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Review

Assessment of the geothermal potential in the region of Ávila (Spain): An integrated and interactive thermal approach

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A R T I C L E I N F O

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A B S T R A C T

Exploring and exploiting a geothermal resource has become one of the most prolific tasks for contributing to the global sustainable development. Despite this fact, several countries, such as Spain, are still far from achieving a generalized use of these renewable systems. The reason for this underuse often derives from the lack of information and characterization of the geothermal energy source. Considering this, the present research aims to provide relevant data about the geothermal potential of the Spanish region of Ávila. The geological context of this province lays the foundations for considering the region as a promising site for different geothermal uses. In order to estimate the geothermal energy potential of the region, the existing geological information has been complemented with thermal surveys carried out in the study area. The experimental measuring has consisted of the register of the underground temperature in piezometers of variable depth and natural springs distributed throughout the province. The processing of these records has allowed knowing the thermal evolution of the subsoil at the different levels evaluated in the research. Results show that there are two main potential areas in the province that could be successfully used for heating purposes (maybe as part of district heating systems) and for future deeper evaluations in the sense of Hot Dry Rock (HDR) techniques. Final conclusions have also been included in an interactive and open-source tool that allows visualizing the thermal findings with the aim of planning future geothermal uses in the region.

1. Introduction

The fight against climate change and the depletion of the traditional energy sources place renewable energies in a strategic position. The necessity of a rapid energy transition from fossil fuels to renewable technologies has become certain (Asgari and Ehyaei, 2015). In this sense, geothermal resources are crucial components for the successful decarbonisation of the future energy supply. In contrast to other renewable alternatives, geothermal energy presents a series of advantages that make it an excellent alternative for covering the world increasing energy needs. It is available at any time of the day, all year round, being able to be used for base load energy, for both power and heat generation. In addition, its exploitation is technologically feasible, regardless of the meteorological conditions and its environmental impact is considerably low (Templeton et al., 2014; Yildirim and Ozgener, 2012). Regarding its applications, geothermal heating is the most extended use and implies the implementation of ground source heat pumps (GSHP) or groundwater heat pumps (GWHP) systems that extract the energy from shallow levels of the ground or groundwater. Geothermal power production is also viable but it is currently more limited and is traditionally linked to the existence of a high enthalpy heat source (Moon and Zarrouk, 2012).

Non-electrical geothermal applications are those that use the Earth's energy for a wide range of applications, usually for heating and cooling purposes. These direct uses are one of the oldest and most versatile ways of utilizing geothermal energy (Dickson and Fanelli, 2013). Direct utilization commonly requires a temperature range of around 10 °C-150 °C (Glassley, 2014), and is present in more than 80 countries with an annual growth rate of 8.7%. At the end of 2019, the total installed capacity for geothermal direct use worldwide was of 107,727 MWt (Lund and Toth, 2020). In this sense, district heating systems are becoming fundamental to take advantage of the maximum potential of shallow

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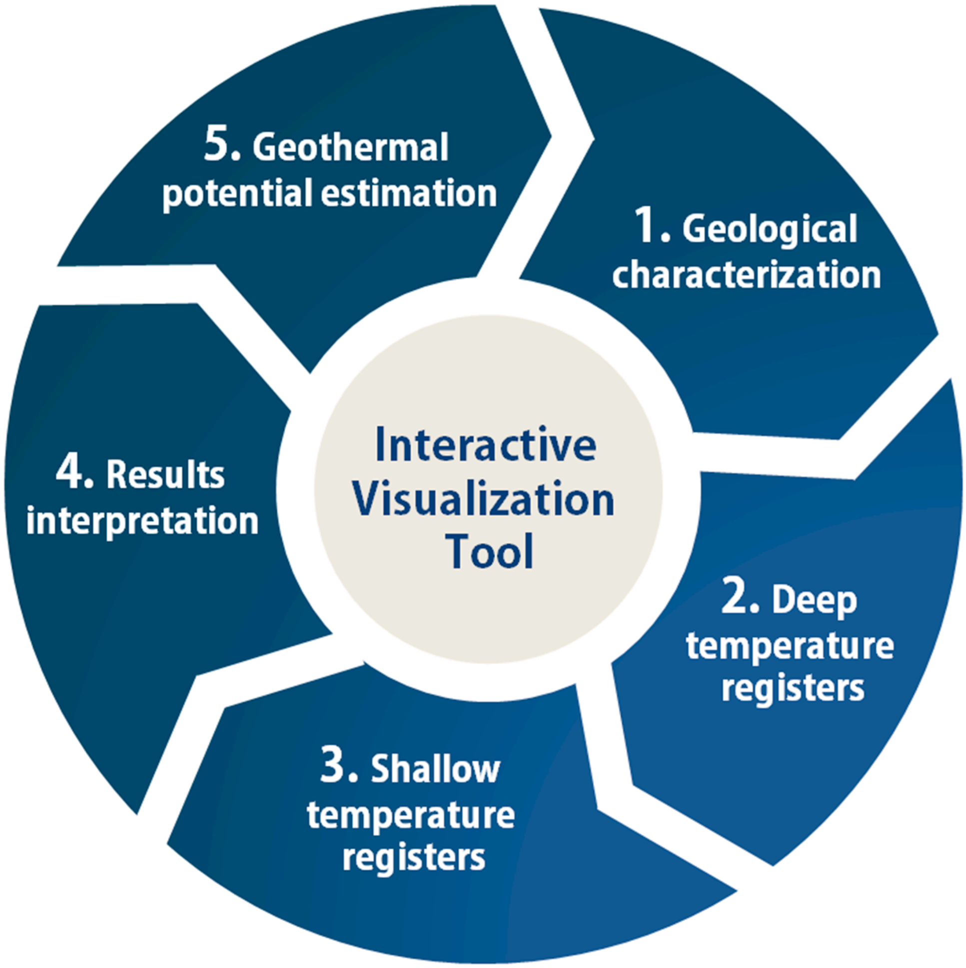

Fig. 1. Description of the workflow followed in the present research.

geothermal resources. Such is the case that, a wide number of countries have implemented this technology during the last decade, especially in Europe (Sáez Blázquez et al., 2018; Abdurafikov et al., 2017).

Geothermal power development is experiencing an increasing growth worldwide. The conventional geothermal power plants produce electricity by steam turbines which use the fluid extracted at depths of more than 3 km below the Earth surface. Within this group, numerous technologies and configurations can be found; single and double flash, dry steam or Organic Rankine Cycle (ORC) power plants (Ahmadi et al., 2020). The *International Panel on Climate Change* estimated that by the year 2050, up to 8.3% of the global world's electricity production is expected to be covered by geothermal resources (International Panel on Climate Change (IPCC) 2007). Up until now, 89 geothermal power plants exist worldwide with clear expectations of increase in the near future (Moon and Zarrouk, 2012). Despite this fact, only a small fraction of the earth's heat is being currently converted to electrical power. In the frame of making use of this renewable source, the concept of Enhanced Geothermal System (EGS), which also includes the earlier concept of Hot Dry Rock (HDR) arises for first time in 1974. The utilization of an EGS consists of extracting heat from a rock that is not naturally fractured and with low permeability. Water, used as geothermal fluid, is pumped through areas of hot rock with the aim of exchanging heat with the ground. The use of this technology allows increasing the geothermal power development in an exponential way since; in this case, geothermal reservoirs are not the search objective, but areas of dry and very hot rock (Olasolo et al., 2016). Once identified the potential areas, wells are drilled into the hot rock, which requires being stimulated in order to generate stable fractures through which the geothermal fluid is injected. When the rock is fractured, the fluid circulates through the permeable paths of the rock for collecting the heat there, which is then extracted through the production wells (Heidinger, 2010). Although this promising solution has been implemented in different parts of the world with satisfactory results, some countries, like Spain, are still at exploratory stages.

1.1. Geothermal exploration in Spain

The exploration of geothermal resources started in Spain in 1948 by the Spanish Geologic and Mining Institute (IGME) at the Canary Islands. Subsequent prospecting activities allowed estimating the global geothermal potential in the country. According to these prospects, Spain stands out for the low-medium enthalpy resources potential in different areas of the country. In fact, Spanish geothermal applications are focused on the heating and cooling sectors, and, currently, there are no real geothermal systems producing electricity. Although in some areas, such as the Canary Islands, the implementation of different geothermal power uses could be technically feasible, only projects under study can be found (Colmenar-Santos et al., 2016).

The geothermal energy contribution in Spain is, indeed, low and, does not represent a significant percentage of the global Spanish

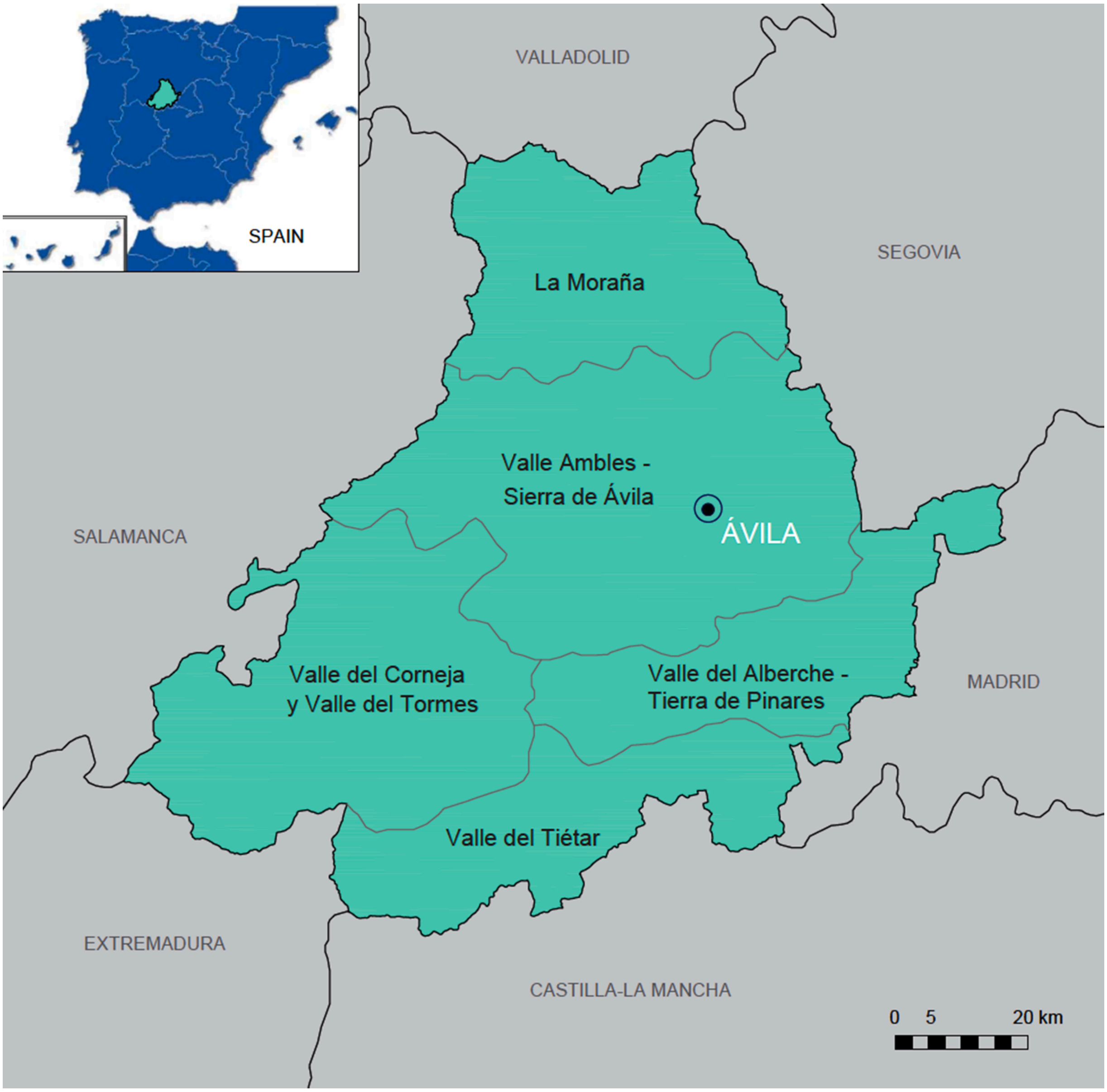

Fig. 2. Location of the province of Ávila in Spain and main valleys and mountains formations of the region.

installed capacity of heating and power systems. Despite this fact, the central region of the country is considered a promising area for new utilizations of geothermal energy. Following the European initiatives, Spain developed the Renewable Energy Plan 2011–2020 that set the goal of 50 MWe for geothermal power production and 66 MWt for direct geothermal applications (PANER 2010).

In this sense, new studies and prospecting works are considered crucial for the future expansion of this energy. Different water and mining exploration boreholes have been used in the past for the measuring of the subsoil temperature. However, these wells are not usually more than 200 m deep and, the existing temperature maps are mainly based on registers in deeper oil boreholes. All this has meant that the analysis of the deep geothermal potential in Spain has not covered the different regions of the country (Sanchez-Guzman and de la Noceda-Marquez, 2005). That is to say, numerous Spanish regions could be underutilizing existing geothermal resources due to the lack of research and studies in some specific areas.

Within the framework of the regional project *"ÁVILA GEONERGYZED"* financed by the Spanish Institution *"Gran Duque de Alba"*, the potential of the geothermal energy exploitation in the Spanish province of Ávila has been evaluated. The main objective of this research is providing a boost to the knowledge and description of new possibilities for the use of renewable energies in the mentioned province of Ávila. The work focuses on the analysis and evaluation of possible geothermal evidence that may be the starting point of the geothermal growth in the region. In this way, an integrated methodology for estimating the geothermal potential of Ávila by considering real temperature registers and the interpretation of the geological environment is proposed. Results are interpreted and analysed for identifying possible alternative geothermal uses within the field of the district heating production nets or even the power generation through EGSs. All the information derived from the experimental stages is then included in an interactive public tool so that any interested user can access it. The following sections include a preliminary geological and thermal setting

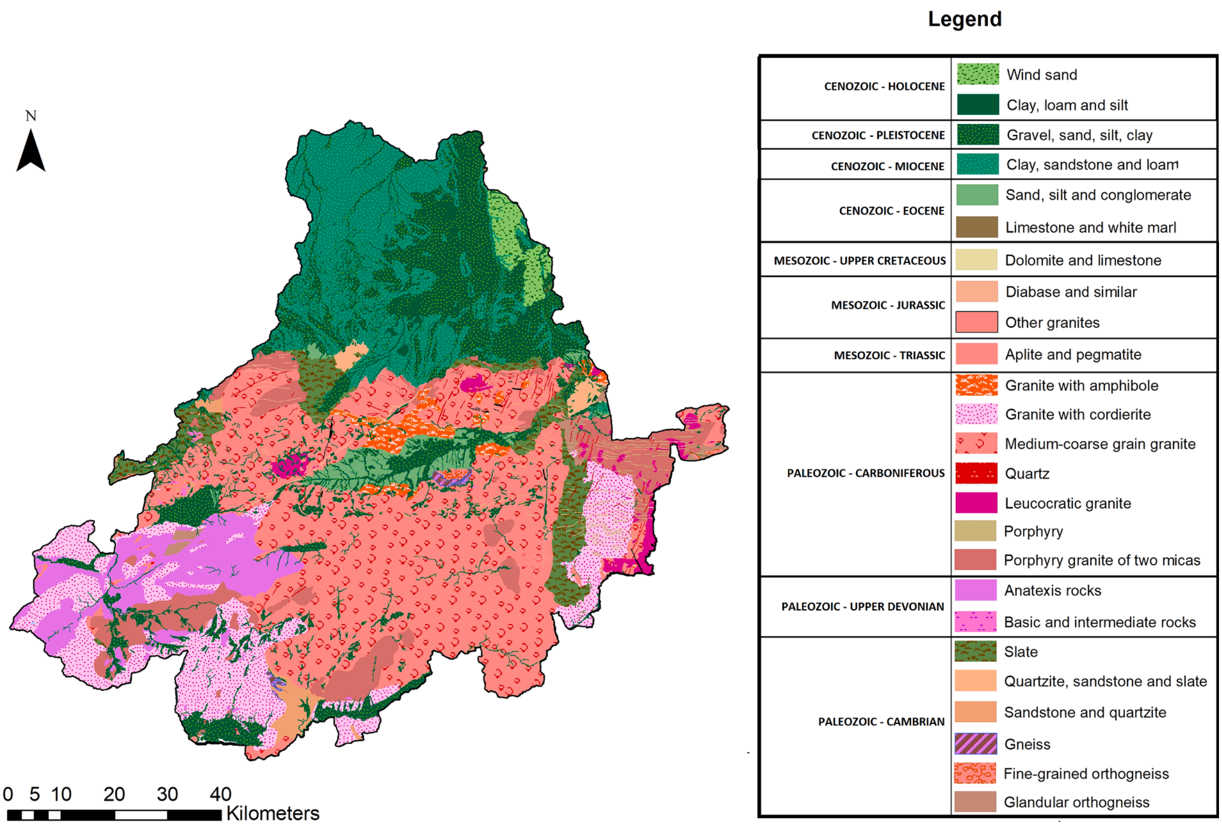

Fig. 3. Geological environment of the area under study (Vera, 2004).

Table 1
CHD control piezometers selected for the thermal analysis of the ground.

Piezometer code*	Locality	Depth (m)
PZ0247038	Horcajo de las Torres	330
PZ0247041	San Esteban de Zapardiel	609
PZ0247047	Palacios de Goda	62
PZ0247057	Barroman	350
PZ0247050	Nava de Arevalo	501
PZ0247053	Constanzana	250
PZ0247055	Fontiveros	240
PZ0245036	Adanero	300
PZ0255025	Maello	200
PZ0247062	San Juan de la Encinilla	290
PZ0260001	Gallegos de Sobrinos	102
PZ0261001	Sanchorreja	81
PC0264003	El Fresno	426
PZ0264005	Ávila	140
PZ0261002	Ávila	88
PZ0264001	Muñana	190
PZ0260002	Zapardiel de la Cañada	70
PZ0266001	Santa Maria del Berrocal	389
PZ0260003	Villafranca de la Sierra	80
PZ0260004	Zapardiel de la Ribera	60
PZ0260005	Barco de Avila (El)	90

*The original piezometer code has been preserved in order to allow for the user own research in the public platform of the CHD. A more detailed description of the structure of the aquifers in the wells of interest can be seen in Fig. 14 and later text.

of the area under study and the experimental phases performed within the ground thermal evaluation. Results of the experimental development are then presented in section 3, and finally, section 4 and 5 include the discussion and conclusions about the possibilities of future geothermal implementations in the region.

2. Methodology

2.1. Research objectives and workflow

As mentioned earlier, this research aims to boost the use of the geothermal energy in the Spanish region of Ávila. The methodology here implemented is based on the combination of the geological information associated to the area and temperature registers performed in existing deep boreholes (when available) and natural springs. From this main integrated approach, the present work also pursues the development of an interactive tool for the location of the most promising areas in the province from the point of view of the geothermal use. In short, the whole research is an attempt to promote new alternatives of implementing geothermal resources in different sectors of the province and to raise awareness within the population of the region, to get them involved in the development of these systems.

To materialize the previously mentioned objectives, the methodological stages followed in this research are summarized in Fig. 1. As can be observed in this Fig. 1, the first step consists of the geological characterization of the area under study. This first phase is essential to identify the most promising areas and to perform a coherent interpretation of the experimental registers. Once defined the geological environment of the region, stages 2 and 3 include the experimental temperature registers carried out on existing boreholes and natural springs in the area. It is crucial to highlight that the temperature register in deep boreholes is the most appropriate condition for the definition of the geothermal potential; however, when these are not available, shallow temperature information is also useful for the pursued estimation. Finally, steps 4 and 5 are based on the interpretation of the results derived from the experimental field work and the geological information, in order to estimate the global geothermal potential of the

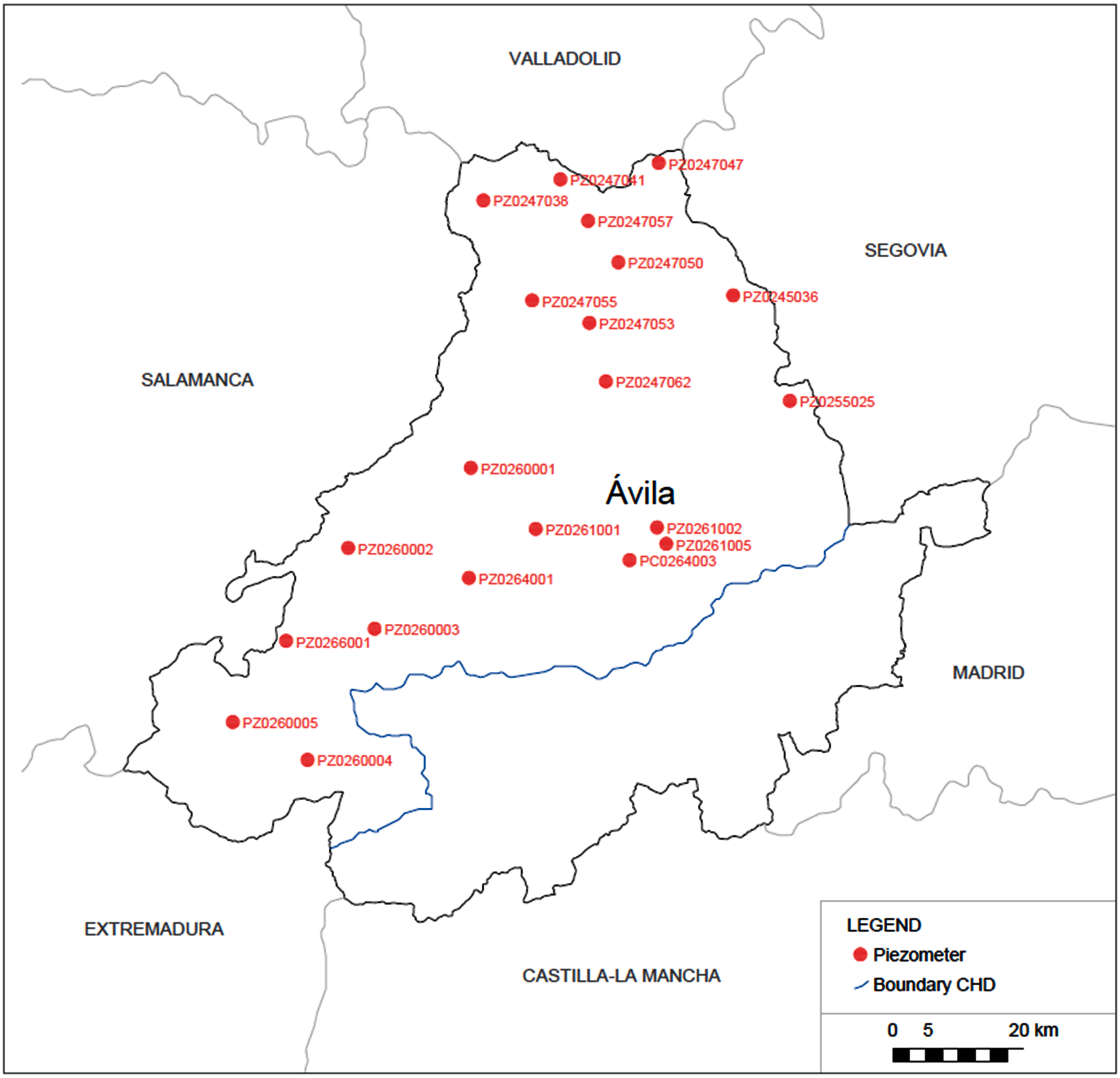

Fig. 4. Location of the piezometers belonging to the CHD included in the present research.

province. Interpreted information and results will be finally included in an interactive visualization tool that will be helpful in the future when deciding possible uses of the geothermal resources in the region.

2.2. Geological and geothermal setting

The region of Ávila is located in the centre of Spain (Fig. 2). In geological terms, it is characterized by the presence of two structures highly differentiated by their nature and formation: an eminently sedimentary level, located in the north-central area of the region; and an igneous level that extends through the rest of the central and southern areas.

The stratigraphy of the sedimentary area is constituted by a series of horizons mainly constant along all the area; (i) surface Neogene materials of heterogeneous composition (principally sands and clays) with thicknesses of around 100–200 m, (ii) Neogene materials constituted by altered clays with different levels of sands and silts and with variable thicknesses of about 250 m, (iii) Neogene with levels of clays, marls, sands and silts and thicknesses between 300 and 500 m, (iv) bedrock constituted by Early Tertiary materials, mainly sandstones, shales and schists.

Regarding the igneous rock environment, it mainly covers the central and southern area of the province, belonging to the Spanish Central System. This area is characterized by the presence of different thicknesses and states of alteration on the surface until reaching the bedrock formation (López Ruiz et al., 1975). In this context, the broad range of rocky formations includes three main groups; (i) pre-Hercynian igneous rocks (glandular and banded biotitic ortho-gneiss, leucocratic ortho-gneiss and foliate pegmatites), (ii) Hercynian granitic rocks (tonalites and quartz diorites, biotitic medium-coarse grained adamellites, porphyritic coarse-grained leucogranites with biotite, biotitic fine-grained leucogranites, and two-mica fine-grained leucogranites),

Fig. 5. Different captures of the experimental field work in the CHD piezometers network.

Table 2
CHT natural springs with available thermal registers.

Station code*	Locality
1027	Navalperal de Pinares – Gaznata
1034	Mombeltrán - La Morañega
1044	Navarrevisca - La Pinadilla
1088	San Martín del Pimpollar - Los Topos
1094	El Arenal – Mailla
1095	Lanzahíta - Del Horcajo
1099	Santa Cruz de Valle - La Sagra
1108	Santa Cruz del Valle-El Pradito
1109	Santa Cruz del Valle-El Lecherón
FM14	M. Los Chorros - San Martín del Pimpollar

*The original station code has been preserved in order to allow for the user own research in the public platform of the CHT.

(iii) philonian rocks (granitic-adamellite porphyries, fine-grained leucogranites and aplite, micro-diorites, quartz, syenite and lamprophyre dykes). It is also worth mentioning the regional metamorphism linked to the existence of the Hercynian collision (de España, 1992; Vera, 2004).

After consulting and interpreting the geological information of the region from the Spanish Geologic and Mining Institute database (Vera, 2004), the different existing formations were downloaded and processed in ArcMap Geographical Information System (GIS). As a result of a thorough process consisting of analysing and assembling geological formations with similar structure and composition, the following Fig. 3 presents the generated geological map of Ávila in which it is possible to observe the previous mentioned geological variations.

In respect of the geothermal setting of the area in which this research is focused, within the sedimentary architecture, medium enthalpy geothermal systems, associated with aquifer units with an adequate geothermal gradient, are expected to represent the main usable

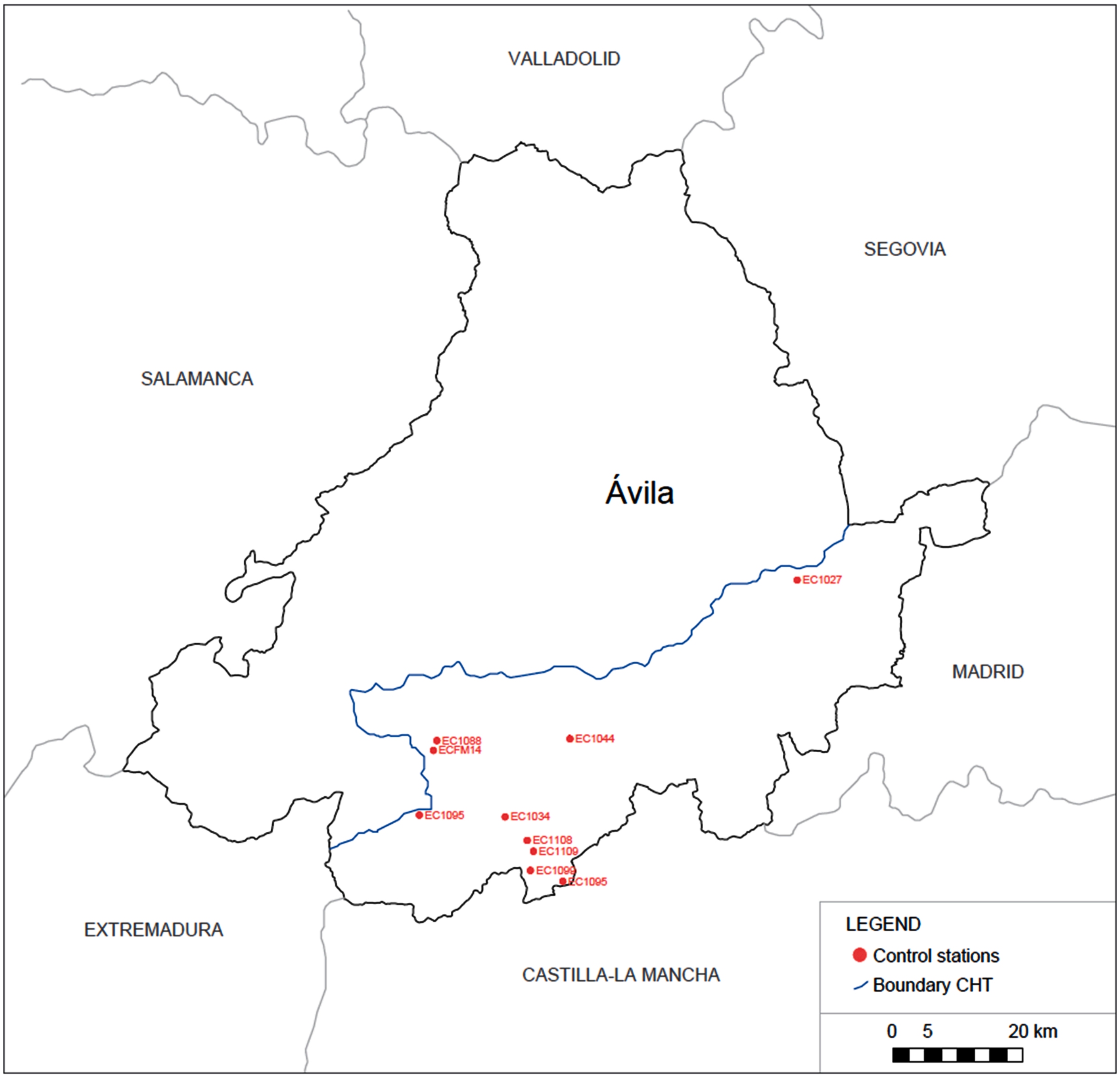

Fig. 6. Location of the natural springs belonging to the CHT included in the research.

resource. However, as shown in previous studies (Downing and Gray, 1986; Norden, 2011; Coppo et al., 2016), the establishment of low enthalpy geothermal systems with appropriate energy performance is also possible. Additionally, previous hydrothermal manifestations confirmed by the IGME indicate that the bedrock of this sedimentary environment could be also a promising area with thermal anomalies (Pérez Menzel, 2000).

Regarding the other geological context predominant in the region, evidence of thermal activity in granite rocks at a certain depth derive from the data of emissivity of certain gases (Radon) as well as in the structure of the different families of fractures (Muñoz Martín et al., 2007). Low enthalpy geothermal resources are especially appropriate in these formations due to the high thermal conductivity of the ground and the technical viability of the drilling process, which usually requires lower initial investments than in sedimentary contexts (Blázquez et al., 2017; Blázquez et al., 2020). The granite geological composition could also indicate the feasibility of exploiting high enthalpy geothermal energy as HDR reservoirs. However, exhaustive geophysical prospecting campaigns would be required in this sense, with the aim of accurately defining the geothermal gradient in the selected areas (Hicks et al., 1996).

As a result of the geological evaluation, a sedimentary island within the granite formations of the Valle Amblés trench is also evinced (also visible in the map of Fig. 3). This geologically sedimentary environment, supported by the granite bedrock, could open the way to hydrothermal exploitation by the contact of the underwater in the sand aquifers levels with areas of underlying hot rock.

Based on all the previously commented, it can be stated that the remarkable geological variety existing in the province involves a promising starting point for predicting alternative geothermal uses from the experimental thermal characterization contemplated in the present research.

Table 3
Temperatures registered (and obtained) in each of the piezometers included in the CHD.

Piezometer code	T (°C) 50 m	T (°C) 100 m	T (°C) 200 m	T (°C) 300 m	T (°C) 400 m	T (°C) 500 m
PZ0247038	15.362	17.905	20.902	21.733	22.465	23.191
PZ0247041	14.654	16.733	21.143	25.177	28.163	29.766
PZ0247047	14.502	16.605	20.985	25.010	28.109	29.652
PZ0247057	15.909	18.512	22.048	23.109	24.179	25.249
PZ0247050	17.060	19.351	21.055	22.395	22.776	23.108
PZ0247053	14.371	14.534	14.853	15.173	15.493	15.813
PZ0247055	14.112	14.297	14.437	14.606	14.786	14.966
PZ0245036	14.502	17.412	19.265	20.109	20.965	21.815
PZ0255025	14.160	14.215	14.387	14.524	14.674	14.824
PZ0247062	15.420	17.718	21.492	21.911	22.320	22.731
PZ0260001	13.917	14.810	16.498	18.218	19.938	21.658
PZ0261001	12.532	13.684	15.984	18.284	20.584	22.884
PC0264003	14.203	15.812	22.282	23.568	24.243	25.221
PZ0264005	13.881	15.311	18.171	21.031	23.891	26.751
PZ0261002	14.193	15.273	17.433	19.593	21.753	23.913
PZ0264001	13.656	14.437	15.997	17.557	19.117	20.677
PZ0260002	12.997	15.045	15.511	16.791	18.071	19.351
PZ0266001	13.978	14.886	15.950	15.957	15.967	15.977
PZ0260003	13.634	14.897	16.205	17.773	19.402	21.025
PZ0260004	13.350	14.526	15.986	17.555	19.114	20.985
PZ0260005	14.320	15.420	17.620	19.820	22.020	24.220

2.3. Experimental development

As already mentioned, the experimental stage (fundamental for the development of this research) is based on the ground temperature recording. In this sense, field work was planned from the perspective of achieving the thermal register of the ground to the greatest depth possible. After analysing the existing wells in the area under study, and considering the possible technical difficulties of measuring in watering holes (generally equipped with pump), the piezometer control networks of the Hydrographic Confederations present in the province were considered as a proper solution for this research. After consulting the available control networks of these institutions, the experimental temperature characterization of the ground was established as follows:

- Temperature registers in the existing piezometers of the Duero Hydrographic Confederation (CHD).
- Surface thermal registers from natural springs belonging to the Tajo Hydrographic Confederation (CHT).

It is convenient to clarify that Spain is organized in different Hydrographic Confederations that allow the organization of the organization of the hydrographic tasks in the country. In the case of the region under study, two different institutions oversee the corresponding hydrological work: the Duero and the Tajo Hydrographic Confederations. The boundaries of these confederations are thus officially established in the whole country, including the province of Ávila.

The recording of the ground temperature in the planned piezometers and surface stations was carried out using a single channel HOBO U12 temperature data logger, capable of continuously recording temperatures at depths greater than 1000 m of water column. The specific characteristics and the reduced size of this device allow the recording in those piezometers with limited diameter, difficult accessibility and, in which the column of water is considerably long.

2.3.1. Temperature register at the piezometer control network of the CHD

The first stage included in the experimental development of this research consists of the measuring of the underground temperature in existing piezometers of the region. From the control network of the CHD,

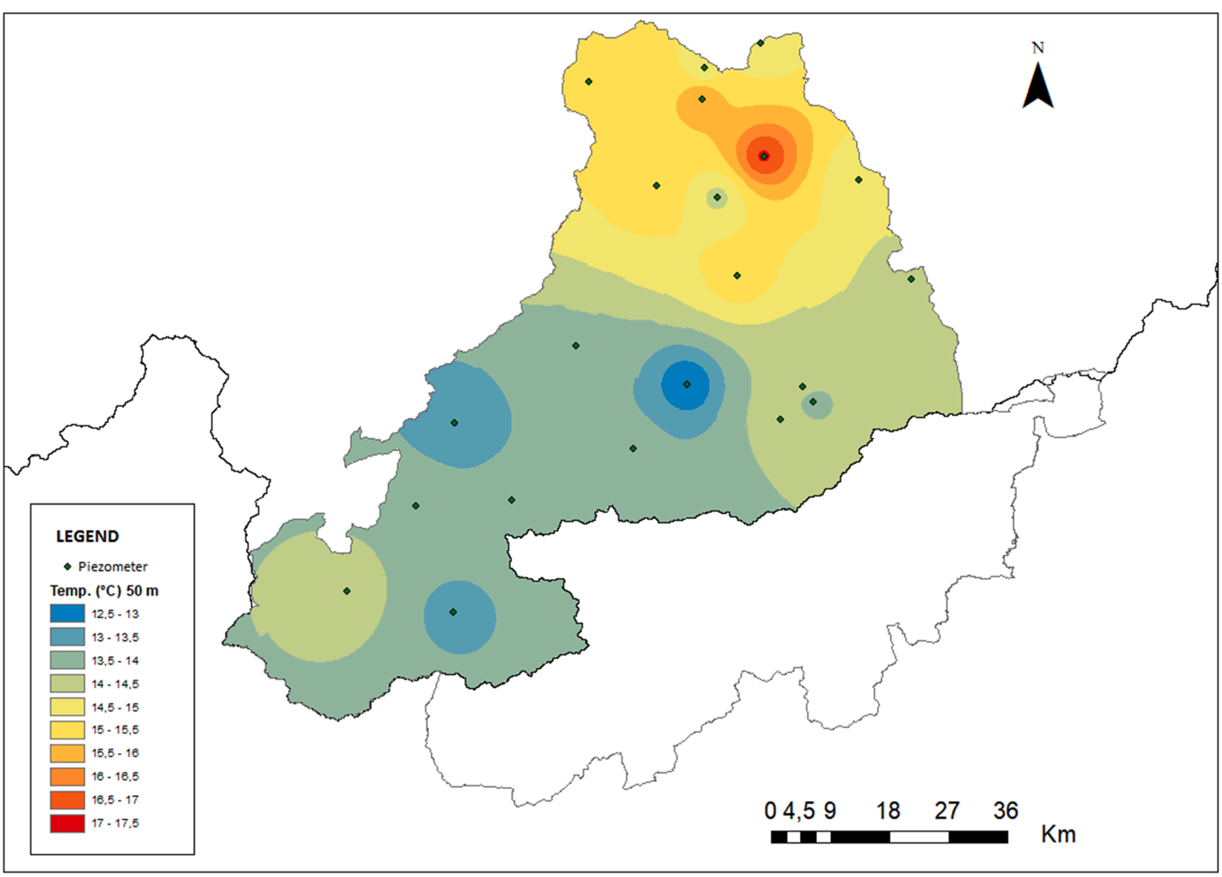

Fig. 7. Temperature distribution in the ground at a depth of 50 m, (Mean error = 0.09; Root-mean-square (m) = 1.28; R^2 = 0.89).

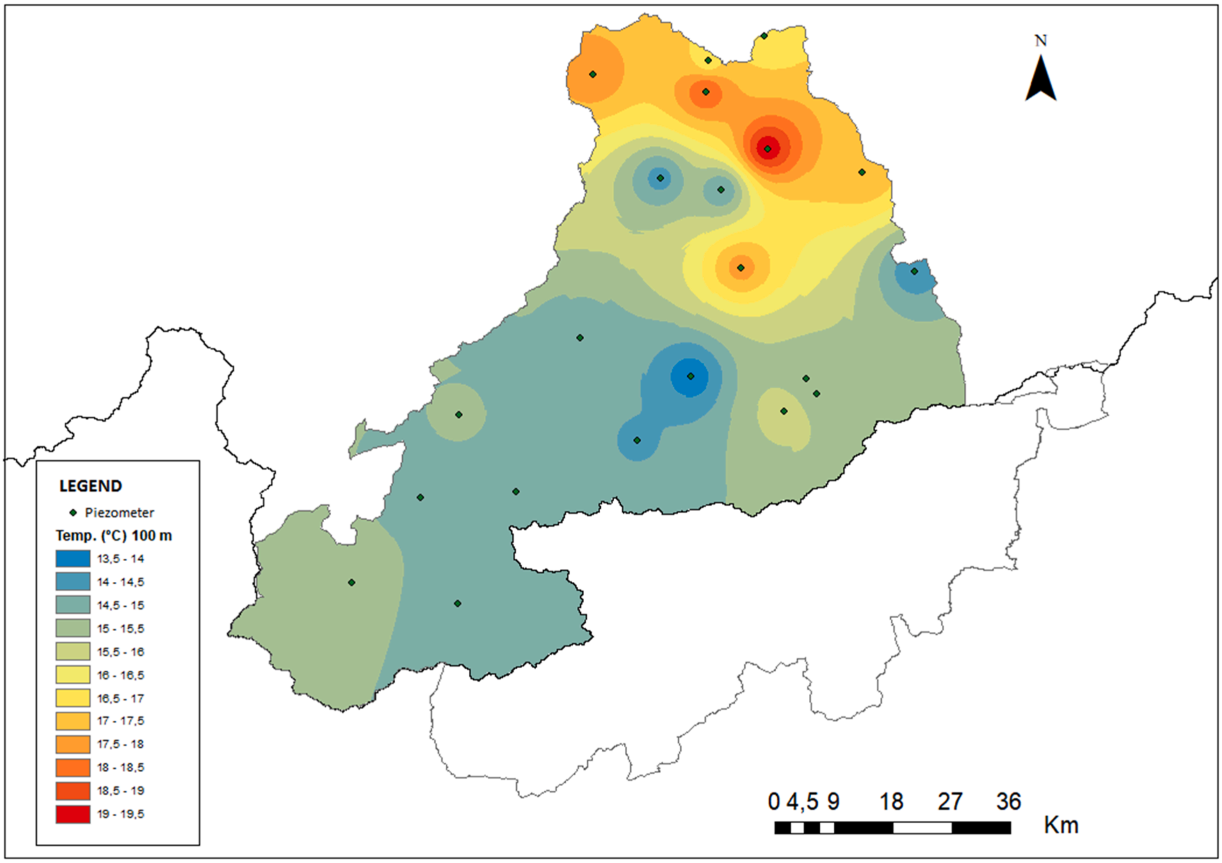

Fig. 8. Temperature distribution in the ground at a depth of 100 m, (Mean error = 0.08; Root-mean-square (m) = 1.25; R^2 = 0.89).

different piezometers were selected to perform the experimental thermal register. This selection was made in order to cover as much area as possible and discarding the shortest boreholes where others deeper were nearby. Table 1 presents the information relative to each of the piezometers, and Fig. 4 graphically shows their location within the area covered by the CHD.

As can be observed in the previous Table 1, the depth of some of the selected piezometers is quite limited (below 100 m); however it is interesting to include them in the evaluation in order to get an idea of the thermal evolution of the subsoil to the greatest extent possible.

Regarding the temperature registers, they were performed at several depths in each of the previously selected piezometers. The first temperature record was carried out at a depth of 50 m and, from this depth; measurements were made at different levels, according to the depth of each borehole. The following Fig. 5 shows different captures during the experimental fieldwork in the CHD.

2.3.2. Temperature register at the control stations of the CHT

As for the area of the province of Ávila outside the limits of the CHD, it is covered by the Tajo Hydrographic Confederation (CHT). However, since this organization lacks underground control piezometers in the province of Ávila, only temperatures records in natural springs can be considered in this study.

From all the available thermal registers of the CHT and, with the aim of ensuring an exhaustive analysis, only the temperature records corresponding to the same period of time (winter months of January - February) were taken into account in this research. In Table 2 and Fig. 6 it is possible to consult the location of each of the natural springs for which historic thermal records are available.

Despite the impossibility of performing the thermal register of the ground in depth, the temperature of the natural springs also constitutes a source of information to locate possible thermal anomalies coming from exceptional phenomena in depth. For this reason and given the lack of piezometers in this area of the region, the thermal information of the mentioned natural springs will be also valuable for establishing the conclusions of this research.

3. Results

3.1. Thermal characterization in depth

The in-depth thermal information obtained from the experimental phase is essential for the analysis pursued in this research. As mentioned in the previous sections, the piezometer network of the CHD constitutes the principal source for knowing the temperature of the subsoil. The variation in the depth of the piezometers made it necessary to perform the thermal registers at different spatial horizons from 50 m to 500 m (considering the deepest boreholes). The first level here considered (50 m) includes the records of all the piezometers, since they all are deeper than 50 m (see Table 1). However, as the depth of the thermal register increases, the measuring at certain levels of depth was not possible in all the selected boreholes (those shallower than the depth considered). In this way, the number of in situ registers gradually decreases as the spatial horizon moves deeply. Due to this fact, results of the

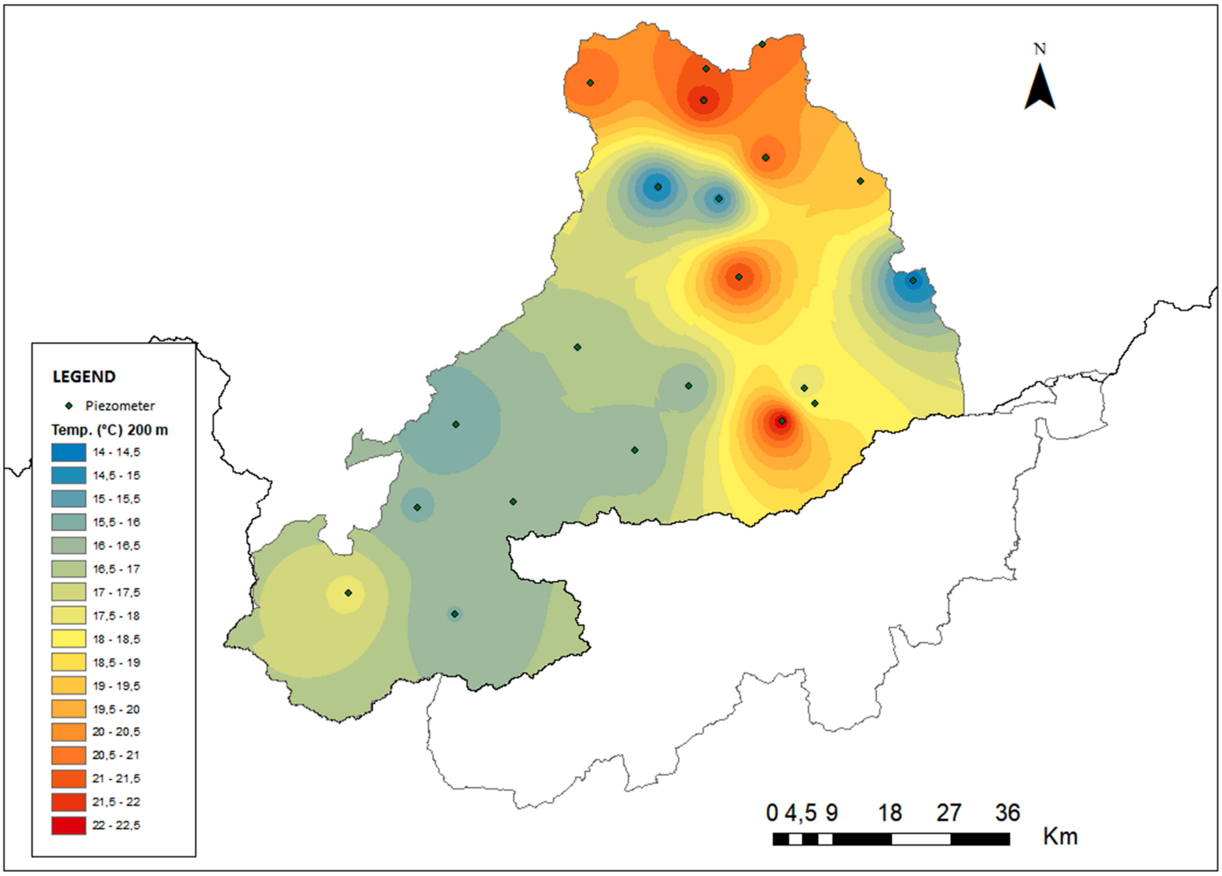

Fig. 9. Temperature distribution in the ground at a depth of 200 m, (Mean error = 0.08; Root-mean-square (m) = 1.29; R^2 = 0.89).

experimental thermal measurements in each of the piezometers were extrapolated in those levels for which registers were not possible to obtain. Table 3 presents the temperatures obtained (from the registers in the field and from the extrapolation analysis) for all the selected piezometers in each depth.

In order to obtain the previous values (Table 3) in the form of continuous areas and to forecast the unknown information (in those piezometers in which the depth does not allow to measure at all the levels studied) with the data from the available registers, temperature values were interpolated to graphically visualize the thermal distribution at each spatial level. The simple Kriging method included in the Geostatistics software package in ArcGIS (version 10.5) was used to obtain the mentioned mapping. This geostatic interpolation has been implemented in similar works, proving to be a precise and robust technique for estimating values at unknown locations from sampled data (Panday et al., 2018). The method can provide the best unbiased linear information about the distribution of the estimation error and clearly presents significant statistical advantages (Xiao et al., 2016). Based on the application of the described technique, the following Figures (Figs. 7-12) show the aforementioned ground thermal conditions at the spatial horizons of 50 m, 100 m, 200 m, 300 m, 400 m and 500 m.

3.2. *Surface thermal characterization*

In line with the explained above, the lack of piezometers in the area of the province corresponding to the CHT obliges to consider only the thermal registers of emerging waters as an indicator of the subsoil temperature. Despite this fact, surface thermal characterization is also valuable as starting point when deeper registers are not available. Data of the temperature registers of the surface control stations are presented in Table 4, as well as the ambient temperature on the measuring date in each station. It must be mentioned that registers from the CHT were performed during different seasons and years, however, only those corresponding to the same period and in the same external conditions (ambient temperature is in all cases in the interval 8.50–9.00 °C), are included in Table 4 and considered in this research.

In the same way, the previously described simple Kriging method (Geostatistics software package in ArcGIS (version 10.5) was used to get a global perspective of the ground thermal evolution. This surface ground thermal distribution is shown in Fig. 13.

4. Discussion

4.1. *Potential geothermal findings*

This contribution aims to predict the geothermal potential associated with the geological environmental of the Spanish region of Ávila. The

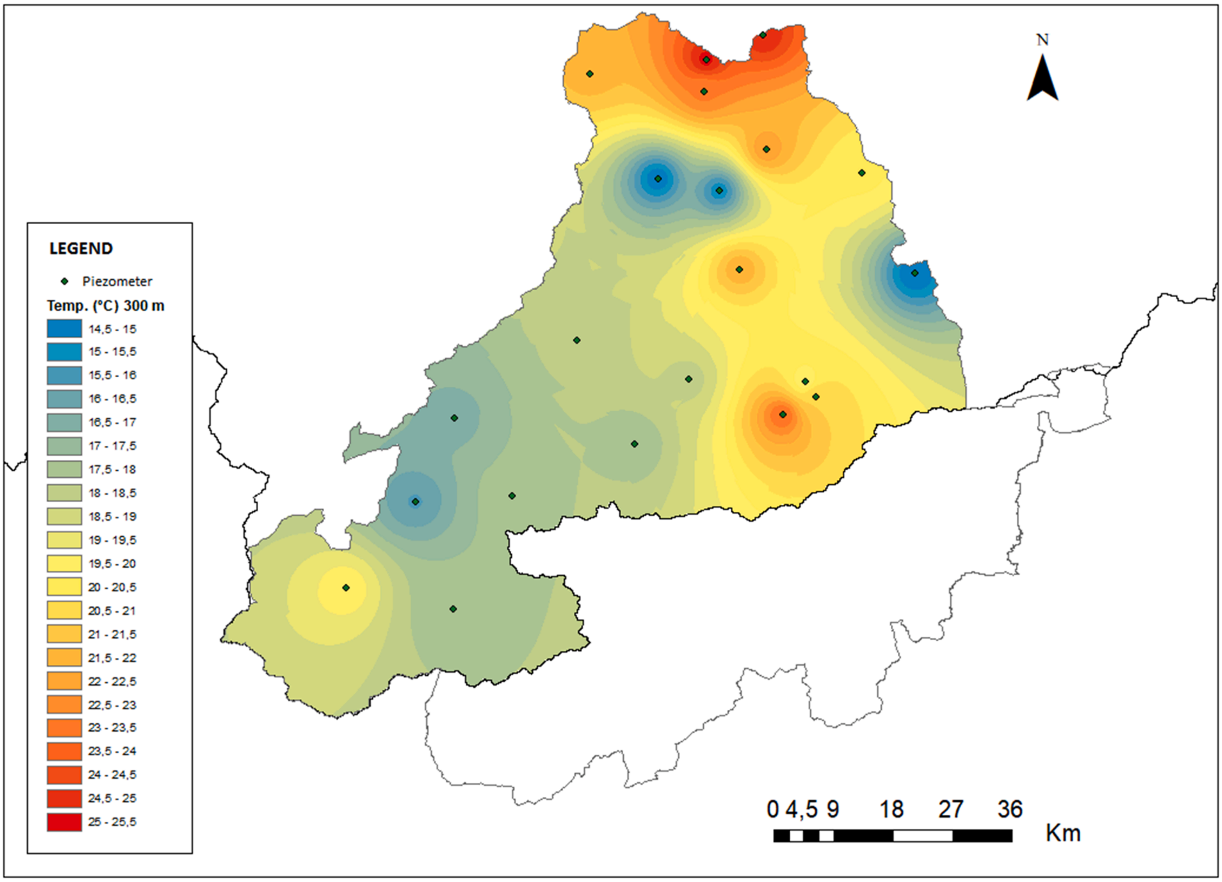

Fig. 10. Temperature distribution in the ground at a depth of 300 m, (Mean error = 0.07; Root-mean-square (m) = 1.22; R^2 = 0.89).

study is based on in situ temperature registers and geological interpretations that have allowed the development of thermal profiles at different depths. Since data are limited (due to the lack of piezometers throughout the entire study area), temperature models have predictive character in some parts of the region mapping. Once analysed the thermal trends reflected in the maps of Figs. 7-13, some important statements can be pointed out. The principal geothermal evidence is found within two defined groups:

The first area, where the greatest thermal anomalies have been recorded, corresponds to the northernmost area of the province, in the region known as "La Moraña". As explained in the geological description section, this site is in a sedimentary environment with numerous aquifer formations, in which thermal anomalies could derive from the contact in deep of these formations with the bedrock. According to the interpretation of the results of this study, the large amount of thermal energy contained in the circulating waters of these aquifers could be used as geothermal resource of medium enthalpy (at the level studied). But it could also constitute a source of greater enthalpy at a higher depth (closer to the contact with the bedrock). This sedimentary environment of the north-central area of the region seems to show some geothermal activity in different wells located in the northern part of the area. In the following Fig. 14 it can be seen to which units the most thermally active wells correspond.

In the mentioned Fig. 14, it is possible to observe the three piezometers with an anomalous temperature gradient found in this thermal prospection. They all belong to aquifer units formed by arkosic sands with some clay content; both permeability and production are in a medium range there. It is worth highlighting the positions of these boreholes, near contacts with other units of different composition. On the one hand, piezometer PZ0247041 is in contact with a very permeable and very productive sandy aquifer, while piezometers PZ0247047 and PZ0247057 are very close to contact with a clay unit that is practically impermeable or with very low permeability and production. All this, together with certain hydrothermal manifestations in the area (Nieto et al., 2020), indicates the possibility of a thermal anomaly in the bedrock underlying the sedimentary structures.

The second area is preliminary deduced, from the records performed on the CHD piezometers, in the area of the Amblés valley pit closest to the city of Ávila (PC0264003). In addition, the evidence of upwelling waters obtained from the measurements of the CHT, allows verifying the thermal increase as the elevation of the upwelling decreases. Therefore, it is observed that the areas closest to the granite nucleus present an abnormally high temperature compared to their surroundings. This fact, together with other evidence collected in previous studies (structures of fracture families, radon emissions, etc.) seems to indicate the presence of an area with significant thermal activity in the direction of the nucleus of the granite mass. In addition, the results of this work seem to agree with other evidence present in the area. For example, the moderate concentrations of radon measured on the surface in some detection campaigns carried out by public health organizations in the region. It is known that

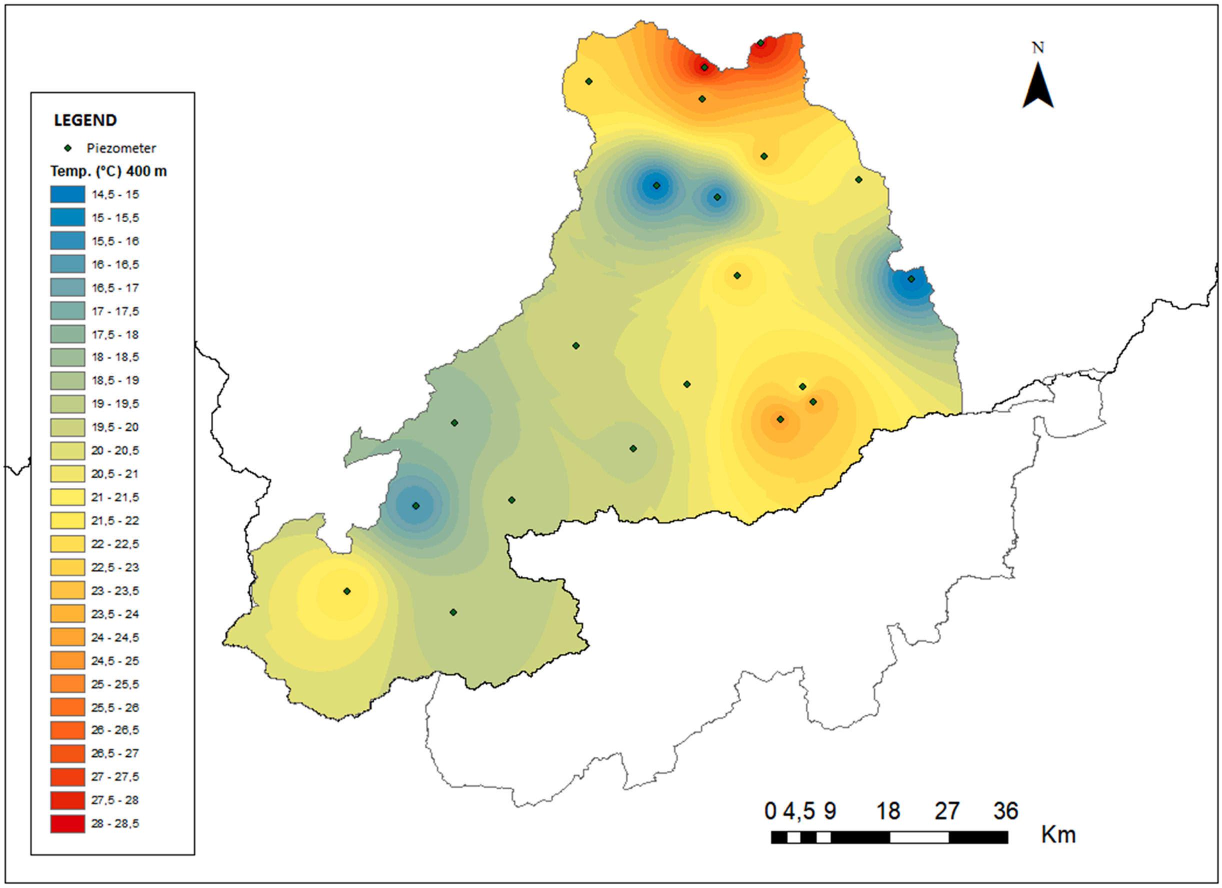

Fig. 11. Temperature distribution in the ground at a depth of 400 m, (Mean error = 0.09; Root-mean-square (m) = 1.26; R^2 = 0.89).

the presence of radon on the surface may indicate the existence in depth of thermally active faults that can be exploited as a geothermal resource (Whitehead, 1984). As mentioned in section 4, here a certain thermal activity could be evidenced in the rock core, considering account the proximity to this of the points where the anomalies are found (Figs. 12 and 13). Furthermore, it is possible that the thermal anomaly indicated in Fig. 13 also corresponds to an area of greater fracturing of the granite massif (33).

In view of a possible geothermal HDR use and taking into account the growth stage of the current drilling and hydraulic fracturing techniques, the southern area of the province of Ávila could constitute a promising enclave for the establishment of high enthalpy geothermal development. However, it is important to clarify that deeper research is required for establishing the real potential of these locations, that is to say, registers at greater depth (greater than 500 m) are necessary to define considerable temperatures at feasible levels both from the technical and the economic points of view.

Furthermore, it should be also noted that in the area with the greatest thermal anomaly (northern sedimentary side of the province), the implementation of HDR systems could be limited due to the need for deep drilling, which is difficult in a predominantly sedimentary environment. However, the circulating water masses in this area could be capable of providing a constant energy flow to be successfully used for the agronomic industry of the district. But again, these high enthalpy uses cannot be properly ensured with the information of this research. However, within the field of low and medium geothermal uses, is sector could benefit from a highly efficient heating system for animal production and other derived processes. It would therefore be used as low-medium enthalpy geothermal resource for thermal purposes, perfectly adapted to the economic activities of the area.

4.2. Interactive visualization tool

The final contribution of this paper is to present an open-source module for visualizing the geothermal findings derived from the results of this work. With simple commands under a user-friendly platform, any of the scenarios evaluated in the research can be easily consulted. For this, the ArcGIS Online infrastructure was used for the storage and analysis by the user of the resources developed in the present work. The tool, available at a public link (https://arcg.is/iW01O), incorporates the limits of each Hydrographic Confederation in the province and the exact location (UTM coordinates and depth of the wells) of the points in which the thermal registers were performed. The principal window of the tool can be observed in the following Fig. 15. As can be observed in this Fig. 15, when selecting a certain piezometer, the complete information of the register at the different depths considered in the study, is shown.

Beyond the general information of the measurement points, the user

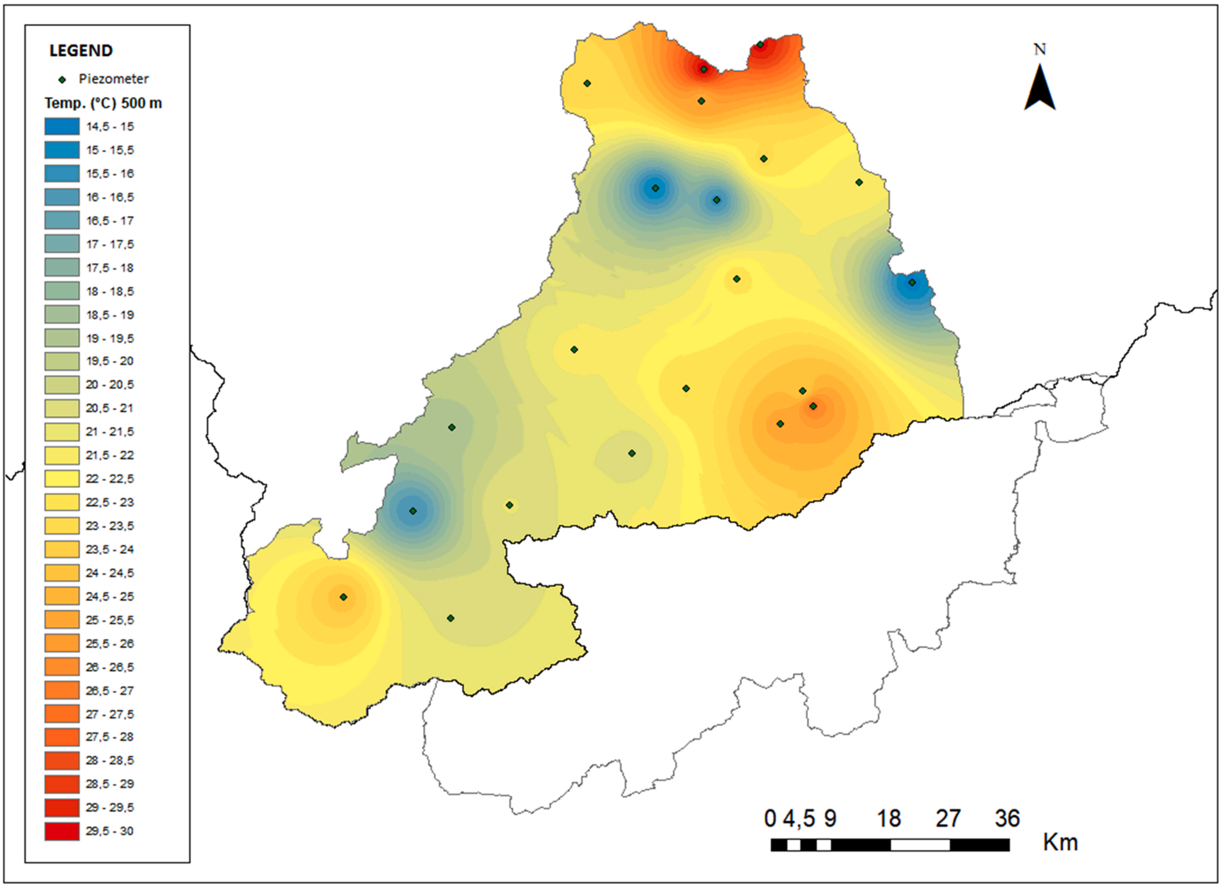

Fig. 12. Temperature distribution in the ground at a depth of 500 m, (Mean error = 0.08; Root-mean-square (m) = 1.27; R^2 = 0.89).

Table 4
Registers of temperature in each of the stations of the CHT in the province of Ávila.

Station code	Register date (day/month/year)	Temperature	
(°C)	Ambient temperature (°C)		
1027	06/02/2017	6.70	8.50
1034	25/01/2017	10.90	8.50
1044	06/02/2017	7.50	9.10
1088	25/01/2017	10.40	8.60
1094	06/02/2017	9.80	9.00
1095	25/01/2017	11.80	8.70
1099	25/01/2017	10.40	8.50
1108	25/01/2017	11.40	8.80
1109	25/01/2017	11.90	8.60
FM14	25/01/2017	9.60	8.50

can also consult (by activating the layer of interest) the temperature maps at each of the studied levels for both regions of the province (CHD and CHT). As an example, some of the possible visualizations are shown in Fig. 16.

5. Conclusions

The technical and economic feasibility of exploiting geothermal systems strongly depends on the site conditions (geology of the ground) and the existence of anomalous thermal activity in depth. The possibility of inferring indications of geothermal activity by means of temperature measurements in sufficiently deep wells can be a complement to other types of studies on indications of thermal activity in an area. The analysis of the temperature measurements obtained together with the geological characterization of the study area constitutes a first estimation about how promising future research in the area may be. The present study shows a possibility of prospecting for geothermal resources by zonal comparison of temperatures that can serve as the beginning of more detailed prospecting of promising areas at a reduced cost and with reasonable expectations of success.

Considering that there are two different areas in terms of their geological structure and therefore in terms of the nature of the possible geothermal resources available in them, separate conclusions for them seem mandatory. The first area, a sedimentary environment located in the north-central area of the region, seems to indicate the presence of potential low-medium enthalpy geothermal resources, that may constitute potential high enthalpy geothermal resources if temperatures at deeper levels followed a similar trend. The geological context of this area could however limit its use to global district heating applications since HDR systems may not be technically feasible. The second area, located in the central/southern area of the province, could constitute an excellent alternative for the exploitation of medium-high enthalpy geothermal resources through the implementation of HDR systems. The higher ground temperatures observed in the contact of the granite formations indicates that the possible geothermal activity in depth could be technically and economically used for the successful energy development of the region. However, as mentioned in the prevision discussion

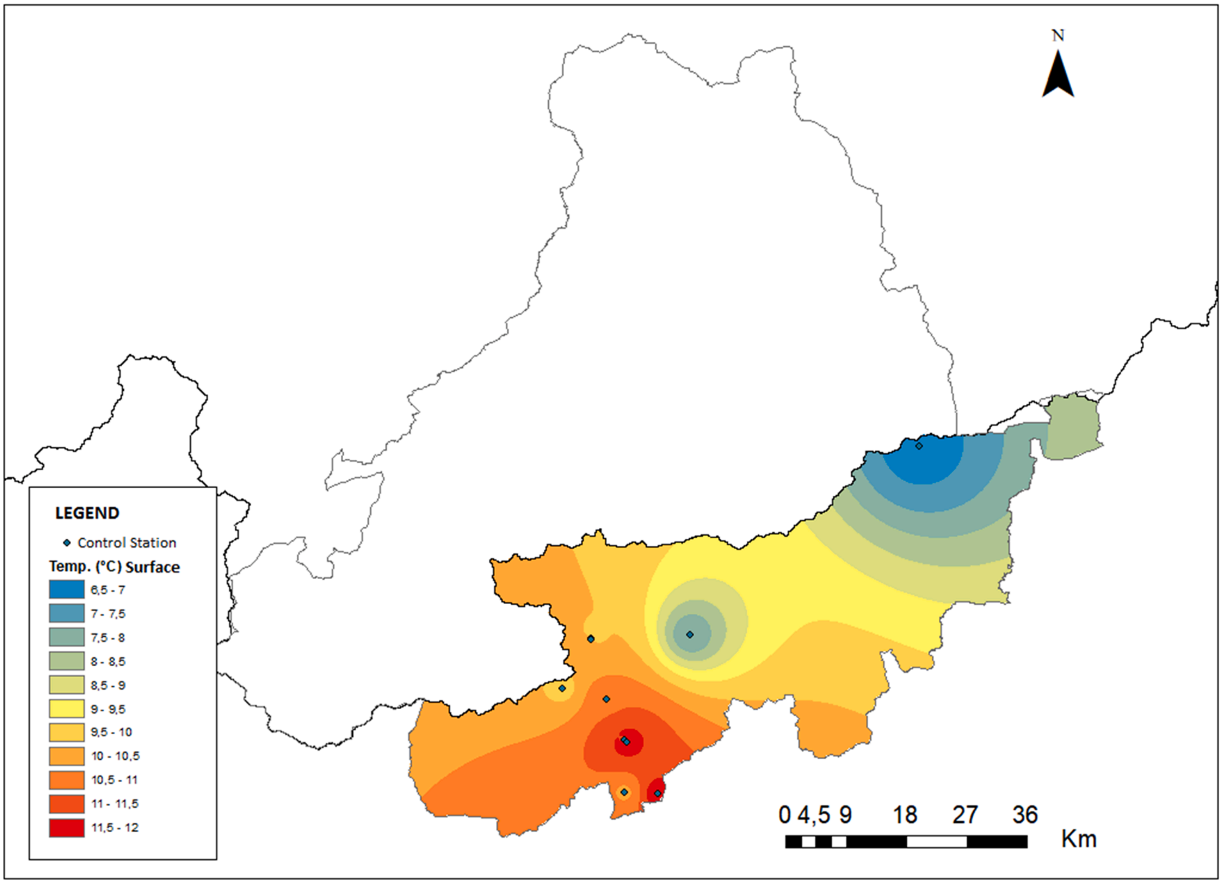

Fig. 13. Distribution of surface temperatures in the area included in the CHT, (Mean error = 0.11; Root-mean-square (m) = 1.33; R^2 = 0.85).

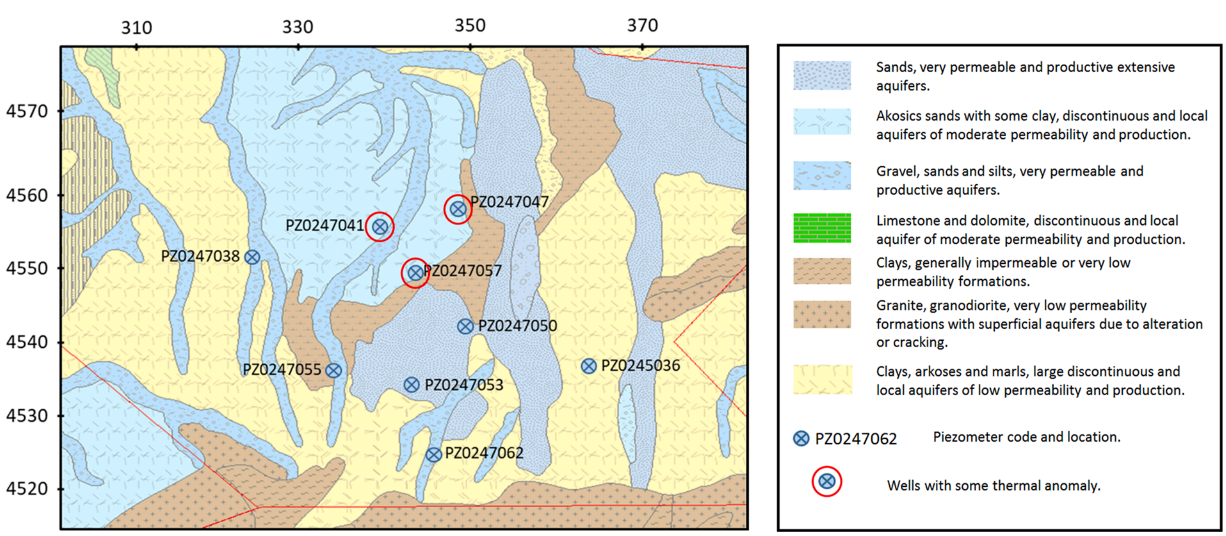

Fig. 14. Location of soundings in the aquifer structure of the área (PANER 17 June 2021).

section, with the information of this research it not possible to guarantee the feasibility of these high enthalpy uses, only to lay the foundations for future in-depth research in the region. Regarding, low enthalpy geothermal potential, this area of the studied region is highly recommended for establishing geothermal direct uses with great expected systems performance.

The present integrated experimental study has effectively brought out the geothermal possibilities of the province of Ávila and the results here presented will constitute a valuable starting point for future research and for the growth of the geothermal development in the region., IGME, 2021.

Declaration of Competing Interest

None.

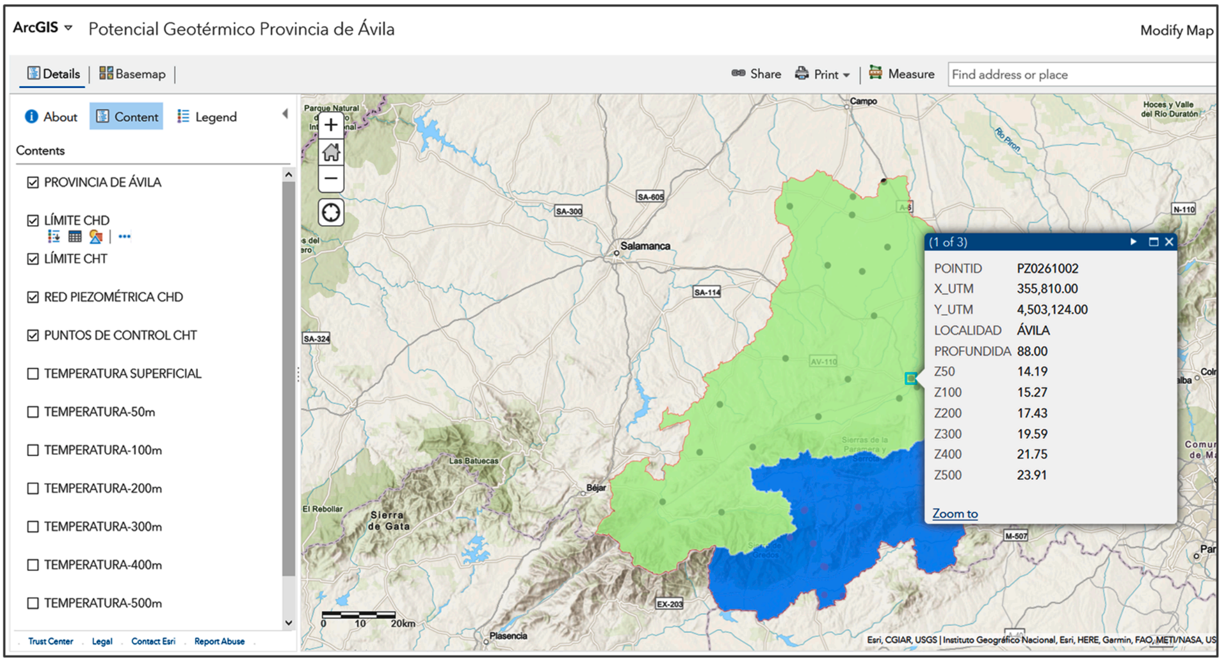

Fig. 15. Main window of the visualization tool developed from the experimental results of this work.

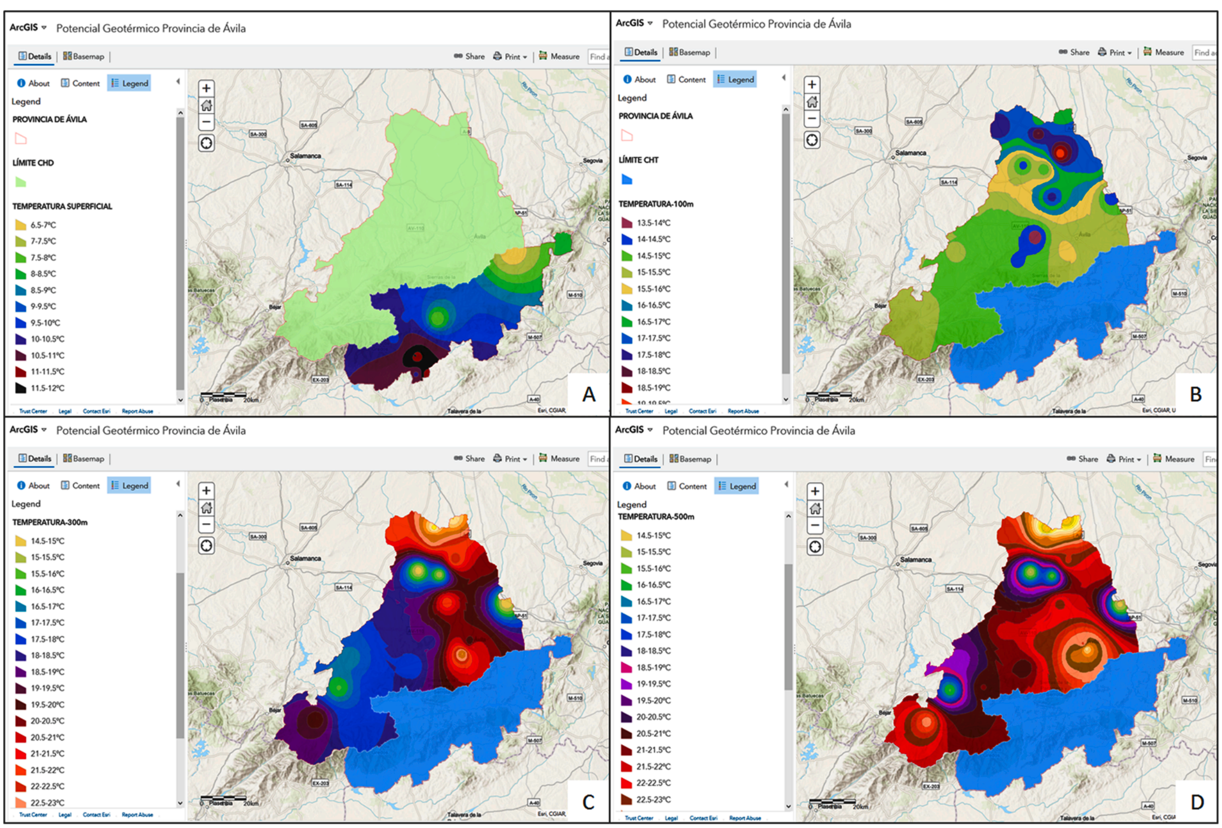

Fig. 16. Different possible visualizations of the ground temperatures at the depths analysed in the present research.

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References

Abdurafikov, R., Grahn, E., Kannari, L., Ypyä, J., Kaukonen, S., Heimonen, I., Paiho, S., 2017. An analysis of heating energy scenarios of a Finnish case district. Sustainable Cities and Society 32, 56–66.

Ahmadi, A., Assad, M.E.H., Jamali, D.H., Kumar, R., Li, Z.X., Salameh, T., Ehyaei, M.A., 2020. Applications of geothermal organic Rankine cycle for electricity production. J. Clean. Prod 122.950.

Asgari, E., Ehyaei, M.A., 2015. Exergy analysis and optimisation of a wind turbine using genetic and searching algorithms. Int. J. Exergy 16 (3), 293–314.

Blázquez, C.S., Martín, A.F., Nieto, I.M., García, P.C., Pérez, L.S.S., Aguilera, D.G., 2017. Thermal conductivity map of the Avila region (Spain) based on thermal conductivity measurements of different rock and soil samples. Geothermics 65, 60–71.

Blázquez, C.S., Nieto, I.M., Mora, R., Martín, A.F., González-Aguilera, D., 2020. GES-CAL: a new computer program for the design of closed-loop geothermal energy systems. Geothermics 87, 101852.

Colmenar-Santos, A., Folch-Calvo, M., Rosales-Asensio, E., Borge-Diez, D., 2016. The geothermal potential in Spain. Renewable Sustainable Energy Rev. 56, 865–886.

Coppo, N., Darnet, M., Harcouet-Menou, V., Wawrzyniak, P., Manzella, A., Bretaudeau, F., Girard, J.F., 2016. Characterization of deep geothermal energy resources in low enthalpy sedimentary basins in Belgium using electro-magnetic methods–CSEM and MT results. In European Geothermal Congress.

de España, M.G. (1992). IGME. RUIZ DE LA TORRE, J.

Dickson, M.H., & Fanelli, M. (2013). Geothermal energy: utilization and technology.

Downing, R.A., Gray, D.A., 1986. Geothermal resources of the United Kingdom. J. Geol. Soc. London 143 (3), 499–507.

Geological and Mining Institute of Spain (IGME), 1972–2003. Geological National Mapping (MAGNA). 2021.

Glassley, W.E., 2014. Geothermal energy: Renewable Energy and the Environment. CRC press.

Heidinger, P., 2010. Integral modeling and financial impact of the geothermal situation and power plant at Soultz-sous-Forêts. C.R. Geosci. 342 (7–8), 626–635.

Hicks, T.W., Pine, R.J., Willis-Richards, J., Xu, S., Jupe, A.J., & Rodrigues, N.E.V. (1996, July). A hydro-thermo-mechanical numerical model for HDR geothermal reservoir evaluation. In International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts (Vol. 33, No. 5, pp. 499-511). Pergamon.

International Panel on Climate Change (IPCC), 2007. Fourth Assessment Report: Climate Change 2007. International Panel On Climate Change. Cambridge University Press, Cambridge, UK.

López Ruiz, J., Aparicio, A., García Cacho, L, 1975. El Metamorfismo De La Sierra De Guadarrama. Sistema Central Español. Instituto Geológico y Minero de España.

Lund, J.W., Toth, A.N., 2020. Direct utilization of geothermal energy 2020 worldwide review. Geothermics, 101915.

Moon, H., Zarrouk, S.J., 2012. Efficiency of geothermal power plants: a worldwide review. New Zealand Geothermal Workshop, pp. 19–21.

Muñoz Martín, A., Olaiz Campos, A.J., Vicente Muñoz, G.D., Antón López, L., Elorza, F.J., Vicente, R.D., 2007. Análisis de la geometría en profundidad de fracturas conductoras en zonas de baja permeabilidad mediante tomografía eléctrica (El Berrocal. Sistema Central Español). Geogaceta 42, 35–38.

Nieto, I.M., Carrasco García, P., Sáez Blázquez, C., Farfán Martín, A., González-Aguilera, D., Carrasco García, J., 2020. Geophysical prospecting for geothermal resources in the south of the Duero Basin (Spain). Energies 13 (20), 5397.

Norden, B. (2011). Geothermal energy utilization in low-enthalpy sedimentary environments.

Olasolo, P., Juárez, M.C., Morales, M.P., Liarte, I.A., 2016. Enhanced geothermal systems (EGS): a review. Renewable Sustainable Energy Rev. 56, 133–144.

Pérez Menzel, N, 2000. Presente y Futuro Del Termalismo Español y Europeo. López Geta. JA.

Panday, D., Maharjan, B., Chalise, D., Shrestha, R.K., Twanabasu, B., 2018. Digital soil mapping in the Bara district of Nepal using kriging tool in ArcGIS. PLoS ONE 13 (10), e0206350.

Mapa Hidrogeológico de España a escala 1:100.000. (Hoja 37), 17 June 2021. Aguas Minerales y Termales de España; IGME, Instituto Geológico y Minero de España, Madrid, Spain. Available onlinehttps://info.igme.es/cartografiadigital/geologica/mapa.aspx?parent=../tematica/tematicossingulares.aspx&Id=19accessed on.

PANER, 2010. Plan De Acción Nacional De Energías Renovables De España (2011–2020). Spanish Department of Industry. Tourism and Commerce, Madrid.

Sáez Blázquez, C., Farfan Martin, A., Nieto, I.M., González-Aguilera, D., 2018. Economic and environmental analysis of different district heating systems aided by geothermal energy. Energies 11 (5), 1265.

Sanchez-Guzman, J., de la Noceda-Marquez, C.G., 2005. Geothermal energy development in Spain–country update report. In: Proceedings.

Templeton, J.D., Ghoreishi-Madiseh, S.A., Hassani, F., Al-Khawaja, M.J., 2014. Abandoned petroleum wells as sustainable sources of geothermal energy. Energy 70, 366–373.

Vera, J.A. (Ed.). (2004). Geología de España. Igme.

Whitehead, N.E., 1984. Geothermal prospecting by ground radon measurements. J. Volcanol. Geotherm. Res. 20 (3–4), 213–229.

Xiao, Y., Gu, X., Yin, S., Shao, J., Cui, Y., Zhang, Q., Niu, Y., 2016. Geostatistical interpolation model selection based on ArcGIS and spatio-temporal variability analysis of groundwater level in piedmont plains, northwest. China. SpringerPlus 5 (1), 1–15.

Yildirim, D., Ozgener, L., 2012. Thermodynamics and exergoeconomic analysis of geothermal power plants. Renewable Sustainable Energy Rev. 16 (8), 6438–6454.