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REPORT

Connectivity of fractures and groundwater flows analyses into the Western Andean Front by means of a topological approach (Aconcagua Basin, Central Chile)

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Abstract

The misunderstanding of hydrogeological processes together with the oversimplification of aquifer conceptual models result in numerous inaccuracies in the management of groundwater resources. In Central Chile (32–36°S), hydrogeological studies have exclusively focused to alluvial aquifers in valleys (~15% of total area) and mountain-front zones remain considered as no-flux boundary conditions. By a topological approach and an analysis of fractures, the hydrogeological potential of the Western Andean Front along the N–S-oriented Pocuro Fault Zone (PFZ) in the Aconcagua Basin were determined. Perennial springs (23) show evidence of groundwater flows into the fractured Principal Cordillera. Topology allows for quantification of the density of connected fractures within the fault zone and its relationship with groundwater circulation. The study results highlight two areas where the density of fractures and connected nodes (Nc) is high (>2.4 km/km^2, 2.5 Nc/km^2). Both areas are topologically related to the main springs of the PFZ: *Termas de Jahuel* (discharge ~14.0 m^3/h at 22 °C) and *Termas El Corazón* (discharge ~7.2 m^3/h at 20 °C). Outcrop-scale mapping reveals that groundwater outflows from NW–SE fractures, which is consistent with the preferential orientation of the fracture network (N30–60 W) within the PFZ. The results indicate that oblique basement faults are discrete high-permeability structures conducting groundwater across the Western Andean Front from the Principal Cordillera up to adjacent alluvial aquifers (focused recharge). Therefore, the simplistic hydrogeological view of the Western Andean Front (i.e. impervious limit) is partially erroneous.

Keywords Springs · Fractured rock · Groundwater exploration · Chile

Introduction

In arid regions, the sustainable exploitation of groundwater resources is limited by a misunderstanding of the hydrogeological processes (e.g. groundwater recharge; Simmers 1997; de Vries and Simmers 2002; Scanlon et al. 2006; Healy and Scanlon 2010), which leads to unsuitable management policies, making groundwater resources and related social-economic activities vulnerable to abrupt climate changes (Custodio 2002; Massuel and Riaux 2017; Taylor et al. 2019).

In Chile, the hydrogeological studies have been generally focused on alluvial aquifers located in valleys and basin floors (Muñoz et al. 2003; Rojas and Dassargues 2007; Oyarzún et al. 2014; Jordan et al. 2015; Ribeiro et al. 2015; Muñoz et al. 2016; Oyarzún et al. 2016; Salas et al. 2016; Fernández et al. 2017; Urrutia et al. 2018; Viguier et al. 2018, 2019; Valois et al. 2020), whilst such lithologies solely constitute ~15% of total area of Chile (SERNAGEOMIN 2003). In Central Chile (32–36°S; Fig. 1a), the hydrogeological relations between alluvial sediments and surrounding rocks have remained unstudied because observation boreholes are missing from the mountain front zones (regionally named Western Andean Front; Rauld 2011). As a result, the recharge from lateral fractured rocks has been

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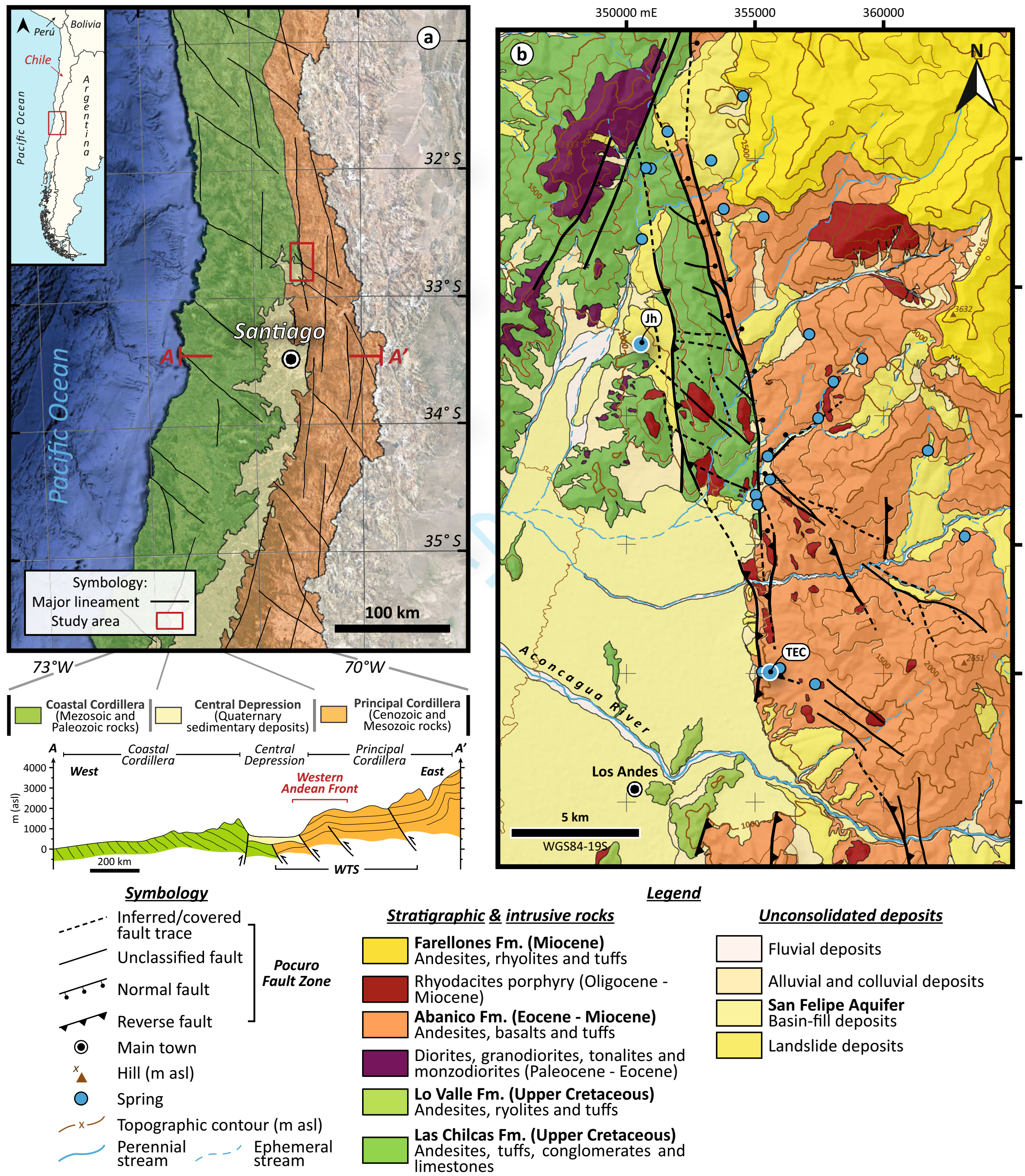


Fig. 1 **a** Morphotectonic context and cross-section (A–A′) of the Andes of Central Chile (based on SERNAGEOMIN 2003): in green the Coastal Cordillera, in pale-yellow the Central Depression and in orange the Principal Cordillera. The N–S-oriented west vergent thrust system (WTS) shapes the Western Andean Front. **b** Geological map of the study area highlighting the major springs: Termas de Jahuel (Jh) and Termas El Corazón (TEC). The lithological information is based on Rivano et al. (1993), Jara and Charrier (2014), and Boyce et al. (2020)

arbitrarily discarded from hydrogeological conceptual models leading to an oversimplification of the boundary conditions. Indeed, the Western Andean Front, separating the Central Depression from the Principal Cordillera (Fig. 1a), is considered as no-flux boundary conditions in the numerical modeling of adjacent alluvial aquifers (DGA 2015, 2016, 2019a). The groundwater recharge of Central Chile aquifers is exclusively considered from meteoric water infiltration and river losses (DGA 2015, 2016, 2019a).

Nevertheless, the Western Andean Front (Fig. 1a) hosts numerous springs with perennial outflows (Hauser 1997; Bustamante et al. 2012; Benavente et al. 2016). The occurrence of those springs suggests that groundwater circulates into the mountain block through fractures and contributes to recharge of the adjacent Central Depression alluvial aquifers (Taucare et al. 2020). Indeed, mountain-block recharge is a major component in the renewal of lowland alluvial aquifers adjacent to the mountain ranges (Wilson and Guan 2004; Aishlin and McNamara 2011;

Gillespie et al. 2012; Nelson and Mayo 2014; Bresciani et al. 2018; Peng et al. 2018; Markovich et al. 2019; Gleason et al. 2020). Mountain-block recharge occurs by diffuse flows along the mountain front as well as by focused flows through oblique faults crossing the mountain front (Wilson and Guan 2004; Kebede et al. 2008; Taillefer et al. 2018; Markovich et al. 2019; Walter et al. 2019). In fact, the Western Andean Front (Fig. 1a), shaped by major N–S-oriented thrust-fold structures (Armijo et al. 2010; Farías et al. 2010; Vargas et al. 2014), is also segmented by oblique faults (Cembrano and Lara 2009; Piquer et al. 2017; Veloso et al. 2019; Yañez and Rivera 2019). Consequently, the assumption that fractured rocks and oblique faults are contributing to recharge of adjacent alluvial aquifers is highly plausible although it has not been characterized yet in Central Chile.

Since 2010 Central Chile has undergone a “megadrought” (Garreaud et al. 2017, 2019) impacting the availability of groundwater resources. This alarming situation, together with increasing social tensions (Rivera et al. 2016), makes it necessary to reevaluate the hydrogeological conceptual models in Central Chile, especially the role of the Western Andean Front in the recharge of adjacent alluvial aquifers.

Therefore, this study aims to assess the hydrogeological potential of the Western Andean Front, exploring the topological relation between the fracture network and perennial groundwater outflows (springs), in the Aconcagua Basin and the Pocuro Fault zone (Fig. 1b). Results will allow verification of the hypothesis of groundwater circulation in discrete permeable structures (e.g. fractures, faults). In addition, the findings could be used in future studies as the basis for quantifying the mountain-block recharge from the Western Andean Front.

Hydrogeological setting

Central Chile (32–36°S) is segmented into three major N–S-oriented morphotectonic domains (Cembrano et al. 2007), identified from west to east as (Fig. 1a): (1) the Coastal Cordillera (up to 2,000 m above sea level, asl) mainly composed of Mesozoic volcano-sedimentary and intrusive rocks (e.g. Las Chilcas Fm and Lo Valle Fm), (2) the Central Depression (~570 m asl) filled by Quaternary alluvial sediments with an average thickness of ~300 m (Yáñez et al. 2015), and (3) the Principal Cordillera (up to 5,000–6,000 m asl) mainly composed of Cenozoic volcano-sedimentary and intrusive rocks (e.g. Abanico Fm. and Farellones Fm.). Those morphotectonic domains were developed by N–S-oriented major faults (Giambiagi et al. 2003; Charrier et al. 2007) segmented by NW-oriented (i.e. NW–SE) and NE-oriented (i.e. NE–SW) faults (Cembrano and Lara 2009; Piquer et al. 2017; Veloso et al. 2019; Yáñez and Rivera 2019).

The studied segment of the Western Andean Front is located in the Aconcagua Basin, at 32°50′S (Fig. 1b). It is shaped by the Pocuro Fault Zone (PFZ; Carter and Aguirre 1965), a brittle deformation zone 150 km long and 4 km wide. At least 23 perennial springs outflow in the Western Andean Front through fractures. Springs are fed by the indirect infiltration (in gullies) of rain and snowmelt occurring above 2,000 m asl in the Principal Cordillera (Taucare et al. 2020). In this zone, Darwin (1839) described the two major springs of the study area: Termas de Jahuel (22 °C) and Termas El Corazón (20 °C). The mean spring discharges are ~14.0 and ~ 7.2 m^3/h, respectively. In both cases, groundwater is used for thermal-bath activities and mineral water bottling (Daniele et al. 2019). To increase groundwater discharge at both springs, galleries ranging from 7 to 30 m long were excavated into the volcano-sedimentary rocks.

The study area is characterized by a semi-arid climate with historic (1980–2010) mean annual precipitation of 270 mm/year in the Central Depression and 525 mm/year in the Principal Cordillera (hydrological data provided by *Dirección General de Aguas*, DGA 2019b). In the Western Andean Front, mean annual air temperature at the ground surface is ~15 °C. Since 2010, Central Chile has been experiencing an uninterrupted sequence of dry years with a rainfall deficit up to 45% relative to the historic period (Garreaud et al. 2017, 2019). Historically, surface water from the Aconcagua River was distributed by gravity-driven channels for family farming activities; however, since the late 1980s, for supplying intensive farming activities (e.g. grapes and avocados), groundwater is mainly extracted by deep boreholes (200–300 m depth) from the San Felipe aquifer contained in the Quaternary alluvial deposits of the Central Depression (Fig. 1b). Between 1980 and 2018, the authorized groundwater extraction increased by around 3,640%, from 0.33 to 12.33 m^3/s (Taucare et al. 2020 after DGA 2019b). Ongoing megadrought, together with the increasing groundwater extraction, has caused the decline of groundwater levels up to 40 m (DGA 2019b), strengthening the risk of groundwater resource depletion.

Topological approach

In fractured aquifers, preferential flow-paths take place within the fracture network, which can be described in terms of connectivity and density of fractures (Berkowitz 2002; Manzocchi 2002; Makel 2007; Maillot et al. 2016; Viswanathan et al. 2018). Thus, the mentioned flow-paths can be properly addressed using a topological approach (Sævik and Nixon 2017). This approach was used to assess the impact of the fracture network on the hydraulic connectivity in crystalline rocks (Zuluaga et al. 2018) and carbonate rocks (Fournillon et al. 2012; Dimmen et al. 2017; Aliouache et al. 2019). Nevertheless, the topological approach is not commonly used for the exploration of groundwater resources in mountain front zones.

The topological approach uses components, such as “nodes” and “branches” (Jing and Stephansson 1997; Sanderson and Nixon 2015, 2018): A “node” is a point where a line ends or intersects another line (Fig. 2). A “node” can be classified as isolated (I-node), abutting (Y-node), or as crossing nodes (X-node). A “branch” is a line bounded by an isolated node (I-) or a connecting node (Y- or X-) (Fig. 2), and it can be classified as an isolated (I–I), partially connected (C–I), fully connected (C–C) branch, but also as an unknown branch (Unk) when this latter intersects the limits of the study area.

At the scale of the study area (650 km^2; Fig. 1a), the topological approach was conducted by the digitalization of morphostructural lineaments such as fractures and faults ($n = 216$) from a high-resolution photomosaic extracted from Google Earth (pixel size ≈2.5 m) and supported by field surveys (Fig. 3a). The spatial distribution of the fracture network topological parameters was processed by a geographic information system (GIS), using the NetworkGT tool developed by Nyberg et al. (2018). A total of 472 nodes and 511 branches were extracted from the fracture network (Fig. 3b): 228 I-nodes, 194 Y-nodes and 50 X-nodes as well as 25 I–I branches, 169 C–I branches, 305 C–C branches and 12 Unk branches. Because groundwater circulates in connected fractures (Makel 2007), only connected branches (C–I and C–C) and connecting nodes (Y- and X-) were further considered. Using a Kernel density tool (e.g. Dimmen et al. 2017), the spatial distribution is shown for the following parameters in the PFZ: (1) the density of fractures, which involves the total branch length per surface unit (km/km^2), and (2) the density of connected nodes, which illustrates the number of connected nodes (Nc = Y-node + X-node) per surface unit (Nc/km^2). In addition, fracture analyses were carried out at the outcrop scale in two areas within the PFZ, at Termas El Corazón ($n = 152$) in the Abanico Fm., and at 5 km to the east of Termas de Jahuel ($n = 45$) in the Las Chilcas Fm. Both areas (~200 m^2) have well-preserved outcrops that enable a three-dimensional (3D) view (cross section and plan-view) of the fracture network.

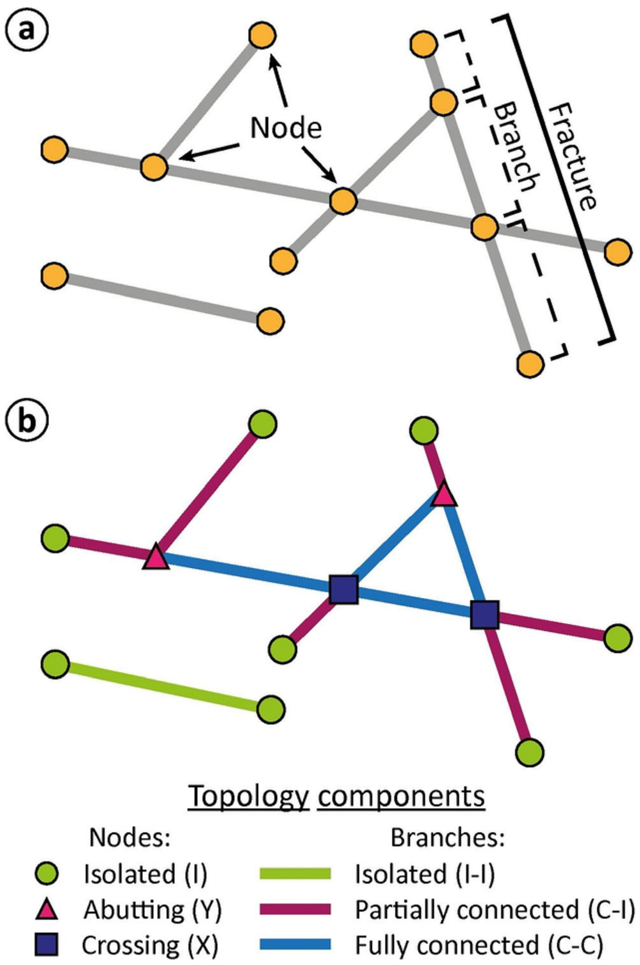


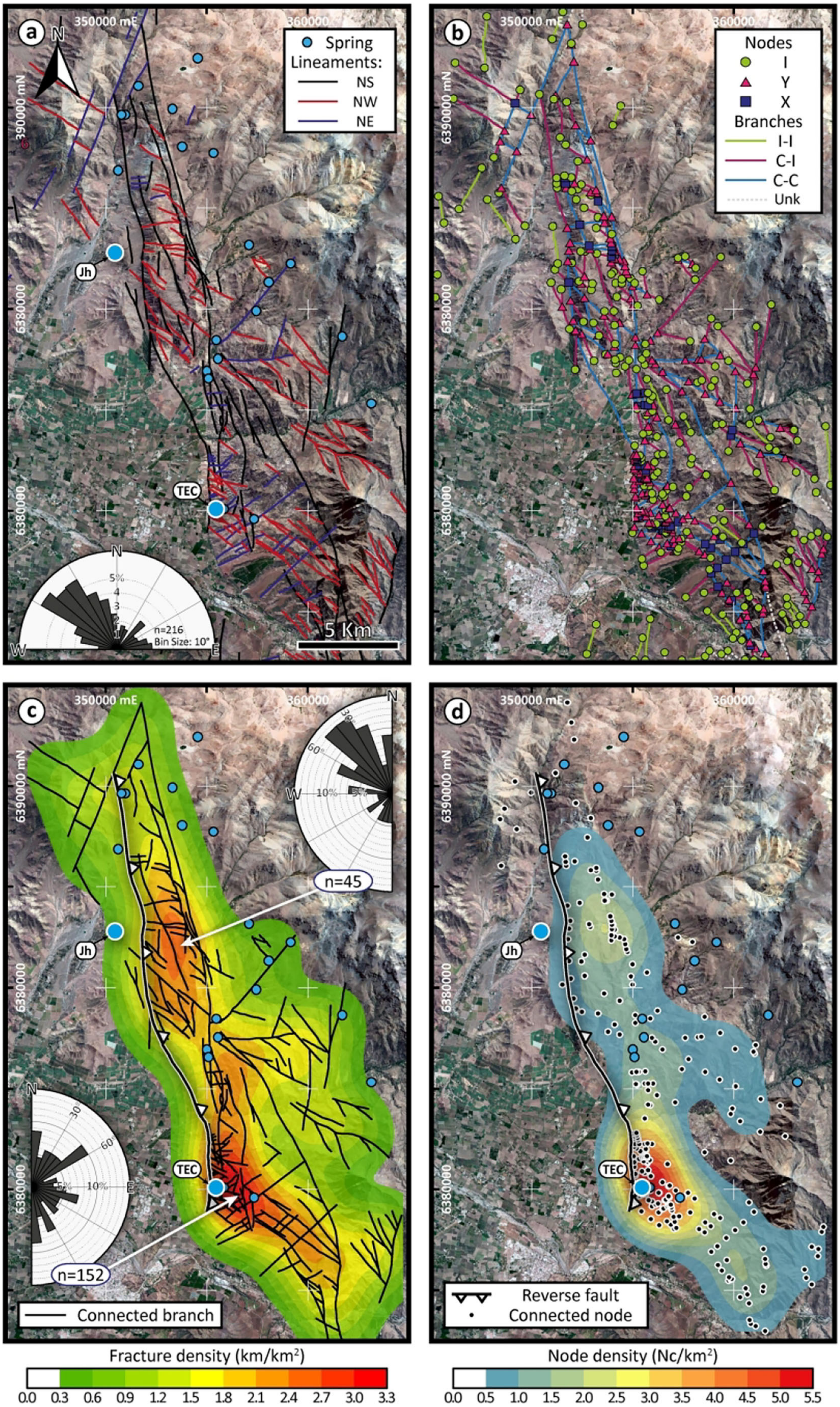
Fig. 2 Topological nomenclature for fracture network characterization after Sanderson and Nixon (2015). **a** Trace map of a fracture network, and **b** its topological characterization

Fig. 3 Topological analysis of the fracture network in the Pocuro Fault Zone (PFZ). **a** Fracture network of PFZ; the different orientations are highlighted in different colours. Rose diagram shows the orientation of 216 mapped lineaments with bin size 10°. **b** Topological characterization of the fracture network. **c** Contour map showing the density of connected branches (C-I and C-C branch). Rose diagrams (bin size 10°) show the orientation of 45 and 152 fractures mapped from representative areas at Termas El Corazón and to the east of Termas de Jahuel. **d** Contour map showing the density of connected nodes (Nc = Y-node + X-node). Coordinate system WGS84-Utm19s. Major springs are highlighted: Termas de Jahuel (Jh) and Termas El Corazón (TEC) ▶

Results

At the scale of the study area, the analysis of the fracture network shows that the damage zone of PFZ is governed by a N30–60 W preferential orientation (Fig. 3a). At the outcrop scale, a well-defined N30–50 W preferential orientation characterizes the fracture network near Termas de Jahuel, while no one preferential orientation pattern is observed in Termas El Corazón (Fig. 3c). This missing preferential orientation pattern may result from the PFZ complexity related to the different tectonic events (Jara and Charrier 2014; Taucare et al. 2018). However, into both galleries, excavated for increasing the groundwater discharge, it was observed that groundwater outflows from N40–60 W fractures (e.g. Fig. 4b). At Termas El Corazón, the NW-oriented fractures are associated to an oblique basement fault that controls the landscape in the gully orientation, where several springs outflow (Fig. 4a). At about Termas de Jahuel, the spring is related to buried oblique basement faults (local landslide), which outcrop to the east, as can be seen in the geological map of Fig. 1b.

The topological analysis highlights two areas of high density of connected fractures (Fig. 3c) and connected nodes (Fig.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Node density (Nc/km²)
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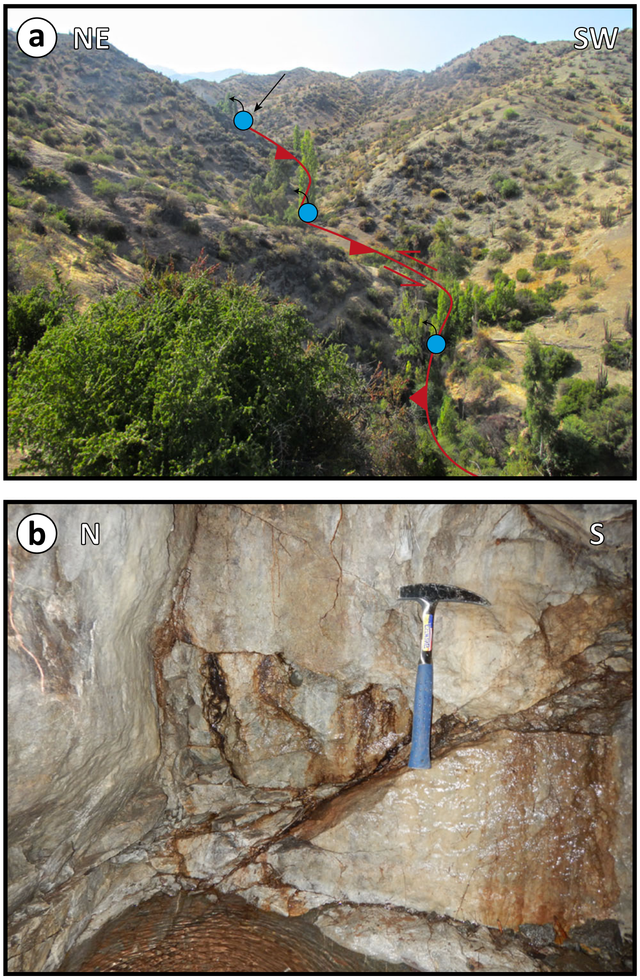

Fig. 4 **a** Spring locations along a fault-controlled gully at Termas El Corazón. **b** Groundwater outflowing from an oblique basement fault in the Termas El Corazón gallery

3d), both related to the main springs of the PFZ. The first one, related to the area in the east of Termas de Jahuel (<5 km), shows a density of fractures and connected nodes reaching 2.4 km/km^2 and 2.5 Nc/km^2, respectively; while the second one, related to Termas El Corazón, shows a density of fractures and connected nodes reaching 3.3 km/km^2 and 5.5 Nc/km^2, respectively.

Discussion

The observed topological relation between the density of fractures, connected nodes and springs, together with the observed congruence between the orientation of fractures in both galleries and areas into the PFZ damage zone, indicates that the NW orientation is a main groundwater-drainage axis. NW-fractures, oblique to the main N–S-oriented fault trace of PFZ, would drain most groundwater into the PFZ damage zone, taking advantage of a higher density of connected fractures than into the Principal Cordillera (Fig. 3c,d). Oyarzún et al. (2017) and Piquer et al. (2019) showed that in Central Chile, the NW- and NE-oriented oblique basement faults are spatially related to the main springs and shallow groundwater circulation in hard rocks, but also to some productive wells (some of them discharging greater than 36 m^3/h; Oyarzún et al. 2017). Yáñez et al. (2015) demonstrated by geophysical exploration (gravity surveys supported by magnetic and geoelectrical surveys) that NW- and NE-fractures, structurally related to basement faults and oblique to the Western Andean Front, are continued into the Central Depression below the Quaternary cover. At a regional scale, the preferential circulation of fluids (including hydrothermal fluids) along the oblique basement faults is due to a N–S preferential extension direction leading to the opening of interconnected fractures along these faults, with respect to the main E–W compression of the Nazca plate subduction (Veloso et al. 2019). Therefore, the oblique basement faults are discrete high-permeability axes crossing the PFZ and contributing likely to recharge of the San Felipe aquifer in the Central Depression (Fig. 5).

This hydrogeological consideration agrees with mountain-front conceptual models (Wilson and Guan 2004; Markovich et al. 2019). These conceptual models highlight the role of oblique faults (crossing the mountain front zone) in the focused recharge of adjacent alluvial aquifers by conducting groundwater circulation originating from the fractured mountain block (Fig. 5). Such a recharge process was likewise observed in other mountain-front zones such as in the Basin and Range Province of USA (Wilson and Guan 2004), East African Rift Valley (Kebede et al. 2008; Walter et al. 2019) and in the eastern part of the Pyrenean range in Europe (Taillefer et al. 2018).

Consequently, the hydrogeological insights defined for the PFZ in the Aconcagua Basin (strengthened by results acquired at different scales) allow transposing this groundwater recharge process to the whole Western Andean Front in Central Chile.

Deep flows, originating from the Principal Cordillera and circulating through basement faults, have probably long residence times (regional groundwater circulation) and may constitute nonrenewable groundwater resources. Thus, the recharge of adjacent alluvial aquifers caused by deep flows through oblique basement faults is expected to be little impacted by the current megadrought (Garreaud et al. 2017, 2019). However, most springs are fed by shallower flows that originate from the focused infiltration of precipitation and snowmelt taking place above 2000 m asl in the Western Andean Front (Taucare et al. 2020). Those springs are more vulnerable to short-term hydroclimatic changes. Therefore, the decrease over the last decade in both precipitation rates (Garreaud et al. 2017, 2019) and snowpack in high elevation Andes (Ohlanders et al. 2013; Ruiz-Pereira and Veetil 2019) is expected to have a dramatic impact on the availability of groundwater resources along the Western Andean Front. As a

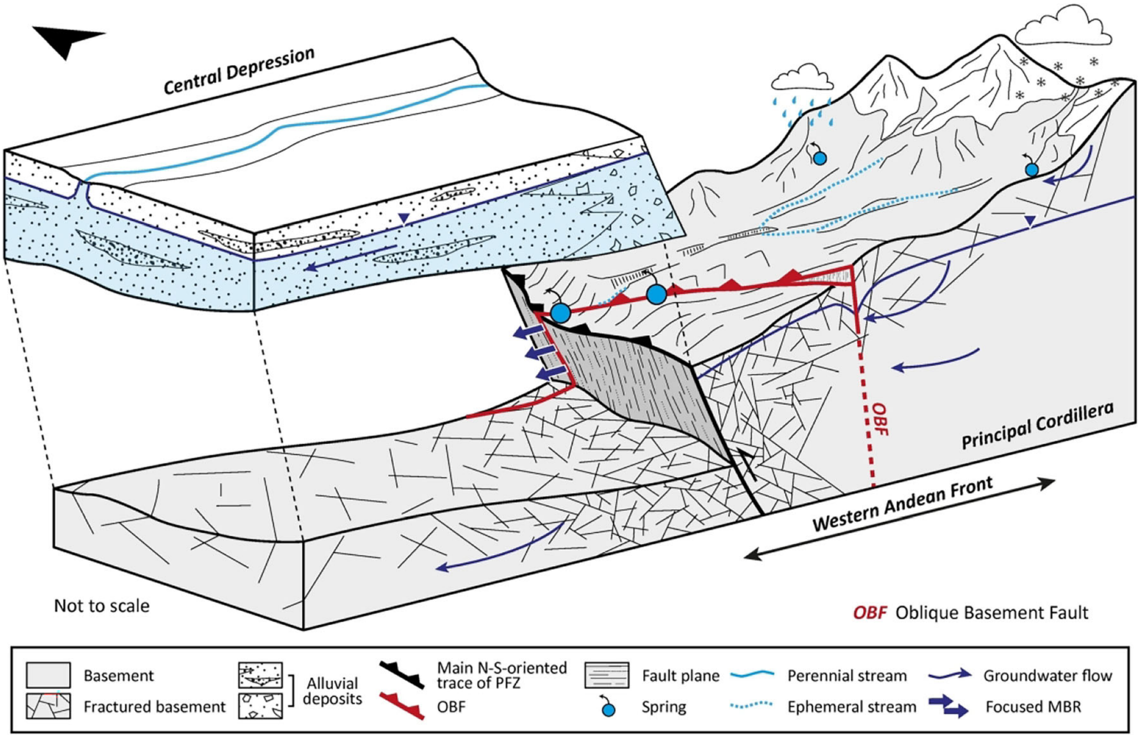

Fig. 5 Western Andean Front hydrogeological diagram highlighting the role of the oblique basement faults with respect to groundwater circulation and the recharge of adjacent alluvial aquifers. The size of each spring symbol reflects its flow rate (large spring symbol represents a high flow while the small ones have a lower flow). MBR mountain-block recharge

consequence, the local communities dependent on this resource for drinking water supply and agricultural activities will be affected.

Conclusion

Exploring the topological relations between fractures and perennial springs in the Pocuro Fault Zone at Aconcagua Basin, this study determined that the current and simplistic hydrogeological view of the Western Andean Front (i.e. an impervious limit) is erroneous. Unlike this former conceptual view, this study finds that the high density of connected fractures in the PFZ constitutes a fractured aquifer and the oblique basement faults allow drainage of groundwater from the Principal Cordillera. Independent of the temporal relationship between the faults, the oblique basement faults crossing the main N–S-oriented fault trace of PFZ control the groundwater circulation and contribute to recharge of the adjacent alluvial aquifers in the Central Depression (focused process). This conclusion is in line to results obtained in Central Chile as well as in other mountain-front zones around the world. Hence, given the similar morphotectonic setting exhibited along the Andes, this model is suitable for Central Chile.

Therefore, taking into account the increasing climatic and anthropogenic pressures in Central Chile, this work suggests a thorough revision of the hydrogeological conceptual models. These new insights into the hydrogeological system will help to better assess the water resource management policies in Chile. Further research is still required to improve the quantification of groundwater recharge and to characterize groundwater vulnerability to near-future hydroclimatic changes.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflicts of interest.

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