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Updated Geothermal Assessment of Lower Cretaceous Aquifer in Lisbon Region, Portugal

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ABSTRACT

The region of Lisbon is an urban area with the highest population density and energy demand in Portugal. It also presents very favorable geological environments for geothermal purposes. The historical and/or current existence of warm springs and deep sedimentary aquifers in Cretaceous and Jurassic formations, identified by hydrocarbon exploration surveys since the mid-fifties, as well as geothermal gradient and heat flux density studies, suggest a considerable geothermal potential (50ºC at 1500 m depth).

This study presents an updated geothermal potential assessment of the Lower Cretaceous formations in the Lisbon region, based on the volumetric deterministic method and definitions formulated by Muffler and Cataldi (1978). Accurate data for this geothermal assessment have been obtained through multidisciplinary approaches, involving geology, hydrogeology, temperature and water flow measurements from groundwater wells and other boreholes, integrating new information from recent geophysical studies providing essential geological information on the structure and geometry (delineating isobaths and isopachs and possible boundaries) of the sedimentary sequence.

The results identified the eastern sector of the city of Lisbon and the south bank of the Tagus River as the most promising areas for geothermal purposes (direct uses of heat or even electricity production). A geothermal potential (*Heat in Place*) of 3.8 GJ/m^2, higher than the previously estimated 1.7 GJ/m^2 for the same reservoir in the Atlas of Geothermal Resources in Europe (Hunter and Haenel, 2002) has been obtained, highlighting the capabilities of the Lower Cretaceous formations for future geothermal exploitation.

1. INTRODUCTION

Thermal waters in deep sedimentary formations probably constitute the most important type of geothermal resource outside volcanic areas (e.g. Goldscheider et al., 2010; Petrini et al., 2013). These medium to low-enthalpy geothermal reservoirs have been exploited in several places for residential and commercial heating, electric power generation and recreational activities, among others purposes (Norden, 2007, and reference therein). The Lisbon region, the urban area with the highest population density and energy demand in Portugal, is part of the well-known largest Portuguese Meso-Cenozoic sedimentary basin (e.g. Lomholt et al., 1996; Rassmussen et al., 1998). Oil and gas prospecting surveys and drilled wells combined with heat flow density maps, provided evidence of deep aquifers with favorable conditions for geothermal purposes in this region (e.g. Carvalho and Cardoso, 1994; Correia et al., 2002; Ramalho, 2013) (Figure 1).

Possible evidences of these "hidden" geothermal resources with potential to be exploited for direct uses are the occurrence of historical and/or current thermo-mineral springs (30-40ºC) at Estoril and Alfama areas (Moitinho de Almeida, 1972; Lopo-Mendonça et al., 2004; Ramalho and Lourenço, 2006) (Figure 1). Physical-chemical composition of these thermal waters shows a complex diversity of hydrochemical facies (HCO_3-Na, HCO_3-Ca and Cl-Na) and mineralization contents (between 0.5 and 6 g/L) (Andrade, 1932; Acciaiuoli, 1952; Almeida, 1952). This hydrochemical diversity has been firstly attributed to different aquifer lithologies, recharge conditions, mixing process with highly mineralized fluids and local vs regional flowpaths (Almeida et al., 1991; Lopo-Mendonça et al., 2004; Ferreira et al., 2011; Carvalho et al., 2013; Policarpo et al., 2014). The origin of these thermal waters has been related to infiltration and deep circulation in Cretaceous and/or Jurassic limestones and sandstones formations and subsequent ascent towards the surface through faults and/or volcanic dykes (Andrade, 1932; Lopo-Mendonça et al., 2004; Marrero-Diaz et al., 2013).

Until now, two geothermal systems for direct uses were explored in Lisbon region, taping Aptian-Albian sandstones (*Grés de Almargem*) (Figure 2): (1) The Air Force Hospital (Lumiar): 5 L/s of thermal water from the AC1-Balum geothermal well, with a bottom-hole temperature of 53ºC at 1500m depth, was exploited between 1992 and 2002 for heating (0.61 MWt), sanitary hot water, and after cooling, for human consumption (Carvalho and Cardoso, 1994; Carvalho et al., 2005a); (2) The Military Social Services Centre (Oeiras): 6 L/s of groundwater from AC1-Oeiras geothermal well, with 30ºC at 500m depth, were also extracted from 1992 to 1997 for sanitary hot water and heating (0.25 MWt) using geothermal (ground-source) heat pumps (Carvalho et al., 2005a). From the hydrogeochemical point of view, water from both geothermal wells was mainly HCO_3-Na-Ca type with mean TDS value less than 1 g/L, and relatively high Fe concentration probably due to dissolution of ferruginous minerals coupled with reduced conditions at depth. These geothermal wells are not exploited any longer due to specific capacity decline related to technical problems (well collapse) and due to progressive salinization processes of the extracted groundwater (Carvalho et al., 2005a). Preliminary analyses of resistivity and gamma-ray well logs at both geothermal wells (Figure 2) do not appear to show any evidence of saline waters or evaporite deposits (which may contain potassium minerals, such as carnallite) overlaying the aquifer. Therefore, mixing processes with (ancient or modern) seawater and/or mineralized fluids coming from partial dissolution of evaporite rocks probably occurring at large depth can be the most plausible explanation (Policarpo et al., 2014). Further isotope and chemical analysis will be necessary to constrain correctly the origin of this salinization processes.

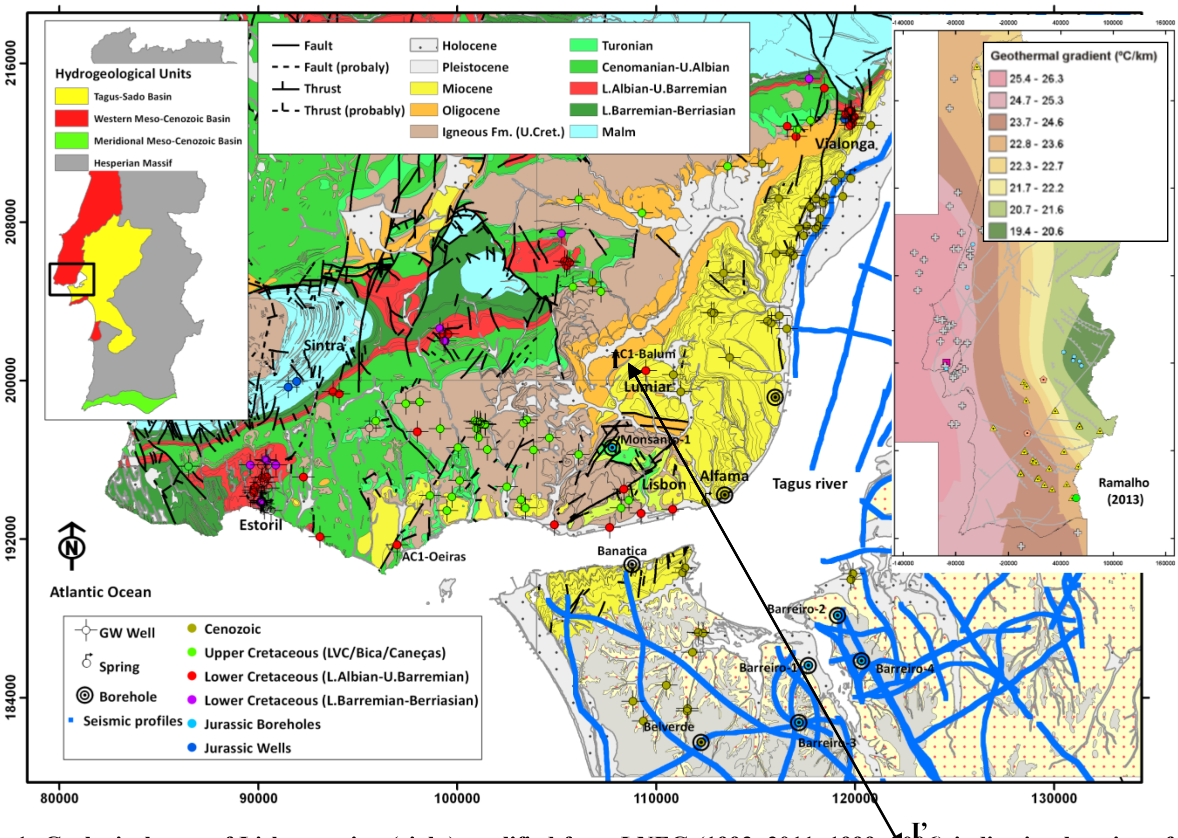

Figure 1: Geological map of Lisbon region (right) modified from LNEG (1993, 2011, 1999, 2006) indicating location of 2D seismic reflection profiles, groundwater wells and hydrocarbon boreholes used to obtain the geological 3D model. Geothermal gradient of mainland Portugal, modified from Ramalho (2013), and Hydrogeological units of mainland Portugal have been also plotted (Almeida et al., 2000) in the right and left up corners, respectively. Black arrow refers to the schematic geological profile in Figure 3.

In addition of the Alfama and Estoril thermal springs and the AC1-Balum and AC1-Oeiras geothermal wells, several groundwater wells already exploiting Cretaceous and Jurassic formations for other purposes (industrial, balneotherapy, irrigation) are documented to have a geothermal potential for direct uses. These are located in three areas along the north bank of Tagus River: Lisbon, Estoril and Vialonga areas (Figure 1) (Marrero-Diaz et al., 2013). At the Lisbon area, 5 groundwater wells, ranging from 345 to 562 m depth, extract between 9 and 42 L/s of a HCO_3-Na hyposaline and hypothermal water (TDS<1g/L and 26-34ºC), for irrigation and industrial purposes, from Cenomanian to Upper Barremian (sandstones, clays and limestones) formations. In close proximity to the Estoril thermal spring, numerous groundwater wells, ranging from 121 to 279 m depth, extracting between 1 and 22 L/s of a Cl-Na mineralized hypothermal water (TDS>2 g/L and 22-40ºC) from Lower Barremian to Berriasian (mainly limestones) formations have been also identified (Lopo-Mendonça et al., 2004). Finally, relatively deep groundwater wells (up to 1000 m depth) extracting ~15 L/s of a HCO_3-Ca low-mineralized hypothermal water (TDS<1 g/L and ~35ºC), mainly for industrial purposes, from Lower Cretaceous to Upper Jurassic (limestones and sandstones) formation have been documented in the northernmost interest zone of Vialonga area (LNEC, 2010).

Since the mid-fifties, hydrocarbon exploration wells Barreiro-1, Barreiro-3 and Barreiro-4, in the south bank of Tagus river, showed evidence of highly mineralized fluids (TDS>5 g/L) with temperatures above 75ºC at 2500 m depth in Upper and Middle Jurassic limestones (e.g. Carvalho et al., 2005a; Lomholt et al., 1996). However, until new deep wells are drilled, which could provide detailed information about reservoir characteristics and fluid availability, it is difficult to make an accurate geothermal potential assessment for these Jurassic formations.

In the context of the last edition of the Atlas of Geothermal Resources in Europe (Hunter and Haenel, 2002), a geothermal potential assessment of the Lower Cretaceous (Aptian-Albian and Valanginian) formations in the Lisbon region was obtained by Correia et al. (2002) (Figure 3). Calculations were based on the volumetric deterministic method and definitions formulated by Muffler and Cataldi (1978). Using information provided by hydrocarbon wells (Barreiro-1, 2, 3 and 4, and Monsanto-1) and the AC1-Balum geothermal well mentioned above and assuming a conservative porosity of 15%, a geothermal potential (*Heat in Place*) of $0.5 \cdot 10^{18}$ J was obtained for both Lower Cretaceous formations, which represents 1.7 GJ/m^2 in 290 km^2 of surface considered (Correia et al., 2002).

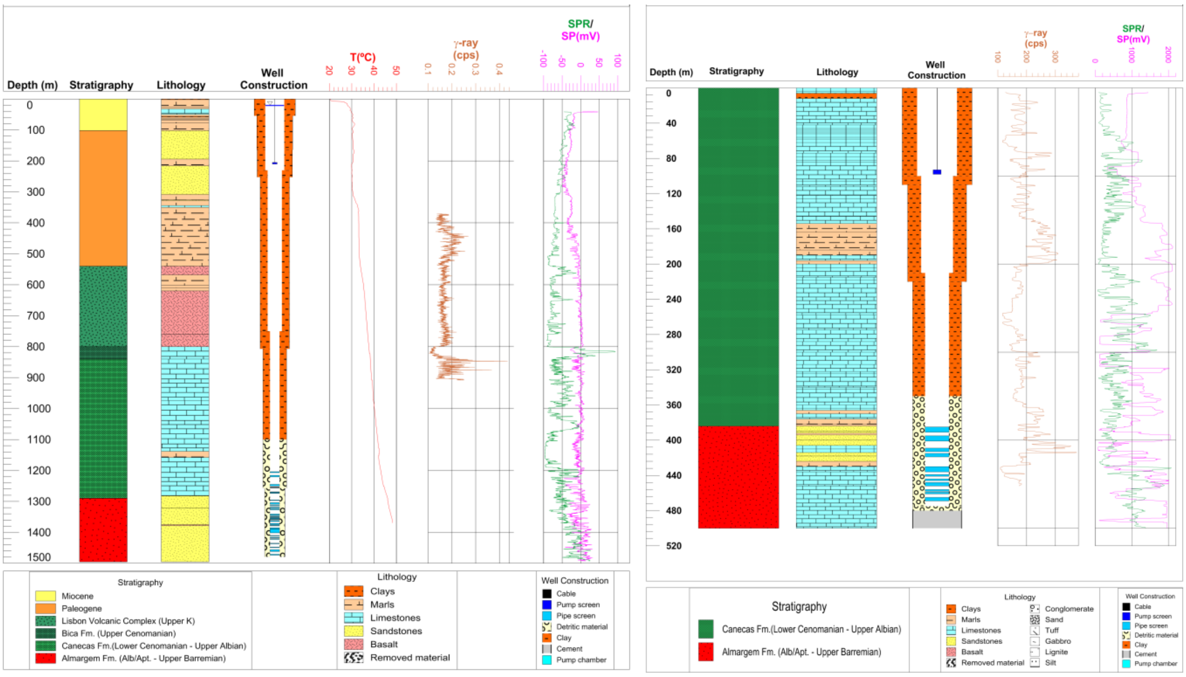

Figure 2: Logs of AC1-Balum (left) and AC1-Oeiras (right) geothermal wells, showing (from left to right) litho-stratigraphic columns, well construction characteristics and different geophysical parameters: water temperature, as T (ºC); gamma-ray, as γ-ray (cps); self-potential, as SP (mV); single-point resistance, as SPR (ohm). See location in Figure 1.

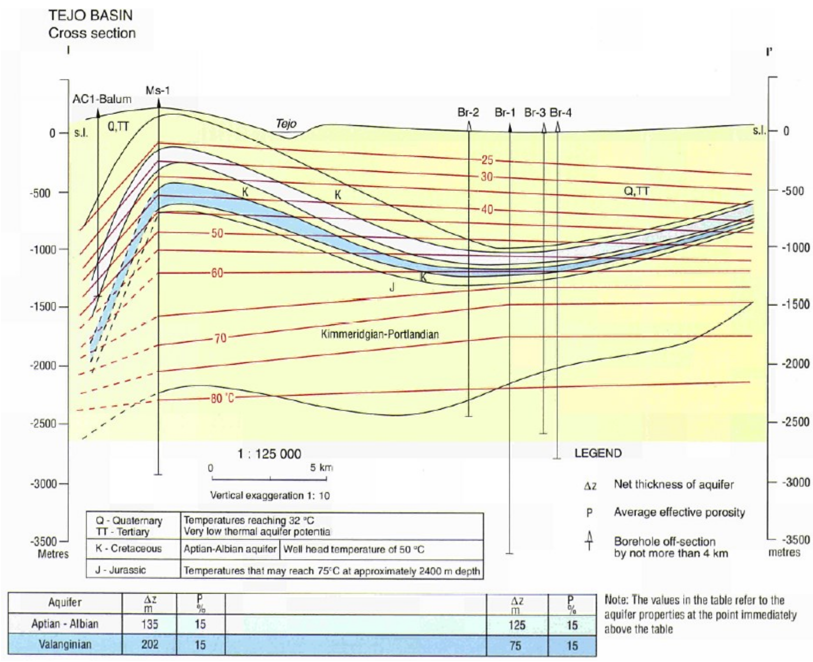

Figure 3: Schematic geological profile, indicated in black arrow in Figure 1, highlighting geothermal reservoir characteristics of Lower Cretaceous (Aptian-Albian and Valanginian) formations. From Correia et al. (2002).

The goal of this study was to update the geothermal potential assessment of the Lower Cretaceous formations in the Lisbon region, integrating information from geology, hydrogeology, and historical and recent geophysical studies on the structure of the different geological formations, with the aim of identifying the most favorable areas for future exploitation of this sustainable and non-polluting thermal energy resource.

2. STUDY AREA

The study area includes the Lisbon and Setubal districts, on both banks of the Tagus River, in the W of Portugal (Figure 1). Climate conditions are typical of a mesothermal sub-humid region with dry summers, following Thornthwaite (1948) classification (Ramalho et al., 2001). The highest precipitation period occurs between October and May, increasing from the W coast to inland areas with mean annual values ranging from 500 to 800 mm, reaching ~1000 mm at Sintra Massif (Quintela, 1975).

From a tectono-sedimentary point of view, the Lisbon region belongs the southernmost sector of the Western Meso-Cenozoic basin, which integrates formations of Lusitanian (Mesozoic) basin partially overlapped by Cenozoic sediments of Lower-Tagus basin (Kullberg, 2000; Rasmussen et al., 1998). The Western Meso-Cenozoic basin, originated for the breakdown of Hercynian Massif by extensive tectonic movements related with the Atlantic Wilson Cycle in progress (LNEG, 2010), is composed by a normal sequence of more than 3 km thickness of Triassic to Holocene sediments, where the Upper Cretaceous corresponds to a stratigraphical gap matching with two important regional igneous formations: the Lisbon Volcanic Complex (LVC) and the Sintra Sub-Volcanic Massif (e.g. Miranda et al., 2009). The Lower-Tagus basin also represents a normal sequence of 1.5 km thickness of Paleogenic to Holocenic deposits (Carvalho et al., 2005b).

A good correspondence exists between the Western Meso-Cenozoic basin and Lower-Tagus basin geologic units with the main hydrogeological units described in Almeida et al. (2000). The Tagus-Sado basin, constituted by Cenozoic sediments at the southern part of the study area, represents the most important aquifer in terms of capabilities of mainland Portugal (Almeida et al., 2000). Given its good reservoir properties (water temperature ≤ 32ºC; transmissivity ~ 150 m^2/d; high productivity ~ 10 L/s; shallow hydrostatic and hydrodynamic levels), this hydrogeological unit must be a priority target for shallow geothermal exploitation with geothermal heat pumps (Costa et al., 2011).

In contrast, due to lack of more detailed urban hydrogeological studies and/or relatively low productivities and storativity characteristics on Mesozoic formations, only one aquifer system (Pisões-Atrozela) has been identified at the northern margin of the study area (Almeida et al., 2000). However, relatively high and continuous flow rates (10-42 L/s) extracted from the Lower Cretaceous sandstones and limestones formations have been confirmed, as mentioned above (Marrero-Diaz et al., 2013). The Lower Cretaceous reservoir is mainly related to a multilayered sequence of limestones, sandstones and clays from Cenomanian to Upper Barremian ages (*Caneças* and *Grés de Almargem* formations; e.g. Rey, 1993), overlaid by low-permeability Upper Cretaceous basaltic lavas and pyroclasts and Paleogenic marls, which confers semi-confined (mostly artesian) conditions. These features allowed an assessment of a potential CO_2 storage location in the south bank of the Tagus river, which was however rejected due to significant risks (earthquakes, faulting, etc.) and relatively low storage capacity (Machado et al., 2011).

3. GEOTHERMAL ASSESSMENT

For a better comparison with the previous work of Correia et al. (2002), the present updated geothermal potential assessment of the Lower Cretaceous formations in the Lisbon region was also based on the volumetric deterministic method of Muffler and Cataldi (1978). It is based on the concept of evaluating the thermal energy stored or *Heat in Place* (*HIP*) in a volume of a reservoir (rock and water) of uniformly porous and permeable rock with homogeneous density and heat capacity at a temperature difference to a usable base temperature, calculated as:

$$HIP = \left(\gamma_w \cdot \phi + \gamma_r \cdot (1-\phi)\right) \cdot \mathrm{A} \cdot h \cdot (\mathrm{T_r} - \mathrm{T_0}) \qquad (1)$$

Where γ_w, γ_r, ϕ, A, h, T_r, T_0 are water and rock matrix heat capacity (kJ/m^3·ºC), effective porosity, surface area under consideration (m), net thickness (m), temperature at the top of the reservoir and mean surface temperature (ºC), respectively. Therefore, the data used for this assessment methodology consist of hydrocarbon boreholes and groundwater wells information (stratigraphy, porosity and temperature measurements) as well as geological and geophysical surveys to determine reservoir geometry (Hurter and Haenel, 2002).

3.1 Reservoir geometry

In order to provide the geometrical configuration and extensions of bottom, roof and thickness of Lower Cretaceous reservoir, the first step was to built a 3D geological (static) model based on available geological, geophysical (mostly seismic reflection) and hydrogeological information, provided in different data formats previously consolidated and integrated (using several software packages) in a GIS based database.

Stratigraphycal and lithological data of considered groundwater wells and hydrocarbon boreholes were previously harmonized into a database using RockWorks® software. The whole database was integrated in the ArcGis® package, allowing a better visualization of the different types of input data and a careful control of the 3D model building (Figure 4). Geo-referenced geological maps at different scales (10K and 50K) and horizons depths from corresponding geological cross-sections have been also digitalized and integrated into the ArcGis based information system. Finally, litho-stratigraphic correlations were obtained only using high-confidence groundwater wells and hydrocarbon exploration boreholes, in which stratigraphic sequences were consistent with the geological history of the study area.

Depth-converted geologic horizons obtained by different authors after reprocessing and reinterpretation of seismic reflection, wells and geological datasets from the Lisbon region (Carvalho, 2003; Carvalho et al., 2005b; Pinto, 2012), have been loaded into this GIS environment. In particular, the top and the base of Cretaceous formations were bound by the available base of the Cenozoic horizon and the top of the Upper Jurassic horizon, respectively. An important constraint was related to the lack of coverage of these depth-converted horizons below the urban area of Lisbon (Figure 1). Therefore, bottom and roof layers of considered geological formations were spread northward, merging and refining depth-converted geologic horizons with stratigraphic correlations from groundwater wells, hydrocarbon exploration boreholes, digitalized geological maps and cross-sections. When real values of Lower Cretaceous bottom depths were not available, a mean net thickness of 130m, obtained from the considered groundwater wells and hydrocarbon boreholes observation points, was assumed, similar to the thickness values of both Albian-Aptian and Valanginian formations in Correia et al. (2002) (Figure 3).

In some areas of the Lisbon region between 60 and ~800 m of volcanic rocks and sedimentary deposits (mainly limestones and marls) from Upper Cretaceous formations (LVC, Bica and Caneças) can overlap the Lower Cretaceous reservoir (Ramalho et al., 2001; Carvalho et al., 1990) (Table 1). Therefore, it was necessary to generate a new layer, taking in account the existing offset between the base of Cenozoic horizon and the top of Lower Cretaceous sandstones formations (*Grés de Almargem*). In order to constrain this offset, an intermediate layer was generated merging stratigraphical information with a Turonian-base horizon obtained around the Monsanto-1 borehole from geophysical (gravimetric) surveys and kindly provided by DPEP/DGEG. A resume of the main characteristics from each geological layer in Lisbon region is show in Table 1 and Figure 5:

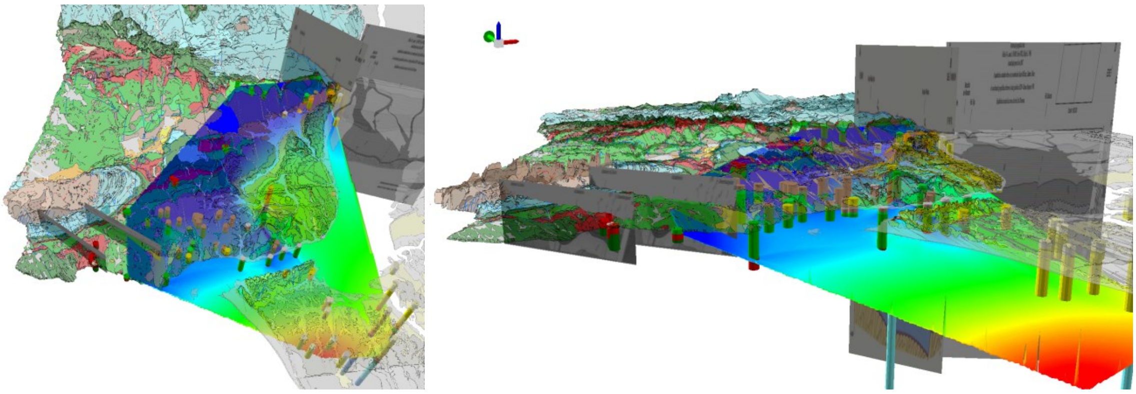

Figure 4: Sub-vertical and sub-lateral views of the ArcGis based geological 3D model of the study area, showing the geometry of the top of the Lower Cretaceous formations obtained through the integration of stratigraphical data from groundwater wells and hydrocarbon exploration boreholes, merged with geological maps and cross-sections at 50k scale, and base of Cenozoic depth-converted horizon from geophysical compilation. (Vertical exaggeration: 5).

Table 1: Simplified lito-stratigraphic column of the main possible geothermal reservoirs at Lisbon region adapted from Carvalho et al. (1990). Statistical thickness and top depth of each formation from the geological database built in this work have been also included. *Data from Carvalho et al. (1990); nd: not determined.

		Lithology	Thickness (m)				Top depth (m)				Geothermal Potential
			Nº	Average	Min	Max (*)	Nº	Average	Min	Max	
Cenozoic	Quaternary	Sand, mud and pebbles	13	10	2	30 (50)	-	-	-	-	High potential for shallow geothermal systems: flow rates ~ 100 L/s; transmissivity ~ 200 m^2/d; water temperature ≤ 32ºC; total mineralization 0.4 g/L*
	Pliocene	Sand and clays	0	nd	nd	nd (170)	1	10	10	10	
	Miocene	Sandstones, limestones and marls	5	612	203	815 (680)	7	125	14	202	
	Eocene - Oligocene	Red clays and conglomerates	6	262	122	438 (440)	8	489	7	1017	Very low potential: aquitard; some evidence of highly mineralized fluids in Oligocene (TDS > 5 g/L).
Cretaceous	Upper	Volcanic rocks (basalts and breccias)	5	101	38	260 (400)	8	107	6	540	
		Compact limestones and marls	52	187	28	502 (400)	83	128	12	800	Low potential: moderate and irregular flow rates*
	Lower	Sandstones with pebbles, limestones	24	231	90	498 (560)	64	342	10	1345	Medium potential for direct uses: water temperature 20-50ºC; flow rates 10-40 L/s; reinjection required (due to possible limitation of fluid availability)
Jurassic	Upper	Marls and limestones	4	1048	946	1191 (1700)	11	779	250	1432	Unknown potential: water temperature > 75ºC at 2500 m depth; total mineralization > 5 g/L
	Middle	Limestones and dolomites	0	nd	nd	nd	4	2380	2186	2502	

3.2 Reservoir properties

A geothermal gradient of ~25ºC/km was recently estimated by Ramalho (2013) in the study area, close to the highest 26ºC/km value estimated in mainland Portugal (see Figure 1). However, an average geothermal gradient of 21ºC/km was suggested by Carvalho et al. (2005a) for the estimation of the temperature in a given depth in the whole Lusitanian basin, with an average shallow groundwater temperature of ~18ºC. In the present work, a intermediate geothermal gradient of 23ºC/km with a mean surface temperature of ~17ºC was obtained from water temperature measurements in groundwater wells, tapping the Lower Cretaceous formations in the study area and available information from hydrocarbon exploration boreholes. Therefore, when water temperature measurements were not available, the input parameter of reservoir temperature T_r was obtained considering the previously interpolated reservoir's top depths and assuming a geothermal gradient of 23ºC/km.

Taking into consideration the relatively low-salinity groundwater of the Lower Cretaceous sandstones, a constant water heat capacity (γ_w) value of 4180 J/kg·ºC was obtained by the product of water specific heat capacity C_w (4180 J/kg·ºC) and water density ρ_w (10^3 kg/m^3). Likewise, a constant γ_r value of 3740 (kJ/m^3·ºC) was obtained assuming typical ρ_r and C_r values of sandstones matrix of 2200 (kg/m^3) and 1700 (J/kg·ºC), respectively (Robertson, 1988).

Effective porosity values were obtained from literature, taking in consideration the type and thickness of the different lithologies of Lower Cretaceous formations identified in each considered groundwater well and hydrocarbon exploration borehole (Custodio and

Llamas, 1983, and references herein). When no lithological information was available, a mean effective porosity value of 11 was assumed. This value is relatively higher than the 6.6% weighted mean effective porosity obtained for the Lower Cretaceous formations by Machado et al. (2011) from hydrocarbon exploration boreholes Barreiro-1, 2, 3 and 4 (Figure 1), but lower than the 14.5% average effective porosity (considering half of 29% bulk porosity) of an analogous detritic Lower Cretaceous formation (Torres Vedras; e.g. Lomholt et al., 1996) in the Lusitanian Basin, reported by Carneiro (2012).

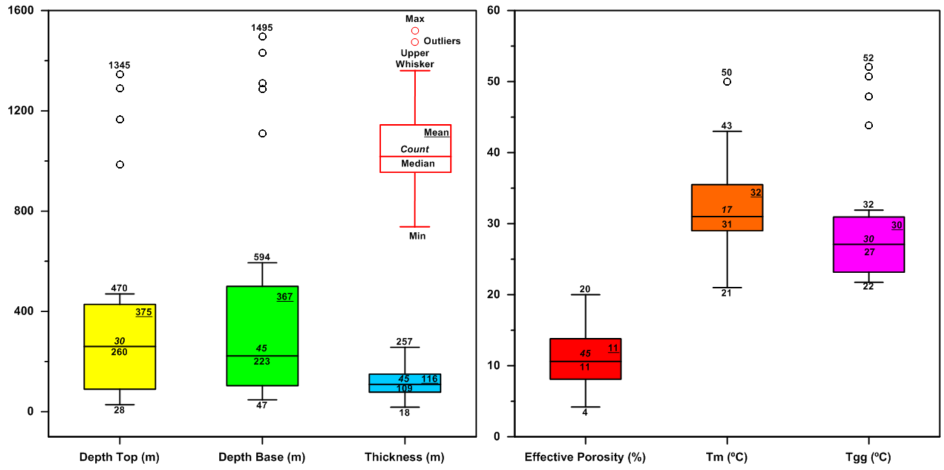

Figure 5: Box-whiskers diagrams of main characteristics of Lower Cretaceous Aquifer. Tm: Temperature measured at sampling point; Tgg: reservoir temperature obtained through the assumed geothermal gradient (2.3ºC/100m) and the top of the reservoir.

4. RESULTS

In order to generate the different layers of Lower Cretaceous reservoir (Figures 6 and 7), digitalized data have been interpolated with ordinary kriging method. Each layer was referred to the topographic surface through a digital elevation model of 250 m resolution obtained from ASTER GDEM (http://www.jspacesystems.or.jp/ersdac/GDEM/E/index.html) satellite images.

A geothermal potential (*Heat in Place*) of 3.8 GJ/m^2, higher than the previously estimated 1.7 GJ/m^2, was obtained in 383 km^2 of surface considered. However, only a part of this resource could be extracted. Reservoir's thermal energy or *HIP* and the portion that can be extracted at the wellhead or *Extractable Heat* (*EH*) are related by the recovery factor R_g as:

$$EH = HIP \cdot R_g \tag{2}$$

Recovery factor usually ranges from 0.05 to 0.5 in regards to reservoir properties and extraction technology used (e.g. Gringarten, 1978/1979; Williams et al., 2008, and references herein): reservoirs uniformly porous, homogeneous, and liquid-phase using injection have *Rg*~0.5, while fractured reservoirs and/or if the extraction of geothermal energy is planned with a singlet, then the recovery factor reduces to ~ 0.1.

The existing data on the Lower Cretaceous aquifer in the Lisbon region indicates that it has a complex geological structure. This complexity results mainly from a high level of compartimentation, probably related to the existence of folds, faults and intrusion of dykes from the Lisbon Volcanic Complex (Carvalho et al., 1990). These structural elements can play an important role in the control groundwater circulation, minimizing lateral and vertical recharge (e.g. LNEC, 2010), and therefore the heat transfer between adjacent blocks of the aquifer system. Aquifer compactation, probably due to over-exploitation, seems to be a real threat in some areas of Lisbon region (Heleno et al., 2011). In addition, the available data from pumping/recovery tests performed in this aquifer seems to show residual drawdowns in several wells, i.e. hydrodynamic levels do not reached original steady-state levels after pumping, suggesting limited groundwater reserves (Kruseman and de Ridder, 1994). This hypothesis is also supported by groundwater residence times of ~12 Ky obtained through radiocarbon analyses after ^{13}C corrections by A.Cavaco-CFG (1989) in AC1-Balum geothermal well, before fluid salinization occurred, suggesting also a very limited rate of modern recharge. This could become a constraint for the exploitation of the geothermal reservoir, since the amount of fluid may not be enough to address economic requirements in some hypothetical projects.

Based on these results, it was assumed that a potential geothermal exploitation of this urban aquifer involves reinjection (by doublet) to ensure reservoir optimal conditions from water and geothermal perspectives. Therefore, assuming a conservative recovery factor (R_g) of 0.15, an *Extractable Heat* of 0.6 GJ/m^2 was obtained for the Lower Cretaceous at the study area. The EH distribution map in the study area is showed in Figure 7 (down).

The results identified the eastern sector of the city of Lisbon and the south bank of the Tagus River as the areas with highest *HIP* and *EH* (Figure 7). These areas correspond to predicted thicker and deeper zones of Lower Cretaceous formations (Figure 6) and, therefore, where potential for higher fluid temperature and flow rates could be found. However, an important constraint is related to the lack of direct information from observation points (groundwater wells and/or hydrocarbon boreholes), which would allow one to confirm the geothermal potential. Note that additionally, the hydraulic parameters of the aquifer were not considered as variables in this geothermal assessment method. Spatial variability of hydraulic conductivity, which is assumed to be constant all over the aquifer, can represent an important factor for the detailed understanding of the real availability of fluid (groundwater) in this region.

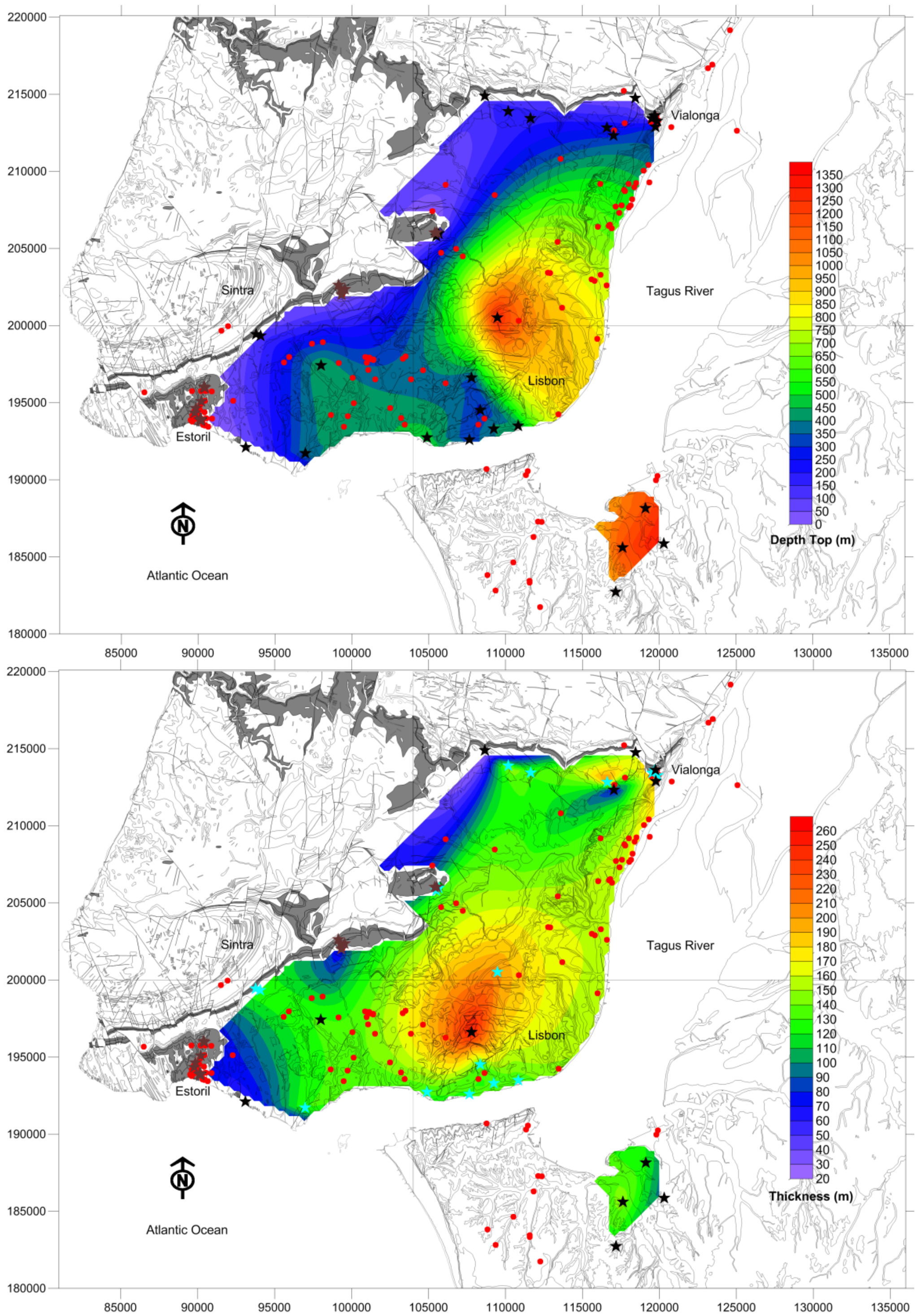

Figure 6: Roof isobaths (up) and isopachs (down) maps of Lower Cretaceous formations in the Lisbon region (outcrops correspond to gray areas). Black-Brown-Blue stars and red circles represent considered and non-considered observation points (groundwater wells and hydrocarbon boreholes) to generate each map, respectively: red, roof constrained; brown: bottom constrained (outcrop); blue: bottom and roof constrained.

5. CONCLUSIONS

A thermal energy stored or *Heat in Place* of 3.8 GJ/m^2, higher than the previously estimated 1.7 GJ/m^2, highlights the potential of the Lower Cretaceous formations for future geothermal exploitation projects. Assuming a recovery factor of 0.15, an *Extractable Heat* of 0.6 GJ/m^2 was obtained. This value is significantly lower than other deep sedimentary formations already exploited for district heating, such as the Paris basin (7 GJ/m^2; Lopez et al., 2010) or the Upper Rhine Graben (15-30 GJ/m^2; Dezayes et al., 2008).

Due to energy loss during transport, the success of low-enthalpy geothermal energy is based on spatial matching between customers and resources availability. From this point of view, the most promising zone for geothermal purposes (direct uses of heat or even electricity production if medium-enthalpy fluids are obtained) is the eastern sector of the city of Lisbon. This area corresponds to the former Lisbon Universal Exhibition area (EXPO-98) currently reconverted as a business hub and where, since 1998, a district heating system using conventional energy (gas) is used for cooling, heating, sanitary hot water and even electricity for several existing infrastructures (http://www.inpal.com/en/Pre-insulated-pipes-references-District-heating-expo98-lisbon-Inpal-Energy.html). In this context, a sustainable and monitored exploitation of Lower Cretaceous formations could provide a renewable and non-polluting input of low to medium-enthalpy geothermal fluids to the conventional district heating.

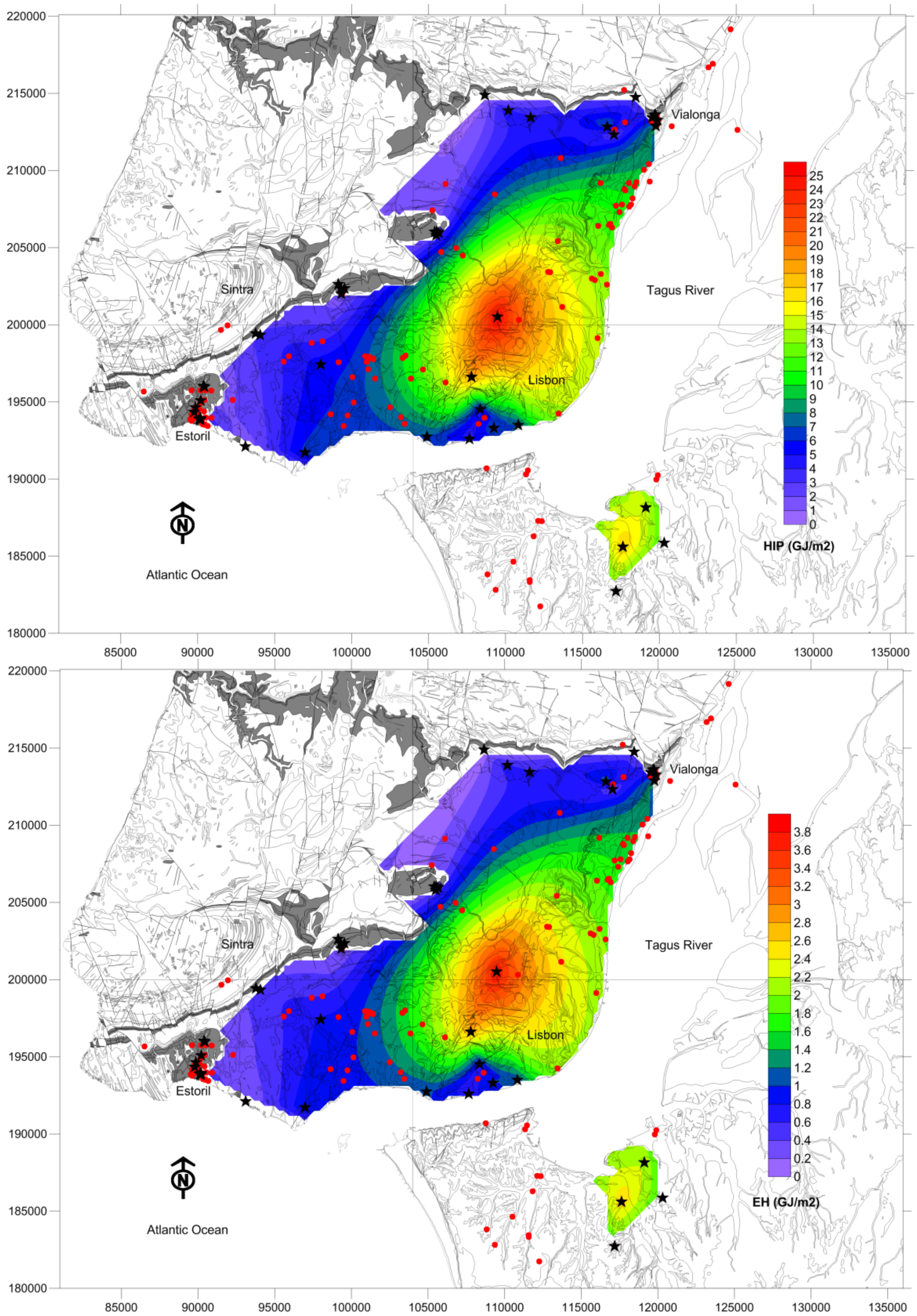

Figure 7: ***Heat in Place* or *HIP* (up) and *Extractable Heat* or *EH* (down) distribution maps (in GJ/m^2) of Lower Cretaceous formations in the Lisbon region (gray areas correspond to outcrop zones). Black stars and red circles represent considered and non-considered observation points (groundwater wells and hydrocarbon boreholes) to generate each map, respectively.**

The GIS based 3D geological model obtained, even as a preliminary version, represents the basis for the future simulation of dynamic processes, which will be simulated to handle the complexity of processes involved (geometry, hydraulics, thermal effects, geochemical reaction, etc.) and to predict the geothermal reservoir behavior under different exploitation scenarios during shortmedium time periods. This model must and should also be subsequently updated when new data becomes available, interacting with the conceptual model in order to obtain a continuous refinement at different scales.

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