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Exploration, mapping and characterization of filtration galleries of the Pica Oasis, northern Chile: A contribution to the knowledge of the Pica aquifer

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ABSTRACT. In arid areas, the efficient management of scarce water resources is key for population survival and development. One of the oldest and greatest ancient water management system in drylands is the filtration gallery. Originated from ancient Persia, they were spread to other regions and cultures, and are found in the oasis of Pica, in the Atacama Desert. A filtration gallery consists of an almost horizontal tunnel dug underground until it reaches a water-bearing zone. It allows to tap and drains out groundwater, and thus a direct contact with groundwater table. With the objective to understand groundwater processes, preserve the water and geoheritage of one of the driest places on Earth and improve land-use planning, the present work explored and studied the filtration galleries, locally called *socavones*, of the oasis of Pica. Through direct exploration, topographical survey and geo-electrical prospection, 24 *socavones* were identified, mapped and their main physical features described, showing common traits with filtration galleries described worldwide, but also proper features highlighting their originality. The findings of the geological and hydrogeological studies of the *socavones*, complemented by physical and chemical analysis, allow to identify new groundwater recharge processes and, thus, to review and complete the hydrogeological model of the local aquifer of Pica. Most *socavones* are abandoned today, owing to physical and socioeconomic changes. Nevertheless, this study concludes that they can still have a role to play in the groundwater management of this arid area.

Keywords: Filtration gallery, Arid area, Groundwater recharge, Pica aquifer, Water and geoheritage, Northern Chile.

RESUMEN. Exploración, cartografía y caracterización de los socavones del oasis de Pica, norte de Chile: Una contribución al conocimiento del acuífero de Pica. En zonas áridas, la gestión eficiente de los recursos hídricos es clave para la supervivencia y el desarrollo de sus habitantes. Uno de los sistemas hidráulicos más antiguos, eficiente y sostenible en zonas áridas es la galería filtrante. Originario de la antigua Persia, se extendió a otras regiones y culturas, y se encuentra en el oasis de Pica, desierto de Atacama. Una galería filtrante consiste en un túnel casi horizontal excavado bajo tierra hasta alcanzar una zona saturada de agua. Permite captar y drenar el agua subterránea hacia la superficie y, por lo tanto, posibilita un contacto directo con la capa freática. Con el objetivo de comprender los procesos hidrogeológicos, preservar el patrimonio geológico e hidráulico de uno de los lugares más secos de la Tierra y mejorar la planificación del uso del suelo, este trabajo se basó en la exploración y estudio de las galerías filtrantes, localmente llamadas socavones, del oasis de Pica. A través de la exploración directa, levantamiento topográfico y prospección geoeléctrica, se identificaron y cartografiaron 24 socavones. Se describieron sus principales características físicas y se señalaron sus similitudes con galerías filtrantes en otras partes del mundo, pero también sus singularidades. Los resultados del estudio geológico e hidrogeológico de los socavones, complementados con análisis físicos y químicos del agua, han permitido identificar nuevos procesos de recarga del acuífero de Pica y revisar y completar el modelo hidrogeológico de este acuífero. Hoy la mayoría de los socavones están abandonados debido a cambios físicos y socioeconómicos; sin embargo, este estudio concluye que ellos pueden todavía desempeñar un papel en la gestión del agua subterránea de esta zona árida.

Palabras clave: Galería filtrante, Zona árida, Recarga de agua subterránea, Acuífero de Pica, Patrimonio geológico e hidráulico, Norte de Chile.

1. Introduction

Drylands represent 40% of the world land areas and are home to about 35% of the world population (FAO, 2011; UN, 2011). They are generally defined as those regions with low, scattered and sporadic precipitations exceeded by a very high evapotranspiration (Joly, 2006; FAO, 2011). As a consequence, available and permanent water reserves in those areas are mainly underground (Joly, 2006).

Historically, local populations living in drylands relied on the surface expression of groundwater (springs) as well as on small, often temporary, streams (UN, 2011). They developed complex hydraulic systems, which enable them to take advantage, as much as possible, of the scarce resources. When springs and surface water were not sufficient or inexistent, survival depended on the possibility to tap groundwater. Among the hydraulic systems that have been developed in the ancient world, filtration galleries are considered as one of the oldest and biggest achievements of human engineering (Motiee *et al.*, 2006) and the knowledge behind their construction as a wonder of human civilizations (Semsar Yazdi and Labbaf Khaneiki, 2017).

A filtration gallery is a traditional water management system used to provide a reliable supply of water in arid and semi-arid climates (Mostafaeipour, 2010). It consists of an underground and almost horizontal tunnel with vertical shaft wells, which tap and drain groundwater to the earth surface. Part of the tunnel is dug into the aquifer, so the water seeps through the tunnel's walls, floor and ceiling (collection section). The other part of the tunnel runs over the water table, down to the exit point (transport section). Water flows downward by gravity in order to supply water for domestic purpose and irrigate downslope lands (Fig. 1; Lightfoot, 1996; Motiee *et al.*, 2006; Semsar Yazdi and Labbaf Khaneiki, 2017).

The extension of the galleries through the aquifer increases the contact area of the tunnel with the water-bearing zone and so the height of the water column in the tunnel. When the tunnel extent is carried out in various directions (side branches), the infiltration area increases and, accordingly, the discharge (Lightfoot, 1996; Semsar Yazdi and Labbaf Khaneiki, 2017). The technology was originated in the ancient Armenian-Persian region, about 600-800 years BC (English, 1968; Beaumont, 1971; Lightfoot, 1996; Motiee *et al.*, 2006; Mostafaeipour, 2010; Semsar Yazdi and Labbaf Khaneiki, 2017). From then on, it was spread to other regions and cultures.

Filtration galleries tap in general into alluvial fan aquifers at the limit between mountains and plains (piedmont aquifers). They rely entirely on passive tapping of the water available by gravity and, consequently, the natural supply of water in a filtration gallery can never exceed groundwater recharge (Lightfoot, 1996). For this reason, filtration galleries represent a sustainable and low-cost water supply system. In many countries, they are nowadays abandoned to the benefit of pumped wells and boreholes (Lightfoot, 1996; Motiee *et al.*, 2006; Mustafa and Qazi, 2007). In North Chile, filtration galleries have been identified in four areas: Azapa, Sibaya, La Calera and Pica (Fig. 2). The latter includes the galleries of the nearby towns of Pica and Matilla, and the locality of Puquio Núñez (Barnes and Fleming, 1991).

Pica is an oasis located in the hyper-arid Atacama Desert, at the foothill of the Andean Cordillera,

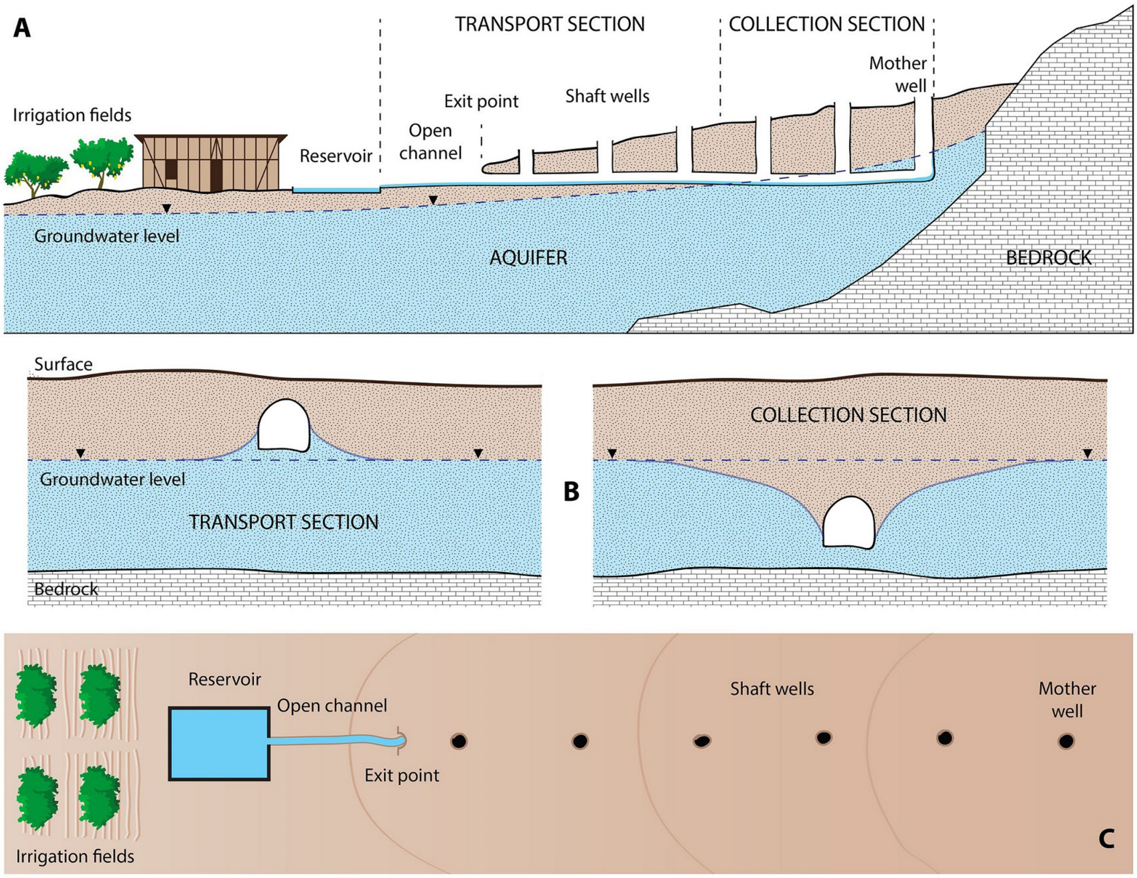

FIG. 1. Illustration of a typical filtration gallery. **A.** Longitudinal section; **B.** Cross section; **C.** Aerial view (modified after English, 1968 and Naghibi *et al*., 2015).

on the Eastern margin of the Central Depression, a relatively flat basin called Pampa del Tamarugal (Fig. 2). The presence of thermal springs and shallow groundwater allows the cultivation of citrus and other tropical fruits, as well as vineyards in the past (Billinhurst, 1893; Bruggen, 1918; Dingman and Gali, 1965). The filtration galleries of Pica, known as *socavones*, are used for irrigation. They tap the groundwater of the local shallow aquifer of Pica. The origin of Pica's groundwater and connection with the regional aquifer of the Pampa del Tamarugal has been the subject of several studies since the 1960s (Dingman and Galli, 1965; Suzuki and Aravena, 1985; Salazar *et al*., 1998; Grilli *et al*., 1999; Scheihing *et al*., 2017). Nevertheless, the hydrogeological processes controlling the recharge and discharge of Pica aquifer are still not fully understood.

Billinghurst (1893) mentioned 13 *socavones* in his publication "The irrigation of Tarapacá" and the discharge flow associated with each gallery. Bruggën (1918) mentioned 23 *socavones* and gave a basic description of their geology, groundwater origin, temperature and flow. He drew a basic location map, which was the only one in existence. Further studies used the information produced by Bruggën (1918).

Today, the *socavones* of Pica area are falling into decay. Most are abandoned while groundwater extraction through wells and boreholes increases, leading to groundwater drawdown and salinization. While they are disappearing from local people memories, their exact location remains unknown and many are even not mentioned in the literature. Because of the development of the towns of Pica and Matilla, problems of subsidence and sinkholes appeared, threatening existing infrastructure. Moreover,

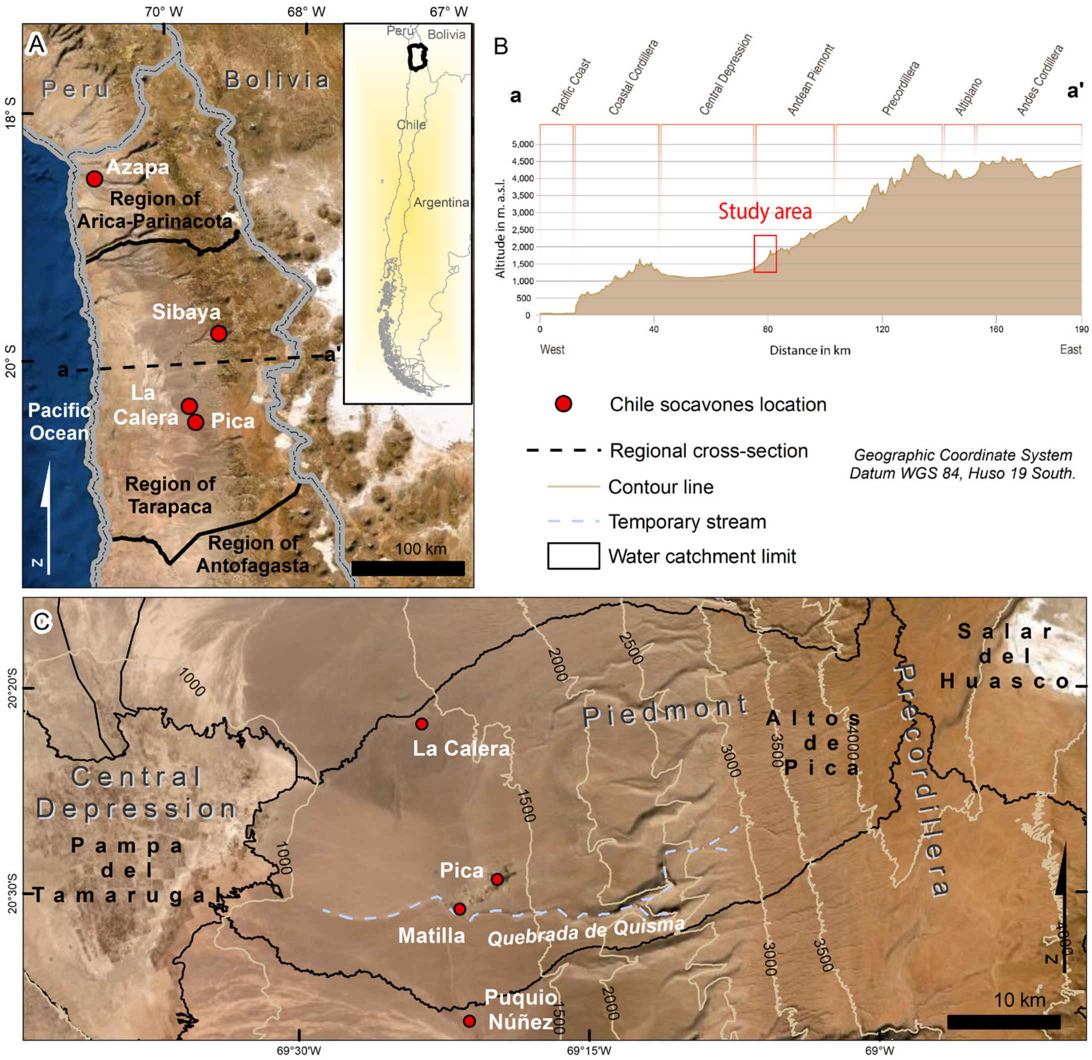

FIG. 2. Location of the study area. **A.** Location of Chile *socavones*; **B.** Topographic and geomorphological profile W-E of Chile at the latitude of the study area; **C.** Map of Pica area.

they were never the subject of a precise description and study, both physical and historical, ruling out the possibility to understand, preserve, highlight and reuse this water management system.

The purpose of this study is to provide the first complete identification and a description of the Pica area filtration galleries with the objectives of **i.** Preserving water and geoheritage, **ii.** Contributing to the hydrogeological knowledge of Pica aquifer, and **iii.** Improve land-use planning. Such information is required to ensure the environmental and socio-economic sustainability of the oasis of Pica area, in particular regarding groundwater management and the potential subsidence risks resulting from the expansion of Pica and Matilla towns. Based on the underground exploration and mapping, completed by geophysical prospection, the physical, geological and hydrogeological characteristics of the *socavones* were studied. The findings allow to highlight the originality of the galleries, as geo and water heritage of the Atacama Desert, and to review and complete the hydrogeological conceptual model of Pica aquifer. Although the *socavones* of Pica are today mostly abandoned, this study gives also an insight of the potential role that the galleries may still play in the groundwater management of the oasis.

2. Methodology

2.1. Study area

Pica is located in the Region of Tarapacá (northern Chile) at about 20°30’ S and 69°20’ W (Fig. 2) and is part of the Atacama Desert, one of the driest places on earth (Weishet, 1975). The oasis lies at an altitude of 1,500 m a.s.l., in the piedmont area, at the junction between the Precordillera (Altos de Pica) and the Central depression (Pampa del Tamarugal, Fig. 2B and C).

Average annual rainfall is almost null in the Pampa del Tamarugal and less than 10 mm in the Pica area therefore no direct recharge occurs from precipitation in the area (Rojas and Dassargues, 2007; Lictevout *et al*., 2013; Viguier, 2016). Rainfall increases with altitude, reaching an annual mean of 150-180 mm in the Precordillera, Altiplano and Cordillera, of which 80% occurs between December and March (Houston, 2006; Acosta and Custodio, 2008; DIHA-PUC, 2009; Lictevout *et al*., 2013). Inter-annual variability is very high, influenced by global phenomenon as El Niño Southern Oscillation (ENSO) and the regional wind patterns (Garreaud and Aceituno, 2001; Montecino and Aceituno, 2003).

Narrow and deep valleys (quebradas) incise the Piedmont from East to West and drain the water from the highlands down to the Central Depression through huge alluvial fans. The Pampa del Tamarugal and Piedmont area consist of sedimentary deposits and pyroclastic flows (ignimbrites) produced by the eruption and erosion of the volcanic arc of the Andean Cordillera from the end of the Oligocene to the modern period (Moreno and Gibbons, 2007). It overlaps with a major discordance the pre-Oligocene volcano-sedimentary, metamorphic and plutonic basement (Lamb *et al*., 1997; Farías *et al*., 2005; Hartley and Evenstar, 2010; Jordan *et al*., 2010, 2014). The Cenozoic cover harbour groundwater reserves recharged in the Precordillera and flowing down through the piedmont area (Rojas and Dassargues, 2007; Jayne *et al.*, 2016; Viguier *et al.*, 2018). The shallow aquifer of Pica is located in the late Cenozoic cover (Pleistocene-Holocene alluvial deposits). A regional structural height (Longacho Flexure, Fig. 3), constituting a natural barrier to the groundwater flows coming from the East, and underlying impermeable layers allow the formation of a shallow aquifer in the Pica basin with the emergence of thermal springs.

Two recharge models have been proposed for the aquifer of Pica: one model (Dingman and Galli, 1965; Fritz *et al*., 1981; Suzuki and Aravena, 1985; Salazar *et al*., 1998; Grilli *et al.*, 1999; Rojas *et al.*, 2010; Jayne *et al*., 2016; Scheihing *et al*., 2017) considers that recharge takes place in Pica’s head catchment (Altos de Pica), above 3,500 m a.s.l. (Precordillera). The precipitation infiltrates through the Huasco ignimbrites strongly fractured and flows downward through the lower layers of the Altos de Pica Formation (Sagasca Member) which consists of Oligo-Miocene volcano-sedimentary deposits, an alternation of thick continental sedimentary sequences (sandstone and conglomerates) and thinner volcanic horizons (Huasco and Tambillo ignimbrites; Figs. 3 and 4). The Altos de Pica Formation unconformably overlies the pre-Oligocene substratum made of volcano-sedimentary and metamorphic rocks, with Cretaceous to Eocene plutonic intrusions (Dingman and Galli, 1965; Salazar *et al*., 1998; Blanco *et al*., 2012a; Scheihing *et al.*, 2017). The other model (Magaritz *et al.*, 1989, 1990; JICA-DGA, 1995) considers a recharge from the Altiplano watersheds (Salar del Huasco) towards Pica and the Central Depression through deep faults and fractures. This hypothesis, often considered “unlikely”, has been refuted in two recent articles (Uribe *et al.*, 2015; Scheihing *et al*., 2017).

Scheihing *et al.* (2017), based on a new analysis of a seismic reflection profile carried out by the National Petroleum Company (ENAP) in 1960, propose that the emergence of Pica thermal springs is induced by plutonic intrusions of Cretaceous to Eocene age that penetrated the Mesozoic basement. These intrusions have, in the long term, destabilized the overlying Oligocene formations (Sagasca Member) and allowed the development of an important system of vertical fractures. The water circulating in the Sagasca Member (OMap 1) uprises to the surface through this system of fractures and feed the thermal springs and the Pica aquifer.

2.2. Methods

The first step of the study consisted in the review of the literature mentioning the *socavones* of the

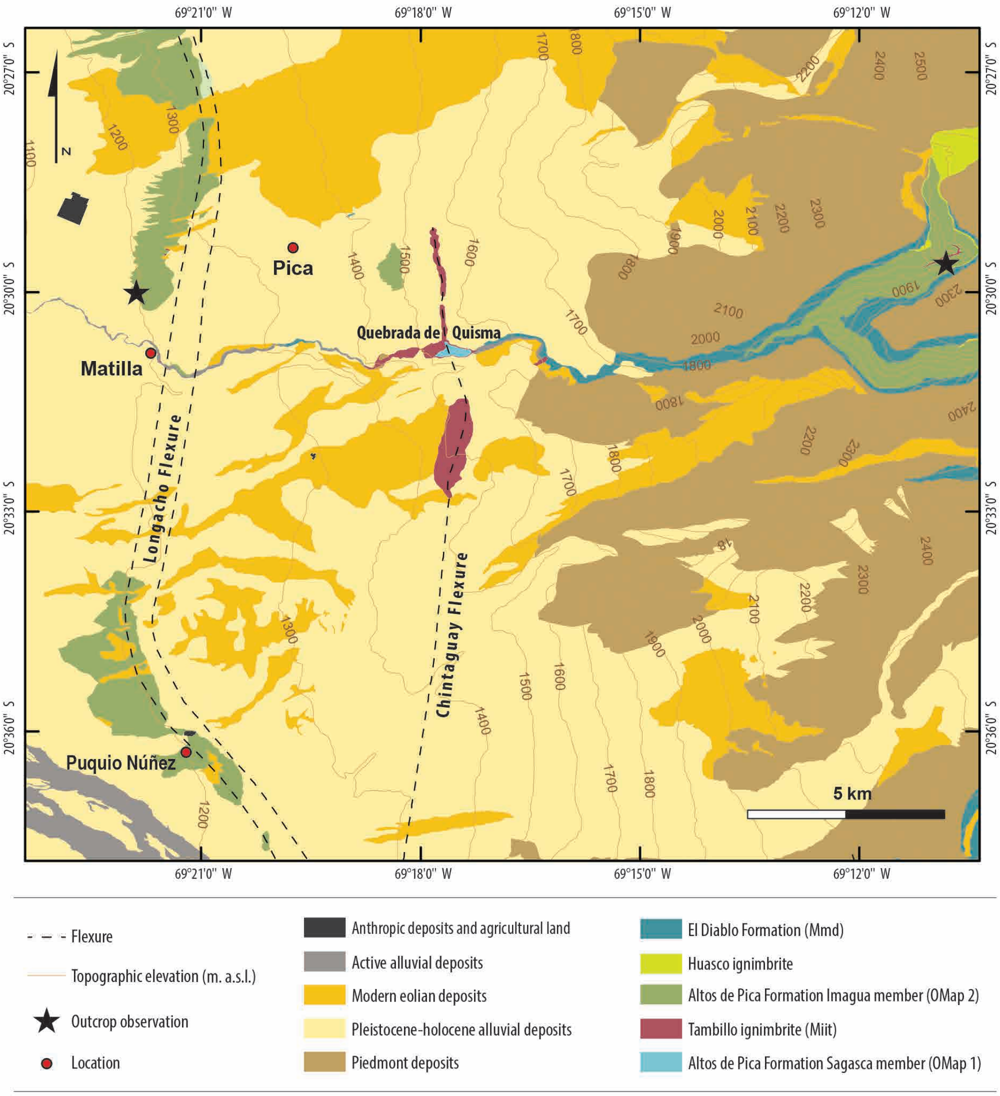

FIG. 3. Geological map of Pica area (modified after Blanco *et al*., 2012a and Blanco and Tomlinson, 2013).

Pica area, the interview of key informants among the Pica and Matilla inhabitants and the review of Google Earth Satellite images. The key informants interviewed included staff from the Municipality of Pica, the responsible of the Museum of Pica and owners of lands with *socavones*. The second step was the survey of all the elements belonging to the *socavones* and visible on the ground surface (entry points, shaft wells, wells, reservoirs, open channels) with an assessment of the access to the underground tunnels. This was followed by the geo-referencing survey of all those elements (third step). The fourth step consisted in the exploration and mapping through a topographical survey of the galleries that were accessible. For this study, tunnels have been accessed from their exit point or from one of the shaft wells when the exit point was blocked. In some cases, it has been necessary to abseil down the shaft wells with ropes and gear. In parallel to the exploration, a geophysical prospection with electric method was carried out (fifth step). Finally, geological and hydrogeological studies of the *socavones* were conducted (sixth step). Steps one to five were undertaken from November 2014

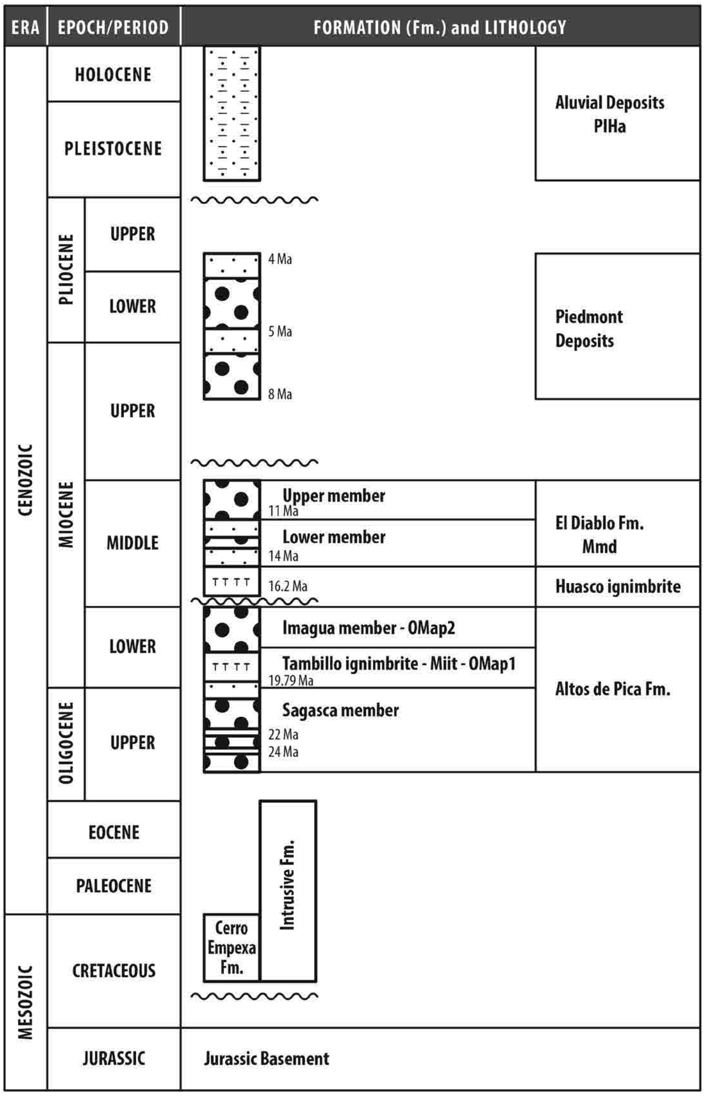

FIG. 4. Lithostratigraphic column of the study area (modified after Blanco *et al.*, 2012b).

to January 2015 and the field campaigns of the sixth step were in July 2017 and January 2018.

2.2.1. Gallery mapping

An underground topographical survey of the galleries was done using hand-held instruments. The distance was measured with a Stanley TLM 330 laser distance measurer and the section dimensions (height and width) combining a traditional tape with the laser one. The bearing and slope were measured with a Suunto Tandem compass and clinometer. A total of 3,072 stations were measured for an overall distance of 14,537 m of tunnels. The drawing data was processed with Visual Topo 4.7 software.

2.2.2. Geophysical survey

An underground gallery represents a sub-superficial empty cavity inside a sedimentary formation. The difference between the air (very resistive to insulator environments) and the sediments (relatively conductive environment) produces a measurable resistivity contrast between these two domains. However, the stress field and associated deformation, causing fractures, and in some case collapse of underground cavities, well documented in the mining industry and tunnels buildings (Terzaghi, 1946), may produce a much larger zone of influence of relatively resistive domain above the cavity. This is a highly permeable domain that allows the efficient transport of fluids, as clearly demonstrated by the crystallization in the walls and roof of the *socavones* (see section 3.3). Therefore, the relatively dry and resistive domain is likely larger than the *socavón* itself, perhaps 2-5 times. Water percolates gravitationally downward where, if still available, it can show up as a relative conductive body. This conceptual model is expressed in figure 5. Thus, the use of the direct current (DC) or electrical tomography resistivity (ERT) geoelectric method appears to be an appropriate methodology to identify the underground galleries.

The method consists of the installation of several electrodes, which are used to inject direct current *I* (between two electrodes) and measure the potential difference *V* in the other 15 pairs of electrodes. This configuration is repeated interchanging the potential-current electrodes, modifying in this way the geometry

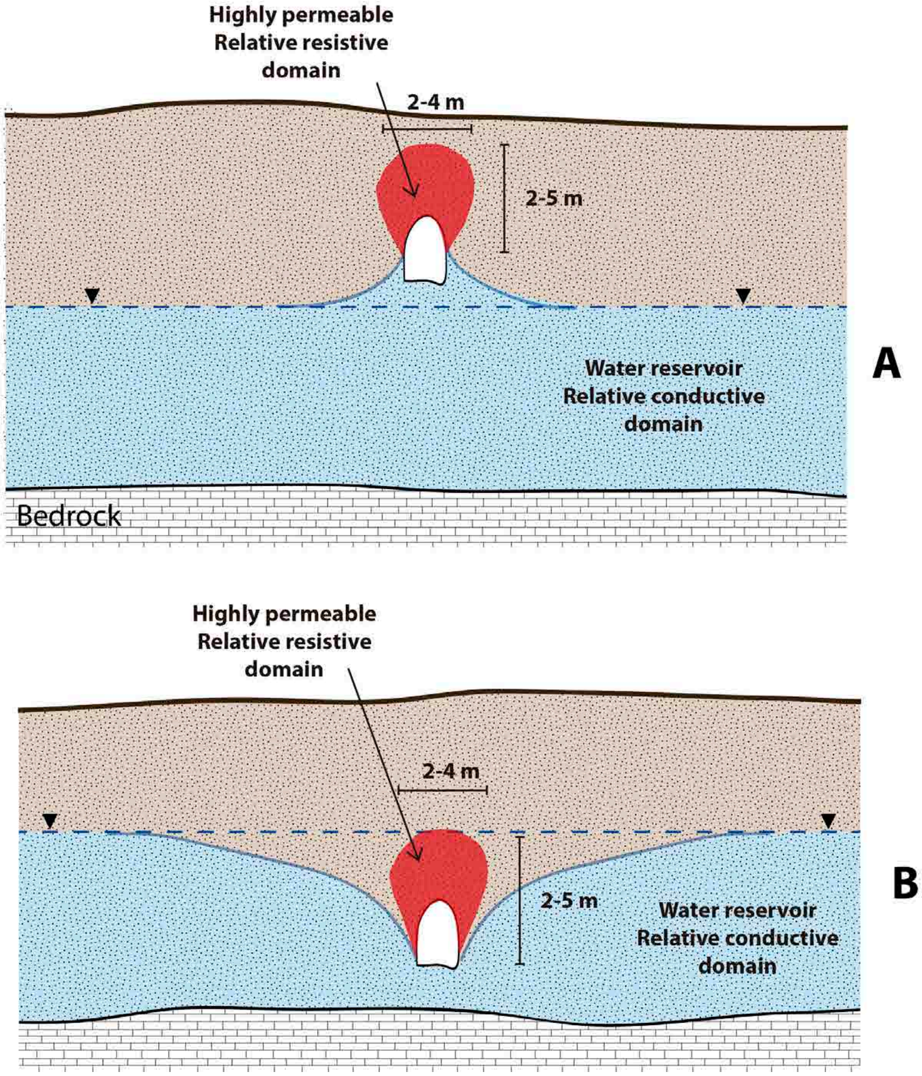

FIG. 5. Conceptual model of the resistivity response of a *socavón*: **A.** Above the *socavón*, a wide permeable domain, product of the stress concentration by the free surface of the *socavón*, with a tentative maximum size of 4x5 m; **B.** Below the *socavón*, if still present, a water reservoir or a humid zone with a relatively conductive domain.

of the current path and associated iso-potential lines. Using this methodology, we were able to map the resistivity distribution along the profile and at different depths of the substratum. The current-potential observations are represented in terms of the apparent resistivity ρ which is the integration of the *in situ* resistivity of the substratum. The physics behind this relation is based on the direct current approximation of Maxwell's equations better known as Ohm's law (see a thorough description of this derivation in Telford *et al*., 1990). This physical relation provides a simple mathematical expression to determine the apparent resistivity ρ in terms of the observations (current I and voltage difference ΔV; equation 1).

$$\rho = \frac{I}{2\pi\Delta V} G(r_1, r_2, r_3, r_4) \quad (\mathbf{1})$$

The geometrical factor G depends on the relative location of the current electrodes (r_1, r_2) and the potential difference electrodes (r_3, r_4).

Knowing the apparent resistivity, we can then determine the resistivity of the geological units by 2D modelling. In addition, due to the highly contrasting resistive response of the cavities (very resistive) and the surrounding geology (relative conductor), we can interpret the 2D resistive modelling image in terms of geological units-cavities configuration. Even though this geophysical technique is quite powerful to image the underground geo-electrical distributions, it has some limitations for this application. The most critical problems are: **1.** If the cavities are very small (less than 2 m^2) or at a depth greater than 30 m, the method is unable to resolve due to the very small associated signals; **2.** When the tunnel is full of water, the premise of a contrasting geo-electrical response between the cavity and the surrounding geology is no longer valid, due to the fact that water in this environments is always a conductive media. Using the model described in figure 5, the influence of the *socavón* should be greater than 2 m^2, perhaps as large as 10 m^2. In this case the chances to identify the *socavón* become higher.

The geo-electrical profiles were conducted perpendicular to the supposed route of the *socavón*. Between two profiles, a straight line was traced in order to join the two identified cavities or *lumbreras*. The error on the route is around 10 m on each side of the identified line. Using this methodology, only the main galleries were identified.

The geophysical deployment considers the use of the TIGRE instrument with 32 electrodes separated at a constant distance of 5 m, with a Schlumberger-array geometry. For each pair of current injection and potential measurement, we have made three measurements to analyse the dispersion of the data. We only accept data with less than 10% of variability. In practice, to inverse the data, we use *Zondres 2D* software (http://zond-geo.com/english/zond-software/ert-and-ves/zondres2d/; last visit 22/07/2020) for resistivity imaging with the Occam algorithm (Constable *et al*., 1987) to carry out the inversion effort and find the best solution. In total, 41 geo-electrical profiles were made.

2.2.3. Geo-referencing survey

The position (latitude, longitude and height) of the elements of the *socavones* that were visible on the ground surface (exit points, shaft wells, wells, reservoirs) was georeferenced with centimetre accuracy using a geodesic GPS (Trimble R6 with double frequency). The point used as reference was the geodesic vertex *Matilla 2* of the Ministry of Public Properties. In total, 154 elements were georeferenced. Due to accessibility problems, 15% of the elements were georeferenced with a navigator GPS (with meter accuracy).

2.2.4. Geological and hydrogeological study of the *socavones*

The geology of each *socavón* has been mapped. All springs have been registered as well as water levels in the galleries along with physicochemical measurements. Chemical analysis of nine springs in the *socavones* were carried out by the Montpellier HydroSciences laboratory by ion chromatography (anions) and ICP-MS (cations and trace elements). As a result, a piezometric map and hydrogeological profiles have been developed as well as a new hydrogeological conceptual model.

3. Results

In the area of Pica, including Matilla and Puquio Núñez, 34 *socavones* have been inventoried. Only 20 galleries are accessible or partly accessible so their exploration has been possible along with the realisation of a topographical survey, completed by the geo-electrical prospection of inaccessible sections for five of them. In some *socavones*, the water built up and fill all or a big part of the tunnel. In those cases, it has not been possible to explore and map the drown sections (San Isidro, El Carmen y Concova). Four *socavones* are entirely inaccessible but have been identified through a geophysical survey. Ten galleries could not be identified in the field. 85% of the galleries have been identified through exploration and 15% through geophysical survey (Fig. 6).

3.1. Identification of inaccessible *socavones* through geoelectric prospection

In total, 41 geo-electrical profiles were deployed. Poor ground conditions, with contact resistance above 1,000 ohm-m, hamper a good quality results. Nevertheless, we were able to obtain reliable data in some sections, which allow to test the proposed conceptual model (Fig. 5). Figure 7 shows two examples in which the galleries are most likely detected. The observation is represented in the upper panel of figure 7A and B, and the 2D model inversion section is represented in the lower panel, whereas the model response is shown in the middle panel.

Geoelectrical observations are represented as apparent resistivity pseudo-sections. Apparent resistivity implies an integration of the real resistivity in the space, and the pseudo section is an apparent estimate of the real depth. In order to translate these observations into depth-dependent resistivity, we need to apply 2D models that fit the data, formally representing a model inversion (*i.e.*, Parker, 1994).

The galleries were detected in almost all the cases and their lengths were estimated. Model response is a test of the goodness of the inversion process and average misfit below 20% is consider a reliable solution in this case, considering the middle to poor quality data available. In the inverted sections of figure 7, we interpret the *socavón* response as relative resistive domains (200-300 ohm-m), surrounded by a conductive domain one order of magnitude less resistive (30-50 ohm-m). The size of this resistive domain is larger than the expected *socavón* size, fitting the size and rounded shape of the proposed model (Fig. 5). The model response of Santa Elena *socavón* (Fig. 7A) indicates a resistive domain of 8-12 m diameter at depths below 10 m, a bit higher than expected by the conceptual model (Fig. 7). However, no clear conductive domain is identified underneath, eventually due to the lack of humidity and/or the loose of resolution at depths greater than 20 m. For the case of La Quinta *socavón* (Fig. 7B), the same configuration in the inversion model is observed (resistive *socavón* response (200-300 ohm-m) inside conductive domain (30-40 ohm-m)). The main difference is the size and depth of the interpreted *socavón*, in this case 4-8 m diameter at depths around 5 m. The size in this case is more in agreement with the conceptual model of figure 5. There upon, it is necessary to point out that shorter wavelengths' bodies can be identified at shallower depths. Thus, it is expected that smaller features can be correctly detected at these levels. As it is evident in the model results shown in figure 7, the geoelectrical representation of the *socavón* is not necessarily unique, other anomalous domains are also likely candidates. In the future, other indirect geophysical approaches can complement the geoelectrical technique used here, for instance georadar. Nevertheless, the results are in agreement with the conceptual model (Fig. 5 and section section 2.2.2) and evidence a *socavón* in the selected examples.

3.2. Characteristics of the *socavones* at Pica area

The 24 *socavones* identified sum up a total gallery length of 18.2 km (main tunnel and side branches; Table 1). Taking into account the unidentified galleries, the total network of the *socavones* is expected to cover a distance of 20 km.

A complete description of the physical feature of the *socavones* of Pica area is given in Appendix 1. The most original feature of the *socavones* of Pica area, compared to the filtration galleries in other regions of the world, is the shaft wells. With the exception of the *socavón* of Loreto, they are not located vertically over the main tunnel but either on the right or on the left side of the galleries, without any apparent logic. As well the *socavones* do not have "mother wells", again with the exception of Loreto.

3.3. Geological and hydrogeological study of the *socavones*

The *socavones* of Pica area are dug in Pleistocene-Holocene alluvial deposits, which consist of poorly consolidated sands with intercalated layers of clay and silts. This formation underlies the modern and active wind deposits and overlies oligo-miocene alluvial and volcanic formations (Blanco *et al*., 2012a; Blanco

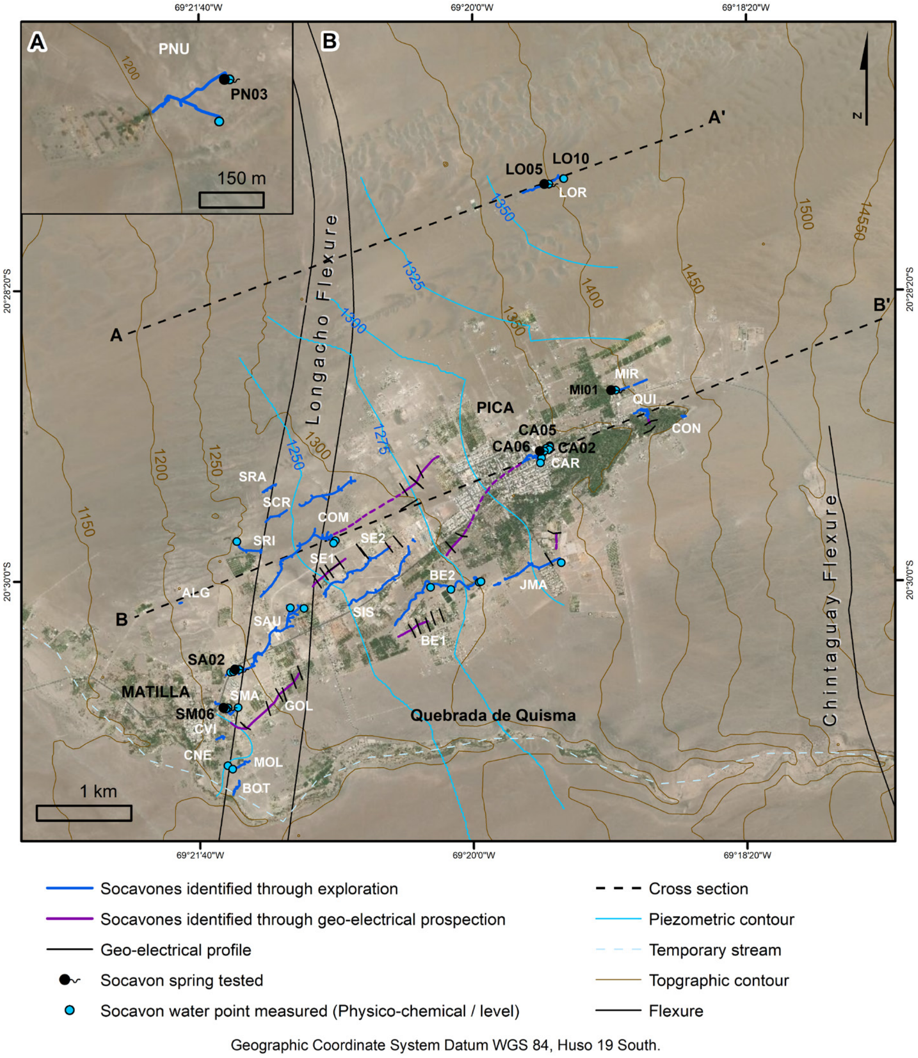

FIG. 6. Map of the identified *socavones* of the Pica area. Insert **A** shows Puquio Núñez *socavón* located 10 km south of Pica. **B.** *Socavones* located in Pica and Matilla Oasis. **A-A'** and **B-B'** cross-sections: Location of the geological and hydrogeological profiles of figure 14. Purple dotted line: Inferred gallery. **PNU:** Puquio Núñez; **LOR:** Loreto; **CAR:** El Carmen; **QUI:** La Quinta; **CON:** Concova; **SRA:** Santa Rosa; **SCR:** Santa Cruz; **SRI:** Santa Rosita; **ALG:** El Algarrobo; **COM:** Comiña; **SE1:** Santa Elena I; **SE2:** Santa Elena II; **SIS:** San Isidro; **SAU:** El Sauque; **SMA:** San Matías; **GOL:** El Gólgota; **CVI:** Cementerio Viejo; **MOL:** Puquio El Molle; **BOT:** Botijería; **BE1:** Buena Esperanza I; **BE2:** Buena Esperanza II; **JMA:** Jesús María; **MIR:** Miraflores; CNE: Cementerio Nuevo.

et al., 2012b). Almost all the *socavones* have a SW-NE orientation, running parallels to the direction of the maximum topographic gradient (Fig. 6).

One of the main findings of the geological study of the *socavones* is the identification of outcrops of Tambillo ignimbrite (MiiT, in Fig.3) in all the *socavones* located in Matilla (Fig. 6), over the (inferred) Longacho Flexure, with their exit point located in the escarpment on the western side of the flexure (San Matías, Cementerio Viejo, Puquio El Molle) (Fig. 8). From their exit point, those galleries are dug in unconsolidated sand and, after a few tens of meters, they come across few meters of Ignimbrite. Then, the galleries are dug in layers of clay intercalated with poorly consolidated sand (collection section). In the *socavón* Puquio El Molle, the contact between

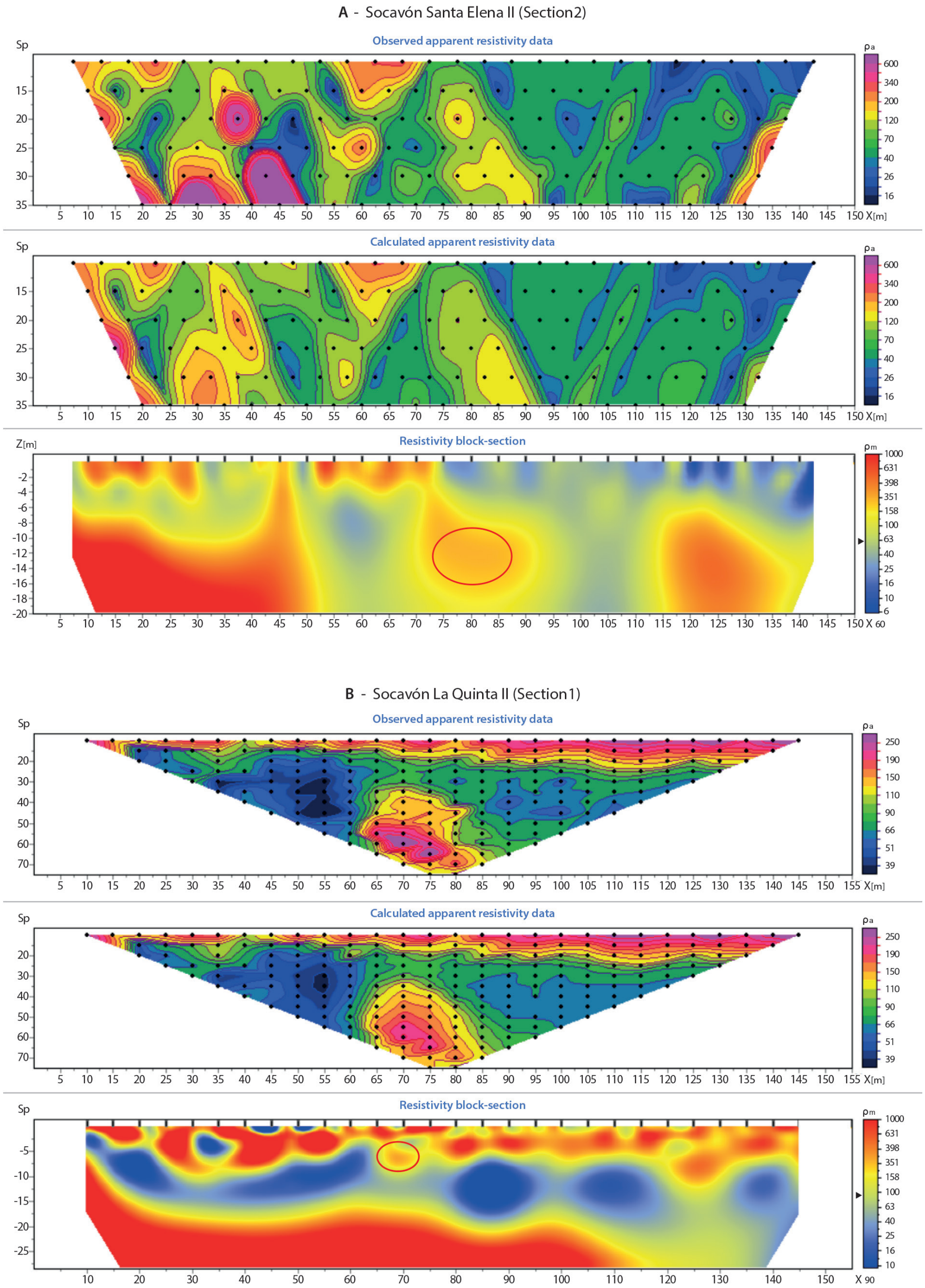

FIG. 7. **A.** Santa Elena *Socavón*. **B.** La Quinta *Socavón*. **Upper panel:** pseudosection of the observations. **Middle panel:** model response. **Lower panel:** 2D model inversion section (in red circle, the interpreted *socavón* in agreement with the conceptual model). The vertical scale in the pseudo sections is apparent depth and the coloured resistivities are apparent resistivities (an integral of the resistivity between the current injection point and the voltage measured point). Observation and model response should match if the model is correct. The inversion section depth is in meter and resistivity corresponds to the resistivity distribution in the space.

TABLE 1. MAIN CHARACTERISTICS OF THE *SOCAVONES* OF THE AREA OF PICA.

Name	ID	Main tunnel length (m)	Total galleries length (m)*	Number of shaft well*	Number of side branches*
Santa Elena I	SE1	380	ND	6	ND
Cementerio Nuevo	CNE	ND	ND	3	ND
El Gólgota	GOL	850	ND	3	ND
Buena Esperanza I	BE1	350	ND	ND	ND
Comiña	COM	2,435	3,007	17	27
El Sauque	SAU	1,267	2,293	8	40
El Carmen	CAR	1,974	2,291	5	17
Buena Esperanza II	BE2	1,317	1,482	8	4
Santa Cruz	SCR	1,133	1,509	12	18
San Isidro	SIS	1,075	1,334	10	18
Santa Elena II	SE2	984	1,178	7	13
Jesús María	JMA	837	986	6	18
Loreto	LOR	534	786	10	22
La Quinta	QUI	289	536	3	9
Santa Rosita	SRI	344	453	1	12
San Matías	SMA	406	545	0	2
Puquio Núñez	PNU	218	398	8	12
Puquio El Molle	MOL	333	356	1	1
Santa Rosa	SRA	204	257	4	7
Botijería	BOT	186	241	1	4
Miraflores	MIR	220	220	3	ND
Cementerio Viejo	CVI	95	144	0	3
Concova	CON	48	86.3	0	4
El Algarrobo	ALG	27	27	0	0
Total		15,506	18,129	116	227

* ND: No data

the ignimbrite and sand deposits on the eastern side of the ignimbrite outcrop shows a contact angle of 55° (non-erosive contact). In most of those cases, the hardness of the ignimbrite obliged the workers to continue the excavation overriding it, one or two meters higher than the initial level of the main gallery (Fig. 8C and D).

The *socavones* located at the northern and southern edges of the area (Loreto and Puquio Núñez, LOR and PNU; Fig. 6) show similar geological pattern, although with some differences. Loreto is not located over the Longacho Flexure but two kilometers to the East. The gallery, after layers of clayey sand and intercalated layers of clay, comes across an ignimbrite layer with an important spring (LO05) flowing through a fracture with a N113 direction. To the East, the gallery follows the ignimbrite layer, which obliged the workers to continue digging overriding it, two meters higher than the initial level of the gallery, up to the mother well at the end of the gallery (Fig. 8D). The presence of the ignimbrite two kilometres east of the Longacho Flexure is an evidence of the presence of another similar structure which do not show on the surface. The structure is confirmed by a gravimetry profile realized by the General Water Department (DGA, 2012) where a basement height is identified at less than 50 m below the surface right down the Loreto *socavón*. In Puquio Núñez, the tunnel did not cross ignimbrite rocks (probably much deeper at the

FIG. 8. Ignimbrite outcrops in Puquio El Molle (**A**), Cementerio Viejo (**B**), San Matías (**C**) and Loreto (**D**).

southern edge of the flexure) but important layers of clay intercalated with poorly consolidated sand in the conduction section. The *socavones* located between Pica and Matilla are dug in homogeneous and poorly consolidated sand layers, evidence of the presence of a deep sedimentary basin, as well confirmed by gravimetric profiles (DGA, 2012; Con Potencial Consultores, 2013).

Another important finding resulting from the exploration of the *socavones* is the observation of important layers of clay in the *socavones*, especially in the sections of the galleries located on the eastern side of the ignimbrite outcrops (Fig. 9). This is confirmed by the stratigraphic columns recorded on deep boreholes (about 100 m deep) between Pica and Matilla (Con Potencial Consultores, 2013) and shows the prevalence of layers of clay in Pleistocene-Holocene alluvial deposits.

Finally, the description of Tambillo ignimbrite outcrops in the Quebrada of Quisma and Matilla (Figs. 3 and 10) shows that the ignimbrite is strongly fractured, owing an important secondary permeability.

Regarding the groundwater, the exploration of the *socavones* allows to identify two different types of springs in the galleries: **i.** Emergence by intersection of the piezometric level in the unconsolidated sands of the Pleistocene-Holocene alluvial deposits with the galleries, which drain the aquifer (Fig. 11A); **ii.** Overflow springs through fractures in the Tambillo ignimbrites (*socavón* Loreto) or sandstones and conglomerates of El Diablo Formation and Imagua Member (thermal springs of Pica, Fig. 11B).

The physicochemical measurements show that the source of Loreto *socavón* (LO05; Fig. 6) has the highest temperature of Pica-Matilla oasis (34 °C).

FIG. 9. Layers of clay in the *socavones* San Matías (**A**) and El Sauque (**B**).

The thermal springs of Pica (Resbaladero RE01, Concova CN01; Fig. 6) have a temperature of 32 °C. However, these have a very low salt content for the region (conductivity ~330 µS/cm) while Loreto show a high salt content (conductivity ~2200 µS/cm). The springs in the *socavones* of Matilla have a salt content between these two extremes (conductivity ~1100 µS/cm) and a temperature of approximately 27 °C (Table 2, Fig. 6).

The analysis of the major elements of nine springs in the *socavones* of Pica (Fig. 12, Table 2) shows two different groups: **1.** sodium bicarbonate to mixed waters in Pica and Puquio Núñez area (Miraflores MI01, Resbaladero RE01, Concova CN01, Puquio Núñez PN03); and **2.** sodium sulfate waters in Loreto and Matilla area (San Matías SM06, El Sauque SA02, Loreto LO05).

These hydrogeochemical facies have already been described by Grilli *et al.* (1999). The sodium bicarbonate facies of the thermal springs of Pica is similar to those found in the springs of the northern, western and southern edge of the Salar of Huasco and is typically observed in waters circulating in volcanic rocks such as ignimbrites (Grilli *et al.*, 1999; Aravena, 1995).

In many galleries, precipitation of calcium carbonate ($CaCO_3$) covers the walls and floor of the tunnels in different proportion. Some tunnels are totally covered with calcium carbonate, as El Carmen *socavón*, where $CaCO_3$ (Fig. 13A and B) precipitates in the form of Aragonite, as it has been observed also in some wells of Pica. Calcium carbonate precipitation is a result of the degasification of excess dissolved carbon dioxide in groundwater when it seeps from the aquifer into the empty gallery (Banks and Jones, 2012). Additionally, in five *socavones*, a sedimentation of manganese oxide (MnO) has been observed on the walls, floor and sometimes ceiling of the tunnel. When both sedimentation occurred ($CaCO_3$ and MnO),

FIG. 10. Ignimbrite outcrops in the Quebrada of Quisma (**A**); Matilla (**B**).

the tunnel sides are covered first by manganese oxide, itself covered by Calcium Carbonate. The height of sediment on the wall shows the past water seepage and level in the gallery. The fact that some galleries show sedimentation, and others do not, shows different groundwater composition. Indeed, precipitation of $CaCO_3$ occurs in the galleries were ignimbrite has been found and groundwater circulates through fractures. Some *socavones* show abundant traces of roots, replaced by iron hydroxide, carbonates or silica (Jesus María, El Sauque and Botijería), related to the paleo-wetland facies of Paleocene-Holocene deposits on the eastern margin of Longacho Flexure (Blanco *et al*., 2012b). It is also possible to find stalactites (but no stalagmites) as well as small pisolites (pearl caverns) and tiny gours or rimstone dams' formations on the gallery's floors. The stalactites are mainly soda straw type with 5-6 mm thick and up to 30 cm long. Other drapery, curtain or bacon rind stalactites, also small size, are visible (Fig. 13C).

3.4. State of the *socavones* today

Although only seven *socavones*, out of 24, still discharge water today (Fig. 6), 17 have groundwater flowing in some sections of the tunnels (70%). Nevertheless, the water level is today much lower than it has been in the past, as evidenced by the marks left by the water on the tunnel sidewalls. Billinghurst (1893) and Bruggën (1918) reported a similar total discharge of the *socavones*, around 40 l/s. This flow was much lower than the total discharge from the springs of the oasis, reported to be 92 l/s in 1865, 119 l/s in 1918 and later on 53 l/s (Dingman and Galli, 1965; Fritz *et al*., 1981; Magaritz *et al*., 1989). The visual estimation of the groundwater flow in the active galleries today gives

FIG. 11. Springs (**A**) in the unconsolidated sand deposits in San Matías; (**B**) in ignimbrite fracture in Loreto.

a total discharge at least 50% lower than in 1918. In three *socavones*, water fills the whole tunnel section (Carmen, San Isidro, Cementerio Nuevo). This may be due to the blockage of downward tunnels by sediments so the groundwater builds up to the water table level.

Although the agriculture in the oasis of Pica has expanded in the last decade, most of the *socavones* are today abandoned. Due to the growth of both Pica and Matilla towns, and the absence of knowledge about the localisation of the *socavones*, several infrastructures have been constructed over them. In particular, the center of Pica has developed over the gallery El Carmen leading to the subsidence of the ground and formation of sinkholes.

In some galleries, part of the tunnel has collapsed. Although earthquakes with magnitude over 7 Mw have occurred in the region in the last decades (1976, 2005, 2014), they did not cause a major destruction of the *socavones* of Pica area. Nevertheless, the impact of recent earthquakes is visible in some galleries, in part because they are not anymore maintained. In general, main galleries are still in excellent conditions although exit points and/or shaft wells may be deteriorated, collapsed, or covered up by sand or garbage.

Only seven *socavones* are still in use (Miraflores, Concova, Loreto, Santa Rosita, San Matías, El Sauque and Botijería), mostly for irrigation purposes, with the exception of Santa Rosita used by the regional water supply company. Miraflores, Concova, along with the thermal spring of Resbaladero are still managed collectively through farmers associations, as it was traditionally. The water is distributed among the farmers through a canal network and strict timing.

Nevertheless, today in the oasis, crops are mainly irrigated through shallow wells (around 30 m deep) or borehole (over 100 m).

TABLE 2. CHEMICAL GROUNDWATER COMPOSITION OF SPRINGS IN THE PICA AREA *SOCAVONES*.

Code	Name	UTM N	UTM E	Altitude [m]	Date	T [°C]	C [µS/cm]	pH	CO_3^{2-} [mg/l]	HCO_3^- [mg/l]	Cl^- [mg/l]	NO_3^- [mg/l]	SO_4^{--} [mg/l]	Na^+ [mg/l]	K^+ [mg/l]	Mg^{++} [mg/l]	Ca++ [mg/l]
CA02	El Carmen	7,734,566	466,054	1,325	7/20/2017	25.4	2,200	7.24	-	157.3	334.0	114.9	463.3	285.7	4.0	14.4	177.7
CA05	El Carmen	7,734,523	465,993	1,307	7/20/2017	26.4	1,111	7.6	-	134.6	134.1	42.2	232.5	118.7	2.3	10.8	97.3
CA06	El Carmen	7,734,524	465,996	1,307	7/20/2017	25.3	811	8.06	-	166.9	96.0	30.6	132.5	109.0	2.1	5.0	59.4
SA02	El Sauque	7,732,214	462,772	1,230	7/19/2017	27.4	1,108	7.98	-	46.3	112.7	6.5	355.2	152.7	5.6	1.3	77.2
LO05	Loreto	7,737,349	466,045	1,360	7/20/2017	34.7	2,164	8.75	-	46.3	112.7	6.5	355.2	152.7	5.6	1.3	77.2
LO10	Loreto	7,737,407	466,203	1,364	7/20/2017	16.7	2,178	8.05	-	37.5	149.0	-	673.0	232.8	14.0	3.4	162.5
MI01	Miraflores	7,735,168	466,750	1,397	7/20/2017	31.5	324	8.21	-	110.7	24.1	3.3	36.9	45.6	0.6	0.1	27.0
PN03	Puquio Núñez	7,721,678	463,429	1,194	7/18/2017	26.7	428	9.06	20.1	105.9	31.3	4.7	55.3	86.5	2.1	0.1	12.6
SM06	San Matías	7,731,809	462,650	1,231	7/18/2017	28	1,097	7.9	-	40.5	102.6	7.8	346.1	154.7	6.3	1.3	79.8

4. Discussion

The filtration galleries of Pica area share many common features with the ones described in other parts of the world. However, they also have distinctive features that make them unique in their kind. As asserted by Villalobos (1979), Chilean filtration galleries represent a local development of the ones found in Spain and North Africa. One of the main differences is the shaft wells structure (with the exception of Loreto). A hypothesis for this type of shaft well construction locally called *lumbreras* is that the area is a windy and sandy desert. If the well is dug vertically over the main tunnel, the sand may accumulate directly in it, obstructing the water flow. If the well is replaced by a diagonal tunnel, the sand accumulates in the branch gallery before reaching the main tunnel. The accumulation of sediments in the main tunnel reduces the water flow and increases the need of maintenance. Today, the main tunnels are not blocked with sediments from the surface although they are abandoned since years. In a few cases, it has been necessary to clear out the tunnels and remove the sand in order to continue the exploration, but in general, the sediments have accumulated in the *lumbrera*. Another hypothesis is that it is more difficult to dig a well vertically over an underground tunnel as it entails levelling expertise.

Another characteristic, which distinguishes the *socavones* of Pica is the absence of mother wells (except Loreto). It may be the reason why the main galleries are not straights lines between the exit point and the end (where the mother well is supposed to be located and dug first). The only exception is again Loreto, which seems to have been built in the rule of the art of filtration galleries construction. This could be an evidence that Loreto was the first *socavón* built in the area.

Those differences observed in Pica may be, on one hand, an adaptation to the climatic context and local geology (important accumulation of sand transported by the wind, presence of a hard ignimbrite layer and earthquakes). On the other hand, it may be due to a lack of expertise of the workers who built the *socavones* compared to the filtration galleries Masters in Iran, China or other places, where hundreds of filtration galleries were built, some with tens of kilometres long. This hypothesis supports Bruggën (1918) observations of several galleries with water built up because of uneven tunnel slope, or galleries in bad state (collapsed)

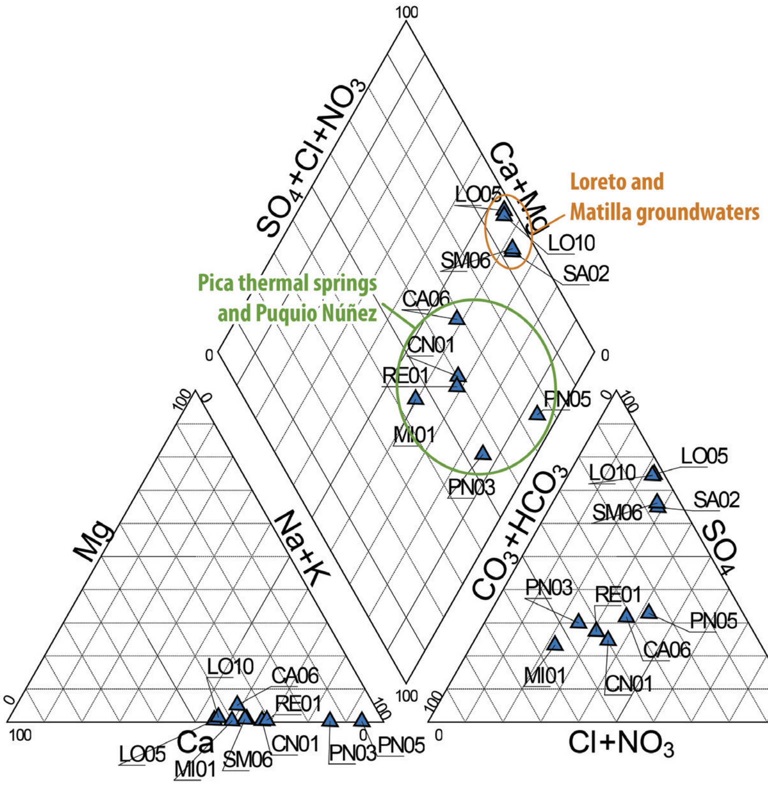

FIG. 12. Piper diagramme of the springs of Pica.

affecting the discharge flow of the galleries. The short distance between galleries, probably affecting the discharge flow, may be another evidence of the lack of expertise in the *socavones* construction.

The alluvial fans of the Central depression are an ideal setting for the development of *socavones* of longer distance. However, this technique has not been developed outside of the Pica area although there has always been irrigated agriculture in the Pampa del Tamarugal. Different hypothesis can be advanced and discussed: the surface water flow, although low, was always sufficient for covering the needs of the local inhabitants or expert knowledge lacked for the construction of longer and deeper galleries.

The geological and hydrogeological information generated through the exploration of the *socavones*, completed by stratigraphic information of deep boreholes and gravimetry profiles (DGA, 2012; Con Potencial Consultores, 2013) allowed for the elaboration of two W-E geological and hydrogeological profiles (Figs. 6 and 14). The presence of the Tambillo ignimbrite on the western edge of the Longacho Flexure, in the galleries located over it and its absence on the eastern side, is an evidence of the presence of the flexure. The ignimbrite outcrops highlight the top of the anticlinal, which is induced by a reverse fault with a western dip. It confirms the proposition of Labbé *et al*. (2015) and refutes the interpretation as a normal fault of Dingman and Galli (1965) and Scheihing *et al.* (2017). Victor *et al.* (2004) interpret the structure as a reverse fault but with an eastern dip. The fault affects only the Mesozoic (Jurassic) bedrock and folds the Sagasca Member (OMap 1) and Tambillo ignimbrite (MiiT). The Imagua Member (OMap 2) and El Diablo (Mmd) Formation are not present on the top of the anticlinal as they end in bevel on the eastern side of the flexure zone (Victor *et al*., 2004; Labbé *et al*., 2015).

The fracturation of the Tambillo Ignimbrite and the continuous groundwater flow over the Longacho Flexure (observed in the *socavones* of Matilla and confirmed by the piezometric map, figure 6 show

FIG. 13. **A** y **B.** Calcium carbonate covering carved steps and iron ladder in El Carmen *socavón*. **C.** Stalactites in El Sauque *socavón*.

that the Tambillo ignimbrite is not the formation that limits at its base the alluvial aquifer of Pica, but the layers of clay of the Pleistocene-Holocene alluvial deposits.

A similar structure (anticlinal), located East of the Longacho Flexure and parallel to it (N-S direction) induced the outcrop of the Tambillo Ignimbrite in the *socavón* of Loreto and the presence at shallow depth (~50 m) of the pre-Oligocene basement. We interpret this structure as the extension, to the north, of the anticlinal and reverse fault, with an eastern dip, inducing the emergence of the Pica thermal springs in the conglomerates of El Diablo Formation (Fig. 14; Victor *et al*., 2004; Blanco *et al*., 2012a; Blanco *et al*., 2012b; Blanco and Tomlinson, 2013).

The physicochemical analysis of the springs in the *socavones* allow us to identify two groundwater poles: **i.** Groundwater with low salt content (conductivity ~320 µS/cm) and thermal (~32 °C) in Pica (located on the eastern border of the aquifer); and **ii.** Groundwater with higher salt content (conductivity ~2,000 µS/cm) and thermal (34 °C) in the northern zone of the aquifer (Loreto; Fig. 13). Between the two poles (central and western zone), the groundwater ha a salt content that can be interpreted as a mixing between these two poles (conductivity ~1,100 µS/cm). The lower temperature of the latter (~27 °C) is probably due to the cooling of groundwater from the two poles in the shallow aquifer of Pica which may, additionally, receives water from infiltration of irrigation waters.

These results allow to review and complete the existing conceptual model of the Pica aquifer, particularly the origin of flows recharging the aquifer. This work confirms the first recharge model (Dingman and Galli, 1965; Fritz *et al*., 1981; Suzuki and Aravena, 1985; Salazar *et al*., 1998; Grilli *et al*., 1999; Rojas *et al*., 2010; Jayne *et al*., 2016; Scheihing

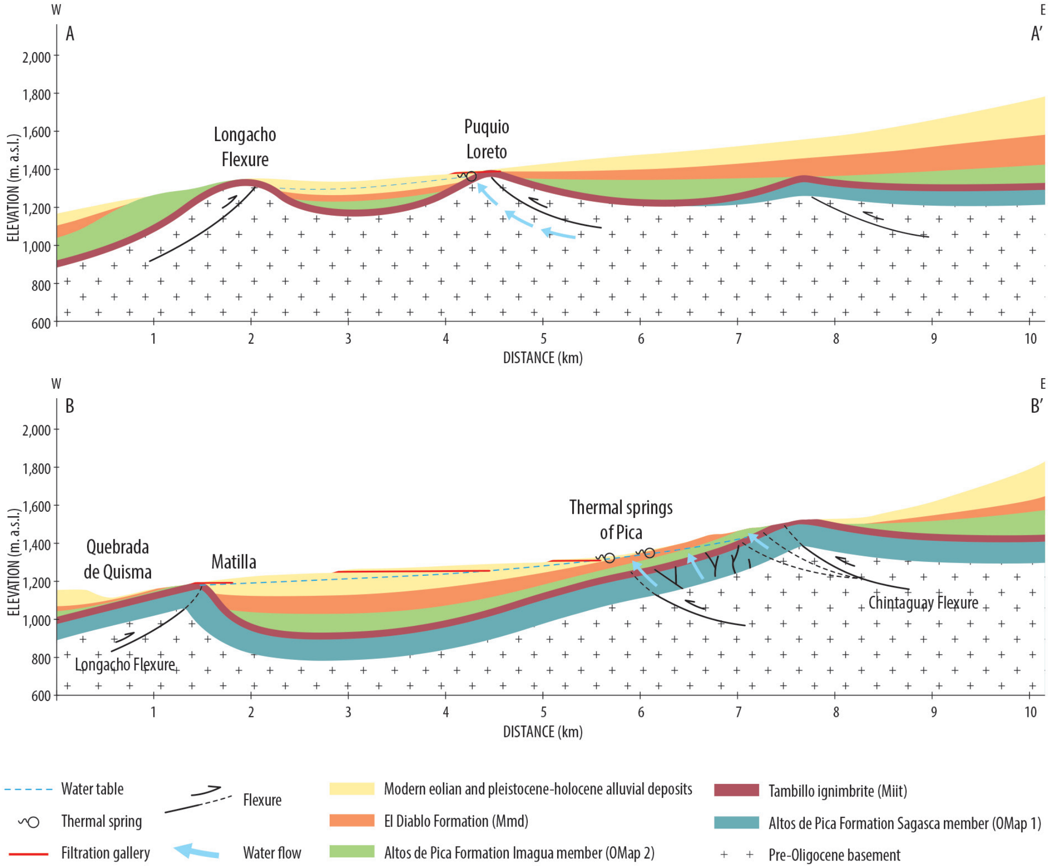

FIG. 14. Geological and hydrogeological W-E profiles of the Pica aquifer. The location of the profiles is given in figure 6.

et al., 2017) but proposes an additional recharge mechanism. Findings show that two processes control the recharge of the Pica aquifer:

1. On one hand, as proposed in previous studies, a recharge from precipitation in the Altos de Pica area, circulating through the Cenozoic cover (Sagasca Member, OMap1) and emerging at Pica (thermal springs) through the fractures affecting the Cenozoic cover. Those fracture may be generated by the fault of Chintaguay that affects the pre-Oligocene basement and strongly folds the Cenozoic cover and the plutonic intrusions of Cretaceous to Eocene ages. This groundwater has a very low salinity and a thermal footprint that corresponds to its depth of circulation (Scheihing *et al.*, 2017). Groundwater flow has a general E-W direction.
2. On the other hand, a recharge from the pre-Oligocene basement, of groundwater inflow with a high salt content (conductivity ~2,000 µS/cm) and high temperature (34 °C). Water emerges through fractures without displacement affecting the horizon of ignimbrite overlying the pre-Oligocene basement (the OMap 1 and 2 members of the Cenozoic cover are probably absent due to the basement height). Similar structures can be observed in the Quebrada de Tarapacá (Viguier, 2016). The main groundwater flows have a rough N-S direction.

A third group is represented by the groundwater of Matilla, which seems to be a mixing between the two types of groundwater described above because located at the convergence flows from the north (Loreto) and from the east (Pica). Based on those findings, a new conceptual model has been elaborated (Fig. 15).

Today the galleries are abandoned and at risk to disappear both physically and from the local population memory, once all exit points and shaft wells will be buried or have collapsed. A lack of maintenance may have led to a reduction of the discharge flow (sedimentation on the tunnel ground, mineral deposits on the tunnel sides reducing seepage, fear of earthquakes and tunnels conditions), or too much and too close galleries affected the flow. Some may have been seriously damaged by earthquakes or a major portion of the tunnel may have collapsed, again reducing the discharge of the gallery. Eventually, the *socavones* may have been abandoned because the water table of the aquifer fell down, reducing the discharge of the galleries. The rise of the number of wells and borehole in a relatively small area (the oasis) may have led to the rapid drawdown of the aquifer and the drying up of the filtration galleries.

We believe that the *socavones* of the Pica area have still a role to play in the modern world. They first deserve to be preserved because they represent a water and geoheritage of one of the driest places on Earth, as well as for their unique characteristics and the human effort engaged in their construction. Some of them could be habilitated so they could be visited for cultural, educational and scientific purposes. In addition, they can still play a role in groundwater management of the Oasis of Pica. The evolution of the groundwater level in the galleries can be used as an indicator for aquifer management. As most of the wells are private and in use, they cannot be used for the monitoring of the water table. Eventually, the abandoned shaft wells and tunnels could be used for managed aquifer recharge. Either surface runoff or reused water could be injected into the shaft wells, so empty tunnels of abandoned *socavones* will be filled with water, which will in turn slowly infiltrate into the aquifer.

5. Conclusions

The underground exploration, topographical survey and geo-electrical prospection of the *socavones* of Pica area have allowed identifying and describing 24 *socavones* with 18.2 km of galleries, that is 70% of them. We expect the other 30% to be completely buried. Even though, it deserves further research.

Our study came across various limitations. During the exploration, some galleries were not explored because of high risk of collapse. Additionally, some supposed galleries (informed by local population) investigated with geo-electrical survey were not found. Although it is possible that the galleries are totally buried, it is also conceivable that gallery is too small or too deep to be detected by the geo-electrical method. Our first attempt to indirectly characterize *socavones* by geo-electrical geophysical techniques delivered promising results, showing a pattern of resistive domains (200-300 ohm-m) inside a more conductive area (one order of magnitude less). But it is still necessary to improve the application

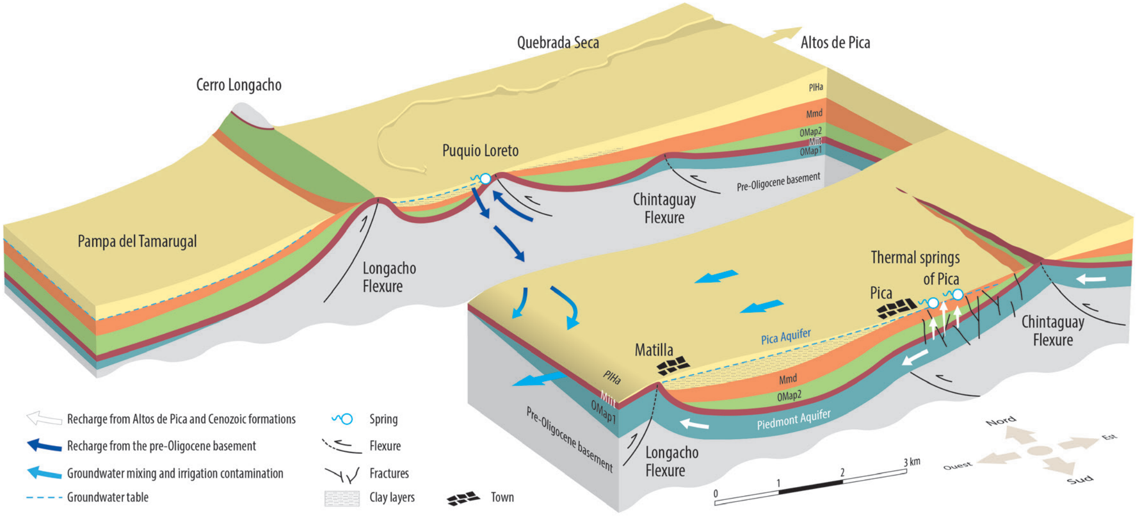

FIG. 15. Hydrogeological conceptual model of the Pica aquifer.

of the technique in order to obtain more reliable results. Future challenges are related to an efficient methodology to improve the electrode contact resistance, and the capacity to detect small objects (2-5 m) at depth larger than 10 m. On the other hand, the use of complementary techniques, like Georadar, can also improve the capabilities of indirect tools to detect cavities.

The study of the *socavones* of Pica-Matilla provided a unique insight and new data that contribute to the understanding of the Pica aquifer and hydrogeological processes in the Piedmont area and Central Depression. It leads to the proposition of a new conceptual model. The base of the aquifer of Pica corresponds to the clays of the Pleistocene-Holocene alluvial deposits. It is recharged, on one hand, through fractures and groundwater flows within the Altos de Pica Formation (Sagasca Member) from the Altos de Pica area (E-W flow). On the other hand, this work identified another recharge mechanism from the the pre-Oligocene substratum (N-S flow) through fractures within the Tambillo ignimbrite in the northern part of the aquifer.

The information provided by this research will allow authorities to take appropriate measures for protecting existing infrastructures from sinkhole as well as for land-use planning of the future oasis development. But, above all, it seeks to encourage the preservation of the *socavones* -an ancient water supply system of arid and water-stressed areas- as water and geoheritage; as well as their reuse for cultural, scientific and water management purposes. Beside the abandonment of most of the *socavones* today, we believe that they could still have a role to play in the groundwater management of the oasis for groundwater monitoring and managed aquifer recharge.

Acknowledgement

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Appendix 1

Description of physical characteristics of the filtration galleries *socavones* of the Pica area

The filtration galleries of Pica, known as *socavones*, are thought to have been built in the late sixteenth century by miners, although not definite evidence has been produced and the earliest mention dates back to 1718 (Barnes and Fleming, 1991)

1. Physical features of the *socavones*

Almost all the *socavones* have a SW-NE orientation, running parallels to the direction of the maximum topographic gradient. The only exceptions are Botijería (near NNE-SSW direction) and La Quinta (which turns with a right angle from its initial E-W direction). Beside the general SW-NE direction, the *socavones* are not straight lines between the exit points and the end of the main gallery but rather a curvy path.

The longest socavon (main tunnel) in the Pica area is Comiña with 2,435 m (Table 1). The shortest is El Algarrobo with 27 m. Six *socavones* have an extension over 1,000 m (Comiña, El Carmen, Buena Esperanza II, El Sauque and San Isidro). For both Comiña and El Carmen, a section in the middle part of the galleries could not be neither accessed nor identified through geophysical survey so the length was estimated approximately.

The topographical survey identified 227 side branches in the 24 *socavones* (Table 1), with a total lenght of 2,480 m. For the ones explored through geo-electrical survey, only the main tunnel was identified. So, 12 galleries (Miraflores, El Carmen, Jesús María, La Quinta, Concova, San Isidro, Santa Elena I, Santa Elena II, Comiña, Santa Cruz, El Gólgota y Buena Esperanza I) probably have a total gallery length higher than specified in table 1.

Besides the underground tunnels, the *socavones* have also a number of elements that are visible on the ground surface. In the Pica area, 154 points related with the *socavones* were identified in the field and georeferenced. Those points are either shaft wells (called *lumbreras*, which literally means luminary), exit points, wells or reservoirs (Fig. 1A).

The identification of the main tunnel where there are many side branches was sometimes complex. In some cases, the main gallery was identified because an iron sign with the mention *matriz* (that can be translated as principal from informal Spanish) was found. Probably the iron-sign helped the orientation of new workers or in case of emergency purposes. In other cases, the main gallery was defined based on its aspect of spine, or because it is the longest or the gallery with the last shaft well.

Many *socavones* have side branches in the water production section, especially at the end of the main gallery (Fig. 1A). The discharge flow of the socavon can be increased by digging side branches that feed into the main tunnel.

The tunnels are generally narrow and tall with a regular and average width of 0.8 m. This is slightly wider than the shoulders’ width of an adult, which is not too narrow for the gallery to be access comfortably and not too wide, which would mean unnecessary digging and longer construction time and cost. The height of the tunnels is more variable, 1.8 m on average. Some galleries (or sections) are only 0.5 m high (sections of El Sauque, end of San Matías, one gallery of Jesús María). The maximum gallery height is 7 m in Loreto, Puquio el Núñez and Buena Esperanza II. In those cases, it is likely that the initial tunnel’s ground was dug deeper to increase the gallery’s flow as shown by the niches done in the walls for the lamps, which are now out of reach.

The slopes of the tunnels vary according to the *socavones*. Most of them have an optimal gradient according to Semsar Yazdi and Labbaf Khaneiki (2017), *i.e.*, between 0.2% and 0.5% (Comiña, El Carmen, Buena Esperanza II). But some galleries have a higher than normal gradient, above 0.5% (El Sauque and Puquio Núñez with 0.9%), even above 1% (Loreto with 1.35% and San Matías, with 2.6%). A higher gradient may cause the erosion of the tunnel ground. In all the galleries with a higher slope, a hard-rocky layer of ignimbrite (volcanic rock originated by pyroclastic flows) is present, except in Puquio Núñez. This is due to the fact that, when the workers came across a layer of ignimbrite, it was probably impossible to continue

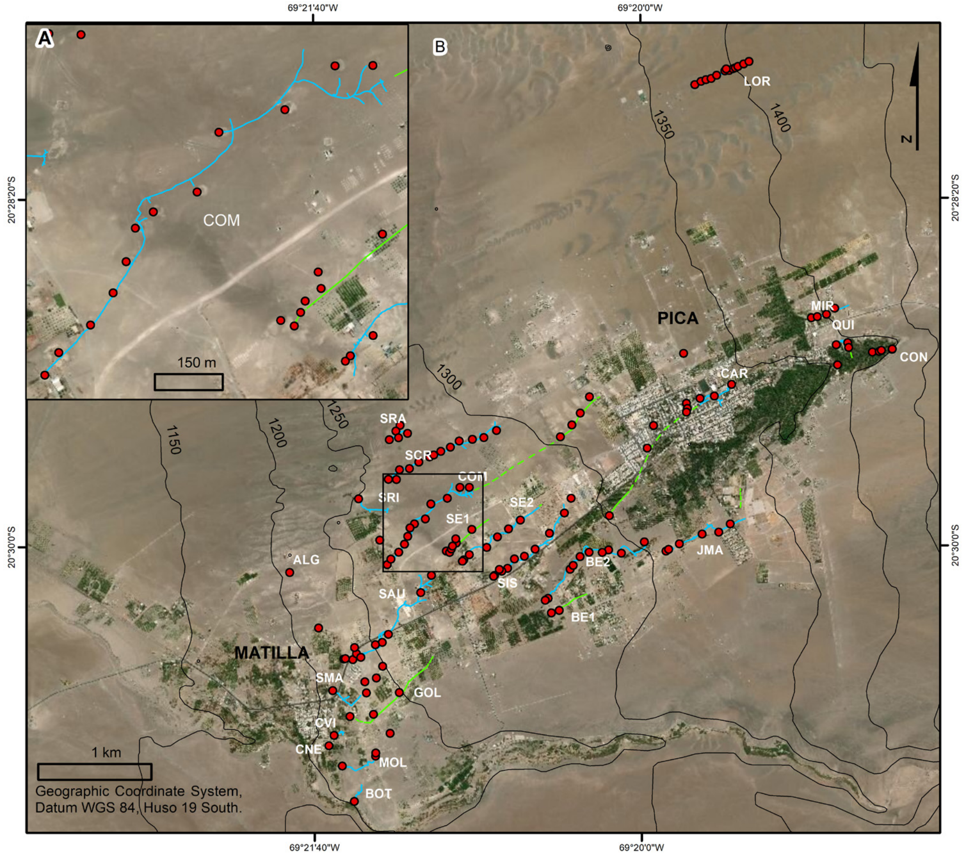

FIG. 1A. Map of the identified *socavones* and elements of the *socavones* visible on the ground surface of the Pica area. The area of Puquio Núñez is not represented on the map. **A.** Zoom of Comiña *socavón*. **Blue line:** *socavón* identified through direct exploration. **Green line:** socavon identified through geophysical survey. **B.** *Socavones* located in Pica and Matilla Oasis. **Dotted line:** inferred gallery. **Red dot:** *Lumbrera*. **PNU:** Puquio Núñez; **LOR:** Loreto; **CAR:** El Carmen; **QUI:** La Quinta; **CON:** Concova; **SRA:** Santa Rosa; **SCR:** Santa Cruz; **SRI:** Santa Rosita; **ALG:** El Algarrobo; **COM:** Comiña; **SE1:** Santa Elena I; **SE2:** Santa Elena II; **SIS:** San Isidro; **SAU:** El Sauque; **SMA:** San Matías; **GOL:** El Gólgota; **CVI:** Cementerio Viejo; **MOL:** Puquio El Molle; **BOT:** Botijería; **BE1:** Buena Esperanza I; **BE2:** Buena Esperanza II; **JMA:** Jesús María; **MIR:** Miraflores; CNE: Cementerio Nuevo.

digging the tunnel. To avoid abandoning the gallery, the only option was to bypass the obstacle. In those cases, workers dug upward at a right angle and then get horizontal again and dug forward so the tunnel carries on over the rocky layer (Fig. 2A).

The main tunnel and side branches end abruptly in general, with two or three horizontal holes which purpose was to increase the draining area and the water flow. The directions and lengths of the side branches are very variable. Many of these galleries were intentionally covered, semi-buried or permanently sealed with stones and few with cement. The reason behind is probably that they were or became dry and were used for the evacuation of sediments (thus avoiding the need to carry back soil extracted up to the surface).

Sometimes the tunnel ground is covered with a channel made of baked clay tiles in the water transport section (Santa Elena II, Comiña; Fig. 3A). This technique was used to facilitate the groundwater flow and prevent filtrations in the water transport section (through the permeable material in which was dug the gallery or through fractures in the hard layers). In recent years, some tunnel grounds have been covered with plastic sheeting or water is conveyed through PVC or cement pipes in order to prevent a loss of flow through filtration (Loreto, San Isidro, Puquio El Molle).

FIG. 2A. Steps in the main galleries. **Left:** *socavón* San Matías. **Right:** *socavón* Loreto.

1.1. Ground surface elements of the *socavones*

In most cases, downward the tunnel exit point, there is an open channel connecting the tunnel with a reservoir and then with the cultivated land (*chacras*). Although most of the *socavones* do not discharge anymore water and the infrastructure and the *chacras* are abandoned, their remnants are often still visible through Satellite images (Fig. 4A).

Near Matilla, the exit point of the *socavones* is often located on an escarpment (steeper ground gradient). The workers probably took advantage of those escarpments, which allowed them to dig shorter tunnels to tap the aquifer. If the ground has a steep slope, the tunnel and ground surface intersect sooner (higher difference between the ground gradient and the tunnel gradient), in contrast to a land with a gentle slope, where the gallery has to travel a longer distance to meet the surface (Semsar Yazdi and Labbaf Khaneiki, 2017). Indeed, the *socavones* which exit point is in the escarpment of Matilla, on the south-western edge of the area, have the shortest galleries, but El Sauque. On the contrary, the *socavones* located in the middle of the basin (flatter area) have the longest galleries. On the north-eastern edge, the ground slope starts to increase, and again the galleries' length is shorter (Fig. 2A).

In the area of Pica, parallelepiped blocks of baked clay and cement around half meter high were located on the ground at a distance of 200 m on each side of the tunnel, defining a buffer zone where no activities harmful for the gallery structure and its discharge flow could be carried out. This rule is however disregarded today.

The *socavones* located in the oasis of Pica are very close to each other. In most cases, they are separated from each other by less than 500 m, and in some cases less than 200 m. As reported by Semsar Yazdi and Labbaf Khaneiki (2017), in Iran, a filtration gallery built in a soft soil should lie at least 1,500 m away from the nearby gallery -and 1,000 m in a hard soil- so they do not affect each other discharge flow.

FIG. 3A. Baked clay tiles channel in Comiña *socavón*.

FIG. 4A. Satellite view of the ground surface elements of the *socavones*

1.2. The shaft wells

In the 24 *socavones*, 116 shaft wells were identified (Fig. 1A). Many shaft wells are today in a poor state, collapsed or blocked by sand and/or garbage. In some cases, they have been totally destroyed by the land owners. Therefore, only some of them are accessible. The gallery with the higher number of shaft wells is Comiña (17) as it has the longest main gallery. Then Santa Cruz has 12 shaft wells, followed by Loreto and San Isidro with 10 shaft wells. The shortest *socavones* have either one or no shaft wells (Cementerio Viejo, Puquio El Molle, Concova, Botijería, Santa Rosita, El Algarrobo). The average distance between shaft wells is 150 m. According to (Semsar Yazdi and Labbaf Khaneiki, 2017), the distance between shaft wells is usually twice the depth of the wells but this rule was not applied in the Pica area.

In Pica, the shaft wells are not located vertically over the main tunnel but either on the right or on the left side of the galleries, without any apparent logic. Actually, in the *socavones*, the shaft wells or *lumbreras* are branch galleries connecting the main tunnel to the ground surface (Fig. 5A). They are perpendicular to the main tunnel with a steep gradient and end with a well connecting the gallery to the surface. In order to facilitate the access through the steep slope, steps were carved on the ground. The well is, in general, a few meters deep and with a square shape. It can be up to 9 m deep and exceptionally 20 m deep (El Carmen, which is the deepest *socavón*). The only exception is Loreto where the *lumbreras* are vertical wells located right over the main tunnel. As well, exceptionally, some *lumbreras* are spiral staircases (Santa Cruz or El Sauque) or a succession of short sections of gallery with turns of 90 degrees. Given that the wells were carved in a very soft material (unconsolidated sand), their walls were consolidated with clay bricks (adobe), or more recently with concrete. Although today many shaft wells are totally covered by sand, fortunately the sediments do not reach and block the main tunnel so far.

FIG. 5A. Typical shaft well (*lumbrera*) in the Pica area.