Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Geothermal Anomaly Identified Under a Dense Urban Area in the Metropolitan Region of Barcelona, Spain

Enric Vázquez-Suñé, Miguel A. Marazuela, Rotman Criollo, Marc Diviu, Leia Mayer-Anhalt; Laura Scheiber and Joan Botey

C/ Jordi Girona 18, 08034, Barcelona, Spain. (IDÆA-CSIC)

enric.vazquez@idaea.csic.es

Keywords: Geothermal anomaly, Urban area, hydrogeology, flow and heat modelling, Barcelona

ABSTRACT

During the drilling of the Barcelona Metro L9 line, at the Fondo station of Santa Coloma de Gramanet (Barcelona) a geothermal anomaly was detected, in which groundwater temperature was found to be up to 55°C. This anomaly was attributed to a rise of deep groundwater through some tectonic structures, in a similar way to other geothermal zones of Catalonia (Spain). This geothermal area is located under a dense urban area where the information of its hydrogeological and geothermal features is limited. Due to the economic benefits of geothermal energy to society, studying and understanding the dynamics of the geothermal system, as well as, assessing its potential for future exploitation of the resource in this dense urban area, are of great interest. In order to study the feasibility of a future energy exploitation of the geothermal resource, a study is being undertaken at local and regional scale. In the regional study, whose first results are presented in this work, the objective is to understand the hydrothermal operation of the system. To achieve this, different works have been performed as are: geological review, borehole drilling, petrology, borehole logging, hydrochemical and isotopic assessment, thermography images, etc. This information has been integrated in numerical models of flow and heat transport.

1. INTRODUCTION

Santa Coloma de Gramenet, a municipality in Catalonia, Spain, is a very density populated city of 120,000 inhabitants and a dynamic commercial sector. This municipality is included in the Barcelona Metropolitan Area. During the civil works for one of the tunnels of the metro (L9 line) a source of hot water (50ºC) was found in the locality named Fondo.

Hot water was detected in some perforations and boreholes while the metro line L9 Fondo station was being built in 2004. Subsequently, during the construction of the L9 Tunnel, hot groundwater was also found to pass through this zone. This hot groundwater (thermal anomaly) was detected at 60-50 m below ground level, approximately. Water temperature was between 35 and 50 °C, depending on the point measured. It can be attributed to the deep water rise by a tectonic accident, which may be an analogous to other Catalan thermal deposits (ICGC and GHS, 2010). In this case, the subsoil is characterized by a top layer of quaternary sediments (15-20 m thick) deposited on fractured granodiorite materials. The granodiorite materials have a decreasing weathering with depth, inside which there are interspersed dikes of porphyry. Blocks of granodiorite materials developed by families of fractures are conductive pathways of groundwater because of the very low permeability of unaltered granodiorite. This system presents a great heterogeneity, which translates into very different productivity in perforations made at a short distances from each other.

The Municipality decided to explore further potential uses of this source. Due to the economic benefits of geothermal energy to society, studying and understanding the dynamics of the geothermal system developed in the surroundings of Santa Coloma de Gramanet is of a great interest, as well as, assessing its potential for future sustainable exploitation of the resource. The Santa Coloma de Gramenet Council is supervising the required actions to carry out the study to evaluate the possibilities of exploitation of hot water springs, in the area of the L9 Fondo station (Ajunt. Santa Coloma de Gramenet, 2019).

In order to study the feasibility of a future energy exploitation of the geothermal resource, a study is being undertaken. The objectives are to understand the hydrothermal behaviour of the system at local and regional scale and to be able to justify the geothermal anomaly identified. To achieve these objectives, different works has been performed: geological review, borehole drilling, geophysics, petrology, hydrochemical and isotopic assessments, thermography images, etc. This information has been integrated in numerical models of flow and heat transport. This paper constitutes a preliminary summary of the results of this ongoing study.

2. COMPILATION AND INTEGRATION OF ALL EXISTING DATA RELATED TO PREVIOUS WORK, GEOLOGICAL AND GEOTHERMAL CHARACTERIZATION.

2.1 Previous Works in the study area

The first contribution of the thermal anomaly in Fondo area was made by Paymacotas (2002, 2003 and 2004) during the execution of works on line 9 of the Barcelona metro". These reports explained the detection of water at 37ºC during the execution of pumping tests. Some of the works included in these reports were carried out by the Polytechnic University of Catalonia (GHS, 2004). After 2004, the Santa Coloma City Council requested the Catalan Water Agency (ACA) to study the feasibility of exploiting the Fondo geothermal anomaly (dated 07/01/2004 and registered in the ACA on 07/05/2004). The ACA final report (ACA, 2005) concluded that in the event that the Santa Coloma City Council want to take advantage of the hydrothermal source from the subsoil of the Fondo station, it would be necessary to undertake several studies of hydrogeological and geothermal characterization in the area.

During the period 2004-2013, several scientific studies and articles were performed related with the construction of metro tunnels in Fondo surrounding area (Martí et al., 2008; Font-Capó et al., 2011 and 2012), which have been significant in understanding the geological and hydrogeological context of the study area. Additionally, there is also a set of studies on geothermal potential at the regional level (ICGC, 2012; BR and GHS, 2006; Buen-Dapena, 2009; ICGC and GHS-IDAEA, 2010; AMB et al., 2013) from which various PhD thesis and articles have been derived (Font-Capo, 2012; Garcia-Gil, 2015; Alcaraz, 2016; Garcia-Gil et al., 2016; Alcaraz et al, 2016a and 2016b; Vázquez-Suñé et al., 2016).

Since 2014, City Council of Santa Coloma de Gramenet, in collaboration with the Besòs Consortium, has implemented the required actions to perform a study to evaluate the possibilities of exploitation of geothermal anomaly detected in the Santa Coloma de Gramenet, "Fondo" area. These studies have been commissioned by GHS (IDAEA-CSIC). Until now two phases of research have been done (GHS-IDAEA, 2015 and 2017) and a third phase is currently in progress.

2.2 Geological setting

The study area is located in the southern part of the Marina Range in Santa Coloma de Gramenet. Specifically, it is located in Fondo neighbourhood, and particularly in the surroundings of the station with the same name and the metro tunnels of the L1 and L9 lines. The district corresponds to District VI, limited to the north by the "Torrent d'en Grau" creek (which separates it from Badalona district), to the south by the Santa Rosa district, to the west by the Latin neighbourhood and, to the east by the ridge of the Serra de Sistrells mountain.

Geological information used (cartographic maps at 1: 50000 and 1:5000 scale) from the Spanish Geological Survey (IGME) and Catalan Geological Survey (ICGC) (IGME and ICGC, 1978, and ICGC, 2011). Drilled boreholes complemented the regional geological knowledge to define the geology used in the project of the L9 metro line (included stations such as Fondo). From the regional point of view, geological evolution begins with intense folding and deformation of the Palaeozoic sediments followed by the intrusion of a granitic batholith (phases of deformation Variscan orogeny). During the Mesozoic, deposition of Triassic facies occurred in a discordant manner on Palaeozoic materials. Subsequently, the Alpine orogeny affects the whole Palaeozoic and Mesozoic materials. The Palaeocene compressive stage developed directional faults, which were reactivated as normal faults during the Neogene distinctive stage. Thus, these basins were filled during Miocene and Pliocene in a context of a marine transgression. At the end of the Pliocene, the coastal plain emerge definitively and was subjected to strong erosion, which lead to a paleorelief, nowadays buried under quaternary sediments. During the first phase of quaternary sedimentation, the morphological structure of the Barcelona plan is generated, which is a gently sloping platform towards the sea, which corresponds to deposits of plain of lateral planation (Old Quaternary). Due to a climatic oscillation, water courses fitted in these deposits. Subsequently, the Miocene and Pliocene substrate emerged at some points. Finally, the establishment of sea level as we know it today, enabled the formation of the Besòs delta, generating a soft slope delta plateau (<1%), estimated in approximately 4,000 years before nowadays.

The study area is located on old Variscan plutonic rocks (270 Ma) of acid composition described as granodiorites intruded by phylonian rocks of porphyrical texture. The entire area has been affected by Variscan and Alpine Orogenesis, causing the presence of two preferential sets of perpendicular faults between each other (Figure 1).

This lithologic composition, alternating granodiorites and porphyries (Figure 1), has strongly conditioned the formation of relief due to differential erosion: the porphyries, which are more resistant, stand out in the relief, whereas the granodiorites, which are less resistant weathering, mainly by dissolving the feldspar, present an increasing weathered profile to the surface, giving rise to what is known as sauló (granodiorite more or less desegregated). At the bottom of the main creeks a superior layer, 15-20 m thick of clayey sediments of quaternary age is found.

A detailed geographical geological survey has also been performed at the regional level, through the study of aerial photographs and the necessary fieldwork.

From these works a more detailed geological map has been produced (Figure 2) that has allowed emphasizing that the extraordinary structural heterogeneity of the area of study is due to several factors:

- Very frequent faults of direction NNW-SSE, of different ages and generally reactivated in post-Miocene times. These faults shift the porphyry dikes with metric displacements. They are usually deep faults.
- Extensional Miocene faults, simultaneous to the formation of the basins and the sedimentation of the Miocene materials.
- Post-Miocene faults. This is usually the reactivation of the Variscan faults. In some cases (E-W faults) there are new faults, with fragile characteristics.
- Presence of granodiorites with numerous metric-shaped porphyries, sub-vertical position and NE-SW direction.
- Pre-Miocene weathering, causing part of the large "sauló" thickness. Upper part of the granodiorites is weathered but the porphyry dikes are resistant to weathering.

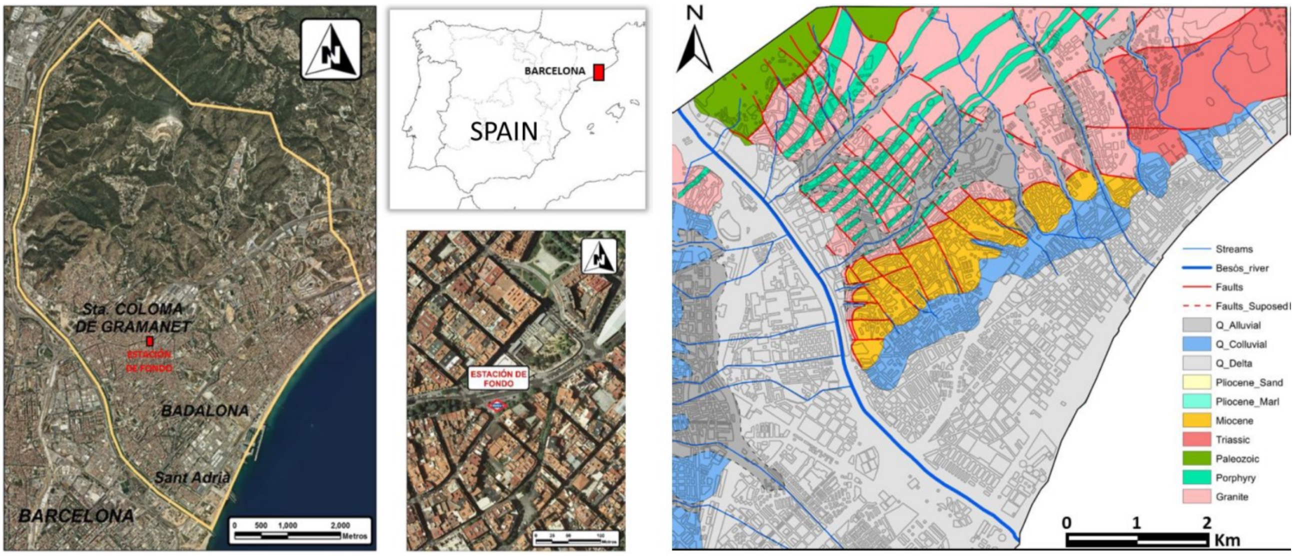

Figure 1.- Geographical and geological setting (Modified from Vázquez-Suñé et al., 2016).

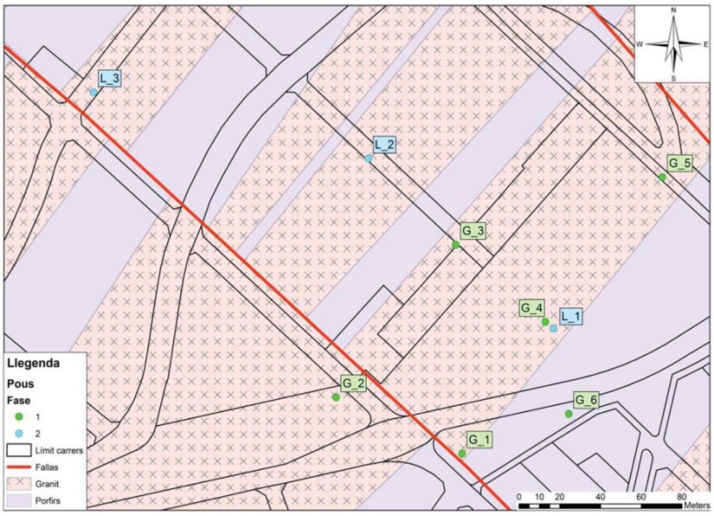

Figure 2. More detailed geological map and new boreholes location.

2.3 Geothermal setting

Some geothermal anomalies are known around Barcelona (Figure 3). On the one hand, the anomaly that motivates this work detected during the tunnel drilling works on the L9 line of Metro around the Fondo station, in Santa Coloma de Gramenet. There was no evidence of its existence until the drilling assessed under the metro project in 2002. The geothermal anomaly was attributed to the deep water rise in favour of a tectonic accident, similar to other Catalan thermal deposits. In this case, the subsoil is characterized by a top layer of quaternary sediments with 15-20 m in thickness. The layer was deposited on fractured granodiorite materials that have a decreasing weathering with depth, containing interspersed dams of porphyries. Granodiorite materials form blocks for the appearance of families of fractures that act as conductive pathways of groundwater is characterized by very low permeability. This system presents a great heterogeneity that translates into different productivities in perforations existed closely from one another. Thermal anomaly detected around the Fondo station and would be approximately 60-50 m deep, and groundwater temperature range between 40 and 55 ºC, depending on the point.

Other cases correspond to the presence of geothermal anomalies along the margins of the Vallès basin area, which manifest themselves on the surface as hot water springs (ICGC and GHS, 2010). These springs have been identified from time immemorial as a result of the Vallès-Penedès fault (NW basin) where there are Caldes de Montbui (70ºC), La Garriga (60ºC) and Samalús (80ºC) thermal spring sources. Opposite occurs in the SE margin of the Vallès basin, where hot water sources have been observed in the depth of Rubí S-11 borehole (55ºC) and also in the galleries of the Berta mine. Their identification have been recent and circumscribed to the so-called Geothermal Nucleus of Sant Cugat and in the neighborhoods of Rubí and El Papiol,

In the sector of the Vallès basin it is observed that the flow is conditioned by the recharge on the reliefs formed by Miocene and Palaeozoic lands. The discharge occurs to the bottom of the creeks, mainly towards alluvial quaternary materials and river courses. In areas where the flow lines are descending (more active recharge), the temperature values of waters tend to decrease, opposite to rising areas. Therefore, these zones of greater discharge have highest thermal gradients. Failures act as a barrier in the case of low permeability or as a preferred route in case they are high. The flow direction in the fault depends on where it is located in relation to the recharging or discharging areas. Thus, in case of permeable faults that are located in recharge areas, they will act as the input channel to surface water, which will produce a clear decrease in the thermal gradient. If the fault is located in the discharging areas, the behaviour is the opposite; the fault acts as a preferred path and makes the thermal gradient significantly more noticeable.

In the study of ICGC and GHS (2010), thermal profile data was collected in wells made in different field campaigns. It is worth to mention that temperatures above 50ºC, in all cases, are found at depths exceeding 130 m, which denotes a special importance in the current study in Santa Coloma, where similar temperatures can be found at 60 m deep.

In the study area, zones of entrance of significant water flow towards the drilling front occur mainly in the crossroads of geological structures that results in a low quality of the rocky massif. This is because the permeability of the massif is conditioned by fractures. The higher fracture index, the greater effective permeability is. Granodiorite weathered profile also has a high permeability. By joining these two factors, it is understood that in the zones of intersections of relevant geological structures most of the inlet groundwater flows occur in the excavation front of the tunnel.

These areas of higher temperature seem to be conditioned by the NNW-SSE direction fractures that correspond, as has already been said, to important tear fractures which allow the flow of deeper water.

Figure 3. Geothermal anomalies around Barcelona: 1.- Fondo, 2.- Papiol, 3.- Caldes de Montbui, 4.- La Garriga, 5.- Samalús, 6.- Caldetes.

3. STUDY OF THE CURRENT STATE OF GEOTHERMAL ANOMALY THROUGH A NEW RECOGNITION CAMPAIGN

3.1 Borehole drilling

Borehole drilling has been done in 2 phases: In phase 1 (2014), 6 boreholes (G wells) have been performed using the rotation drilling system, reaching a depth of 60 m. In phase 2 (2016) 3 boreholes (L wells) have been made reaching a depth of about 120 m. In all cases, it has been equipped with a PVC casing of 3" outer diameter. The well screen has an aperture (slot) of 1.5 mm. In the 60-meter boreholes (G Wells) the slotted sections have left the last 9 m, while in those of 120 m (L wells) they left the last 15 meters without any casing. The protective permanent casing was for avoid the mixing with the most polluted shallow waters recharged from the surface urban context.

These new holes (Figure 2) have been key to characterizing the hydrothermal anomaly and this has allowed understanding the hydrogeological and thermal system of the Fondo area. All of them have been equipped with pressure and temperature sensors to measure the variations of groundwater head and temperature and to observe the interactions between points during the execution of the different essays.

3.2 Geophysical logging

The geophysical logging allows knowing the structure of the subsoil and extrapolating it a little beyond the well where they are made. In particular, the well loggings made in this study are: sonic logs, gamma-ray, Borehole Televiewer (BHTV), Dipmeter and Caliper.

Natural gamma logging allowed the characterization of the different geological materials; establish the exact location of lithological changes and / or the detection of clayey layers. The most weathered areas, and therefore with a higher proportion of clay materials, show higher gamma. The main changes in materials have been identified (quaternary coating, weathered granodiorite and granodiorite.

From the structural analysis of the well logging data it can be concluded that: (1) the well L1 shows two sets of fractures, dipping to the southeast (majority) and the rest to the northwest, but both with an angle of about 60º; (2) the well L2 has fractures with a more heterogeneous dipping, although predominantly southwest. There are also two minority groups that run north-east and west-northwest. The dip angle, however, is again quite uniform: of about 70 degrees in this case; (3) In the well L3 an important fracture is identified at about 107 meters deep with a ditch 86º to the southeast (110º); (4) the stereographic projection allows a joint reading, where all the discontinuity sets described are identified but where the set that stands in the southeast with an angle of 60º and 70º stands out; and (5) all these structures fits with those determined in the detailed geological mapping.

3.3 Petrology

During the drilling of the new boreholes, formation samples were recovered in order to know the petrological composition of the subsoil. Specifically, a sample was taken every 10 meters in the lower half of each one of L wells (about 120 m deep).

A first visual inspection allows reconstructing the lithological profile of the wells in which three main zones are identified: (1) quaternary: silts and red clay of about 15-30 m thickness. The origin is colluvium material and soils; (2) weathered granodiorite: quartz and mica grains (Muscovite), mainly. They are desegregated materials formed by the physicochemical weathering of the granodiorite; and (3) granodiorite: its composition is typical of acid plutons, that is, mainly quartz, potassium feldspar (microcline) and sodium (albite), and phyllosilicates.

Beyond this first visual inspection, a X-ray diffraction analysis of samples was performed with the aim of identifying potential hydrothermal alterations in the mineralogical composition. Therefore, the main Minerals detected are: Quartz, Albite, Microcline, Muscovite, Clinoclor, Calcite, Fluorite, Gypsum, Laumontite. The first four minerals are the originals of the rock: quartz, albite, microcline and muscovite. The clinoclor comes from the weathering of another phyllosilicate: the biotite. The calcite, the fluorite and the gypsum come from the precipitations to the fractures by the circulation of groundwater. And, finally, laumontite corresponds to the precipitation of a mineral at high temperatures (120 - 200 ºC). All this is consistent with the hydrothermal context.

3.4 Borehole geothermal assessment

In these new wells, the temperature profiles have been monitored several times. These measures have been performed with iButtons® automatic temperature sensors and with a continuous SEBA® multi-parameter manual probe. In addition, the temperature was also monitored during the pumping test on the well L1, which shows a greater thermal potential.

In temperature well log corresponding L wells, the temperature stabilizes in depth, which confirms that faults or conductive fractures through which the thermal water rises or, at least, fractures that are connected. The maximum temperature is recorded in well L1, with 58°C (64ºC with a Mount Sopris® Temperature probe) (Figure 4).

This temperature (between 55 - 60ºC) agrees with that measured during the pumping test on the well L1, which confirms that this temperature is representative of the aquifer (or, at least, the area affected by the pumping).

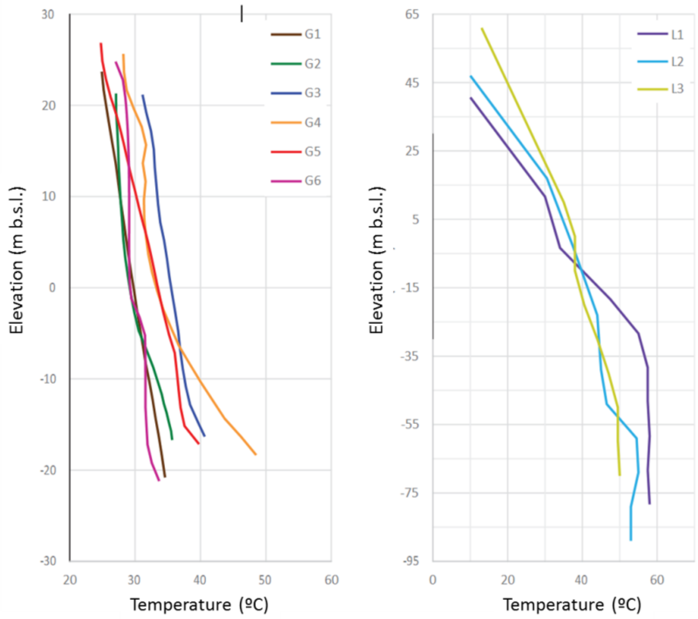

Figure 4. Temperature profiles in G wells (November 2014) and L wells (January 2017)

3.5 Thermographic images in the metro tunnels

Besides the area where the perforations have been made, the extent of the geothermal anomaly has been determined. For this purpose, a thermometric study has been performed inside the metro tunnels of the area. Thermography is a technique that allows measuring exact temperatures remotely and without having to be in contact with the object to study. By capturing the infrared radiation of the electromagnetic spectrum using thermographic cameras, the energy radiated can be converted into temperature information.

This study has consisted in making infrared photographs of the tunnels lining that measure the surface temperature of the image objects. Several zones have been detected where the temperature is much higher than the rest. During the construction of the L9 metro line by means of Tunnel Boring Machine, several hot water inputs were detected. These inputs have been correlated with the higher temperatures measured during the thermography of the tunnel (Figure 5). The result is that high temperatures are maintained over time. In addition, the temperature peaks are consistent with the new geologic interpretation, since all the peaks are located on the contacts between porphyries dykes and granodiorites (fractured zones) in SW-NE strike direction. This consistency confirms the hypothesis that the fracture zones are responsible for transporting this geothermal anomaly, and it is shown that these high temperatures have remained in time. During the field campaigns performed inside the tunnels, seepage has been observed that have reached 42°C (points A and B corresponding the hydrochemical sampling).

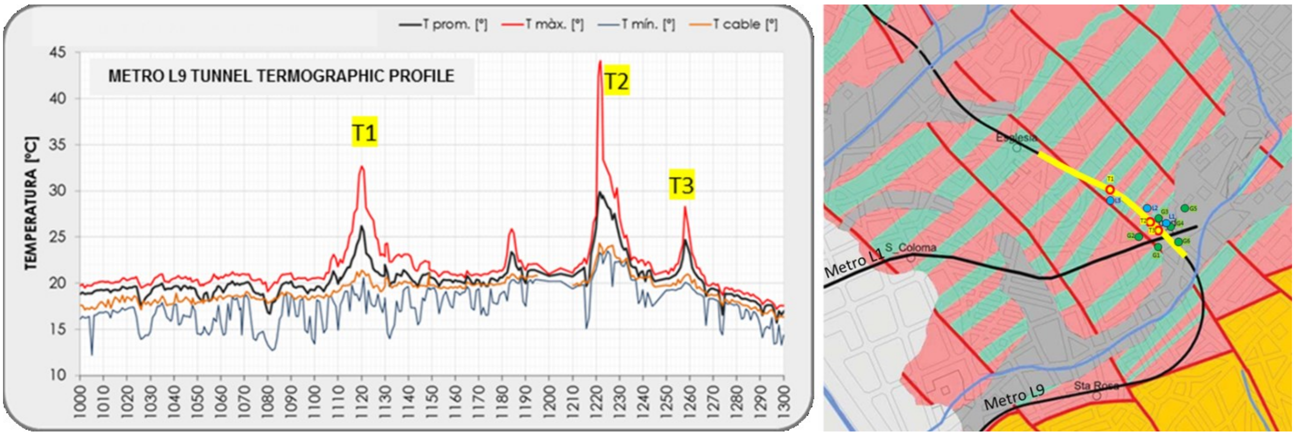

Figure 5. Left: Thermographic results obtained in each tunnel lining ring (ring number in X axis); Blak, red, blue and orange corresponds to average, maximum, minimum and wire temperatures in each lining rings respectively. Right: Map showing profile situation (yellow line) and hottest spots (red circles). Black lines correspond to Metro Tunnels (L1 and L9). For geological legend see Figure 1.

3.6 Hydrogeology

In order to understand the spatial distribution of the hydrothermal anomaly and its operation, it is necessary first to characterize the groundwater flow. Piezometric maps were performed and hydraulic parameters were estimated by pumping and injection tests. To carry out these tasks, pressure sensors were installed at all points together with the measures made during the field campaigns.

The piezometric study included the spatiotemporal monitoring of groundwater heads. The space analysis allowed extracting conclusions about the groundwater flow direction and the relationships or connections between wells. The temporal analysis allowed estimating the response of groundwater heads to certain perturbations, such as, perforations or pumping tests. As a consequence of the study area extension, two piezometric maps were performed, one of them at a regional scale and the other one at a local scale to improve the groundwater flow estimation near the hydrothermal anomaly.

The regional piezometric map of the study area was performed based on the data of groundwater heads measured in 32 points (14 piezometers, 13 wells, 2 springs and 2 mines) distributed across the entire area during the fieldwork carried out between March-April 2016 (Figure 6).

In the eastern zone, the groundwater flow showed a NNW-SSE direction and moves from the highest area of the Sierra de Marina to the coastal plain. In the higher zones, the topographic gradient is significantly more accused than in the coastal plain. This fact is reflected in the lower distance between contour lines that cover the higher zones. In the granodiorite massif, along approximately 1.5 km, the piezometric gradient descends from 320 to 100 meters above sea level (m a.s.l.). As the groundwater flow descends to the coastal plain, the gradient gradually becomes smoother, making the distances between the contour lines larger and, thus, giving rise to a flow with a much higher horizontal component. By contrast, in the coastal plain, the gradient decreases from 100 to 20 m a.s.l., considering the same distance. Finally, all this groundwater flows into the southern limit of the study area. In the westernmost part, it is observed that the groundwater flow follows an NNE-SSW direction. In this specific area, the water descends from the elevated gradients of the Sierra de la Marina to download in the western boundary of the study area, where is the Besós river that has an N-SSE direction. Here the piezometric gradient decreases 140 m a.s.l. in 1 km.

The local piezometric map (Figure 6) was obtained from the measurement and monitoring carried out by permanent sensors (pressure sensors) and manual measurements in the wells distributed in the study area. Remarkable facts of the piezometric maps are:

- The minimum piezometric heads due to the drainage of the Fondo station. Its magnitude is large enough to modify the groundwater flow in its closed surroundings and moves the groundwater to the drainage system of the metro station (Figure 6).
- The presence of vertical flows due to the drainage of the Fondo station. For this reason, two wells close to one another, such as G4 and L1 (distanced a few tens of centimetres), have a difference in the piezometric level of more than 5 m. The different depth of them allowed to observe and allows explaining this fact.
- The high hydraulic conductivity that shows the main fault of NW-SE direction, located near the Fondo station, on the southwestern side. This high conductivity modified the groundwater flow around it and is reflected in the piezometric contour lines.

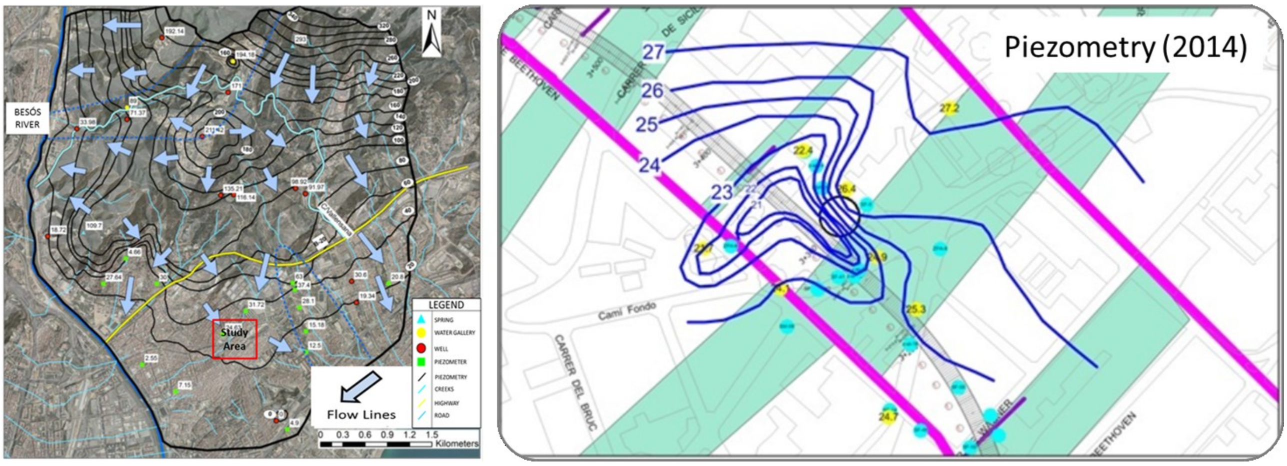

Figure 6. Left: Regional piezometric map (2016). Right: Study area piezometic map (2014)

Pressure and temperature sensors have been installed at the analysed points. In general, the piezometric surface does not show many temporary variations during the measured period, although the seepage to the metro structures affects all the points. Thus, it corresponds to a clearly stationary regime.

In order to quantify the hydraulic parameters of the ground materials in the Fondo station area (Santa Coloma de Gramenet), pumping tests were performed in the wells of phase 1 (G Wells). The study is complemented with the reinterpretation of ancient pumping test carried out during the works on line 9 in 2004.

The new L wells drilled in the study phase 2 are deeper than the G wells and allowed to extend the study of the hydraulic parameters in depth. Thus, the response of the G wells groundwater heads to the drillings and the pumping tests on the L wells was studied.

The effect of pumping in well L3 was analysed and heads drawdown in the observation wells (G2, G3 and G5 wells) was measured. The results obtained are summarized in the (Table 1). These results demonstrated the high heterogeneity of the area, due to the presence of numerous fractures and the alternation of highly differentiated geological materials. In this context, the G5 point stands out as the most transmissive, probably, due to the presence of some discontinuity of high permeability that connects both wells (L3 and G5 wells).

3.7 Hydrochemical and isotopic assessment

Hydrochemical analysis allows determining the chemical composition of water, the spatial and temporal distribution of the compounds analysed, studying the hydrochemical evolution of the aquifer, and identifying reactions and processes that take place in this system. Additionally, the isotopic analysis complements it, and allows determining the origin and traceability of groundwater. All this helps to define and propose a conceptual model of the hydraulic and hydrochemical functioning of the study area.

During the field campaign, the following parameters were measured in situ: pH; Electrical Conductivity, temperature, total alkalinity (TAC), total organic carbon (TOC) and dissolved (DOC). Samples have been collected for the analysis of: Br, Cl, NO3, NO2, PO4, SO4, F, Ca, Na, K, Mg and NH4; and minority elements and trace: Al, As, Cu, Fe, Mn, Ni, P, S, Yes, Sr, Zn, W and B. Stable isotopes: δ2H / δ18O of the water molecule.

The study of the chemical composition of the sampled waters evidences the presence of two clearly differentiated groups:

(1) calcium-magnesium bicarbonate water: they correspond to the samples of the shallowest piezometers (G wells). These are groundwater mixed with urban recharge water (a mixture of infiltrated water, water supply and wastewater). This is especially highlighted by the high concentrations especially of nitrates but also sulphates.

(2) sodium-chloride water: they correspond to samples from metro L9 tunnel seepage (less than 0.1 L/s) (points A and B). This second type of water corresponds to the samples of filtrations in the metro (points A and B). The concentrations of some elements such as fluorine or strontium reinforce their hydrothermal origin.

The groundwater of the new L wells are located halfway between them: L2 sample is very similar to the G wells, the L1 sample is very similar to the metro tunnel seepage (points A and B), and the L3 sample is in between L1 and L2.

The high concentrations of sodium and chlorine in metro tunnel seepages (points A and B) and well L1 suggest a certain degree of mixing with marine water, which is feasible due the geographic location near the sea (2.75 Km from the coast), its depth (below sea level) and the geology of the area. The analysis of deuterium and oxygen 18 isotopes of the water molecule reinforces this hypothesis.

The concentration of fluoride, bromide, boron or tungsten and its correlation with the concentration of chlorine is another factor that reinforces the idea that these samples correspond to a mixture of geothermal water with marine water.

3.8 Hydrochemical thermometry

Hydrochemical thermometry analysis of water samples support the estimation of the temperature of the reservoir, the origin of this water, and, therefore, what is the maximum temperature that could be found.

Results obtained using this methodology at the G4 well estimates the temperature in the reservoir of 49.5 - 54.71 ºC, while the temperatures estimated at well L1 range from 78.2 - 90.5 ºC. Notice that natures of waters sampled from G wells and metro tunnel seepage (points A and B) are notably different while L wells are in between of them. That is, L2 and L3 presents results closer to G wells and L1 to seepage in the L9 line tunnel. This means that the estimations of the temperature in the reservoir differ clearly: from 50 - 60 ºC (for G wells, L2 and L3) to 80 - 120 °C (well L1 and seepage points A and B).

In order to judge which waters present a chemical composition closer to the reservoir and, therefore, which waters allow estimating the temperature better, it is only possible to assess which modifications are more predictable in each case and, depending on their nature, which ones may have a greater or lesser effect. In this sense, waters of the G wells and the L2 and L3 wells present a chemical composition that clearly indicates the mixture with shallow water, as it is indicated by means of the hydrochemical assessment. Conversely, the wells themselves can connect different waters, even though protection measures (casing) were taken to try to avoid this pollution or, at least, reduce it.

Additionally, samples from seepage from the metro tunnel lining (points A and B) may have been modified their composition while the water cross the lining of the tunnel and interacting with the cement and the armour, although it should be a minor modification. At the same time, they may also present modifications due to the interaction of groundwater flow with the geological material, but this is a much more uncertain and difficult to estimate with the current information available in the zone. In any case, the chemical composition of these samples from seepage in metro tunnel (points A and B) fits with those of other Catalan thermal sources (ICGC and GHS, 2010).

Having these considerations in mind, the waters that seem more reliable to estimate the temperature in the reservoir are the waters of the metro seepage (points A and B) and the well L1. The temperatures of the reservoir obtained in them range from 90 to 120 ºC. According to this conclusion, it could be possible to obtain hotter water more in deep, either because other deeper or conductive faults or fractures are crossed.

3.9 Numerical modelling

For the numerical modelling, the commercial code FEFLOW® (Diersch, 2014) has been used. This code implements the law of Darcy in its totally dependent form of density and viscosity, by difference of concentration and temperature.

Different steady-state numerical models of flow and heat transport have been performed with constant density to date. For the modelling of fracturing planes 2D discrete features have been used. In these critical geometries, the mesh reaches a resolution of 10 m, with 2,650,000 total elements.

The hydraulic heads resulting from the steady-state flow model (Figure 7) show an important control of the topography in the groundwater flow (as it is deduced in the regional piezometry), as a consequence of a higher recharge in the mountains. In these areas, the flow is downwards while in the areas of lower elevation the predominant flow is upwards. The Mediterranean Sea, the River Besós and several creeks, are the main groundwater discharge areas.

In a typical framework, the velocity of the groundwater flow is slow enough to equilibrate in each depth with the temperature of regional geothermal gradient. However, the presence of fracturing planes can significantly increase the velocity in these planes. This causes the flow to be fast enough so that there is no time for the groundwater to equilibrate at each depth with the regional geothermal gradient, giving place to a geothermal anomaly.

The result of the heat transport model allows demonstrating this hypothesis. It is observed that in the recharge zones where the flow is downwards, the temperatures are lower than expected, according to the geothermal gradient, and that in the zones of lower topography, the geothermal anomaly causes a significant increase in the temperature near the surface (Figure 7).

These models are preliminary ones. Future works will try to improve the knowledge of this anomaly incorporating the density-dependent effects of temperature and salinity differences in order to evaluate a future exploitation of the resource. It is also intended to analyse the effects that this event causes in the urban environment (e.g. in the metro tunnel).

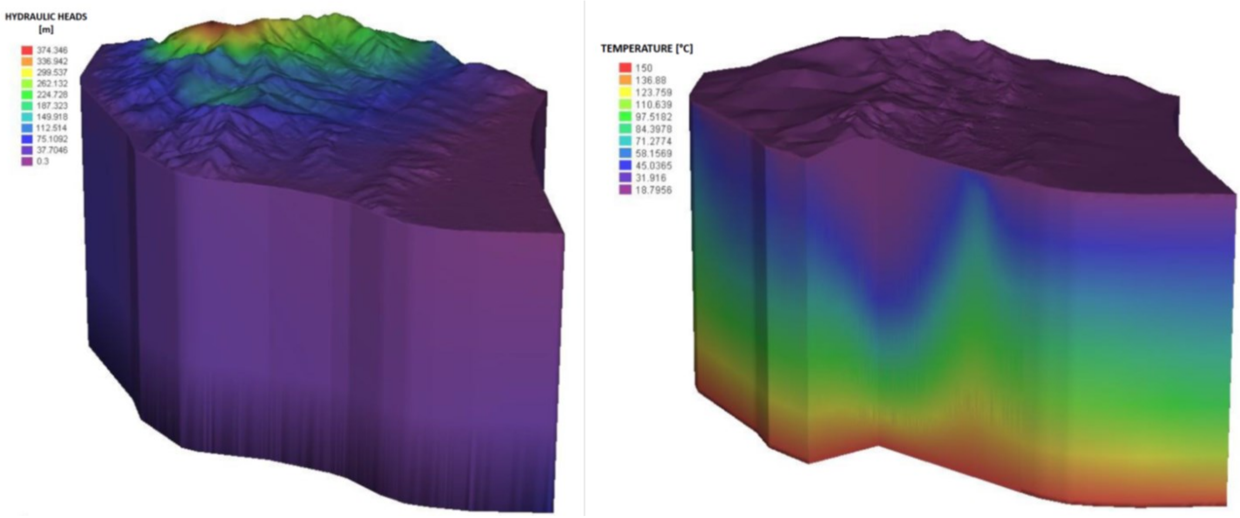

Figure 7. Figure 7. Example of outputs corresponding flow (left) and Head (right) modelling.

4. CONCLUSIONS

A study of the geothermal anomaly identified in Santa Coloma de Gramenet (Barcelona) is being carried out. In the first stages of work, the following conclusions can be highlighted.

The mineralogical analysis of the detritus collected during the perforations of the new L wells detects (1) the presence of common minerals of granodiorite materials; (2) mineralizations due to the circulation of water by fractures; and (3) some minerals evidencing the presence of hot springs (e.g.: laumontite).

The geophysical analysis detects the predominance of discontinuities that sweep to the southeast with an angle of 60-70º, although there are also sets that sweep southwest and minor discontinuities oriented to the northeast and west-northwest, always with the same angles.

Piezometric studies conclude that:

- Drainage in the Fondo station significantly alters the local groundwater flows, directing them to the station and generating vertical flows.
- The high hydraulic conductivity of the main fault in northwest-southeast direction, located just southwest of the station, also alters the flows around it, being well reflected on the piezometric map.
- The study of hydraulic parameters shows the high heterogeneity of the area, due to the presence of numerous fractures and the alternation of highly differentiated geological materials.

Regarding chemical characterization:

- The presence of two clearly differentiated water types is demonstrated:
  - Calcium-magnesium bicarbonate water: it corresponds to the samples of the most superficial piezometers (G wells). There are groundwater mixed with water supply, rainwater and hot water. This is especially emphasized by the high concentrations of nitrates but also of sulphates.
  - Sodium-chloride waters: they correspond to the samples of the seepage in the L9 metro tunnel (points A and B). The concentrations of some elements such as fluorine or strontium reinforce their hydrothermal origin.
- The high concentrations of sodium and chlorine and other elements such as fluoride, bromide, boron or tungsten in the tunnel seepage (points A and B) and the well L1 indicate a certain degree of mixing between thermal and marine waters

With respect to the thermal characterization:

- The L1 well confirms the first estimations made by extrapolation of the measured temperature profiles (60 - 80 ºC at 100 m of depth) with measurements of 58 - 64 ºC at 100 m.
- The hydrochemical thermometry estimations of the difference of temperature in the reservoir may be attributed to the chemical composition of the waters and presents two differentiated results: according to the wells G, L2 and L3, about 50 - 60 °C; according to the filtrations and the well L1, 80 - 120 °C.

A numerical 3D model of flow has been performed to understand the hydrogeological dynamics of the system at regional scale. The 3D heat transport model allows explaining the origin of the geothermal anomaly found in the Fondo station area. A reference has been established to focus the next studies at a local level and to be able to evaluate the energy of the resource and its effect on urban infrastructures.

5. ONGOING WORK AND FUTURE PERSPECTIVES

The Santa Coloma de Gramenet Municipality has reviewed the potential uses of the source and aimed at identifying which options could be the most beneficial for the greatest public interest (Ajunt. Santa Coloma Gramenet, 2019). Possible exploitation options of the geothermal source for heating and water have been identified.

Initial analyses identified the following potential areas: (1) Heating supply to public buildings, amenities and industry in the municipality using a locally available renewable energy; and (2) feeding of the existing and potential new water sports and health amenities (pools and spa centers).

The results of the studies performed so far have been used as starting point to carry out a geothermal exploitation project for public and municipal uses. The extension of the project will be depending on results of the phase 3 of the geothermal characterisation. Up to now, detailed studies including analyses on nine groundwater wells have not been completed. It is predicted that the phase 3 of drilling will begin with three more boreholes up to 200 m depth or more. These surveys will complement the activities done in phase 1 and 2. With these new perforations, it is intended: (1) to obtain more information and improve the characterization of geological structures of the area; (2) to intersect faults and fractures at a greater depth and with greater conductivity, which is critical to achieve higher temperatures; (3) to carry out new pumping tests for better characterization of the connection between wells and of the discontinuities of the subsoil and to evaluate with greater precision the thermal potential of the area; (4) to perform a new hydrochemical and isotopic sampling campaign, in order to determine the origin and the possibilities of using these waters.

Future task should also include the exploration and analysis of technical solutions, outline key risks for the different possible exploitation options, and identify optimal business model(s) for the carrying out of potential investments or, on the contrary, recommend stepping out from this opportunity. In this sense the results to be achieved are (1) Local market and sector regulatory studies for geothermal energy and water sources; (2) exploration of possible technical solutions and business models for the use of this shallow geothermal source, including an estimation of investments and operational costs and forecast of revenues, as well as detailed risk assessments to support the selection of the preferred solution; and (3) outline of the legislative framework for the exploitation of such geological resources, including, but not limited to, social and environmental impacts during the realisation and operation of the planned project.

REFERENCES

ACA (2005). Sobre la sol·licitud de l'Ajuntament de Santa Coloma de Gramenet perquè s'estudiï la possibilitat d'explotar l'anomalia geotèrmica detectada durant les obres de perforació del túnel de la futura línia L9 de Metro, al voltant de l'estació "Fondo". Technical report.

Ajunt. Santa Coloma Gramenet (2019). Search "termal" in: https://ajuntamentinforma.gramenet.cat/es/buscador/

Alcaraz, M. (2016) GIS platform for management of shallow geothermal resources. PhD. Thesis, Technical University of Catalonia (UPC). https://upcommons.upc.edu/handle/2117/96311

Alcaraz, M. García-Gil, A., Vázquez-Suñé, E. and Velasco, V. (2016). Advection and dispersion heat transport mechanisms in the quantification of shallow geothermal resources and associated environmental impacts. Science of the Total Environment 543 (2016) 536–546, doi: 10.1016/j.scitotenv.2015.11.022

Alcaraz, M. García-Gil, A., Vázquez-Suñé, E. and Velasco, V. (2016). Use rights markets for shallow geothermal energy management. Applied Energy, 172 (2016) 34–46. doi:10.1016/j.apenergy.2016.03.071

AMB, BR, GHS-IDAEA, 2013. Avaluació i zonificació de les possibilitats d'aprofitament tèrmic del subsòl a l'àmbit de l'Àrea Metropolitana de Barcelona. Technical report.

BR and GHS, 2006. Estudi de la viabilitat d'implementació de sistemes de climatització d'edificis mitjançant aigües subterrrànies a l'àmbit de la Sagrera. Technical report.

Buen-Dapena, 2009. Model hidrogeològic en perfil de flux, transport de solut conservatiu i transport de calor del riu besòs a l'alçada de la Plaça de la Vila de Sant Adrià de Besòs (Barcelona). Master Thesis in Hydrogeology. UPC.

Diersch, H., 2014. FEFLOW: finite element modeling of flow, mass and heat Transport in Porous and Fractured Media doi.org/10.1007/978-3-642-38739-5.

Font-Capo, J., Vázquez-Suñé, E., Carrera, J., Martí, D., Carbonell R., Pérez-Estaún, A. (2011), Groundwater inflow prediction in urban tunneling with a tunnel boring machine (TBM), Engineering Geology 121 (2011) 46-54. doi:10.1016/j.enggeo.2011.04.012.

Font-Capó, J., Vázquez-Suñé, E., Herms, I. and Carrera, J. (2012) "Groundwater characterization of a heterogeneous granite rock massif for shallow tunneling" Geologica Acta 10 (4) (2012) 395 - 408. Doi: 10.1344/105.000001773

García-Gil, A. (2015). Criterios Técnicos para la Gestión de Recursos Geotérmicos Someros en Acuíferos Urbanos. PhD. Thesis, Universidad de Zaragoza.

García-Gil, A., E. Vázquez-Suñe, M. Alcaraz, A. Serrano-Juan, J.A. Sánchez-Navarro, M. Montlleó, G. Rodríguez, J. Lao (2015) GIS-supported mapping of low-temperature geothermal potential taking groundwater flow into account. Renewable Energy 77 (2015) 268–278. doi:10.1016/j.renene.2014.11.096

GHS (2004). Estudio térmico en Fondo, L-9. Technical report.

GHS-IDAEA, 2015. Avaluació de les possibilitats d'aprofitament de l'anomalia geotèrmica detectada al sector de Fondo de Santa Coloma de Gramenet. Technical report.

GHS-IDAEA, 2017. Avaluació del potencial geotèrmic del sector Fondo de Santa Coloma de Gramenet. Technical report.

ICGC and GHS-IDAEA, 2010. Construcció d'un model numèric 2D de flux d'aigua i transport de calor d'un perfil del sector del Vallès Occidental. Technical report.

ICGC, 2012. Atles de Recursos Geotèrmics de Catalunya. http://www.icgc.cat/content/download/50024/354667/version/2/file/20120412_prg_atles_geotermia.pdf.

ICGC, 2011. Geotreballs III. Mapa geològic de les zones urbanes 1:5.000. Santa Coloma de Gramenet 290-123 (421-2-3). http://www.icgc.cat/Descarregues/Cartografia-geologica/GT-III.-Mapa-geologic-de-les-zones-urbanes-1-5.000

IGME and ICGC 1978). Mapa Geologico de España 1:50.000. Hoja 421 Barcelona. 2ªed. 30 pp.

Martí, D., R. Carbonell, I. Flecha, I. Palomeras, E. Vázquez-Suñé, J. Font-Capó, and A. Pérez-Estaún (2008) High-resolution seismic characterization in an urban area: Subway tunnel construction in Barcelona, Spain. Geophysics, vol. 73, no. 2 , p. b41–b50, 8 figs. doi: 10.1190/1.2832626.

Paymacotas, (2002). Informe dels resultats de l'assaig de bombament efectuat al sondatge SF-29. Technical report.

Paymacotas, (2003). Consideraciones hidrogeológicas en la zona de Fondo para la ejecución de las obras de la Linia 9 del metro de Barcelona. Technical report.

Paymacotas, (2004). Informe sobre el agua termal detectada en el subsuelo del municipio de Santa Coloma de Gramanet. Technical report.

Vázquez-Suñé, E., Ángel Marazuela, M., Velasco, V., Diviu, M., Pérez-Estaún, A., and Álvarez-Marrón, J. (2016). A geological model for the management of subsurface data in the urban environment of Barcelona and surrounding area. Solid Earth, 7, 1317-1329, doi:10.5194/se-7-1317-2016, 2016.