dipole-dipole lines (total length 23.4 km), excepting a NNE-SSW one, and the pole-dipole lines (total length 11.9 km) were carried out perpendicular to the axis of the graben. The two dimensional models achieved (Fig. 4), show large low resistivity zones (<15 Ohm.m), eastwards of the Chaves fault. North-northeastwards of the Chaves town, in the granitic formations, a resistivity of 180 Ohm.m was measured in the zone crossed by the NNE-SSW, N70-80°E and NW-SE faulted systems. In the NNE-SSW dipole-dipole line model, a low resistivity zone (12 Ohm.m) extending in depth, is well displayed northwards of the Caneiro fault; southwards of the above mentioned fault, resistivities of 3000 Ohm.m extending downwards in depth were calculated, probably associated with quartzitic formations. These formations could constitute a NW-SE impermeable barrier, constraining the assumed hydrothermal fluid, probably associated with the above mentioned low resistivity (12 Ohm.m) zone, to circulate westwards, towards Chaves hot springs. A rectangular array measured in the Caneiro area is well correlated with the suggested hypothesis.
The models achieved from the vertical electrical soundings data inversion, corroborate the existence of the above mentioned low resistivity areas, in the crossing zones of the existing faulted systems and reflect intensive tectonic activity

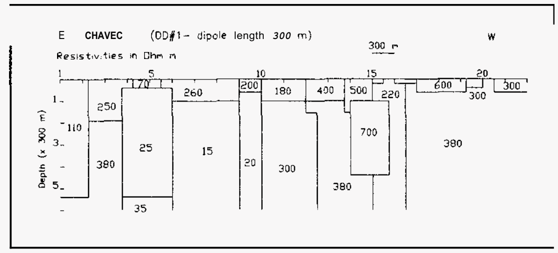

Figure 4. Two-dimensional dipole-dipole model.

The three-dimensional integrated processing of the available resistivity data, provided a better definition of the electrical structure in the central part of the Chaves Depression.
Inside the Chaves Depression, the AMT models are well correlated with the resistivity ones.

3.3. Geochemical surveys

Hydrogeochemistry

All saline waters, which have low temperature and pH (≈7), belong to the HCO_3 / ***Nu*** / CO_2*-rich* ***type,*** which is typical of a circulation that develops mainly within the granites (Michard, 1990). Chaves thermal waters are hot waters with temperatures and TDS ranging between 50-76°C and 1600-1800 mg/l respectively and free CO, of about **350** ppm. Vilarelho da Raia spring waters, with chemical composition similar to Chaves thermal waters but low temperature (≈ 16°C), display TDS values between 1790-2260 mg/l and free CO, of about 790 ppm. Vidago and Pedras Salgadas waters are distinguished from the other mineralized waters in the region by their higher calcium, magnesium and free CO, content (CO_2 of about 1490 ppm) and their output temperatures are of about 17°C. The CO, effect could be the responsible for the small increase (and even is some cases decrease) in dissolved species in waters sampled during the dry period.

Isotope geochemistry

Stable isotopic composition of Chaves thermal waters, characterized by -8.02 $\delta^{18}O$ and **-55.3** 6D mean values, lie on or close to the world meteoric water line ($\delta D = 8\ \delta^{18}O + 10$), corroborating the idea that they are meteoric waters which have not been subjected to surface evaporation. Vilarelho da Raia mineral waters have an isotopic composition similar to that of Chaves thermal waters. The richer heavy isotopic composition of Vidago and Pedras Salgadas waters generally fit fairly well the world meteoric water line, being the waters from well AC18 (Vidago) characterized by a slight positive oxygen-18 shift which could be the result of waterhock isotopic exchange. Stable isotope values from cold superficial and shallow groundwaters (low mineralized) of Chaves area lie along the world meteoric water line. The more depleted waters (with $\delta^{18}O$ and 6D values similar to Chaves thermal waters) are those located at higher altitudes sites where tritium content is significant (> 6.0 T.U.) indicating recent recharge. Samples from the Chaves plain, between the Heights of Barroso and Padrela mountain, contain high $\delta^{18}O$ and 6D values, being characterized by low tritium activity.

Geothermometry

A methodology based on the computation of the saturation indexes of some hydrothermal minerals (as a function of temperature) was adopted. The saturation indexes (*S.I.*) of quartz and chalcedony reach equilibrium ***(log S.I.*** = *0*) in a range of temperatures (90-121°C) that are in good agreement with the conventional silica geothermometers. The saturation indexes of montmorillonites, albite and microcline become zero in a wide range of temperatures (83-120°C). The equilibrium with montmorillonites being reached at lower temperatures seems to indicate the existence of secondary dissolution that could invalidate the Na/K temperatures (188-204°C).

4. DISCUSSION

4.1. Geophysical surveys

The regional strike between Faiões and S. Cornélio (N65° ± 10°E), probably correlated with fractures originating during the D3 phase of the tardi-hercynian episode, as well as, the low resistivity zone displayed in the model obtained from the Mairos-Bolideira profile, suggest that the meteoric waters could infiltrate in this area and percolate at great depths.

In a second phase, the N70-80°E faulted system would favor the circulation of the above mentioned waters, towards "Chaves Depression".

A "two-dimensional model" obtained from the MT data (Fig. 5), displays a very low resistivity zone inside the Chaves Depression area. Altered geological formations, probably originated by the hydrothermal circulation with a great water content, would extend at depth in the neighborhood of the Chaves faulted system. Through this fault system, CO, from the mantle would rise and would be responsible, at least partially, for the gas content of the thermal waters.

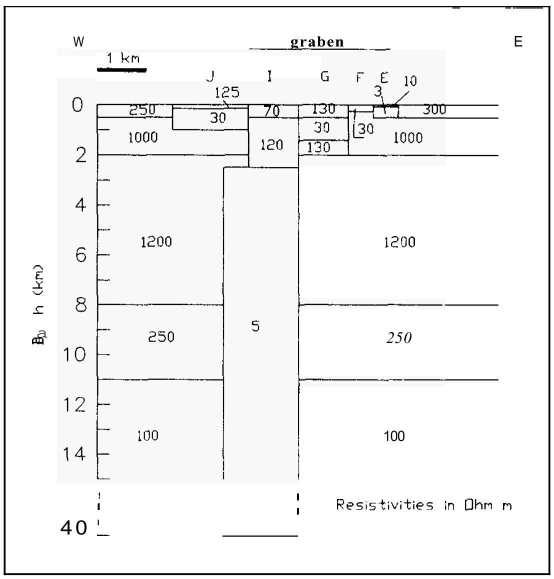

Figure 5. Two-dimensional model from MT (TE mode) data.

Inside the graben area, the detected low resistivity areas could be related to clayey detritic formations and/or deeply altered granitic or metamorphic ones, containing in its pores and/or fractures high mineralized waters. It must be emphasized that these areas are linked to the crossing zones of the above mentioned faulted system with the N70-80°E and the NW-SE ones, as we can conclude from the dipole-dipole, pole-dipole and vertical electrical soundings (Fig. 6) resistivity data, as well as, from the AMT models. On the other hand, we can infer from the resistivity data. that inside the graben all the low resistivity zones would be connected in depth. So, we could assume the existence of a geothermal reservoir related to the above mentioned low resistivity zones, recharged by the fault systems existing in the area.

South of the Chaves Depression. the resistivity values in the neighborhood of the Caneiro fault could be related to a SE-NW constrained (by a quartzitic barrier $p = 3000$ Ohm.m) hydrothermal circulation ($p = 12$ Ohm.m), towards Chaves hot springs. In fact, a borehole drilled in the Chaves geothermal pole area, detected thermal waters (78°C) in silurian schists enclosed by quartztic formations.

The above mentioned 180 Ohm.m resistivity zone, located north-northeastwards of the Chares town, could be related to intense hydrothermal alteration of the granitic formations.

4.2. Geochemical surveys

The positive linear correlations observed berween HCO_3-Cl, Na-Cl, K-CI, Li-Cl, Rb-CI and Cs-CI, among others, strongly support the idea that hot and cold mineral waters of Vilarelho da Raia, Chaves, Vidago and Pedras Salgadas could be expressions of a same type of system or even of the same system, suggesting different degrees of water-rock interaction. The altitude dependence of meteoric waters was determined by ^{18}O and D analyses of cold superficial and shallow groundwaters of the Chaves plain and its bordering mountains. The altitude difference for the analyzed waters is of about 650m and altitude increase is accompanied by 2n almost regular isotope depletion (Fig. **7).**

The stable isotopic composition (mean values: $\delta^{18}O = -7.21$ ‰ and $\delta D = -48.0$ ‰) found in cold waters from Chaves plain is similar to that of springs located at low altitude sites, either from the eastern or western block of the Chaves Depression. The source region for the Chaves thermal waters must be recharge areas situated at high elevations, such as those observed in Padrela region (East-Chaves) which presumably feeds the local infiltration. The presence of tritium in Pedras Salgadas and Vidago waters can be interpreted as the result of mixing between deep waters with more recent waters derived from local infiltration (Fig. 8), consistent with the stable isotopic data.

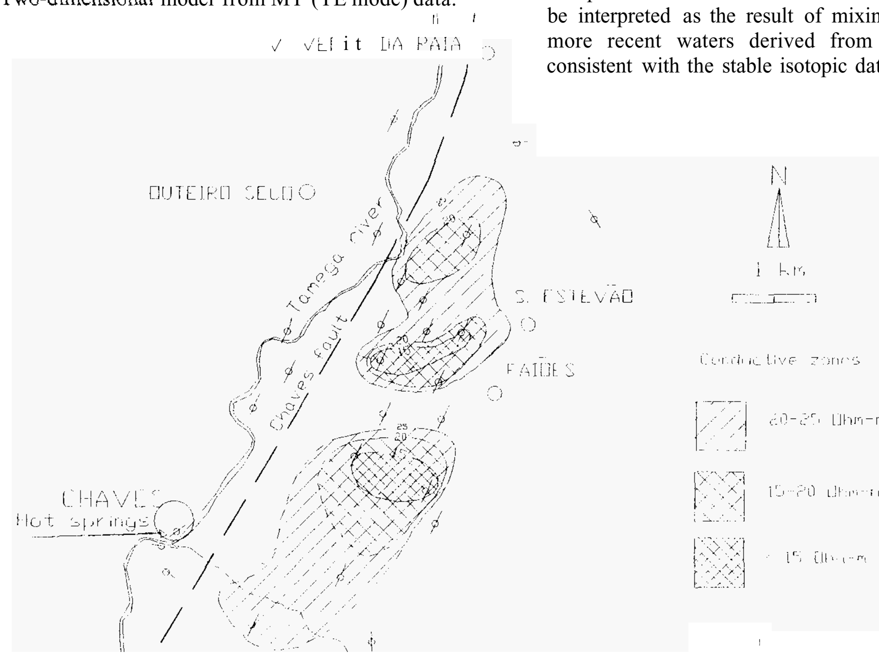

Figure 6. Map of the conductive zones, from the 1D interpretation

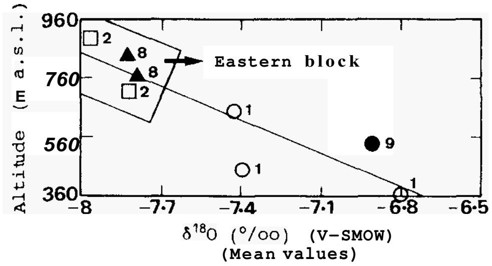

Figure 7. Correlation between oxygen isotopic composition and altitude for low mineralized water samples of Chaves area with tritium content > 6 T.U. (1) and (2) spring waters. (8) and (9) shallow drilled well waters.

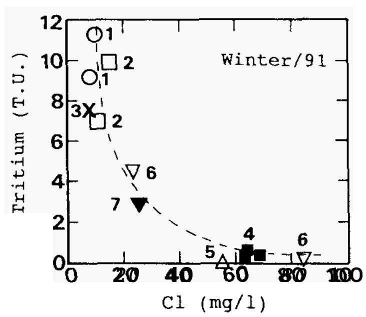

Figure 8. Tritium contents plotted as a function of Cl, for waters of Chaves region collected during 4/91 field work campaign. Curved line represents approximate fit to the data points. (1), (2) and (3) low mineralized spring and stream waters; (4) Chaves; (5) V. Raia; (6) Vidago; (7) Pedras Salgadas.

The low tritium, high conductivity and Cl contents of Vidago (well AC18) waters is probably evidence for a deeper circulation path through the subsurface rocks. Chaves thermal waters showing no oxygen-18 shift could represent either, an old geothermal system in which the isotopic water - rock interaction is adjusted to equilibrium, or a deep reservoir recharged by local meteoric waters with short circulation times and no isotope exchange with rocks. Although we don't have ^{14}C measurements related to Chaves thermal waters, their high mineralization, stable isotopic composition and low tritium values seem to support the idea that they are "*fossil*" geothermal waters, i.e. with an "*age*" higher than 150 years.

5. CONCLUSIONS

The geological and electrical regional models suggest an assumed flow path of the hydrothermal fluid strongly constrained by the NNE-SSW, N70-80°E and NW-SE faulted systems. Indeed, the low resistivity zones detected in the Mairos-Bolideira region could be related to infiltrated meteoric waters. The N70-80°E faulted system, crossing the Chaves Depression in the neighborhood of Faiões and Chaves, would favor the assumed fluid circulation at depth, towards the Chaves graben area. The existing strain field, favor the existence of decompression zones in the crossing areas of the above mentioned fault systems, which coincide with very low resistivity zones. So, these low resistivity zones would be related to the existence of a geothermal reservoir fed by warmed meteoric waters through the existing fault systems. This assumed model is supported by the geochemical surveys, which suggest an underground water flow system characterized by the infiltration of meteoric waters flowing downwards and mineralized waters flowing upwards. Meteoric waters infiltrate at the highest topographic points, where rainfall is important (Padrela granitic outcrop/eastern block of Chaves Depression), percolate at great depth (Fig. 9) and then emerge in a discharge area at lower altitude. Part of the meteoric waters, representative of precipitation which falls al low elevations, seem to flow into a shallow aquifer at Chaves plain.

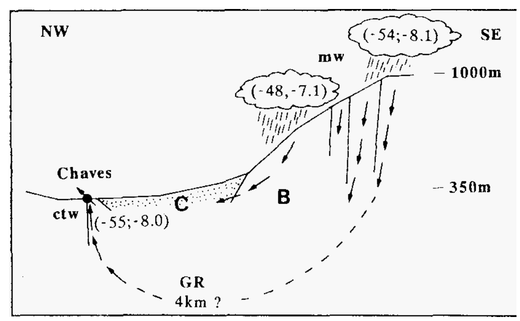

Figure 9. Simplified sketch of the proposed circulation model of the Chaves geothermal system deduced from geochemical observations. (B) basement; *(C)* cover; (mw) meteoric waters; (ctw) Chaves thermal waters. (GR) geothermal reservoir.

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