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Geomorphologic and Glacial Evolution of the Cachapoal and southern Maipo catchments in the Andean Principal Cordillera, Central Chile (34°-35º S)

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ABSTRACT. We present here a reconstruction of the post late Miocene landscape evolution of the western slope of the Andean Cordillera Principal near 34°20' S. We base our analysis on the available geological information, a morphological characterization of the landform assemblages in the Cachapoal and southern Maipo catchments, and the first ^{10}Be exposure ages for moraines in this area. The Cachapoal drainage basin is characterized by a variety of morphological features, like an elevated low-relief surface, volcanoes and lava flows on valley slopes, U-shaped valley sections, roches moutonnées, and large glaciated areas. Different kinds of deposits have been included in the study, such as moraines, lacustrine and landslide deposits, and a well-developed system of fluvial terraces in the more distal part of the Cachapoal catchment. Landslides are mostly developed on rocks of the late Eocene-early Miocene Abanico Formation. and are less frequent in outcrops of the overlying, early to middle Miocene Farellones Formation. We estimate that the lowest end moraine in the Cachapoal catchment is located next to the locality Bocatoma Chacayes (~950 m altitude), though covered by a major landslide. No evidence exist for glacial deposits further down stream in this region. Lateral moraine ridges of the Cachapoal Glacier at Los Cerrillos yielded ^{10}Be exposure ages of 20.3±2.9 and 21.9±5.3 ka that indicate they are associated with the Last Glacial Maximum (LGM). Holocene moraines exist next to all glacier tongues. Of particular interest in this region is the 12 km-long debris-covered Cachapoal Glacier, the longest valley glacier in the central Chilean Andes, and its distal and proximal moraine deposits. Two lateral moraines adjacent to the present-day Cachapoal Glacier yielded exposure average ages of 13.5±2.4 ka for the external ridge, indicating the Younger Dryas, and 3.8±0.8 ka for the internal ridge, an age that coincides with the 4.2 ka global climatic event that marks the beginning of the Meghalayan Age, at the end of the Holocene. The large size of this moraine on both sides of the ice tongue indicates the great development of the glacier at that time. Some of these ages coincide with ages obtained further north in the Maipo drainage basin, at the latitude of Santiago, and in the eastern flank of the cordillera, however, no pre-LGM deposits were found here, unlike the other mentioned regions. This difference together with the much lower altitude of the LGM moraine deposits in the study region suggests that the Cachapoal catchment is a transition zone to a more humid region further south, and indicates the great need for further reconnaissance and dating of glacial deposits in this Andean region. Our analysis of the geomorphological evolution is consistent with incision start for the Cachapoal Valley in latest Miocene. In this process, glacier incision was apparently not much effective until mid-Pleistocene time, when volcanism was active in the higher regions of the mountain range covering areas not yet incised, whereas in the western Principal Cordillera lavas flowed in deeply incised valleys. Pleistocene glaciers deepened and shaped the already incised valleys, which are presently mostly occupied by rivers.

Keywords: Post-Miocene landscape evolution, ^{10}Be exposure ages, LGM, Younger Dryas, Cachapoal drainage basin, Principal Cordillera, Central Andes, Chile.

RESUMEN. Evolución geomorfológica y glaciar de las hoyas de los ríos Maipo superior y Cachapoal en la Cordillera Principal Andina, Chile central (34°-35° S). En este artículo presentamos una reconstrucción de la evolución post-Mioceno tardío del paisaje de la vertiente occidental de la Cordillera Principal a los 34°20' S. Este análisis se basa en la información geológica disponible, en una caracterización de los rasgos morfológicos en las cuencas de drenaje del río Cachapoal y de la parte sur del río Maipo, y en las primeras edades de exposición obtenidas por el método de ^{10}Be en morrenas laterales del glaciar Cachapoal. La hoya del río Cachapoal se caracteriza por una serie de rasgos morfológicos, como una superficie elevada de bajo relieve, volcanes y flujos de lava adosados a las laderas de algunos valles, secciones de valles en forma de U, rocas aborregadas, y extensas áreas cubiertas por hielo. Se han incluido en el análisis diferentes tipos de depósitos, tales como morrenas, depósitos lacustres, deslizamientos de rocas y sistemas de terrazas bien desarrollados en la parte distal de la hoya de Cachapoal. Los deslizamientos se concentran en rocas de la Formación Abanico (Eoceno superior-Mioceno inferior) y son menos frecuentes en sectores donde aflora la Formación Farellones (Mioceno inferior a medio). Estimamos que la morrena frontal más baja se ubica en el sector de Bocatoma Chacayes, a ~950 m de altitud, aunque estaría cubierta por depósitos de un gran deslizamiento. No existen evidencias de depósitos glaciales aguas abajo de la localidad mencionada. Uno de cuatro cordones de morrenas laterales del glaciar Cachapoal en la localidad de Los Cerrillos entregó edades de exposición ^{10}Be de 20,3±2,9 y 21,9±5,3 ka, que indican que estos cordones se pueden asociar al Último Máximo Glacial (LGM). Morrenas holocénicas existen en relación con todas las lenguas glaciares actuales. De especial interés en esta región son el glaciar Cachapoal, una lengua de hielo de unos 12 km de longitud cubierta de detritos, que constituye el glaciar de mayor longitud en los Andes chilenos centrales, y sus morrenas distales y proximales. Dos morrenas laterales adyacentes al glaciar dieron una edad promedio de exposición de 13,5±2,4 ka para el cordón exterior, lo que corresponde al Younger Dryas, y 3,8±0,8 ka para el cordón interno, una edad que coincide con el evento climático global a los 4,2 ka, que marca el inicio de la edad Meghalayana, al final del Holoceno. El gran tamaño de esta morrena a ambos lados de la lengua de hielo representa el fuerte desarrollo del glaciar en ese momento. Algunas de estas edades coinciden con otras obtenidas más al norte en la cuenca del río Maipo, a la latitud de Santiago, y en la vertiente argentina de la cordillera; sin embargo, en la región de estudio no se han encontrado depósitos anteriores al LGM como ha ocurrido en las otras regiones mencionadas. Esta diferencia y la considerablemente menor altitud de los depósitos datados para el LGM en la región de estudio sugieren que la cuenca del Cachapoal corresponde a una zona de transición hacia una región más húmeda hacia el sur y pone en evidencia la necesidad de continuar con estudios de este tipo para precisar la cronología glacial y las condiciones climáticas que imperaron en la región central de Chile en el Pleistoceno tardío y el Holoceno. Nuestro análisis de la evolución geomorfológica muestra que la incisión del valle de Cachapoal en la Cordillera Principal se inició en el Mioceno tardío. En este proceso, la incisión glacial aparentemente no fue muy eficiente hasta mediados del Pleistoceno, momento hasta el cual el volcanismo fue activo en las regiones más altas de la cadena cubriendo áreas aún no excavadas por los ríos, mientras que en la parte occidental de la Cordillera Principal las lavas fluyeron por valles fuertemente excavados. Los glaciares del Pleistoceno profundizaron y modelaron los valles parcialmente incididos, que actualmente están ocupados en su mayoría por ríos.

Palabras clave: Evolución morfológica post-Miocénica, Edades ^{10}Be, LGM, Younger Dryas, Cuenca del río Cachapoal, Cordillera Principal, Andes Centrales, Chile.

1. Introduction

We present here a geomorphological characterization of the Cachapoal and southern Maipo catchments in the western slopes of the Andean Principal Cordillera in central Chile, at ~34°20'S (Fig. 1). Based on it and on available geologic information for this region we attempt reconstruction of the post late Miocene morphological evolution in which we include the glacial evolution of the Cachapoal Glacier. Most of the geomorphological studies made in this region have been oriented to determine its glacial history through descriptions of the glacial morphology and establishing a relative chronology of the preserved glacial fronts (Brüggen, 1929; Lliboutry, 1956; Borde, 1966; Paskoff, 1970, 1977; Caviedes, 1972). Recent studies contributing absolute dating have been made by Puratich (2010) and Herrera (2016). Brüggen (1929) and Lliboutry (1956) considered that in the Maipo and Cachapoal drainage systems the Pleistocene glaciers reached the Central Depression down to altitudes of 700-800 m and 675 m a.s.l. respectively. Later studies in the Aconcagua (Caviedes,1972), Maipo (Borde, 1966; Chiu, 1991; Ormeño, 2007; Herrera, 2016), and Cachapoal (Santana, 1967) catchments concluded that the glaciers descended only to altitudes between 1,100 m and 1,300 m, and at somewhat lower altitudes further south, but still far from the Central Depression as in the Lontué valley, at 35º30' S (Puratich, 2010) (Fig. 1B). Paskoff (1977) correlated the glacial stages recognized by Santana (1967) with the ones described by Borde (1966) at

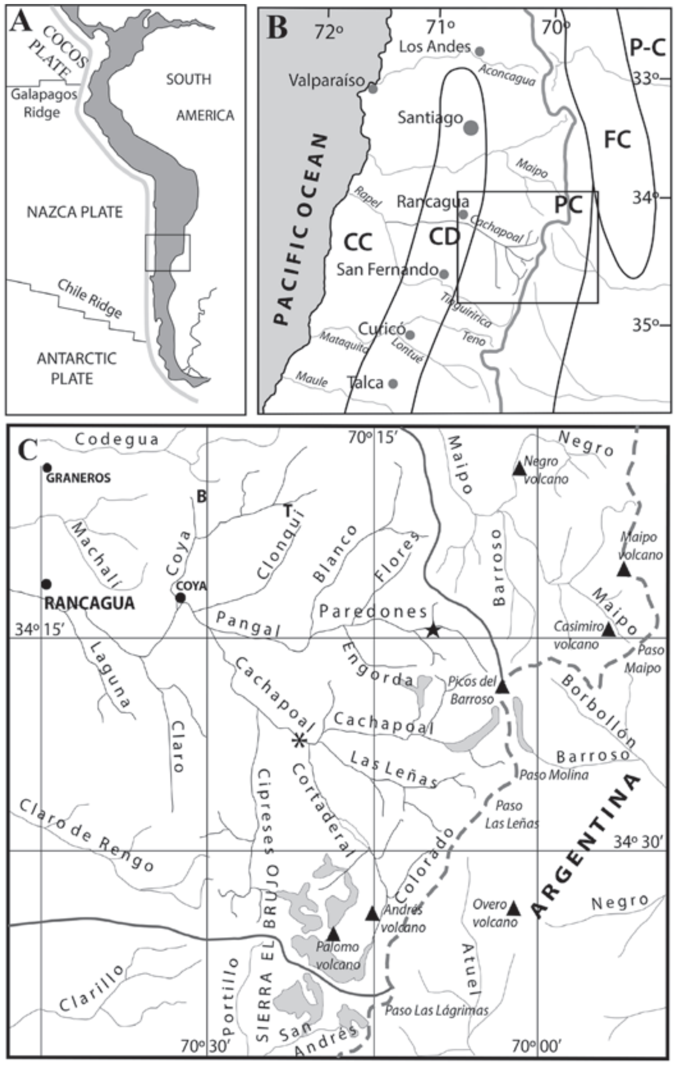

FIG. 1. **A.** Location of the study region in the Central Andes; square indicates location of figure 1B. **B.** Morphostructural subdivision of the Andean Principal Cordillera in central Chile and Argentina; square indicates location of figure 1C. Thick gray line indicates the international boundary between Chile and Argentina. **CC**: Coastal Cordillera; **CD**: Central Depression; **PC**: Principal Cordillera; **FC**: Frontal Cordillera; **P-C**: Precordillera. **C.** Fluvial systems in the western Principal Cordillera, between approximately 34° to 34°45'S. The Cachapoal catchment before its junction with the Tinguiririca River east of the Coastal Cordillera covers a surface of 6,370 km^2 (Niemeyer Fernández, 1980) and of 1,902,2 km^2 in the Principal Cordillera (Caviedes, 1979). Major glaciers are represented in light gray and the volcanoes with black triangles. Solid gray lines separate the Cachapoal from the Maipo and Tinguiririca catchments; **B**: Barahona region; **T**: Location of the El Teniente copper mine; **Black star**: Location of the Paredones Lavas mentioned in text; **Asterix**: Approximate location of meteorologic station, where the referred pluviometric data for the Cachapoal catchment stem.

Los Queltehues, in the Maipo Valley, and by Caviedes (1972), at Portillo, in the Aconcagua Valley.

The main motivation for this work is to fill the gap in geomorphological knowledge of the Cachapoal catchment in the Andean Principal Cordillera. We hope that this lead to future contributions to develop absolute chronological information on the existent glacial deposits. This is critical to understand the climatic and geologic evolution of this region, itself a key location between the Dry and Wet Andes, a climatic and glaciologic subdivision of the Argentinian and Chilean Andes proposed by Lliboutry (1998) to differentiate glaciers formed in the high and arid northern Central Andes from those formed in the more humid southern Central Andes. Another reason for our study is to put the considerable information amassed by the two first authors about the regional geology, volcanism, and geomorphological features acquired along decades in several field campaigns, integrated and published for the first time. Additionally, this information can be now complemented with the much better understanding of the Neogene tectonic and paleogeographical evolution of the Andean Principal Cordillera in central Chile obtained more recently (see Farías *et al.,* 2008; Rodríguez *et al.*, 2015 and literature therein). Therefore, the present work represents a multi-proxy approach based on geomorphological mapping, geological information, ^{10}Be dating, analysis of aerial and satellite images, and historical data. During two recent, 7 and 10 days field campaigns in 2012 and 2013, the samples for cosmogenic dating were collected in order to provide further evidence on the extension and chronology of the Quaternary glaciation in the framework of a project on the glacial geomorphology in the Wet or Tropical and the Dry Andes sponsored by the german Alexander von Humboldt Foundation. These observations included two of the main tributary river valleys of the Cachapoal (the Cortaderal and Cipreses valleys), the Cachapoal Glacier and associated moraine deposits, roches moutonnées, valley cross sections, lacustrine deposits, fluvial terraces, and landslides deposits, as well as a revision of the geomorphological features described by Charrier (1981).

We were encouraged to try ^{10}Be exposure dating by preliminary field-work that had shown the existence, at the bottom of the southern cliff of the Picos del Barroso Massif and on both sides of the present day Cachapoal Glacier, of an 11 to 12 Ma old quartz dioritic pluton (Muñoz *et al.,* 2009) suggesting higher probability for finding quartz bearing blocks on the moraines of the glacier enabling us to obtain enough quartz to apply the method (Fig. 2). Similarly, other widely exposed plutons of similar composition exist in lower regions of the Cachapoal catchment that would provide quartz bearing blocks on Pleistocene moraines downstream (Charrier, 1981).

Few absolute age determinations of moraine and associated deposits (*i.e.*, lacustrine deposits) have been made in the Chilean Andes: ^{10}Be dates have been reported in the El Encierro valley, in the Huasco catchment (29° S) by Zech *et al.* (2006), in the Cordón de Doña Rosa, in the Limarí catchment (30°30' S) by Zech *et al.* (2007), AMS radiocarbon dates in the Elqui drainage basin, at La Laguna (30°30' S) by Riquelme *et al.* (2011), although the last deposit has been considered a landslide by Abele (1984), and, most recently, ^{36}Cl have been performed at Puntas Negras, in northern Chile, in the Tatio region (24.3° S) (Thornton and Ward, 2017). Recently, optical stimulated luminescence (OSL), ^{14}C and ^{36}Cl dates have been reported for the upper

FIG. 2. Panoramic westward air view (March, 2007) of the foot of the southern cliff of the Picos del Barroso Massif showing a quartz diorite outcrop (white arrow) at the bottom of the orange colored slope. The Cachapoal Glacier is covered by an avalanche of black Jurassic shale underlying the lavas forming the upper part of the unstable and steep southern flank of the Picos del Barroso Massif. According to historical images provided by Google Earth similar avalanches occur rather often. In the background, red outcrops of the Late Jurassic continental Río Damas Formation (Fig. 3).

Maipo drainage basin, immediately north of the study region (Herrera *et al.*, 2009; Herrera, 2016).

We present next a summary of antecedent data on the present-day glacial cover, knowledge about the Pleistocene glaciation of this area of the Andes, and the key geologic features needed to understand our analysis. We describe in the Results section a description of the geological and geomorphological observations made during this study in the southern Maipo and the Cachapoal catchments. Interpretations about these features, like origin, age and correlation, are made later in chapter 8, Discussion. We conclude with an overall interpretation of the geomorphic evolution of the area.

2. Present-day glacial cover in the Cachapoal catchment

Climatically, the Cachapoal and the neighboring upper Maipo drainage basins in Central Chile are located in the transition zone between the Dry Central Andes and the Wet Andes. This region is affected mainly by winter precipitation derived from the Westerlies, with a sharp southward increase in annual precipitation from 400 to 800 mm/year (New *et al*., 2002; Farías, 2007). The Cachapoal catchment located at 34°20' S has a variable historical pluviosity between 750 and 1,400 mm/year, near the junction of the Cachapoal and Cortaderal rivers (Dirección General de Aguas (DGA)-Ministerio de Obras Públicas (MOP), http://snia.dga.cl/BNAConsultas/reportes (última visita 19/09/2018) (see location of station in Fig. 1). Similarly, the present-day 0ºC isotherm decreases from approximately 3,000 m altitude, at 32º S, to less than 2,500 m, at 36º S (Carrasco *et al.,* 2005).

The Cachapoal catchment is a tributary of the larger Rapel catchment (Fig. 1B) being fed mostly by two major tributaries, the Cachapoal and Tinguiririca Rivers (Niemeyer Fernández, 1980). In the Principal Cordillera, it covers a surface of 1,902.2 km^2 (Caviedes, 1979) and displays a dendritic drainage pattern with several major rivers that flow from the highest regions of the Principal Cordillera and few minor rivers that drain smaller catchments in the western areas (Fig. 1C). In the western part, next to the Central Depression, two rather small, north-south oriented tributaries flow into the Cachapoal: the Coya river, flowing from the north, where its drains the area where the El Teniente copper mine is located, and the Claro, that flows from the south. Further east, the Cachapoal receives waters from several tributaries: the Pangal-Paredones and the upper Cachapoal rivers, as well as, from the Las Leñas and Cortaderal rivers, and the north-south oriented Los Cipreses river (Fig. 1C). No glaciers and no evident glacial features exist in the catchment areas of the westernmost Coya and Claro tributaries. No major glacier development exists in the Pangal-Paredones valley, however, young moraine deposits are well preserved in this region, especially in the El Diablo valley, and a small glacier exists at the head of the La Engorda valley, which is a southern tributary of the Pangal-Paredones valley. The uppermost area of the Cachapoal Valley hosts one of the largest debris-covered glaciers of the region, the presently 12 km long Cachapoal Glacier (Lliboutry, 1956; Caviedes, 1979). This glacier, which has been a major object in this study, is located at the foot of the 5,180 m high Picos Barroso that forms a prominent peak on the continental water divide in this region. A reduced glacial development exists in the uppermost parts of the Don Manuel and La Calería valleys, two northern tributaries of the upper Cachapoal (Fig. 1C). No glaciers are developed in the Las Leñas valley, however, a well developed moraine in this valley dammed the Yeso Lake. The Cipreses and Cortaderal basins, instead, drain a highly glaciated region comprised between the Cachapoal and Tinguiririca catchments in the southeastern region of the Cachapoal drainage basin. In the Sierra del Brujo ridge (Fig. 1C) two peaks close to 5,000 m altitude, the Altos de los Arrieros (4,980 m) and the Palomo volcano (4,860 m), are the nourishment area of four major glaciers: Cipreses, Palomo, Cortaderal and Universidad; the later flowing southward into the Tinguiririca drainage basin. The Cortaderal river and its tributaries the Cipresillos and Blanco rivers drain the glaciated eastern side of the Sierra del Brujo that separates the Cipreses and the Cortaderal catchments. The Cortaderal river has its source in a glacier that drains the area southeast of the Palomo volcano flowing first to the south and eastward, and then northward into the Cortaderal valley. The Cipreses glacier pierced its way to the west into the Cipreses valley across the Sierra del Brujo and drains the glaciated area located on the western flank of the Sierra del Brujo (Fig. 1C).

The Cachapoal catchment contains an important amount of glaciers and snow covered areas. Caviedes

(1979) in an inventory of glaciers in this drainage basin based on air photos from years 1955 and 1968 determined the existence of 146 glaciers in the 6 main catchments: Blanco, Pangal, Cachapoal, Las Leñas, Cortaderal and Cipreses (Fig. 1), and indicated that the total surface covered by ice, including rock glaciers, is 222.4 km^2. According to this author, the catchments most covered by glaciers are the Cortaderal, with 79.4 km^2, the Cipreses, with 55.2 km^2, and the Cachapoal, with 42.4 km^2. A recent study in this same catchment determined the existence of 389 glaciers, including rock glaciers (47%), that cover 274.47 km^2 (Geoestudios Ltda., 2011).

3. The Pleistocene and Holocene Glaciation in the Andes

Compilations of Holocene glacier fluctuations in the Andes are provided by Masiokas *et al.* (2009) and Rodbell e*t al.* (2009) highlighting the fact, that chronological studies are underrepresented in the research area analysed in this paper. Earlier views on Pleistocene glaciations in the Andes suggested overall synchronicity of glaciations along the Andes (Clapperton, 1993, 1994) and even an interhemisphere likage of the climate and glacier advances during the Last Glacial Maximun (Denton *et al.*, 1999). An alternative hypothesis suggested an asynchronous Pleistocene glaciation pattern north and south of the Arid Diagonal (Ammann *et al.*, 2001), arguing for temperature- and precipitation-controlled Pleistocene glacier changes in the different latitudinal Andean segments. A more regional reconstruction of the timing of the late Quaternary glaciation in the Andes, between 15º and 40° S, confirmed the asynchrony and summarized chronological data on the timing of glaciations based on cosmogenic dating of moraine boulders (Zech *et al.*, 2008). On this basis, these authors proposed that temperature would have been the principal factor in the high northern or humid tropical Andes, where the glaciers show advances coinciding with periods of temperature minima, like the global Last Glacial Maximum (LGM), the Heinrich 1 event, and the Younger Dryas, whereas south and westward of the Cordillera Oriental and, as far south as 30° S latitude, glaciers would have been increasingly more precipitation sensitive. Therefore, in the region between 30° to 40° S glaciers would have been very sensitive to precipitation changes and reached their maximum extent before the global LGM (35-40 ka). According to these authors, this condition would have been caused by a northward shift of the Westerlies and of the Arid Diagonal. Finally, south of ~40° S, where precipitation is much higher, but the Andes considerably lower, glaciers become more temperature sensitive again (Zech *et al.*, 2008).

In central Chile, there is only one recent study on the positions of the Equilibrium Line Altitude (ELA) during the last glacial-interglacial cycle, and the position and temporality of glacial advances during the middle and late Pleistocene (Herrera, 2016). In the neighboring upper Maipo drainage basin, in the Principal Cordillera east of Santiago, this author reported optical stimulated luminescence (OSL) ages of ~45 and 36 ka from fluvio-glacial deposits, in the Yeso river valley next to the junction with the Maipo river (San Gabriel drift). This ages have been interpreted as an evidence for a glacial advance during a Local Last Glacial Maximum (LLGM) and are consistent with events of greater precipitation and humidity in Central Chile, as proposed by Zech *et al.* (2008). Further east, near the junction of the La Engorda river with the Las Arenas, and Colina rivers, samples extracted by the same author from two end moraine ridges corresponding to two glacial pulses from the La Engorda drift yielded ^{36}Cl ages between ~24-18 ka and ~10 ka that coincide with the LGM and with wet periods reported from the Laguna Tagua Tagua paleoclimate record (Valero-Garcés *et al.*, 2005). Several ^{14}C ages between ~10 ka and ~2 ka were obtained in glacio-lacustrine and outwash deposits at La Engorda suggest a local glacial activity associated with the Younger Dryas event (Herrera, 2016).

In the present study, special emphasis has been given in the geomorphological survey to the exact determination of the different kinds of debris accumulations existing in the region that could correspond either to moraines or landslides. A major issue related with climatic interpretations based on moraine deposits has been raised in the last decades by the frequent confusion between moraines and landslides (Hewitt, 1999, in Asia; Schulmeister, 2009, in New Zeland; Poschinger, 2002, in the Alps; and Fauqué *et al.*, 2009; Moreiras, 2010; Moreiras and Sepúlveda, 2015, in the central Chilean-Argentinan Andes, between 32º and 34º S). In Chile, the pioneer works by Abele (1981, 1984) demonstrated that several alleged moraine deposits are actually landslides, some of them of huge dimensions.

4. Geologic setting

The study region is located immediately south of the flat-slab subduction segment. Here, a well developed Central Depression separates the Coastal Cordillera, to the west, from the Andean Principal Cordillera, to the east, which includes the edifices of the volcanic arc located close to the international border (Young Andean Volcanism) (Fig. 3A). The western flank of the Principal Cordillera is located in Chile, while the eastern flank is located in Argentina. In this region, the geologic units exposed in the Principal Cordillera belong to the three stages of the Andean tectonic cycle (Fig. 3A). The middle-late Eocene to Oligocene mostly volcanic rocks of the Abanico and the Miocene Farellones formations make the bulk of the western Principal Cordillera. The easternmost part consists of Jurassic and Early Cretaceous marine backarc deposits, separated by a thick evaporitic (gypsum) and a detritic continental intercalation (Río Damas Formation) of Late Jurassic age (Aguirre, 1960; Klohn, 1960; González and Vergara, 1962; Charrier, 1973, 1981, 1983; Thiele, 1980; Charrier *et al*., 2002; Godoy, 2011) (Fig. 3A). Exposures of Mesozoic deposits extend to the east in Argentina.

The Abanico Formation forms two north-south oriented swaths separated from each other by the overlying Farellones Formation (Klohn, 1960; Thiele, 1980; Charrier, 1981, 1983; Sernageomin, 2002) (Fig. 3B). These rocks consist of a locally strongly folded, ~3,000 m-thick succession of volcanic, pyroclastic volcaniclastic and sedimentary rocks including abundant subvolcanic intrusions of the same age (Vergara *et al*., 2004). All this unit is pervaded by a well-developed paragenesis of low-

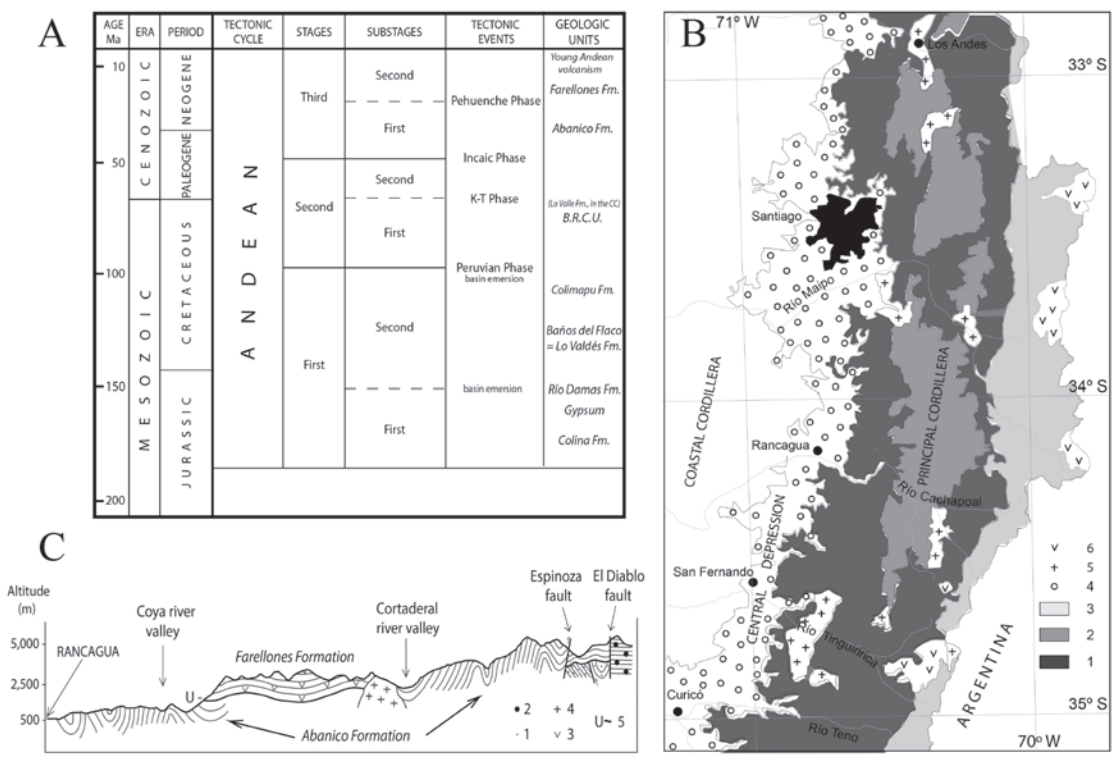

FIG. 3. **A**. Andean stages, tectonic events and geological units in the Principal Cordillera in the central Chilean Andes. **B**. Distribution of the Mesozoic and Cenozoic Abanico and Farellones formations in the Principal Cordillera. **1**. Abanico Formation; **2**. Farellones Formation; **3**. Mesozoic units in the eastern Principal Cordillera in Chile; **4**. Quaternary deposits in the Central Depression; **5**. Plutonic bodies; **6**. Volcanic deposits of the present-day magmatic arc or Young Andean Volcanism. **C**. Generalized east-west geological cross section of the Principal Cordillera at approximately 34º15'S along the Cachapoal river drainage. **1**. Callovian and Early Cretaceous marine deposits; **2**. Río Damas Formation; **3**. Farellones Formation; **4**. Miocene plutons; **5**. Unconformity.

grade metamorphic minerals (Vergara *et al.*, 1993; Aguirre *et al.*, 2000; Fuentes, 2004; Muñoz *et al.*, 2009). The Abanico Formation was deposited in a rift-basin that underwent tectonic inversion in late Oligocene to early Miocene times (Pehuenche orogeny) (Charrier *et al.*, 2002; Tapia, 2015) (Fig. 3A). To the east it is separated from the Mesozoic backarc deposits by the El Diablo fault (Fig. 3C). Tectonic inversion of the El Diablo fault (Fig. 3C) triggered the development of an east-vergent thrust-fold belt east of the El Diablo fault and mostly on the eastern flank of the Principal Cordillera (Muñoz-Sáez *et al.*, 2014). Considering its location east of the trace of this fault, the Cachapoal Glacier is located in the westernmost part of the Malargüe thrust-fold belt.

In the western flank of the Principal Cordillera, in the Coya region and somewhat north of it, in the Barahona region (B in Fig. 1C), a light yellow coarse clastic deposits cover the Abanico and Farellones formations. This deposit is matrix supported with sub-rounded volcanic blocks, up to 60 cm in diameter, and pumice fragments, up to 10 cm diameter, enclosed in an abundant ashy matrix. It corresponds to what Cuadra (1986) and Encinas *et al.* (2006) included in the Colón-Coya Formation, and Godoy *et al.* (1994) and Antinao and Gosse (2009) mentioned as the Colón-Coya Avalanche. According to Godoy *et al.* (1994), this avalanche consists of two events: **i.** The earliest one that corresponds to the precursor avalanche reaches locally 300 m thick, covers a wide, slightly south dipping erosional surface and is cut by hornblende andesite dikes dated at 2.9±0.6 Ma (Cuadra, 1986) and, therefore, is considered to be pre-late Pliocene, tentatively late Miocene according to Godoy *et al.* (1994), and **ii.** The main avalanche, for which there is no absolute age determination, has been channelized along an already well incised valley, which parallels the present-day Coya river valley (Fig. 1C). Its age would be late Pliocene or earliest Pleistocene based on the age of overlying ash-flows, possibly ignimbritic, that have been dated at 1.7±0.7 Ma (K-Ar on wholerock) by Cuadra (1986) and 1.3±0.7 Ma (K-Ar on glass particles) by Godoy *et al.* (1994). Attemps by Encinas *et al.* (2006) to date this deposit by means of apatite fission tracks yielded an over all Pliocene age. According to Encinas *et al.* (2006), the Colón-Coya Avalanche, although without specifying which one of both avalanches, though most probably the main avalanche, would have reached the western Coastal Cordillera, where it would interfinger with marine deposits and yielded a K-Ar weighted mean age of 4.6±0.4 Ma (early Pliocene).

Finally, west of Coya, at the outlet of the Machalí creek (Fig. 1C) into the Central Depression, a >20 m thick ryolithic ash deposit yielded a 440±80 ka age and has been related to the explosion of the Maipo caldera (Stern *et al.,* 1984). All these deposits indicate an important volcanic activity in the Plio-Pleistocene in this region.

Still in the western flank of the Principal Cordillera, the Cachapoal Lavas form several flat-lying exposures on the western slopes of the Coya valley, west of Coya, and on the slopes of the Cachapoal valley between Coya and the Cachapoal-Claro junction (Fig. 4). These lavas, mentioned by Klohn (1960), overlie the Pliocene Colón-Coya Avalanche deposits described above and rocks of the Abanico Formation and are covered by a much thinner deposit, similar to the underlying avalanche. West of Coya, at Club de Campo, it is possible to recognize two massive lava flows with thicknesses of 10 and 30 m. Down-stream along the Cachapoal valley and southwest of Termas de Cauquenes, the lavas form a cliff with well-developed vertical columnar jointing at approximately 150 m above the thalweg (Fig. 5A). In this same region, at a lower topographic level, a red, brecciated, dacitic lava deposit has been observed. Remains of lava flows along the south side of the Cachapoal valley have been followed downstream almost to the Central Depression (Charrier and Munizaga, 1979; Charrier, 1981, 1983). Petrographically the lavas from Club de Campo and from the region next to Termas de Cauquenes correspond to pyroxene porphyritic andesites dated at 1.8±0.2, 1.8±0.4 and 2.3±0.2 Ma (K-Ar on whole rock) (Charrier and Munizaga, 1979). These dates point to an early Pleistocene age for this volcanic activity. Based on the rather low position of the lavas in the Cachapoal valley, Farías *et al.* (2008) deduced that initiation of incision in this region would have occurred between 3.85 and 1.8 Ma ago, in the late Pliocene-early Pleistocene. The location of the volcanic center from which these lavas were produced is unknown.

In the western flank of the Principal Cordillera, in the upper Paredones valley, a reduced outcrop of undated lavas is exposed ~750 m above the thalweg on the southern slope of the Paredones valley, immediately east of the La Mamá valley and facing the El Diablo valley. These lavas form an ~200 m thick, light red-colored and flat-lying

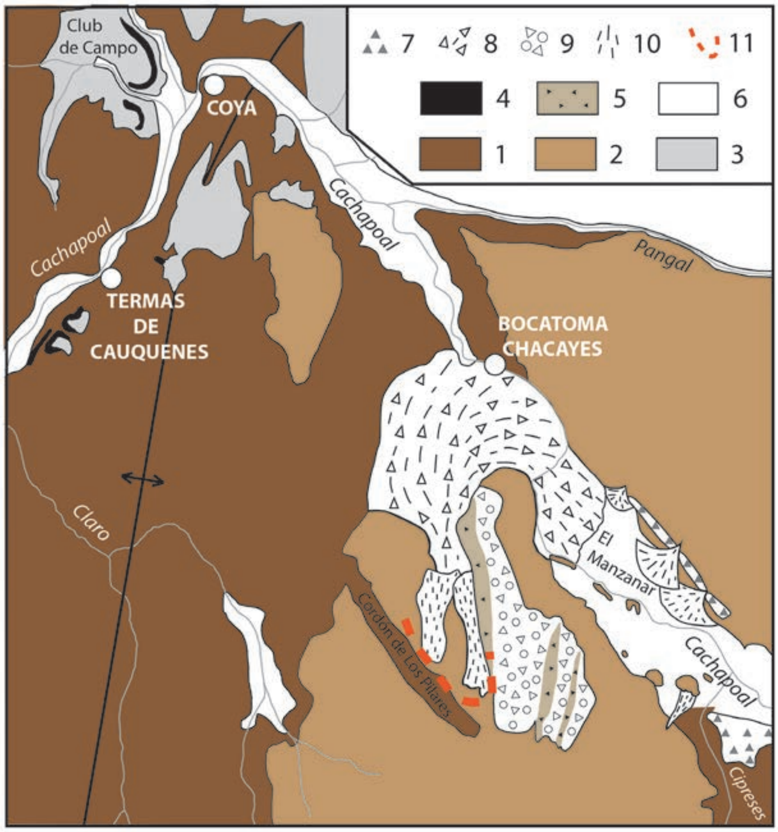

FIG. 4. Geological map along the Cachapoal River valley in the region comprised between the outlets of the Claro and Cipreses rivers into the Cachapoal river showing distribution of the Abanico and Farellones formations and younger deposits treated in text; based on Santana (1967) and Charrier (1981). **1.** Abanico Formation; **2.** Farellones Formation; **3.** Tuff, lahar and avalanche deposits including the Colón-Coya Avalanche; **4.** Cachapoal Lavas; **5.** Mud-flow levee; **6.** Fluvial deposit; **7.** Moraine; **8.** Bocatoma Chacayes landslide; **9.** Mud-flow deposit; **10.** Debris cone; **11.** Landslide scar.

succession that rests unconformably on steep dipping, folded sedimentary layers of the Abanico Formation (Charrier, 1973, 1981, 1983) (Fig. 5B). Because of their proximity to the volcanic Picos del Barroso massif (Klohn, 1960) and the absence of other volcanic vents in this catchment, their origin is tentatively attributed to this volcanic massif.

The two volcanic centers in the Cortaderal valley, the Palomo and the Andrés volcanoes lie on the western slope of the valley in an already parcially incised relief (Fig. 6). The available $^{40}Ar/^{39}Ar$ ages (in fundamental mass) for lavas from the upper part of these volcanoes are 100±20 ka and 40±30 ka respectively (Bertin and Orozco, 2015; Orozco *et al.*, 2013).

In this region there is good information about the location of the trace and activity of the El Diablo fault (Charrier *et al.,* 2002, 2005; Barrientos *et al.*, 2004; Farías *et al.*, 2010) only 8 km west from the tip of the Cachapoal Glacier. Present-day dextral strike-slip movement along the El Diablo fault triggers a shallow, rather continuous seismicity (Charrier *et al.*, 2005), and occasionally strong earthquakes, among which presumably the Las Melosas in September 1958 (Mw=6.9) (Barrientos *et al.*, 2004; Charrier *et al.*, 2005), and the Mw=6.5 earthquake on August 28, 2004 located in the upper Teno drainage at a depth of ~10 km (Barrientos *et al.*, 2004), which was followed 16 days after by a Mw=5.6 event 125 km to the north-northeast along the fault. The trace of this major fault can be followed for about 300 km along the Principal Cordillera, between the Aconcagua and Maule valleys (Muñoz-Sáez *et al.*, 2014).

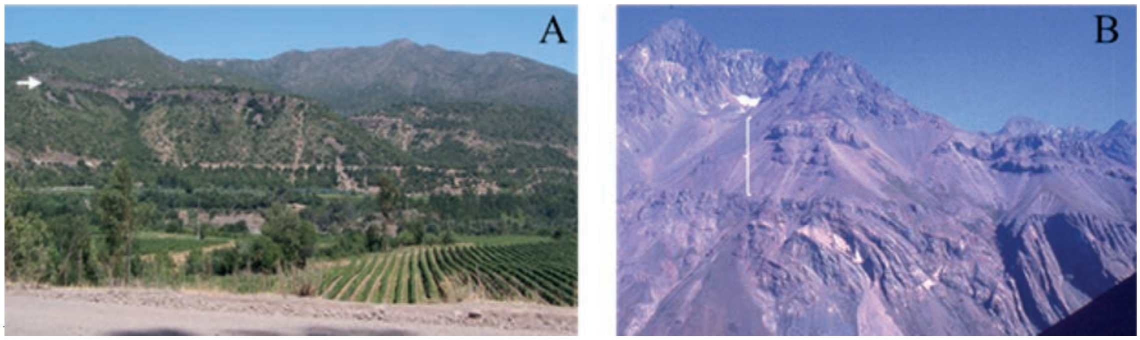

FIG. 5. Relics of lava flows in the Cachapoal and Cortaderal valleys. **A.** View of the Cachapoal lavas (arrow) in the lower Cachapoal valley between Termas de Cauquenes and the Claro river valley (see Fig. 4). **B.** South view of the Paredones Lavas (bracket) filling an old valley incised in folded layers of the Abanico Formation. For location see black star in figure 1C).

5. Results

5.1. Structural control on volcanic vents and thermal sources

The El Diablo fault is the major fault in this region, separating the Cenozoic units, to the west, from the Mesozoic units, to the east (Fig. 3C). This causes a major change in the general aspect of landscape in the Principal Cordillera between the more abrupt relief, west of the fault, where volcanic deposits predominate, and the smoother relief, east of it, where softer sedimentary deposits are exposed. This is particularly evident between ~33º20' and 34º15' S, in the Maipo catchment, where the Principal Cordillera extends more to the east than further south.

Besides from separating different lithologies, the El Diablo fault controls the location of volcanic vents and sources of thermal springs, most of which are associated with travertine deposits (Fig. 6). The Andrés (Charrier, 1979) and the Palomo (Lliboutry, 1956; Klohn, 1960; González-Ferrán, 1994) volcanoes and the thermal sources of the La Calería valley are located along its trace. Further north, the thermal source at Baños Morales, in the El Volcán river valley, in the Maipo catchment, is located next to its trace. To the south, the Tinguiririca, the Planchón-Peteroa-Azufre and the Descabezado Grande-Azul-Quizapu volcanic complexes, as well as, several well-known thermal localities, like the Baños del Flaco, next to the Tinguiririca complex (Pavez *et al.*, 2016), the Baños del Azufre, next to the Planchón volcano (González-Ferrán, 1994), and the El Médano, in the Maule river valley, are aligned along this fault.

Based on the straight course of streams, and presence of thermal springs, two north-south oriented lineaments can be traced on the western part of the study region. The westernmost one is defined by the volcanic region in the Barahona area, north of Coya (Figs. 1 and 6), from where the Colón-Coya Avalanche originated, the Termas de Cauquenes thermal source and the north-south trending Claro valley. This lineament coincides with the southward prolongation of the San Ramón Fault that runs along the western border of the Principal Cordillera, east of Santiago (Vargas *et al.*, 2014). The next one to the east is defined by the Cipreses and Portillo river valleys with the sources Agua de la Vida and Agua de la Muerte, in the Cipreses valley. The northward prolongation of this lineament roughly coincides with the location of the El Teniente ore deposit (Fig. 6). A third lineament is defined by the straight north-south alignment of the Negro volcano, the Picos del Barroso volcanic massif and the Overo volcano (Fig. 6). Further south in Argentina, along this same alignment, other volcanoes are known, like the Sosneado and Risco Plateado. Two thermal sources are known in Chile along this lineament: Puente de Tierra, near the junction of the Maipo and Negro rivers, and the splendid development of travertine ponds at Los Azules, in the Estero El Circo, a tributary of the Barroso river, in the Maipo catchment.

5.2. Elevated low-relief surface

An elevated low-relief surface is well developed on the southwestern side of the Cachapoal valley southeast of Bocatoma Chacayes and on the ridge

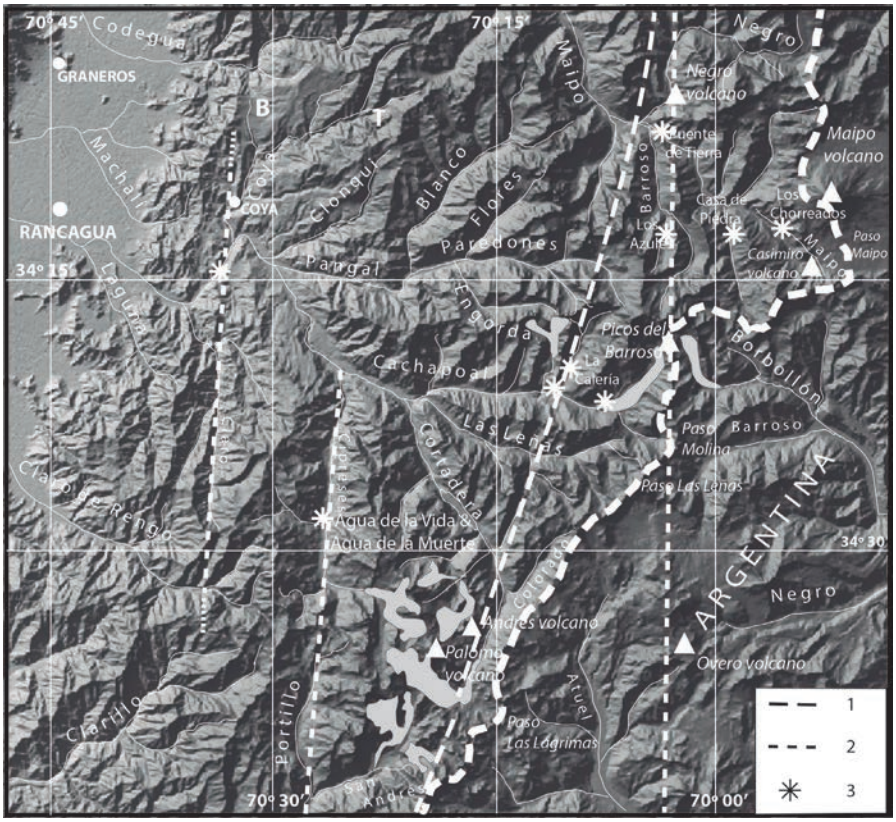

FIG. 6. Cachapoal and upper Maipo catchments with the trace of the El Diablo fault and lineaments with associated thermal sources and volcanoes. **1.** El Diablo fault; **2.** Lineament; **3.** Thermal source. **B**: Barahona region; **T**: El Teniente Cu-Mo porphyry copper. The thick segmented line is the international boundary.

immediately east of the Cipreses valley (Placeta Collay) (Fig. 7). Further east, it probably reaches the western tip of the ridge separating the Las Leñas from the Cortaderal valley. This surface is not present on the opposite side of the Cachapoal valley. To the southwest, it is bounded by the Cordón de los Pilares, a NNW-SSE oriented ridge consisting of folded rocks assigned to the Abanico Formation (Charrier, 1981, 1983) (Fig. 4). Southwest of this ridge a similar, but less preserved feature is recognizable on the eastern side of the Claro river valley. The surface developed on the slightly west dipping volcanic strata of the Farellones Formation (Charrier, 1981, 1983) and, therefore, dips in that direction. Different kinds of deposits cover the surface: mudflow deposits and mudflow levees that form conspicuous elongated ridges, fluvial, and debris cone deposits, all of them derived from the Cordón de los Pilares (Fig. 4). Because of this sedimentary cover, the surface is also slightly inclined towards the Cachapoal valley (Fig. 7). Because of the intense alteration affecting the rocks on which the surface was formed, no age determinations have been practiced on them. This surface can be followed northward up to the Barahona locality, north of Coya and west of the El Teniente copper mine (B in Figs. 1C and 6).

5.3. Cross-sectional characteristics of valleys

U-shaped valley sections are typical in the Cachapoal drainage basin in the Principal Cordillera. This is not so evident in the Maipo catchment region (Figs. 1C and 8), probably because of the existence of softer sedimentary units, widely exposed in that drainage basin east of the El Diablo fault, a feature that favors erosion and smoothing of the slopes.

One of the best preserved U-shaped valleys is the Paredones valley, which is the eastern prolongation of

FIG. 7. **A.** Southeast view of the elevated low-relief surface on the southwestern side of the Cachapoal valley (left of the picture) developed on slightly west-dipping volcanic layers assigned by Charrier (1981, 1983) to the Farellones Formation. The prominent ridge on the right side of the picture is the Cordón de los Pilares consisting of Abanico rocks. On the right side of the Cordón de los Pilares in the Claro valley it is possible to distinguish the southern prolongation of this surface. **B.** Same picture showing the delineated surface (white) in the foreground and its prolongation east of the Cipreses valley indicated by the small white patch in the background.

the Pangal Valley east of its junction with the Blanco River. The U-shape is well developed down-stream up to the Pangal Landslide somewhat below the Pangal-Paredones and Blanco rivers junction (Antinao and Gosse, 2009) (6 in Fig. 8). A well-developed U-shaped Cachapoal valley, as well as those of the upstream tributaries, the Las Leñas, Cortaderal and Cipreses, can be observed down to the rather low region of the Bocatoma Chacayes landslide (Fig. 9A, B). In both catchments, the Paredones and the lower Cachapoal, the U-shape disappears or is less evident where the river begins to cut the Abanico Formation after having crossed the Farellones Formation swath.

5.4. Moraines and landslides, and associated lacustrine deposits

One of the difficulties found in this work was, in some cases, to precisely discriminate between end moraines and landslides. This is a problem that can make interpretation of the former glacial extent controversial. The looseness of the criteria to discriminate between moraines and landslides shows the necessity for detailed observations on more characteristic features, like fabric and composition of the deposit itself. However, because this article is a first regional and general characterization of the upper Maipo and the Cachapoal catchments in the Principal Cordillera, we think that by the application of the simple criteria mentioned next the following analysis of the geomorphologic features in the study region will represent a novel and reasonable first approach to this subject. Essential features associated to landslides are the existence of a concave scar or headscarp on the valley slope above them and the lithological correlation between the rocks exposed in the debris supply area and the deposit itself. Old moraines and moraine relics are generally located at or close to the bottom of the valleys and show no distinctive morphological feature to allow an easy differentiation from landslides. In some cases, an elongated shape along a valley is suggestive of a retreating end moraine or of ablation moraine deposits, and allowed us to discard a landslide deposit, if there is no recognizable scarp on the slopes next to it. On the other side, end moraines and landslide accumulations often coincide and some of these deposits are combined features, such as the "Morena de la Laguna Negra" in the upper Maipo drainage basin (Abele, 1984; Deckart *et al.*, 2014; Moreiras and Sepúlveda, 2015). In the case of landslides, we

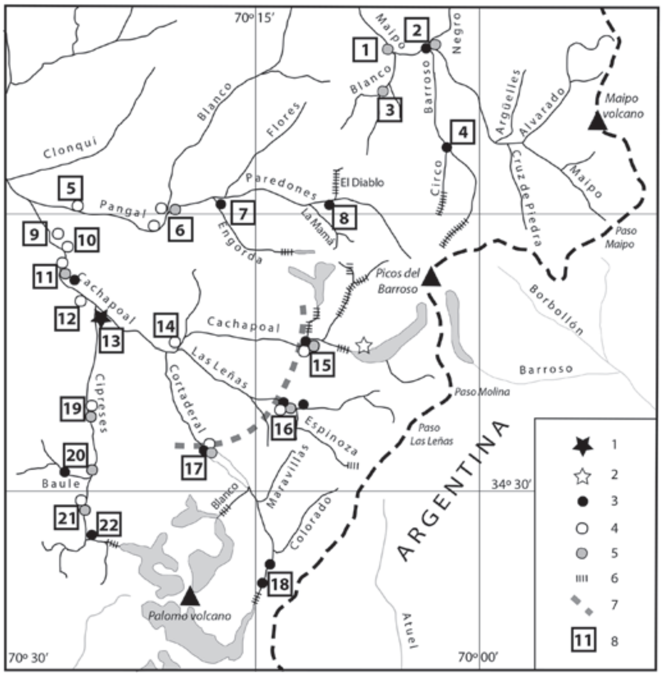

FIG. 8. Distribution of the glacial, lacustrine and landslide deposits observed in the study region and southern Maipo drainage basin. Glaciers are represented in light gray. **1.** Old lateral moraine at Los Cerrillos (dated); **2.** Young lateral moraines of the present day Cachapoal glacier (dated); **3.** Old moraine; **4.** Landslide; **5.** Fluvial or lacustrine deposit; **6.** Recent moraine; **7.** Tentative age correlation between old moraines in the Cachapoal drainage basin based on size and distance from the glacier heads; **8.** Number of the landform or deposit described in text.

followed criteria provided by Abele (1974), Hewitt (1999) and Evans *et al.* (2006) to differentiate landslides from glacial deposits.

In figure 8 we present the location of such deposits with a number for each one in order to facilitate their identification. Some of the landslides mentioned next have been indicated by Antinao and Gosse (2009) in their figure 3. Some landslides and moraines caused river embankment and fluvial or lacustrine sedimentation immediately up-stream. Some of the lake basins formed behind moraine accumulations have been totally filled by sediments. Only the Yeso Lake at Las Leñas is still in its filling process (15 in Fig. 8). Coarse grained deposits represent the last phase of the lacustrine sedimentation and form extended and flat gravelly and cobbly surfaces on which the rivers generally form a braided system. In places, along some valleys, river embankment has been caused also by the development of major debris cones on the sides of steep, generally U-shaped, valley sections causing accumulation of part of the river load.

5.4.1. Southeastern Maipo Drainage Basin [1], [2], [3], [4]

Old moraines in the southern Maipo catchment have been observed at two localities (**i**) the junction of the El Circo and Barroso Rivers ([4] in Fig. 8) and (**ii**) the junction of the Maipo, Negro and Barroso rivers ([2] in Fig. 8). Moraine [4], a possible frontal moraine, forms a small accumulation at 2,600 m altitude that has been almost completely covered by coarse fluvial material from the El Circo valley. Moraine [2] is a major deposit with an altitude of 2,200 m at its summit exposed next to and down-stream of the junction of the three most important rivers in this region of the Maipo catchment. This deposit is probably a moraine complex with contributions of all three valleys; however, the major contributor seems to be the Negro valley because most of the deposit is located at the mouth of this valley. This deposit is close to a possible landslide located almost immediately up-stream in the Negro valley.

Younger ablation moraines and rock glaciers exist in the headwaters of the Barroso catchment.

FIG. 9. **A.** Southeastward view of the U-shaped lower Cortaderal valley upstream from its junction with the Cachapoal river. In the foreground, a granodioritic pluton intruding the Farellones Formation (white arrow). **B.** Westward view of the lower Cachapoal valley in the Principal Cordillera showing the U-shaped valley section west of the junction with the Cipreses river excavated in rocks of the Farellones Formation. In the foreground, the lateral Cachapoal moraine at Los Cerrillos (7 in Fig. 4 and 4 in Fig. 10A) covered with white granodioritic blocks. A horse-rider gives the scale (white arrow). To the left is the steep cliff below the low-relief surface (black arrow) from which blocks of Farellones Formation slid downslope to the bottom of the valley (see 4 in Fig. 10A and 12). In the middle of picture, damming the valley is the Bocatoma Chacayes landslide (1) incised by the Cachapoal river and up-stream the El Manzanar flat surface (2) forming the top of the lacustrine deposits (see Fig. 4).

Fluvial deposits in the Blanco Valley [3] correspond to an accumulation of coarse material upstream of two debris cones formed in front of each other on the valley sides. Lacustrine deposits indicated with [1] form a 4 km long, wide and flat surface extending down-stream from the junction of the Maipo, Negro and Barroso rivers to the Alfalfalito creek, located 2 km downstream of the junction of the Blanco and Maipo rivers. Below this surface in the steep cliff cut by the Maipo river an, at least, 30 m thick accumulation of fluvio-lacustrine deposits is exposed. The cause of this embankment seems to be the abundant supply of fine clastic quartzdioritic material, that once blocked the Maipo river drainage, that fall from the exposures of the 12 Ma old Alfalfalito pluton on the western slope of the valley (Charrier, 1981, 1983; Kurtz *et al*., 1997). Finally, Antinao and Gosse (2009) report for the upper Maipo catchment a major landslide in the Argüelles Valley that slid from the eastern valley slope. No direct observations have been made on this landslide during this study.

5.4.2. Cachapoal Drainage Basin

We organized the description of the deposits in this catchment from north to south describing each valley and in each valley depending of its orientation, from west to east or from north to south.

5.4.2.1. Pangal-Paredones valley [5], [6], [7], [8]. A major landslide (site [5] in Fig. 8) appears on the northern slope of the valley up-stream of its junction with the Cachapoal river. The semicircular scar on the northern valley slope is well preserved and easy to recognize. On the eastern border of the landslide and continuing immediately up-stream from it, there is a 100 m high relic of a terrace that suggests lacustrine deposition to this side of the landslide.

At location [6] (Fig. 8) the valley name changes from Pangal to Paredones, the latter name meaning big walls in Spanish, named after the high steep slopes of this U-shaped valley up-stream of the junction with the Blanco River. Here the Paredones River cuts deeply through the quartzdioritic Las Callanas pluton causing a strong narrowing of the valley that increased the steepness of its slopes. This situation favored landslide production on both sides of the valley from the pluton and the Farellones Formation exposures, up-and down-stream of the junction of the Paredones and Blanco rivers (Pangal Landslide, in Antinao and Gosse, 2009). The down-stream facing slope of the landslide forces the vehicle road to climb a more than 200 m high slope, named Cuesta de los Caracoles. In both cases head-scars on the same valley-slope above the debris masses are well preserved. Further supply of detrital material to these deposits occurs presently from debris cones from the same side of the valley, as well as, from the opposite side, in which there is also evidence for minor landslides and debris flows. Up-stream from the Blanco-Paredones junction, at Las Callanas, a ~5.6 km long and up to 600 m wide flat cover of coarse grained fluvial deposits is developed. These deposits that extend up to the junction with the Flores Valley (Fig. 8) represent the last infill phase of a previously existing lake dammed by the landslides and that most certainly overlie a thick accumulation of finer lacustrine deposits.

Over the right side of the mouth of the La Engorda valley (site [7] on Fig. 8), and 80 m above the thalweg there is a considerably eroded accumulation that we interpret as an old frontal moraine seated on rocks of the Farellones Formation. However, a couple of small landslides covering the deposit immediately up-stream do not allow observe eventual lateral moraines ridges associated with this frontal moraine. For this reason, the assignment to a moraine might not be correct.

Further east, (site [8] in Fig. 8), between the junctions of the Paredones and the La Mamá and El Diablo rivers, on the valley bottom, there is a small deposit that we tentatively describe as a remain of a frontal or end moraine. This deposit located at an altitude of 2,400 m a.s.l. seems to grade to the outer ring of lateral moraines coming down the Diablo valley and, therefore, we suggest it is related to a former glacier flowing from that valley.

5.4.2.2. Cachapoal valley [9] to [14]. In the lower Cachapoal valley, a short distance upstream from the junction with the Pangal river there are two landslides (sites [9] and [10], Fig. 8) on the right-side slope of this valley, both derived from rocks of the lower Farellones Formation. Rotation of the down-slided material on the listric detachment fault of the westernmost landslide [9] formed a small depression at its proximal end that allowed formation of a small lake (Laguna del Venado), at 1,450 m altitude. Landslide [10] is located below the summit of the Cerro Agujereado and forms a 1.4 km long and rather horizontal cornice at ~1,300 m altitude. Provenance of the down-slided material is from the cliff located immediately above. This landslide is located in front of the Bocatoma Chacayes major landslide [11] in figure 8 (see also Fig. 4); however these two landslides, [10] and [11], have no genetic relationship with each other.

The Bocatoma Chacayes Landslide [11] (Las Arpas Landslide, 2 in Fig. 3 of Antinao and Gosse, 2009) is a major, Pleistocene debris mass originated on the northeastern slope of the Cordón de los Pilares (Figs. 4 and 7) (Charrier, 1981). It consists mostly of material from the Abanico Formation exposed at this ridge. The debris mass moved first northwards on the elevated low-relief surface and then slid down slope towards the bottom of the Cachapoal valley, where it extended down and upstream, and caused the embankment of the river and formed the El Manzanar terrace (Figs. 4 and 10). The up-stream displacement of the landslide mass is evidenced by the abundance of meter-sized blocks at the northwestern end of the El Manzanar terrace, which are partially covered by lacustrine sediments that onlap on the landslide deposit. Approximately 2 km upstream from the Bocatoma Chacayes, the river incision reached the bottom of the landslide and volcanic rocks are exposed in the thalweg.

Santana (1967) observed on the right side slope of the Cachapoal valley, between the Cipreses junction and El Manzanar, a moraine ridge covered by volcanic and granodioritic blocks (moraine in site [11] in Fig. 8; 3 in Fig. 10A) that must have been rafted from regions upstream where such rocks are exposed and support the glacial origin of this ridge. This ridge has an altitude above the thalweg that varies, from southeast to northwest, from 200 m to 100 m. This inclination corresponds to an angle of 9º, and, according to it, the moraine ridge may well correspond to a lateral moraine that could have been connected to an end moraine located at Bocatoma Chacayes. If this were so, it is then possible that the moraine and the landslide coincided at the same place and that the latter covered the end moraine and not *vice-versa* as described by Santana (1967).

Santana (1967) interpreted the Bocatoma Chacayes Landslide (site [11] in Fig. 8) as a variegated volcanic breccia originated by a volcanic event in the Palomo volcano. According to this author, this deposit formed a barrier to the flow of the Cachapoal glacier. However, in our opinion, the debris mass is a local and young event that covered the lateral moraine ridge observed by Santana (1967) on the northeastern flank of the Cachapoal valley (3 in Fig. 10A)

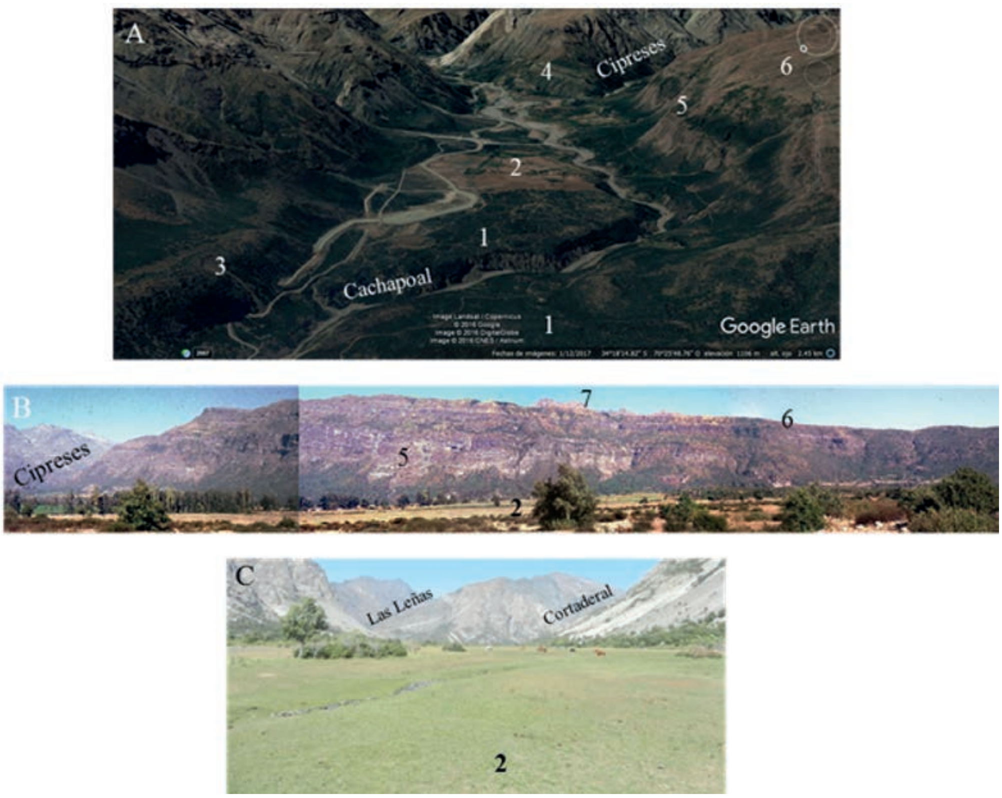

FIG. 10. **A.** Eastward (upstream) view of the lower part of the Cachapoal river valley in the Principal Cordillera (this view is partially represented in figure 4). In the foreground on both sides of the river and covered with dark green vegetation is the Bocatoma Chacayes landslide deposit (**1**). Further east the yellow surface corresponds to the El Manzanar terrace consisting of lacustrine deposits (**2**). On the left side of the picture is the right side lateral moraine described by Santana (1967) (**3**), and on the right side upstream from the Cipreses river, the dated Los Cerrillos moraine ridges (**4**). On the same side, downstream from the Cipreses valley is the steep cliff formed in deposits of the Farellones Formation (**5**) and on top of it is the described low-relief surface (**6**) of Fig. 7. In the background in the middle of the picture, white debris cones formed on the sides of the Cortaderal pluton, which can also be observed in figure 10C. **B.** Southward view of the Cachapoal valley, west of the junction with the Cipreses River, showing the El Manzanar fluvial terrace (**2**), the cliff (**5**) and the low-relief surface on top of the cliff (**6**); behind the surface, the Cordón de los Pilares (**7**). **C.** View to the east of the Llano Blanco (**2**), which is the eastward prolongation of the El Manzanar lacustrine terrace, in the Cachapoal valley west of the junction with the Cortaderal and the Las Leñas river valleys (photo taken from El Carrizal). Observe the well preserved U-shape of the valley section to the left of picture and on both sides of the valley the white debris cones with white granodioritic blocks from the Cortaderal pluton.

that had no effect on the glacier advance, though caused a major embankment of the Cachapoal river.

This embankment caused the development of a ~7 km long lake that extended from El Manzanar, to the northwest, up to the junction with the Cortaderal valley, to the southeast. The extension of this lake can be deduced from the existence, between the mentioned localities, of a discontinuous, flat lying and incised surface that represents the uppermost deposit accumulated in this lake (2 in Fig. 10). This surface has an altitude of 1,100 m at El Manzanar and of ~1,200 m, at Llano Blanco, close to its southeastern end, where it forms a wide and flat-lying meadow between the Cipreses and the Cortaderal Valleys (Fig. 10C).

According to Santana (1967), the lacustrine deposits consist of a thick varved succession that increases its thickness downstream and reaches locally thicknesses of 5 m (Santana, 1967; Fig. 2). These deposits are generally overlain by a thin cover of alluvial and fluvial deposits. Santana observed that upstream up to the junction with the Cipreses river valley the lacustrine deposits rest on the variegated volcanic breccia (Fig. 11), which at Bocatoma Chacayes (in his paper, Bocatoma Rapel) is cut by the Cachapoal River forming a deep and steep gully (Santana, 1967; Fig. 4). At some places, this author observed underneath the lacustrine deposits a massive, thick and poorly sorted deposit with an abundant sandy and silty matrix that he interpreted as a moraine deposit.

At site [12] (Fig. 8), up-stream from Bocatoma Chacayes and northwest of the junction with the Cipreses river, the left side slope of the Cachapoal valley forms an almost vertical cliff cut in slightly westward dipping volcanic layers assigned to the Farellones Formation (Charrier 1981, 1983) (Fig. 9B, 5 in Fig. 10A, B). At the foot of this cliff there are several blocks of huge dimensions surrounded and partially covered by Cachapoal fluvial deposits (Figs. 4 and 12). These blocks, which have been mentioned by Santana (1967), consist of the same volcanic layers exposed on the cliff and have dips of 20º to 30º to the southwest. The lithology of these blocks and their inclination suggests that they slid downslope from the cliff and rotated during the same process (Fig. 12). Considering the high steep walls of the Cachapoal valley in this region we consider the possibility that these blocks slid downslope once the major Cachapoal glacier retreated depriving the valley wall of the lateral support exerted by the ice, as has been suggested by Poschinger (2002) and González Díaz (2003, 2005) for similar settings elsewhere.

FIG. 11. Downstream view (enlarged) of the steep and approximately 80 m deep gully formed by the incision of the Cachapoal river in the Bocatoma Chacayes landslide deposit. The image corresponds to the NW-SE oriented gully in the foreground of figure 10A. In the lower right corner, a general view from the same place.

FIG. 12. Rotated slided blocks of Farellones Formation at the foot of the steep southwestern slope of the Cachapoal valley downstream of the junction with the Cipreses valley (5 in figure 10A). Note the steep dipping stratification (white lines) in the slided blocks compared with the almost flat-lying Farellones deposits in C. **A** and **B** views to the southeast; **C.** View to the west.

At site [13] (Fig. 8), the moraine deposits at Los Cerrillos, next to the junction between the Cachapoal and Cipreses rivers (also in Fig. 8) correspond to four lateral moraine ridges of the Cachapoal glacier preserved at an altitude comprised between 1,500 and 1,300 m. These deposits have been dated in this study and will be treated more extensively later. Santana (1967) described these deposits and recognized their glacial origin (Cerrillos de Chacayes).

At site [14], down-stream from the junction of the Cipresitos and the upper Cachapoal and in front of the outlet of the Las Leñas river into the Cachapoal (Figs. 8; 3 in Fig. 13), there is an elongated debris accumulation (~1.4 km long; 130 m high above thalweg) located below the even and steep wall above it. The deposit viewed from the opposite side of the river shows two differently colored materials that coincide with the rocks on the cliff immediately above. The whitish material corresponds to a granitic to quartzdioritic pluton and the gray material, to the volcanic deposits of the Abanico and Farellones formations that are in superposed contact at this place (Charrier 1981, 1983). Based on this observation we consider this deposit to be a landslide and not a moraine as indicated in Charrier (1981, 1983).

At site [15] (Fig. 8), up and down-stream from the junction of the Don Manuel and Cachapoal valleys (2 in Fig. 13), at an altitude of 2,290 m, there is a major accumulation of debris. This deposit forms an elongated ridge that extends for about 4.5 km from almost the Reyes valley to the La Calería valley. At its highest point it reaches an altitude above the thalweg of more than 300 m (Fig. 14). Because of the reddish color of the lower part of the deposit, its provenance is from further east, where the red colored Río Damas Formation is exposed. Based on that, it might represent a frontal moraine of the Cachapoal glacier. In this deposit, we did not find blocks suitable for cosmogenic dating. On the southern border of the deposit, at the foot of the southern slope of the Cachapoal valley, abundant mass removed material accumulated on the moraine increasing considerably the thickness of the deposit. The well-developed ablation moraine in the Don Manuel valley reaches the Cachapoal valley and its distal part merged with the Cachapoal moraine and forms part of the deposit. The Cachapoal river cuts across the deposit at the Don Manuel-Cachapoal junction exposing a complete section of this complex accumulation.

The Cachapoal moraine probably caused embankment of the river forming a lake up-stream. Reduced relics of fine lacustrine sediments are exposed few metres above the thalweg on the left side valley slope in front of the La Calería valley. However, these deposits are too low to correspond to a major lake formed up-stream from the Cachapoal moraine, but might indicate some late embankment of the river caused by younger landslides in this region. Up-stream of the Don Manuel-Cachapoal junction the valley floor widens and forms a 4.5 km long and up to 0.6 km wide flat alluvial surface covered by gravel and cobble. Further east, up to the lower extremity of the Cachapoal Glacier, reworked ablation moraine deposits form a more irregular deposit.

FIG. 13. Google Earth® view of the tributaries of the upper Cachapoal river and location of: **1.** The dated recent lateral moraines of the Cachapoal glacier; **2.** The moraine and landslide deposits in the Don Manuel valley and at the junction of this valley and the Cachapoal (site [15] in Fig. 8); **3.** The landslide deposit at the Cachapoal-Las Leñas junction (site [14] in Fig. 8). White arrows indicate the direction followed by the mass removed material that covers the Cachapoal moraine at this locality.

FIG. 14. East view of the upper Cachapoal valley with the Don Manuel valley (left) and its ablation moraine connected to the main Cachapoal moraine (15 in Fig. 8 and 2 in Fig. 13), which is covered by landslide deposits partly fallen from the southern valley slope (following direction indicated by arrow). In the middle of the picture and behind the moraine, the flat and light gray gravelly alluvial surface that forms the valley bottom between the tip of the Cachapoal Glacier and the moraine can be observeed. At the distance, in the middle of picture, is the continental water divide ridge.

The abundance of debris material fallen from the southern slope of the valley can be explained by the pervasive fracturing of the rocks due to the existenc of two faults, the Espinoza and El Diablo (Charrier *et al.*, 2002), that intersect close to each other the ridge that separates the Cachapoal and the Las Leñas river valleys (Fig. 3C) at the locations indicated by the arrows in figure 13.

5.4.2.3. Las Leñas valley. In the Las Leñas valley, a major moraine deposit with an altitude at its top of 2,230 m dammed the valley and formed the Yeso Lake (Laguna del Yeso) (site [16] in Fig. 8) down-stream of the junction with the Espinoza valley (Fig. 15A). The very steep slopes at this place provide the abundant scree material that covers the sides of the lake (Fig. 15B). The moraine is covered by abundant rock blocks of a landslide fallen from the southern valley slope (Fig. 15C). This moraine, which dams the partially sediment filled Yeso Lake, is tentatively correlated with the two other major moraines in the upper Cachapoal [15] and the Cortaderal valleys [17] in figure 8.

Immediately east of the partially filled Yeso Lake, on the right valley side, there are two, west dipping lateral moraine ridges separated from each

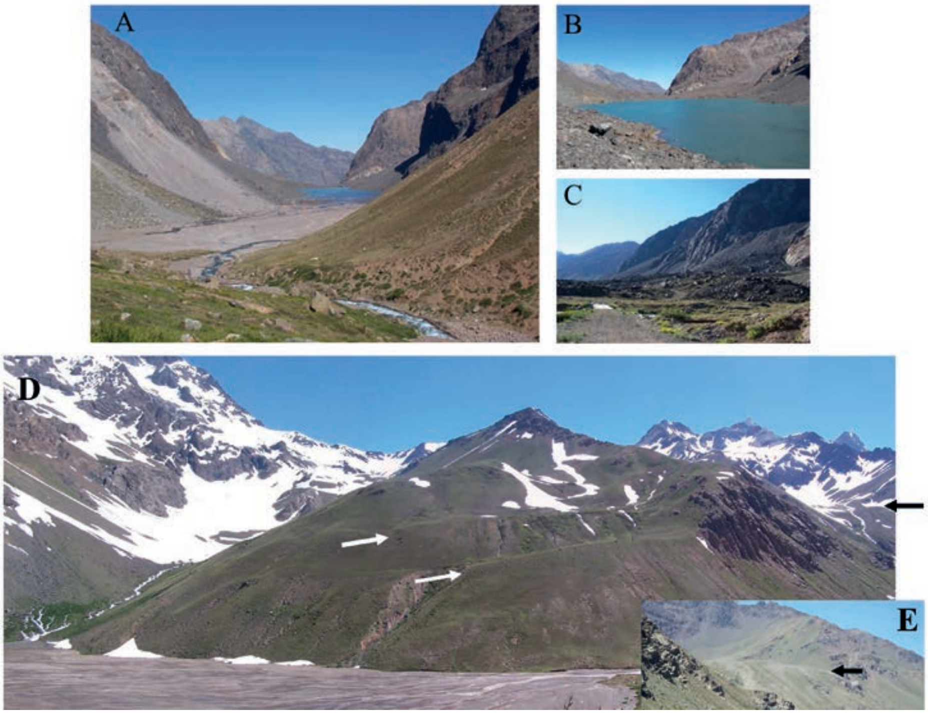

FIG. 15. The Yeso Lake moraine in the Las Leñas river valley [16]. **A.** Westward view of the U-shaped section of the Las Leñas valley and the partially filled lake showing a gravelly surface at its filled upstream end with the anastomosed river pattern on top of it. **B.** Westward view of the lake and the scree covered lake shore. **C.** Eastward view with landslide blocks covering the moraine. **D.** Northward view of the two lateral moraine ridges exposed east of the Yeso Lake (white arrows) and their prolongation in the next tributary valley (black arrow). **E.** View of the eastward prolongation of the moraine ridges in the next tributary valley to the east (black arrow points to the eastward prolongation of the ridge in figure 15D).

other by approximately 70 m in altitude (Fig. 15D). The lower ridge has an altitude above the thalweg that varies from 130 m to 100 m. The eastward prolongations of these ridges is insinuated in the next small tributary valley (Fig. 15E).

5.4.2.4. Cortaderal valley. At [17] in figure 8 a moraine at an altitude of 1,700 m forms an accumulation 180 m hight that dammed the valley causing development of a 6 km long lake, the Laguna de Los Pejerreyes, which is presently almost totally filled with sediments (Fig. 16A). The fill of the lake determines the development of an anastomosed river system on top of the flat surface formed on the lacustrine sediments (Fig. 16B).

In the upper Cortaderal Valley (site [18] in Fig. 8), lateral, ablation and frontal moraine deposits are rather continuous from the glacier tongue along the entire NNE-SSW trending river segment downward up to the junction with the Colorado river. The major and most distinctive frontal moraine deposit is located at Los Pincheiras, immediately north of a tributary gully flowing directly from the Palomo volcano. This is a dark gray deposit with abundant granodioritic blocks on its surface (Fig. 17).

5.4.2.5. Cipreses valley. Three old landslides from the right side of the Cipreses river valley at site [19] in figure 8 are apparently covered by soft material that might correspond either to old moraine material or has fallen from the slope above them. A similar landslide apparently dammed the river forming a small lake that is presently totally filled-up showing a gravely surface behind the landslide with an anastomosed river system (site [20] in Fig. 8).

In the Baule valley there is a possible ablation moraine (site [21] in Fig. 8) and in the Cipreses thalweg, a flat gravely surface with similar features, but larger than the one described for site 20.

FIG. 16. Laguna de Los Pejerreyes in the Cortaderal river valley. **A.** Southward view from the moraine that dams the almost completely filled lake to the left of the image. The moraine ridge is presently covered with abundant block sized debris from the steep sides of the U-shaped Cortaderal valley. To the right note the large difference in elevation between the lake surface (1,680 m a.s.l.) and the river downstream (1,400 m a.s.l.). **B.** The Laguna de Los Pejerreyes towards the northwest from its southeasten end close to the junction with the Blanco river (Fig. 8). Note the well-developed anastomosed drainage system and the U-shaped valley section.

FIG. 17. Southward view in the Cortaderal valley towards the Los Pincheiras moraine deposit in the middle of the left half of the picture.

Next to Rincón del Guanaco (site [22]), at least, two older major superposed landslides from the east-west oriented slope of the Cipreses river valley form a conspicuous relief consisting mostly of Farellones Formation material (Fig. 18). The western and older landslide moved southward downslope and continued somewhat downstream along the Cipreses valley probably covering older glacier deposits. The younger one rests on the older landslide. Above the deposit a major concave scar immediately north of the tip of the present day glacier tongue indicates its provenance. Most of its southern part has been removed by the erosive glacier and fluvial action. At its lower part, the landslide is covered by ablation deposits consisting

FIG. 18. Southeastward view of the landslide at Rincón del Guanaco in the Cipreses river valley (middle of picture). To the right side of the picture, at the foot of the landslide, a flat light gray surface consisting of coarse fluvial sediments is formed by the damming of the valley by the landside and probably represents the final stage of the filling of a lake.

mostly of granodioritic material supplied by the formerly much more extended glacial tongue of the Cipreses Glacier (see Araneda *et al.*, 2009). At this place, ablation deposits cover also the valley floor.

6. Fluvial terraces

Fluvial terraces can be observed almost continuously along all major valleys in the study region. A particularly beautiful array of, at least, four well developed fluvial terraces is exposed along the Cachapoal valley, from immediately west of the junction with the Pangal river downstream up to the Coya locality (Fig. 19). The difference in altitude between terraces labeled I and II in figure 19 is 15 m, the difference between terraces II and III is 25 m and the difference between terraces III and IV is 8 m. The particularly well developed terrace system is probably controlled by the westernmost lineament figured in figure 6 that might have caused the strong deflection of the Cachapoal in this region.

7. Geochronology of Cachapoal moraines

Samples were collected along the Cachapoal valley in order to obtain ^{10}Be exposure ages on the largest quartz-bearing plutonic blocks exposed on the surface of the moraine ridges (Fig. 20). The dated samples correspond to quartz diorite and granodiorite, and consist of ~5 cm thick fragments extracted from the upper part of the blocks.

7.1. Sampling method and sample processing

Geochronological dating was oriented to determine exposure ages from moraine deposits in the Cachapoal catchment. During two field campaigns (2012 and 2013), 18 samples were hammered from the upper surface of blocks exposed on moraine ridges in order to determine their exposure ages or the amount of time that these blocks have remained exposed to the cosmic radiation. Most of the collected samples correspond to quartz-diorite and granodiorite, the others were a rhyolite, an andesite (in case the pyroxene content would be enough for dating this sample by cosmogenic ^{3}He), and a crystallized bearing quartz geode, extracted from a dacitic block. The rock samples consist of fragments of about 5 cm thick taken at the top of angular blocks exposed on the moraine ridges (Figs. 20 and 21A, B). This sampling procedure is thought to minimize the unknown effect of erosion rate on the ^{10}Be ages, although this cannot be entirely excluded (Putkonen and Swanson, 2003). In order to obtain a more accurate estimate of the ages, given the small height (>30 cm) and age of the sampled blocks, we collected according to Putkonen and Swanson (2003) several samples in the same moraine ridges.

Crushing, mineral separation and sieve of the samples to isolate the 0.5-1 mm fraction was made at the Laboratorio de Separación de Minerales at the Departamento de Geología, University of Chile. Previous to the quartz separation, thin sections were made on 3 of them to ensure obtain enough quartz and pyroxene to perform the analyses. Quartz separates were processed at the CEREGE laboratory, Aix-en-Provence, France. The quartz surface was etched by successive HCl, H_2SiF_6 and HF leaching. Pure quartz was spiked with ^{9}Be carrier [ASTER in house carrier solution (^{9}Be)=3025±9 μg/g, uncertainty on Be concentration: 0.298% (Merchel *et al.*, 2008)], and then dissolved with HF. Acetyl acetone was

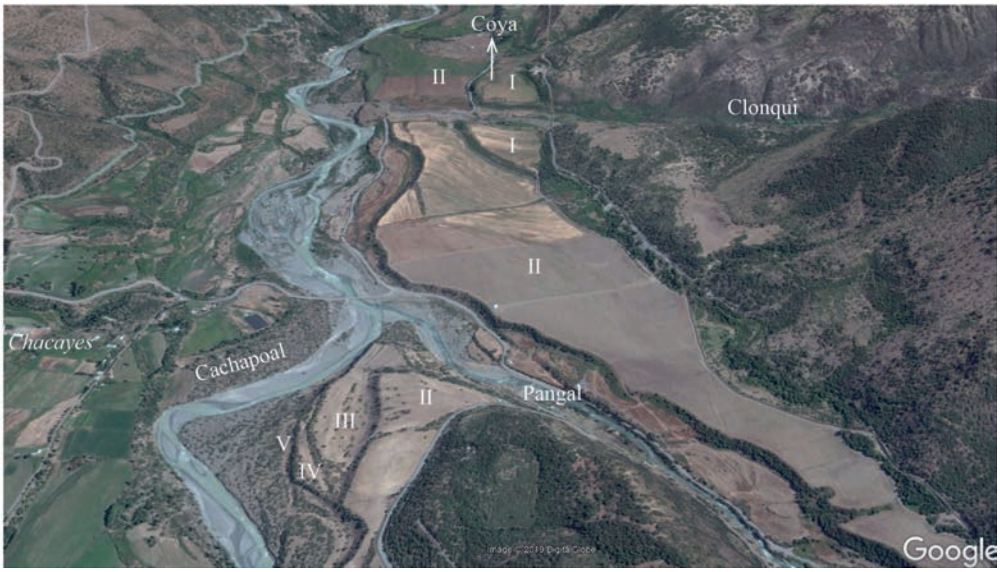

FIG. 19. Westward view from the junction of the Cachapoal and Pangal rivers to an array of five well developed terraces.

used to complex Beryllium in a 50% EDTA solution. Beryllium hydroxides were extracted using solvent (Braucher *et al.*, 2015). They were dried and oxidized at 800 ˚C to produce BeO. The measurement of $^{10}Be/^{9}Be$ ratio was carried out at ASTER the French Accelerator Mass Spectrometer located at CEREGE. Data were normalized directly against a house standard STD-11 with an assigned $^{10}Be/^{9}Be$ ratio of $(1.191\pm0.013)\cdot10^{-11}$ (Braucher *et al.*, 2015) and a ^{10}Be half-life of $(1.36\pm0.07)\cdot10^{6}$ years (Chmeleff *et al.*, 2010). For the exposure ages the production rates of Desilets *et al.* (2003, 2006), Dunai (2001), Lifton *et al.* (2005), and Lal (1991)/Stone (2000) were used. The CRONUS v2.3 calculator was used to compute ages and uncertainties (cf. Balco *et al.*, 2008) and a correction for the topographic shielding has been included. The uncertainties include internal uncertainty, blank correction and uncertainty on production rate. The computed ages assume zero erosion. Analytic results are given in Table 1 and the obtained ages are given in tables 2 and 3.

7.2 Description of sampled localities

After detailed microscopic analysis of the collected samples and careful separation of the crushed material, moraine dating has been performed in two different sites in the Cachapoal Valley in the Principal Cordillera: **1.** Los Cerrillos (Cerrillos de Chacayes, according to Santana, 1967), in the lower part of the Cachapoal valley on the ridge east of the Cachapoal-Cipreses junction (black star in Fig. 8; Figs. 4, 9B, 20B), and **2.** In the uppermost Cachapoal valley, on the northwestern side of the present-day Cachapoal Glacier (white star in Figs. 8 and 20C, D).

7.2.1. Lateral moraine ridges at Los Cerrillos (Cerrillos de Chacayes in Santana, 1967)

Four well developed moraine ridges resting on the southwestern flank of the Cachapoal valley are well exposed at altitudes between 1,500 and 1,330 m. The high altitude of these ridges relative to the present day thalweg of the Cachapoal valley (>300 m), their position resting on the valley flank, and their orientation parallel to that of the Cachapoal valley are the reasons for considering them as left side lateral moraines of an old glacier flowing in the Cachapoal valley. The ridges are separated from each other by shallow depressions. The two upper ridges are separated in average from each other by a difference in altitude of 30 m, while the two central ridges are separated in average from each other by a difference in altitude of 10 m and the two lower ones are separated from each other by a difference in altitude of only few meters (Figs. 20B, 21A). The orientation of these ridges is 100º-110ºE, and their inclination based on several averaged measures is 2º to the northwest or down valley. On the steep slope below these ridges, between an altitude of 1,400 m and

TABLE 1. ANALYTICAL RESULTS.

Sample	Total Counts	$^{10}Be/^{9}Be$	Uncertainty $^{10}Be/^{9}Be$ (%)	$^{10}Be/^{9}Be$ corrected of chemical blank	Uncertainty $^{10}Be/^{9}Be$ corrected of chemical blank	Mass dissolved quartz g	Spike ^{9}Be at/g	Error ^{9}Be	$[^{10}Be]$ at/g	Uncertainty $[^{10}Be]$
4A	74	5.0400E-14	11.6979	4.7779E-14	5.9486E-15	9.1506	2.0460E+19	6.0907E+16	106,831	13,305
4B	221	1.1735E-13	6.8524	1.1473E-13	8.0411E-15	9.6420	2.0450E+19	6.0877E+16	243,330	17,070
25	165	5.7166E-14	7.9127	5.4545E-14	4.5234E-15	5.3514	2.0460E+19	6.0907E+16	208,544	17,306
26	40	1.0667E-14	15.8652	8.0457E-15	1.6924E-15	0.7810	2.0464E+19	6.0919E+16	210,821	44,350
P2-a	112	1.2152E-13	11.8601	1.1890E-13	1.4412E-14	7.0703	2.0444E+19	6.0859E+16	343,797	41,686
P2-b	74	6.6720E-14	13.3105	6.4098E-14	8.8807E-15	8.5233	2.0426E+19	6.0805E+16	153,610	21,287
2c	44	5.3963E-14	15.1320	5.1341E-14	8.1657E-15	3.5515	2.0426E+19	6.0805E+16	295,284	46,972
6b	25	2.7549E-14	20.0426	2.4927E-14	5.5215E-15	8.1168	2.0440E+19	6.0847E+16	62,773	13,906
Chemical Blank	11	2.6216E-15	30.1794	-	-	-	2.0442E+19	6.0853E+16	-	-

TABLE 2. AGES OBTAINED WITH CRONUS V2.3 WITH THE DIFFERENT PRODUCTION MODELS WITH CORRECTION FOR ALTITUDE.

Production scheme for spallation								Desilets *et al.*, 2003, 2006		Dunai, 2001		Lifton *et al.*, 2005		Lal (1991)/ Stone (2000)	
Sample name	Latitude (DD)	Longitude (DD)	Elevation (m)	Thickness (cm)	Shielding correction	Thickness scaling factor	Internal uncertainty (yr)	Exposure age (yr)	External uncertainty	Exposure age (yr)	External uncertainty	Exposure age (yr)	External uncertainty	Exposure age External (yr)	External uncertainty
4A	-34.352	-70.0126	2,819	5	0.98	0.959	522	4,469	772	4,295	733	4,493	756	4,404	685
4B	-34.352	-70.0126	2,819	5	0.98	0.959	671	9,525	1,324	9,246	1,260	9,462	1,261	9,598	1,119
P2-a	-34.3622	-70.0851	2,710	5	0.98	0.959	1,755	1,4504	2,479	14,167	2,390	14,351	2,387	14,399	2,206
P2-b	-34.3617	-70.0851	2,700	5	0.98	0.959	898	6,568	1,204	6,416	1,163	6,573	1,177	6,540	1,092
2c	-34.3624	-70.0846	2,700	5	0.98	0.959	1,987	12,566	2,509	12,250	2,422	12,448	2,436	12,493	2,308
6b	-34.3672	-70.0938	2,607	5	0.98	0.959	620	3,061	771	2,854	715	3,082	767	3,047	732
25	-34.3502	-70.3872	1,505	5	0.99	0.959	1,605	20,429	2,989	19,755	2,839	20,247	2,852	18,949	2,369
26	-34.3335	-70.3962	1,412	5	0.99	0.959	4,399	22,094	5,376	21,358	5,163	21,897	5,257	20,408	4,716

TABLE 3. AGES OBTAINED WITH THE PRODUCTION MODEL PROPOSED BY LIFTON *ET AL.* (2005)

Sample	Age (ka)	Uncertainty (ka)	Average (ka)	Uncertainty (ka)
4A	4.5	0.8	3.8[a]	0.8
4B	9.5	1.3	excluded	-
P2-a	14.4	2.4	13.5[b]	2.4
P2-b	6.6	1.2	excluded	-
2c	12.5	2.4	-	-
6b	3.1	0.8	-	-
25	20.3	2.9	21.1[c]	4.1
26	21.9	5.3	-	-

[a] Average age for samples 4A and 6b.
[b] Average age for samples P2-a and 2c.
[c] Average age for samples 25 and 26.

almost the bottom of the valley there are exposures of roches moutonnées on rocks of the Abanico Formation.

At this locality, we collected two samples (25 and 26) in the third moraine ridge, from top to bottom (Fig. 21A).

7.2.2. Lateral moraine ridges of the present day Cachapoal glacier

On both sides of the Cachapoal glacier there are two well developed and continuous lateral ridges that bound the debris covered glacier (Fig. 20C, D). At the sampled locality (Fig. 20D), an internal and a smaller external ridge are well exposed and accessible (Fig. 21B). In the region comprised in figure 20D, the internal ridge varies its altitude from 2,800 to 2,600 m, and forms a steep, 25 m high cliff towards the glacier. The external ridge is located at an altitude of 2,700 m and forms a conspicuous white stripe richly covered by different sized quarzdiorite blocks. Dated samples 4A, 4B and 6b were collected at two places on the internal lateral moraine (Fig. 20D), and samples P2-a, P2-b and 2c were collected on the smaller lateral moraine ridge (Figs. 20D, 21B).

7.3. Dating of the moraine ridges

The ages obtained with the different production models plus a correction for the altitude are indicated in table 2. These dates are quite coherent with each other. The obtained age range is constrained between 27.2 and 2.3 ka, considering the associated errors (Table 3), and the ages are consistent with the relative age of the sampled moraines according to their location in the drainage basin and at the sides of the present-day Cachapoal glacier. We consider next the ages obtained with the production model proposed by Lifton *et al.* (2005) in order to compare ages obtained with the same production model (Table 3).

8. Discussion

8.1. Beginning of incision in the Principal Cordillera

We have interpreted landscape evolution in this region as consistent with the ideas of Farías (2007) and Farías *et al.* (2008), who concluded that because of the eastward shift of deformation since the Miocene, the two flanks of this mountain range evolved differently and that the tectonic and geomorphologic processes on the present-day western Andean flank began to shape two morphostructural units: the Coastal Cordillera and the Central Depression. Following these authors, the erosional response to the uplift experienced by the mountain range in late Miocene would have begun at the coast and progressed with the eastward advance of knick-points in each valley. Some of these knick-points during their eastward progression would have been delayed by the hard Jurassic and Late Cretaceous granitic intrusive swaths in the Coastal Cordillera, whereas knick-points progressing in regions where these hard rocks are absent or more deeply emplaced would have reached earlier regions located further east. These knick-points would, then, have captured the headwaters of rivers flowing from the higher mountain regions, which would have switched their course to the north or south depending from their relative position

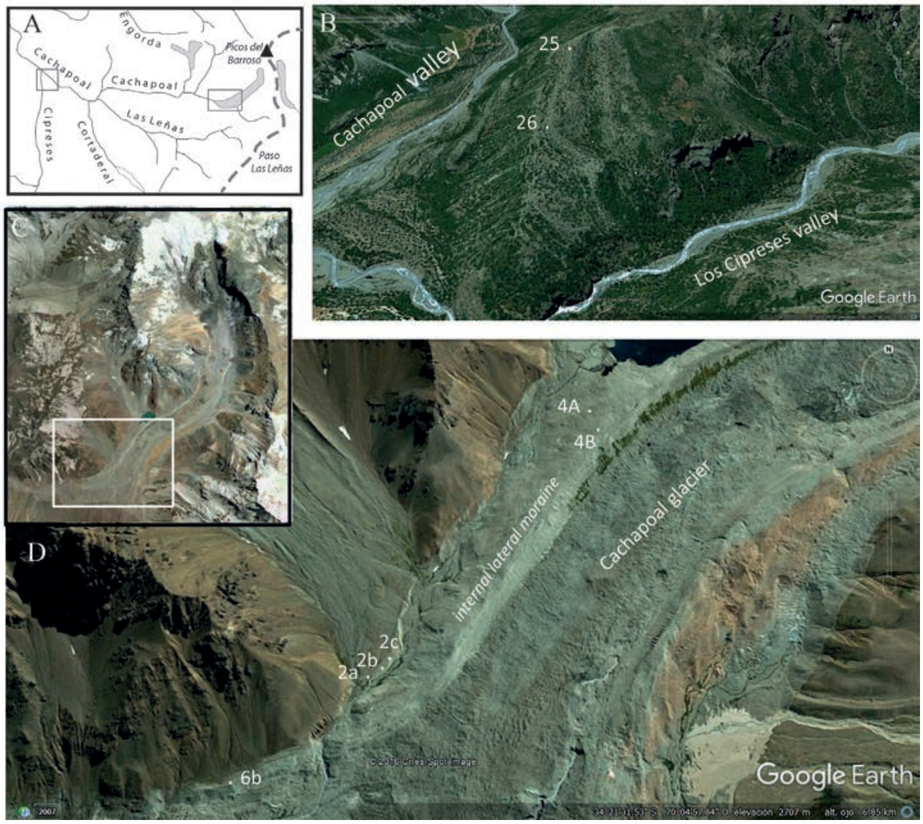

FIG. 20. Location of the dated samples at Los Cerrillos and on the side of the present day Cachapoal Glacier. **A.** Location of the sampled regions in the Cachapoal catchment. **B.** Moraine ridges at Los Cerrillos. **C.** General view of the Cachapoal Glacier. The white square corresponds to the area represented in D, where the dated samples were collected. **D.** Lateral moraine ridges with location of samples.

to the main streams and formed major longitudinal (north-south) drainages bordering the eastern side of the plutonic swaths. According to Farías *et al.* (2008), progression of the knick-points would have continued in early Pliocene (3.85 Ma) into the present-day Principal Cordillera until they reached the uppermost mountain ridges.

We consider that the elevated low relief surface described in the Cachapoal valley, southeast of Bocatoma Chacayes (Fig. 7), which can be followed northwards to the Coya and still further north to the Barahona region (Coya-Barahona Surface), immediately west of the El Teniente copper mine (Figs. 1C and 6), is a relic of the relief existent before beginning of incision in the Principal Cordillera. This surface is covered in the last region by the pre-late Pliocene, tentatively late Miocene, precursor avalanche of the Colón-Coya Avalanche (Godoy *et al.*, 1994). The following main avalanche, in turn, flowed in an already deeply incised valley. Considering the overall Pliocene age of the tuffaceous deposits that overlie the main avalanche and the early Pliocene age (4.6±0.4 Ma) of its prolongation in the western Coastal Cordillera (Encinas *et al.*, 2006), we deduce that incision should actually have begun, at least, in latest Miocene, somewhat earlier than proposed by Farías (2007) and Farías *et al.* (2008). If, indeed, the main avalanche propagated westwards, as far as, the western Coastal Cordillera, this would represent good evidence supporting existence already at that time of well incised valleys through the Coastal Cordillera as proposed by the last authors.

In order to form low-relief surfaces like the one described above it is necessary that at a certain moment before latest Miocene, the erosional process be temporarily paused by the influence of a base level,

FIG. 21. Sampled moraine ridges. **A.** Eastward view of the two lower moraine ridges at Los Cerrillos on the southwestern slope of the Cachapoal valley south-east of the junction with the Cipreses river (Fig. 4; site [13] in Fig. 8). Dated blocks (samples 25 and 26) were collected on the ridge pointed by the white arrow. In the foreground a granodioritic block. In the background the granodioritic Cortaderal pluton (Charrier, 1981, 1983; Muñoz *et al.*, 2009). **B.** North-eastward view of the sampled right side, external lateral moraine of the Cachapoal Glacier covered with blocks, some of which consist of quartz diorite (samples P2-a, P2-b and 2c). To the right, the internal lateral moraine of the Cachapoal glacier is visible. The crest in the background forms the Andean water divide in this region.

probably the one that controlled the development of the Central Depression. The lack of continuity between this surface and other similar surfaces known to the west (see Farías, 2007) is most probably due to post-Miocene activity on faults that controlled uplift on the western side of the Principal Cordillera, like the San Ramón fault. After glacial erosion in the Pleistocene, further incision into deeper Farellones levels was caused by fluvial incision.

Although the latest Miocene age concluded above for the development of these elevated low-relief surfaces seems coherent with the field obervations and the available chronological information, we consider that it is still necessary to gather much more information before give a definite answer to the origin and age of these morphological features. This aspect is important also for its bearing on the tectonic events that participated in this region to the uplift of the Principal Cordillera.

8.2. Origin of the elevated low-relief surface on the southwestern side of the Cachapoal valley southeast of Bocatoma Chacayes

According to the discussion presented above, the oldest geomorphological feature in the study region would be the elevated low relief Coya-Barahona Surface that extends to the south in the Cachapoal valley southeast of the Bocatoma Chacayes and on the ridge immediately east of the Cipreses valley (Figs. 4, 6 and 7). This feature would have been followed by the river incision that controlled the flow of the early Pliocene main avalanche of the Colón-Coya Avalanche (Godoy *et al.*, 1994; Encinas *et al.*, 2006) and the early Pleistocene (2-1.8 Ma) Cachapoal Lavas in the Cachapoal river valley next to Coya and Termas de Cauquenes, at altitudes of 150 m above the thalweg (Figs. 4, 5A).

The existence of the elevated low-relief surface in the Cachapoal valley implies a longer geological and morphological evolution than the one needed to explain other features considered in this article. This process would have begun with the development of a relief excavated in rocks of the Abanico Formation, of which the Los Pilares ridge would represent a topographic relic, and continued with the filling of that relief with deposition of the almost flat-lying lavas assigned to the Farellones Formation by Charrier (1981) or younger lavas. In the first case and considering that the Farellones rocks form the highest portions of the landscape adjacent to the Cachapoal valley in this region, it is necessary that a long lasting erosional process and incision occurred to exhume the layers on which the low-relief surface formed. This erosional event would have occurred between the late Miocene after, at least, 8.3±0.1 Ma (K-Ar whole rock), which is the youngest age obtained for this formation in the study region (Charrier and Munizaga, 1979) and the latest Miocene, according to the above discussion, for the beginning of the present-day incision in the western Principal Cordillera in this region.

However, there is another possible explanation for the origin of this surface. Because there are no age determinations on the lavas on top of which the Cachapoal low-relief surface developed it is possible that they do not belong to the Farellones Formation and, instead, are the result of a younger, post-Farellones volcanic event. In this case, the lavas would have filled a more deeply incised valley than the present-day Cachapoal river incision, which would have been excavated, first, in Farellones deposits and, then, in rocks of the Abanico Formation. This excavation would have occurred after deposition of the Farellones Formation (after 8.3±0.1 Ma) in the late Miocene and before initiation of present-day incision in latest Miocene. In this case the low-relief surface would represent the upper level attained by this volcanic filling and the surface on top of it would not be the result of an erosional process. Lateral erosion associated with slope diffusion might have reduced the altitude of this surface. In latest Miocene, once the volcanic event stopped, the present-day incision process would have begun cutting through the accumulated lavas.

8.3. Triggering mechanisms of landslides

The triggering mechanism for great landslides (>10^6 m^3) at high altitude mountain ranges is complex and might be related to deglaciation processes, which vary from immediate slope faulting after glacial retreat to a late relaxation in the stress conditions affecting the bedrock slopes. These processes may be favored by meteorization (Poschinger, 2002; González Díaz, 2003, 2005), permafrost degradation and defreezing during the Holocene (Abele, 1974, 1984), and seismic triggering (Moreiras, 2006; Antinao and Gosse, 2009).

In the study region, major landslides are present in all valleys of the Cachapoal catchment. Most of them are caused by slope instability due to the deep incision in these valleys, mostly because of glacial erosion. For this reason we consider that most of them are younger than the LGM, as already pointed out by Antinao and Gosse (2009). Apart from slope instability, we observed that landslides predominate in exposures of the Abanico Formation and for this reason we consider that meteorization on pervasively altered rocks is an important factor in landslide development in this region of the Andes. Apart from the major subduction earthquakes, the local seismic activity associated with the El Diablo Fault might have played an important role in landslide occurrence in this region.

8.4. Chronology of the moraine deposits

8.4.1. Moraine ridges at Los Cerrillos

The ages obtained for the dated ridge at Los Cerrillos (samples 25 and 26) are: 20.3±2.9 and 21.9±5.3 ka (average age of 21.1±4.1 ka) (Table 3). These ages are consistent within error with each other, and regionaly consistent with the much younger age of the ridges adjacent to the present-day Cachapoal glacier ~30 km upstream. The age range between the two dates coincides with the one assigned to the Last Glacial Maximum (LGM) (~25-18 ka). Considering that the dated ridge is one of the lowest ones and, therefore, one of the youngest ridges exposed at this locality, we consider that the highest ridge would represent the highest level attained by the LGM glaciation in this valley and that the three lower and younger ridges, including the dated one, correspond to stages during the LGM ice retreat.

8.4.2. Moraine ridges adjacent to the present-day Cachapoal glacier

8.4.2.1. External ridge. On the right side of the present-day Cachapoal Glacier, in the external ridge, we obtained three ages (Table 3). Two of them are consistent within error of 14.4±2.4 (sample P2-a) and 12.5±2.4 ka (sample 2c) (average age of 13.5±2.4 ka), and the third one is inconsistent (6.6±1.2 ka for sample P2-b) and was not considered for dating the moraine ridge. The much younger age in sample P2-b might have been caused by a more recent exhumation of the sampled block. The age range obtained from samples P2-a and 2c coincides well with the Younger Dryas interval, generally accepted between 13 and 11.5 ka, and with the 12,900 years age determined by Firestone *et al.* (2007) for the Younger Dryas Boundary. This is the first report for Younger Dryas moraines on the western versant in this Andean region.

8.4.2.2. Internal ridge. From the three samples collected on the large internal ridge that borders the present-day Cachapoal glacier, two of them, samples 4A and 6b, yielded ages consistent within error of:

4.5±0.8 and 3.1±0.8 ka respectively (average age of 3.8±0.8 ka) (Table 3). The much older age obtained from the third sample (4B), which has not been considered for dating the moraine ridge, is possibly due to a previous exposition to the cosmic radiation of the sampled block before its incorporation to the internal ridge. The age range given by the two consistent ages coincides with the 4.2 ka global climatic event that marks the beginning of the Meghalayan Age, at the end of the Holocene (Walker *et al*., 2012; International Chronostratigraphic Chart 2018). The great size of this internal ridge, as well as that of its homologous on the left side of the glacier, is consistent with a strong glacial advance at that time due to cooler conditions probably associated with an increase in precipitation.

8.5. Extension of the glaciation in the Maipo and Cachapoal catchments

Little can be said about the southern Maipo drainage basin considered in this study apart from the existence of one major moraine in the junction of the Negro, Maipo and Barroso river valleys (site [2] in Fig. 8). Its altitude (2,200 m) is similar to the altitude of the three moraines in the Cachapoal catchment (sites [15], [16] and [17]) that we tentatively correlated with each other; therefore, we consider the possibility that the Maipo moraine could be also included in this correlation.

The glacial deposits along the Cachapoal valley are the result of glacial advance and retreat since middle Pleistocene time. Glaciers in this drainage system that includes the Cachapoal, Pangal-Paredones, Las Leñas, Cortaderal and Cipreses valleys, reached lengths of up to 60 km descending to, at least, Bocatoma Chacayes, at an altitude of 950 m a.s.l. (Fig. 1C).

According to Santana (1967), the farthest point reached by the glaciers in the Cachapoal catchment is Bocatoma Chacayes, at 950 m altitude. At this place, the lateral moraine ridge described by Santana (1967) on the northeastern valley side, between Bocatoma Chacayes and some point in front of the Cachapoal-Cipreses junction, comes to its end (Fig. 4, 3 in Fig. 10), and in his opinion, the glacier would have been stopped by the breccious deposit that he interpreted of volcanic origin and that we interpret as a landslide (Bocatoma Chacayes landslide; Figs. 4, 10). If, in fact, the glacier reached this point, then according to our observations the landslide deposit would cover the frontal moraine.

The oldest moraine deposits recognized in the Cachapoal catchment are the lateral ridges at Los Cerrillos. Although these ridges are exposed at a higher altitude than the lateral moraine mapped by Santana (1967) on the opposite or right river side they are exposed somewhat upstream and can perfectly be correlative to the right side moraine ridge. In fact, the downstream inclination of the ridges at Los Cerrillos if prolonged downstream would intersect the Cachapoal thalweg approximately at Bocatoma Chacayes, similarly as do the moraine ridge on the opposite right river side. Hence, the major Cachapoal glacier advance would have reached Bocatoma Chacayes and, according to the age obtained for the moraine ridge at Los Cerrillos, this would have occurred during the Last Glacial Maximum. We haven't found in this catchment evidence for a glacier advance previous to the Last Glacial Maximum as those detected in the Maipo drainage basin by Herrera (2016), in the Lontué river valley (Puratich, 2010), and in Argentina, in the Mendoza and Grande drainage basins (Espizúa, 2004, 2005).

Another aspect to be mentioned is the difference in altitude and age of the most distal moraines in the Cachapoal and Maipo catchments. The more distal moraine deposit in the Cachapoal basin would be according to our observations located at 950 m altitude and its age, according to the age of the moraine ridges at Los Cerrillos, which are probably connected to it, coincides with the LGM. Instead, in the Maipo drainage, the altitude of the more distal glacial deposits is ~1,200 m and the age is pre-LGM (45-36 ka). The altitude of moraine ridges dated at the LGM in the El Volcán valley in the Maipo basin lie at ~2,500 m altitude (Herrera, 2016). Relative to this point, there are two aspects that can be considered: one, is the greater length of the valleys in the Maipo catchment compared to those of the Cachapoal drainage system; the second one, is the higher amount of precipitation in the Cachapoal region relative to the Maipo region. These differences show the necessity to continue with similar studies to better determine their causes, the extension of ice, and the glacial chronology in the central Chilean Andes.

8.6. Comparison with other glaciated neighboring regions and implications for the middle Pleistocene to Holocene climatic model

The recent chronological studies performed in northern Chile on moraines and associated deposits (*i.e.*, lacustrine deposits): Cordón de Puntas Negras

(Thorton and Ward, 2017), El Encierro valley, (Zech *et al*., 2006), La Laguna River (Riquelme e*t al*., 2011), and Cordón de Doña Rosa (Zech *et al*., 2007), seem to confirm the climatic model for the late Quaternary presented by Zech *et al.* (2008). Apart from the existence of a wet or humid tropical region in the northern central Andes, this model proposes the existence of several other glaciated regions southwest of the Arid Diagonal that have been differently influenced by temperature and precipitation. According to this model the region south and west of the Eastern Cordillera (southern Bolivia and northern Argentina) up to ~30° S would be a transition zone between a northern arid region, where glaciation has been mainly temperature sensitive, and a region, between 30° and 40° S, where glaciation would have been mainly precipitation sensitive, and where the maximum extent of glaciation occurred before the global LGM at ~35-40 ka. According to the same authors, the region south of 40° S would have been again temperature sensitive.

In the Maipo catchment, immediately north of the here analyzed region, a more recent study on the positions of the Equilibrium Line Altitude (ELA) during the last glacial-interglacial cycle, and the position and temporality of glacial advances during the middle to late Pleistocene (Herrera, 2016) obtained results are consistent with the model proposed by Zech *et al.* (2008). The ~45 and 36 ka ages reported by Herrera (2016) from the San Gabriel drift evidence a glacial advance during a local Last Glacial Maximum (LLGM) and are consistent with events of greater precipitation and humidity in Central Chile, as proposed by Zech *et al.* (2008). Similarly, the LGM aged La Engorda drift coincides with wet periods reported from the Laguna Tagua Tagua paleoclimatic record, in the Coastal Cordillera at approximately the same latitude (Valero-Garcés *et al*., 2005).

The ages obtained for the dated ridge at Los Cerrillos coincide well with the La Engorda drift and the ages obtained by Porter (1981) for the Llanquihue II glacier advance in the Lake District, in south-central Chile, between 40º and 41º S. Although further studies are required to confirm the following idea, we propose that the not dated upper ridges observed at Los Cerrillos could be correlated with the oldest advances of the Llanquihue glaciation. No evidence for a cooler event at the boundary of the Middle and Late Holocene Stages, at ~4.2 ka, has been recorded yet for the Maipo catchement, north of the study region.

The apparent absence of glacial deposits older than the LGM and the topographically much lower location of the glacial deposits corresponding to the LGM in the study region are important differences relative to the region located immediately to the north, in the Maipo catchment. These differences together with the great accumulation of glacial detritus in the internal moraine adjacent to the present-day Cachapoal glacier suggest that the Cachapoal drainage basin might represent a transition zone towards the more humid zone located south of 40° S.

9. Geomorphologic post late Miocene evolution of the study region

We present here a brief pre-late Miocene geological evolution of the Andes in this region to give an overview of the general context that preceded the geomorphologic evolution of the study region described next. This evolution is summarized in figure 22.

Tectonic inversion of the Abanico rift-basin in late Oligocene and early Miocene time (Pehuenche orogeny) (Fig. 3A) caused development of a positive relief in the depressed region previously occupied by the basin. The resulting relief was developed between the present-day Central Depression and the western Principal Cordillera. The volcanic activity in the uplifted region increased this relief with deposition of the Farellones Formation. Compression continued uninterruptedly until present controlling the tectonic evolution of the southern central Andes and together with the associated erosive processes shaped its modern morphostructural configuration. At ~16 Ma, deformation shifted eastward affecting the sedimentary and mostly marine Mesozoic successions located immediately east of the previous Abanico basin (east of the El Diablo fault; Fig. 3C). With this shift of deformation an east-vergent fold-thrust system developed, which is known in this region as the Malargüe fold-thrust belt. At about 8.6 Ma, a further eastward shift of deformation caused the rise of the Frontal Cordillera on a crustal-scale fault-ramp (Giambiagi and Ramos, 2002). Shortly after, still in the late Miocene, and somewhat to the north, the easternmost morphostructural unit of the Andes in this region, the Precordillera, began also to rise.

Hence, in the middle Miocene, the existent mountain range would have been located in the present-day Central Depression and western Principal Cordillera, which is the region occupied

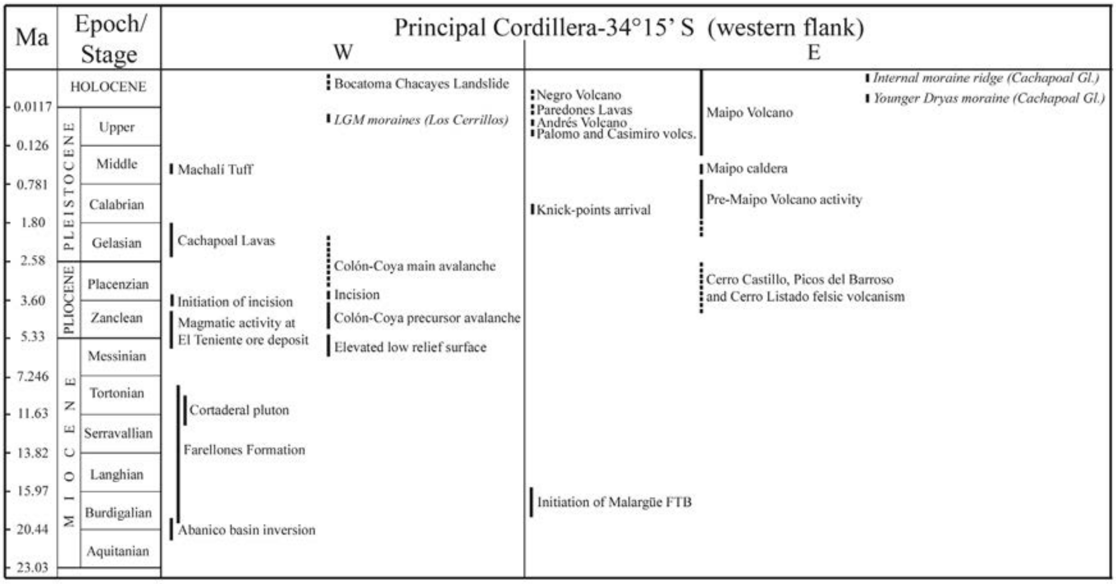

FIG. 22. Chronologic outline of the post-Oligocene tectonic, volcanic and geomorphologic evolution in the Chilean Principal Cordillera, between 34° and 35° S. Events in the western part of the western Principal Cordillera are represented separatedly from those in the eastern part of this Andean flank. Moraines dated in this article are indicated in italic. Full bars correspond to the dated age of the corresponding event; segmented bars indicate estimated age for the event. Epochs/stages and ages taken from the International Chronostratigraphic Chart (2018).

by the former Abanico basin. Considering that the Farellones volcanic arc was mostly located on the eastern side of the former Abanico basin, the water divide of this mountain range would have been located at about 20 km west from the present-day water divide. The western flank of this range, in the present-day Coastal Cordillera, consisted of a deeply eroded relief formed during the mid-Cretaceous Peruvian phase (Boyce, 2015) (Fig. 3A), and the eastern flank consisted of a retroarc foreland with an east-vergent developing thrust-fold belt and an eastward oriented drainage system.

According to the previous discussion on the age of the elevated Coya-Barahona low-relief surface exposed in the Coya-Barahona region (Fig. 6) and on the southwestern side of the Cachapoal valley southeast of the Bocatoma Chacayes (Fig. 7), valley incision in the western Principal Cordillera would have begun, at least, in the latest Miocene and would have reached the eastern region approximately 4 million years later. In fact, in the next major valley to the south, the Tinguiririca river valley, about 15 km away from the continental water divide (international border), ~1 Ma old lavas from the Tinguiririca Volcanic Complex cover the uppermost relief surface on both sides of the Tinguiririca valley (Arcos, 1987; Arcos *et al*., 1988). This implies that before ~1 m.y. ago they built a continuous layer across the region presently occupied by the Tinguiririca valley. According to Farías *et al*. (2008), this situation means that the knick-point in this valley would have reached this region and incised these lavas after ~1 Ma, tentatively in late early to middle Pleistocene. This would indicate that notwithstanding the altitude attained so far by the mountain range, no or reduced pre-1 Ma glacial erosion occurred in this region. We suggest that similarly to the Tinguiririca valley, the volcanic activity associated with the Picos del Barroso that still covers the uppermost parts of the mountain range in this region would have taken place before insept of the major glacial or fluvial incision, that is, before ~1 Ma.

Shortly after ~1 Ma, at the upper part of the now probably higher mountain range, glacial and fluvial incision would have participated in the shaping of the drainage system. Glacial valleys close to the Picos del Barroso, would have controlled the distribution of volcanic flows, like the Paredones Lavas, located high on the valley slope (approximately half altitude of the slope), indicating that they deposited at an intermediate stage between initiation of valley incision and present (Fig. 5B). If the conclusions reached for the upper Tinguiririca Valley are also valid for the Cachapoal drainage basin, then these lavas, which are located close to the water divide, were deposited in a post-1 Ma incised valley and would be younger than the Cachapoal Lavas described for the Coya and Termas de Cauquenes region.

This would imply existence in this Andean region of two swaths with volcanic activity during the latest Miocene to early Pleistocene: **1.** A western swath including the Cachapoal Lavas, in the Coya region, the volcanic activity in the Barahona region, with which the Colón-Coya Avalanche is associated, and the probably related, and if not, at least, partially coeval, subvolcanic activity of the El Teniente porphyry Cu-Mo deposit (Cuadra, 1986; Maksaev *et al.*, 2004). Other lavas in the western Principal Cordillera that could be included in this swath are the ~1 Ma old volcanic deposits of the Sierra de Bellavista, at 34°45' S (Klohn, 1960; Vergara, 1969; Malbran, 1986; Eyquem, 2009), and **2.** An eastern swath consisting of the felsic volcanics forming the Cerro Castillo (Thiele, 1980), the Picos del Barroso Massif, the Cerro Listado and the andesitic pre-Maipo caldera lavas (Charrier, 1981, 1983), and further south the oldest units in the Tinguiririca and Planchón Volcanic Complexes (Arcos, 1987; Arcos *et al.*, 1988; Orozco *et al.*, 2013).

In Middle Pleistocene (450±60 ka, according to Stern *et al.*, 1984), occurred the explosion that formed the Maipo caldera and produced huge volumes of ash and/or ignimbritic deposits emplaced on both sides of the central Andean Principal Cordillera in a single or series of closely spaced eruptions. Somewhat later, developed the activity of the present-day volcanoes along the axis of the cordillera, including that of the Maipo, Casimiro and Negro volcanoes, in the Maipo catchment, and the Palomo and Andrés volcanoes in the Cachapoal catchment.

The activity of the Palomo volcano (Fig. 6) would have begun shortly after initiation of incision, considering its location on the upper part of the western slope of the Cortaderal valley. In a later stage of incision in this valley, the Andrés volcano would have begun its activity. Considering the age of the dated lavas of the Palomo volcano (100±20 ka, according to Bertin and Orozco, 2015; Orozco *et al.*, 2013), and the associated analytical error, these ages are not much indicative of the beginning of the volcanic acivity. However, they give a rough age range that allows a chronological approximation of the geomorphologic evolution of the study region, as for example, that incision would have reached the upper Cortaderal valley in the early Pleistocene clearly before 80 ka ago, an age that considering the analytic error is the least age for the upper lavas in this volcano (Orozco *et al.*, 2013). This means that incision occurred in this region before deposition of the oldest glacial deposits known in the Maipo drainage basin. A similar situation occurs in the southern Maipo catchment with the Casimiro volcano located on the southwestern slope of the Maipo valley that yielded $^{40}Ar/^{39}Ar$ ages of 111±17 ka and 90±60 ka (Orozco *et al.*, 2013), which coincide with that of the Palomo volcano. The Negro volcano, in the Maipo catchment (Fig. 1), developed at a more advanced stage of incision, but old enough to have presently its lavas totally incised by the river.

Later, in the LGM in the Cachapoal drainage (this work) and pre-LGM in the Maipo basin (45-36 ka) (Herrera *et al.*, 2009; Herrera, 2016) and the adjacent eastern Principal Cordillera (Espizúa and Bigazzi, 1998; Espizúa, 2004), major glacier tongues would have deepened the drainage systems formed by the eastward progressions of the knick-points. Younger Holocene moraines located at higher altitudes than the Los Cerrillos ridges exist up-stream in almost all valleys of the Cachapoal and the upper Maipo catchments, and indicate considerable glacial retreat since the LGM (Fig. 8).

Although the study region is considerably close to the Maipo catchment, where pre-LGM deposits have been found, no evidence for deposits older than the LGM have been recognized in the study region and the present authors have no explanation to this. Among several possible explanations, the most probable ones are that such deposits have been eroded downstream in the Cachapoal catchment or that they lie in the Central Depression and are covered by Quaternary deposits.

Related to the absence of evidence for glacial activity downstream of Bocatoma Chacayes, it has been pointed out previously in this paper that U-shaped valleys disappear or are less evident where the river begins to cut the Abanico Formation after having crossed the swath of Farellones Formation. To explain this situation, we propose one or both of the following factors. The first one could be that the Pleistocene glaciation did not reach such low regions and, if it did, the volume of the Cachapoal glacier would have been considerably reduced when reaching those regions and, consequently, would have incised less than upstream. In case that the glaciers reached these low regions, the second factor could be the softer condition of the Abanico deposits relative to the rocks exposed up-valley given the pervasive regional low-grade metamorphic process that affected the Abanico Formation and not any younger rock unit (Aguirre *et al.*, 2000). The resulted intense modification of the original mineralogy of the Abanico rocks made them much softer to weathering and erosion, facilitating obliteration of a possible U-shaped valley section in this region. The well preserved U-shaped valley sections observed in the eastern Abanico swath may be explained by the more prolonged glacier incision in this eastern swath before the glacier retreat, between the Last Glacial Maximum and the Younger Dryas, according to the chronologic results exposed in this article.

10. Conclusions

This study combines pre-late Miocene geological information, geomorphological observations from the southern Maipo and the Cachapoal catchments, and ^{10}Be chronology on lateral moraines of the Cachapoal glacier that allow reconstruction of the post-late Miocene landscape and glacial evolution in this region.

The El Diablo Fault separates two well-defined domains with different morphology: a more abrupt western domain, in which late Paleogene and Neogene volcanic rocks predominate, and a smoother eastern domain consisting mostly of softer Mesozoic sedimentary deposits.

After the late Miocene Andean uplift, eastward progression of valley incision in this region of the Principal Cordillera began in latest Miocene and reached the highest regions of the mountain range only in late early Pleistocene (~1 Ma). Glaciers apparently made no major contribution to incision before this time, and Holocene glaciers deepened and shaped already incised valleys, which are presently mostly occupied by rivers.

The oldest topographic feature in the study region is a late Miocene low relief surface well exposed in the Coya-Barahona region that apparently extends further south into the Cachapoal valley (Coya-Barahona Surface).

Volcanism in latest Miocene to early Pleistocene, in the Principal Cordillera in central Chile, developed along two swaths: one, in the western Principal Cordillera, and the other along the axis of the mountain range. In the eastern swath, in the highest part of the mountain range, the volcanic deposits covered areas not yet affected by valley incision, whereas in the western Principal Cordillera, pre-late Pliocene avalanches, like the main Colón-Coya Avalanche and early Pleistocene lavas flowed in already deeply incised valleys.

Our observations suggest existence of a dendritic LGM Cachapoal-glacier-ice stream formed by the Cachapoal tributaries, the Pangal-Paredones, Las Leñas, Cortaderal and Cipreses major drainage systems reaching a length of ~60 km and flowing down to, at least, ~950 m a.s.l.

Exposure ages on lateral moraines in the Cachapoal River valley, at Los Cerrillos and on the sides of the present-day Cachapoal Glacier, indicate major glacial pulses in the Last Glacial Maximum (average age of 21.1±4.1 ka), the Younger Dryas (average age of 13.5±2.4 ka), and the "4.2 event", at the beginning of the Meghalayan Age (average age of 3.8±0.8 ka).

Landslides occurred and still occur frequently in this region mostly because of the steep valley slopes formed by the deep glacial and fluvial incision. Some of them might have been triggered by local seismic activity associated with the nearby El Diablo fault, and most of them concentrate in areas with exposures of Abanico Formation, probably because of the intense alteration that affects this pervasively low-grade metamorphosed formation.

The observations and interpretations presented in this study show the harmonious relationship that exists between the geological processes that built the mountain range and the geomorphological processes that shaped the landscape in this Andean region. This study improves our understanding of climate and landscape evolution of the Andes at these latitudes, and we hope will stimulate a number of studies in this and neighbor regions focused on their geomorphological and glacial evolution, which have been until present scarcely explored.

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References

Abele, G. 1974. Bergstürze in den Alpen, ihre Verbreitung, Morphologie und Folgeerscheinun-gen. Wissenschaftliche Alpenvereinshefte, Heft 25: 230 p. München.

Abele, G. 1981. Trockene Massenbewegungen, Schlammströme und rasche Abflüsse. Dominante morphologische Formen in den chilenischen Anden. Mainzer Geographische Studien, Heft 23: 102 p.

Abele, G. 1984. Derrumbes de montaña y morenas en los Andes chilenos. Revista de Geografía Norte Grande 11: 17-30.

Aguirre, L. 1960. Geología de los Andes de Chile Central, provincia de Aconcagua. Boletín del Instituto de Investigaciones Geológicas 9: 1-70. Santiago.

Aguirre, L.; Robinson, D.; Bevins, R.E.; Morata, D.; Vergara, M.; Fonseca, E.; Carrasco, J. 2000. A low-grade metamorphic model for the Miocene volcanic sequences in the Andes of central Chile. New Zealand Journal of Geology and Geophysics 43 (1): 83-93. doi: 10.1080/00288306.2000.9514871.

Ammann, C.; Jenny, B.; Kammer, K.; Messerli, B. 2001. Late Quaternary Glacier response to humidity changes in the arid Andes of Chile (18-29° S). Palaeogeography, Palaeoclimatology, Palaeoecology 172: 313-326.

Antinao, J.L.; Gosse, J. 2009. Large rockslides in the Southern Central Andes of Chile (32-34.5°S), Tectonic control and significance for Quaternary landscape evolution. Geomorphology 104 (3-4): 117-133.

Araneda, A.; Torrejón, F.; Aguayo, M.; Alvial, I.; Mendoza, C.; Urrutia, R. 2009. Historical records of Cipreses glacier (34°S): Combining documentary-inferred "Little Ice Age" evidence from Southern and Central Chile. The Holocene 19 (8): 1173-1183. doi: 10.1177/0959683609345079.

Arcos, R. 1987. Geología del Cuadrángulo Termas del Flaco, provincia de Colchagua, VI Región, Chile. Memoria de Título (Inédito), Universidad de Chile, Departamento de Geología: 279 p. Santiago.

Arcos, R.; Charrier, R.; Munizaga, F. 1988. Volcanitas cuaternarias en la hoya superior del río Tinguiririca (34º 30'L.S.-70º 21' L.W.): Características geológicas, antecedentes geoquímicos y geocronológicos. *In* Congreso Geológico Chileno, No. 5, Actas 3: I245-I260. Santiago.

Balco, G.; Stone, J.O.; Lifton, N.A.; Dunai, T.J. 2008. A complete and easily accessible means of calculating surface exposure ages or erosion rates from ^{10}Be and ^{26}Al measurements. Quaternary Geochronology 3: 174-195.

Barrientos, S.; Vera, E.; Alvarado, P.; Monfret, T. 2004. Crustal seismicity in central Chile. Journal of South American Earth Sciences 16: 759-768.

Bertin, D.; Orozco, G. 2015. Petrografía, geoquímica y peligros volcánicos de los volcanes Palomo y Tinguiririca, VI Región. *In* Congreso Geológico Chileno, No. 14, Actas 3: 124-127. Coquimbo.

Borde, J. 1966. Les Andes de Santiago et Leur Avant-Pays: Etude de Géomorphologie. Union Française d'impression d'Impression: 559 p. Bordeaux, France.

Boyce, D. 2015. Modelo de evolución tectónica y paleogeográfica del margen andino en Chile central durante el Cretácico medio-tardío: el registro estructural y sedimentario en la Formación Las Chilcas. Universidad de Chile, Departamento de Geología: 296 p.

Braucher, R.; Guillou, V.; Bourlès, D.L.; Arnold, M.; Aumaître, G.; Keddadouche, K.; Nottoli, E. 2015. Preparation of ASTER in-house ^{10}Be/^{9}Be standard solutions. Nuclear Instruments and Methods in Physics Research Section B, 361: 335-340. doi: 10.1016/j.nimb.2015.06.012.

Brüggen, J. 1929. Zur Glazialgeologie der chilenischen Anden. Geologische Rundschau 20: 1-35. Berlin.

Carrasco, J.F.; Casassa, G.; Quintana J. 2005. Changes of the 0°C isotherm and the equilibrium line altitude in central Chile during the last quarter of the 20th century. Hydrological Science Journal 50 (6): 933-948.

Caviedes, C.N. 1972. Geomorfología del Cuaternario del valle del Aconcagua, Chile Central. *In* Freiburger Geographische Hefte 11: 153 p. Freiburg.

Caviedes, J. 1979. Inventario de glaciares en la hoya del río Cachapoal y predicción de la escorrentía del deshielo, Andes centrales. Memoria de Título (Inédito), Universidad de Chile, Departamento de Geología: 217 p.

Charrier, R. 1973. Geología de las Provincias O'Higgins y Colchagua. Instituto de Investigación de Recursos Naturales (IREN), Publication 7: 69 p. Santiago.

Charrier, R. 1979. Los volcanes Andrés y Don Casimiro, dos centros descubiertos en la Cordillera de los Andes entre 34º y 34º45'S. Revista Geológica de Chile 8: 79-85. doi: 10.5027/andgeoV6n2-a04.

Charrier, R. 1981. Geologie der chilenischen Hauptkordillere zwischen 34° und 34°30' südlicher Breite und ihre tektonische, magmatische und paläogeographische Entwicklung. *In* Berliner Geowissenschaftliche Abhandlungen Reihe A: Geologie und Paläontologie 36: 270 p. Berlin.

Charrier, R. 1983. Hoja El Teniente. Carta Geológica de Chile. Informe No. 929 (Inédito), Universidad de Chile, Departamento de Geología: 155 p.

Charrier, R.; Munizaga, F. 1979. Edades K-Ar de volcanitas cenozoicas del sector cordillerano del río Cachapoal, Chile (34°15' Lat. S). Revista Geológica de Chile 7: 41-51. doi: 10.5027/andgeoV6n1-a04.

Charrier, R.; Baeza, O.; Elgueta, S.; Flynn, J.J.; Gans, P.; Kay, S.M.; Muñoz, N.; Wyss, A.R.; Zurita, E. 2002. Evidence for Cenozoic extensional basin development and tectonic inversion south of the flat-slab segment, southern Central Andes, Chile, (33º-36º S.L.). Journal of South American Earth Sciences 15: 117-139.

Charrier, R.; Bustamante, M.; Comte, D.; Elgueta, S.; Flynn, J.J.; Iturra, N.; Muñoz, N.; Pardo, M.; Thiele, R.; Wyss, A.R. 2005. The Abanico Extensional Basin: regional extension, chronology of tectonic inversion, and relation to shallow seismic activity and Andean uplift. Neues Jahrbuch für Geologie und Paläontologie Abhandlungen 236(1-2): 43-77. doi: 10.1127/njgpa/236/2005/43.

Chiu, D. 1991. Geología del relleno Cuaternario de las hoyas de los ríos Yeso, Volcán y Maipo, este último entre las localidades de Guayacán y los Queltehues, Región Metropolitana, Chile. Ph.D. Thesis (Unpublished) Universidad de Chile, Departamento de Geología: 111 p.

Chmeleff, J.; von Blanckenburg, F.; Kossert, K.; Jakob, D. 2010. Determination of the ^{10}Be half-life by multicollector ICP-MS and liquid scintillation counting. Nuclear Instruments and Methods in Physics Research B 263 (2): 192-199.

Clapperton, C. 1993. Quaternary Geology and Geomorphology of South America. Elsevier: 779 p. Amsterdam.

Clapperton, C. 1994. The glaciation of the Andes: a review. Revista Chilena de Historia Natural 67: 369-383.

Cuadra, P. 1986. Geocronología K-Ar del yacimiento El Teniente y áreas adyacentes. Revista Geológica de Chile 27: 3-26. doi: 10.5027/andgeoV13n1-a01.

Deckart, K.; Pinochet, K.; Sepúlveda, S.A.; Pinto, L.; Moreiras, S.M. 2014. New insights on the origin of the Mesón Alto deposit, Yeso Valley, central Chile: A composite deposit of glacial and landslide processes? Andean Geology 41 (1): 248-259. doi: 10.5027/andgeoV41n1-a10.

Denton, G.H.; Heusser, C.J.; Lowell, T.V.; Moreno, P.I.; Andersen, B.G.; Heusser, L.E.; Schlüchter, C.; Marchant, D.R. 1999. Interhemispheric linkage of paleoclimate during the last glaciation. Geografiska Annaler 81 A: 107-153.

Desilets, D.; Zreda, M. 2003. Spatial and temporal distribution of secondary cosmic-ray nucleon intensities and applications to in-situ cosmogenic dating. Earth and Planetary Science Letters 206: 21-42.

Desilets, D.; Zreda, M.; Prabu, T. 2006. Extended scaling factors for in situ cosmogenic nuclides: New measurements at low latitude. Earth and Planetary Science Letters 246: 265-276.

Dunai, T. 2001. Influence of secular variation of the magnetic field on production rates of *in situ* produced cosmogenic nuclides. Earth and Planetary Science Letters 193: 197-212.

Encinas, A.; Maksaev, V.; Pinto, L.; Le Roux, J.; Munizaga, F.; Zentilli, M. 2006. Pliocene lahar deposits in the Coastal Cordillera of central Chile: implications for uplift, avalanche deposits, and porphyry copper systems in the Main Andean Cordillera. Journal of South American Earth Sciences 20: 369-381.

Espizúa, L. 2004. Pleistocene glaciations in the Mendoza Andes, Argentina. *In* Quaternary Glaciations: Extent and Chronology. Part III: South America, Asia, Africa, Australasia, Antarctica (Ehlers, J.; Gibbard, P.; editors). Developments in Quaternary Sciences 2. Elsevier, Cambridge: 69-73.

Espizúa, L. 2005. Holocene glacier chronology of Valenzuela Valley, Mendoza Andes, Argentina. The Holocene 15 (7): 1079-1085.

Espizúa, L.; Bigazzi, G. 1998. Fission-track dating of the Punta de Vacas glaciation in the Río Mendoza valley, Argentina. Quaternary Science Reviews 17: 755-760.

Evans, S.G.; Scarascia Mugnozza, G.; Strom, A.L.; Hermanns R.L.; Ischuk, A.; Vinnichenko S. 2006. Landslides from Massive Rock Slope Failure and Related Phenomena. *In* Landslides from Massive Rock Slope Failure (Evans, S.G.; Scarascia Mugnozza, G.; Strom, A.; Hermanns, R.L.; editors). NATO Science Series IV. Springer 49: 3-52.

Eyquem, D. 2009. Volcanismo cuaternario de Sierras de Bellavista. Comparación geoquímica con el magmatismo contemporáneo del arco comprendido entre los 34º30' y los 35º30'S. Memoria de Título (Inédito). Universidad de Chile, Departamento de Geología: 107 p.

Farías, M. 2007. Tectónica y erosión en la evolución del relieve de los Andes de Chile Central durante el Neógeno. Ph.D. Thesis (Unpublished). Universidad de Chile, Facultad de Ciencias Físicas y Matemáticas: 194 p.

Farías, M.; Charrier, R.; Carretier, S.; Martinod, J.; Fock, A.; Campbell, D.; Cáceres, J.; Comte, D. 2008. Late Miocene regional surface uplift and slow response of erosion in the Andes of Central Chile: Implications for the geodynamics in subduction zones. Tectonics 27 (TC2005). doi: 10.1029/2006TC002046.

Farías, M.; Comte, D.; Charrier, R.; Martinod, J.; David, C.; Tassara, A.; Tapia, F.; Fock, A. 2010. Crustal scale architecture in central Chile based on seismicity and surface geology: Implications for Andean mountain building. Tectonics 29 (TC3006). doi: 10.1029/2009TC002480.

Fauqué, L.; Hermanns, R.; Hewitt, K.; Rosas, M.; Wilson, C.; Baumann, V.; Lagorio, S.; Di Tommaso, I. 2009. Mega deslizamientos de la pared sur del cerro Aconcagua y su relación con depósitos asignados a la glaciación pleistocena. Revista de la Asociación Geológica Argentina 65 (4): 691-712. Buenos Aires.

Firestone, R.B.; West, A.; Kennett, J.P.; Becker, L.; Bunch, T.E.; Revay, Z.S.; Schultz, P.H.; Belgya, T.; Kennett, D.J.; Erlandson, J.M.; Dickenson, O.J.; Goodyear, A.C.; Harris, R.S.; Howard, G.A.; Kloosterman, J.B.; Lechler, P.; Mayewski, P.A.; Montgomery, J.; Poreda, R.; Darrah, T.; Que Hee, S.S.; Smith, A.R.; Stich, A.; Topping, W.J.; Wittke, H.; Wolbach, W.S. 2007. Evidence for an extraterrestrial impact 12,900 years ago that contributed to the megafaunal extinctions and the Younger Dryas cooling. *In* Proceedings of the National Academy of Sciences (PNAS) 104 (41): 16016-16021. doi: 10.1073/pnas.0706977104.

Fuentes, F. 2004. Petrología y metamorfismo de muy bajo grado de unidades volcánicas oligo-miocenas en la ladera occidental de los Andes de Chile Central (33ºS). Ph.D. Thesis (Unpublished). Universidad de Chile, Departamento de Geología: 398 p.

Geoestudios, Ltda. 2011. Catastro, exploración y estudio de glaciares en Chile central. Ministerio de Obras Públicas de Chile, Direccion General de Aguas, S.I.T. 265: 176 p. Santiago.

Giambiagi, L.B.; Ramos, V.A. 2002. Structural evolution of the Andes between 33°30' and 33°45'S, above the transition zone between the flat and normal subduction segment, Argentina and Chile. Journal of South American Earth Sciences 15: 101-116. doi:10.1016/S0895-9811(02)00008-1.

Godoy, E. 2011. Structural setting and diachronism in the Central Andean Eocene to Miocene volcano-tectonic basins. *In* Cenozoic Geology of the Central Andes of Argentina (Salfity, J.A.; Marquillas, R.A.; editors). Instituto del Cenozoico, Universidad Nacional de Salta: 155-167. Salta.

Godoy, E.; Lara, L.; Burmeister, R. 1994. El "lahar" cuaternario de Colón-Coya: una avalancha de detritos pliocena. *In* Congreso Geológico Chileno, No.7, Actas 1: 305-309. Concepción.

González, O.; Vergara, M. 1962. Reconocimiento geológico de la Cordillera de los Andes entre los paralelos 35° y 38° latitud Sur. Instituto de Geología, Universidad de Chile, Anales de la Facultad de Ciencias Físicas y Matemáticas 19 (19): 121.

González-Díaz, E.F. 2003. El englazamiento en la reión de la caldera de Caviaue-Copahue (Provincia del Neuquén): su reinterpretación. Revista de la Asociación Geológica Argentina 58: 356-366. Buenos Aires.

González-Díaz, E.F. 2005. Geomorfología de la región del volcán Copahue y sus adyacencias (centro-oeste del Neuquén). Revista de la Asociación Geológica Argentina 60: 72-87. Buenos Aires.

González-Ferrán, O. 1994. Volcanes de Chile. Instituto Geográfico Militar: 635 p. Santiago.

Herrera, M. 2016. Estimación de las altitudes de las líneas de equilibrio en glaciares de montaña para el último ciclo glacial-interglacial en los Andes de Santiago, Chile central. Tesis de Posgrado (Inédito), Universidad de Chile, Departamento de Geología: 171 p. Santiago.

Herrera, M.; Vargas, G.; Sepúlveda, S. 2009. Cronología del Último Máximo Glacial y registro del Younger Dryas en los Andes de Santiago. *In* Congreso Geológico Chileno, No. 12, Actas: 680-682. Antofagasta.

Hewitt, K. 1999. Quaternary moraines versus catastrophic rock avalanches in the Karakoram Himalaya, Northern Pakistan. Quaternary Research 51: 220-237.

Klohn, C. 1960. Geología de la Cordillera de los Andes de Chile Central, provincia de Santiago, O'Higgins, Colchagua y Curicó. Instituto Investigaciones Geológicas, Boletín 8: 1-95. Santiago.

Kurtz, A.; Kay, S.M.; Charrier, R.; Farrar, E.1997. Geochronology of Miocene plutons and exhumation history of the El Teniente region, Central Chile (34º-35ºS). Revista Geológica de Chile 24: 75-90. doi: 10.5027/andgeoV24n1-a05.

Lal, D. 1991. Cosmic ray labeling of erosion surfaces: *in situ* nuclide production rates and erosion models. Science 104: 424-439.

Lifton, N.; Bieber, J.; Clem, J.; Duldig, M.; Evenson, P.; Humble, J.; Pyle, R. 2005. Addressing solar modulation and long-term uncertainties in scaling secondary cosmic rays for in situ cosmogenic nuclide applications. Earth and Planetary Science Letters 239: 140-161.

Lliboutry, L. 1956. Nieves y glaciares de Chile: fundamentos de glaciología. Editorial Universidad de Chile: 471 p. Santiago.

Lliboutry, L. 1998. Glaciers of the Dry Andes. *In* Glaciers of South America (Williams, R.S.; Ferrigno, J.; editors). United States Geological Survey, Professional Paper 1386-I: I109-I147.

Maksaev, V.; Munizaga, F.; McWilliams, M.; Fanning, C.M.; Mathur, R.; Ruiz, J.; Zentilli, M. 2004. New chronology for El Teniente, Chilean Andes, from U-Pb, $^{40}Ar/^{39}Ar$, Re-Os, and fission-track dating: implications for the evolution of a supergiant porphyry Cu-Mo deposit. Society of Economic Geologists, Special Publications 11: 15-54.

Malbran, F. 1986. Estudio geológicoestructural del área de río Clarillo, con énfasis en la Formación CoyaMachalí, hoya del río Tinguiririca, Chile. Ph.D. Thesis (Unpublished). Universidad de Chile, Departamento de Geología: 221 p.

Masiokas, M.H.; Rivera, A.; Espizúa, L.E.; Villalba, R.; Delgado, S.; Aravena, J.C. 2009. Glacier fluctuations in extratropical South American during the past 1000 years. Palaeogeography, Palaeoclimatology, Palaeoecology 281: 242-268.

Merchel, S.; Arnold, M.; Aumaître, G.; Benedetti, L.; Bourlès, D.L.; Braucher, R.; Alfimov, V.; Freeman, S.P.H.T.; Steier, P.; Wallner, A. 2008. Towards more precise ^{10}Be and ^{36}Cl data from measurements at the 10^{-14} level: Influence of sample preparation. Nuclear Instruments and Methods in Physics Research B 266 (22): 4921-4926. doi: 10.1016/j.nimb.2008.07.031.

Moreiras, S.M. 2006. Chronology of a Pleistocene rock avalanche probable linked to neotectonic, Cordón del Plata (Central Andes), Mendoza-Argentina. Quaternary International 148 (1): 138-148.

Moreiras, S.M. 2010. Geomorphologic evolution of the Mendoza River Valley. *In* Field Excursion Guide Book (Del Papa, C.; Astini, R.; editors). International Sedimentological Congress, No. 18, Actas FE-B2: 20 p. Mendoza.

Moreiras, S.M.; Sepúlveda, S. 2015. Megalandslides in the Andes of central Chile and Argentina (32º-34ºS) and potential hazards. *In* Geodynamic Processes in the Andes of Central Chile and Argentina (Sepúlveda, S.A.; Giambiagi, L.B.; Moreiras, S.M.; Pinto, L.; Tunik, M.; Hoke, G.D.; Farías, M.; editors). Geological Society, Special Publications 399: 329-341. London. doi: 10.1144/SP399.18.

Muñoz, M.; Deckart, K.; Charrier, R.; Fanning, C.M. 2009. New geochronological data on Neogene-Quaternary intrusive rocks from the high Andes of central Chile (33º45'-34º30'S). *In* Congreso Geológico Chileno, No. 12, Resúmenes expandidos: S8-008. Santiago.

Muñoz, M.; Aguirre, L.; Vergara, M.; Demant, A.; Fuentes, F.; Fock, A. 2010. Prehnite-pumpellyite facies metamorphism in the Cenozoic Abanico Formation, Andes of central Chile(33º50'S): chemical and scale controls on mineral assemblages, reaction progress and the equilibrium state. Andean Geology 37 (1): 54-77. doi: 10.5027/andgeoV37n1-a03.

Muñoz-Sáez, C.; Pinto, L.; Charrier, R.; Nalpas, T. 2014. Influence of depositional load on the development of a shortcut fault system during inversion of an extensional basin: The Eocene-Oligocene Abanico Basin case, central Chile Andes (33°-35°S). Andean Geology 41 (1): 1-28. doi: 10.5027/andgeoV41n1-a01.

New, M.; Lister, D.; Hulme, M.; Makin, I. 2002: A high-resolution data set of surface climate over global land areas. Climate Research 21: 1-25.

Niemeyer Fernández, H. 1980. Hoyas hidrográficas de Chile, Sexta Región. Ministerio de Obras Públicas, Dirección general de Aguas: 350-372. Santiago.

Ormeño, A. 2007. Geodinámica de la hoya hidrográfica del río Maipo en la zona cordillerana de la Región Metropolitana: Implicancias neotectónicas. Tesis de Magister en Ciencias, mención Geología (Inédito), Universidad de Chile, Departamento de Geología: 177 p.

Orozco, G.; Amigo, A.; Bertin, D.; Lara, L. 2013. Peligros Volcánicos de la Central de Chile, Regiones Metropolitana, del Libertador General Bernardo O'Higgins, del Maule y del Biobío. Servicio Nacional de Geología y Minería, Carta Geológica de Chile, Serie Geología Ambiental: 75 p., 1 map at 1:250.000 scale, 1 map at 1:2.000.000 scale. Santiago.

Paskoff, R. 1970. Recherches géomorphologiques dans Le Chili semi-aride. Bordeaux, Biscaye Freres Imprimeurs: 420 p. France.

Paskoff, R. 1977. Quaternary of Chile: The state of research. Quaternary Research 8 (1): 2-31.

Pavez, C.; Tapia, F.; Comte, D.; Gutiérrez, F.; Charrier, R.; Benavente, O. 2016. Characterization of the Hydrothermal System of the Tinguiririca Volcanic Complex, Central Chile, using Structural Geology and Passive seismic tomography. Journal of Volcanology and Geothermal Research 310: 107-117.

Porter, S.C. 1981. Pleistocene Glaciation in the Southern Lake District of Chile. Quaternary Research 16: 263-292.

Poschinger, A. von, 2002. Large rockslides in the Alps: A commentary on the contribution of G. Abele (1937-1994) and a review of some recent developments. *In* Catastrophic landslides: Effects, occurrence, and mechanisms (Evans, S.G.; DeGraff, J.V.; editors). The Geological Society of America 15: 237-255. doi: 10.1130/REG15-p237.

Puratich, J.G. 2010. Influencia del desarrollo glaciar en la evolución morfológica de la alta Cordillera de los Andes en la parte norte de la región del Maule (35º15'S-35º50'S). Ph.D. Thesis (Unpublished), Universidad de Chile, Departamento de Geología: 109 p.

Putkonen, J.; Swanson, T. 2003. Accuracy of cosmogenic ages for moraines. Quaternary Research 59: 255-261.

Riquelme, R.; Rojas, C.; Aguilar, G.; Flores, P. 2011. Late Pleistocene-early Holocene paraglacial and fluvial sediment history in the Turbio valley, semiarid Chilean Andes. Quaternary Research 75 (1): 166-175.

Rodbell, D.T.; Smith, J.A.; Mark, B.G. 2009. Glaciation in the Andes during the Late Glacial and Holocene. Quaternary Science Reviews 28: 2165-2212.

Rodríguez, M.P.; Aguilar, G.; Urresty, C.; Charrier, R. 2015. Neogene landscape evolution in the Andes of north-central Chile between 28 and 32° S: interplay between tectonic and erosional processes. *In* Geodynamic Processes in the Andes of Central Chile and Argentina (Sepúlveda, S.A.; Giambiagi, L.B.; Moreiras, S.M.; Pinto, L.; Tunik, M.; Hoke, G.D.; Farías, M.; editors). Geological Society, London, Special Publications 399: 419-446. doi:10.1144/SP399.15.

Santana, R. 1967. Rasgos de la glaciación cuaternaria en El Manzanar, Valle del Cachapoal, Andes de Rancagua. Revista Geográfica de Valparaíso 1: 85-98.

Stern, C.R.; Amini, H.; Charrier, R.; Godoy, E.; Hervé, F.; Varela, J. 1984. Petrochemistry and age of rhyolitic pyroclastic flows which occur along the drainage valleys of the río Maipo and Cachapoal (Chile) and the río Yaucha and río Papagallos (Argentina). Revista Geológica de Chile 23: 39-52. doi: 10.5027/andgeoV11n3-a03.

Schulmeister, J.; Davies, T.R.; Evans, D.J.A.; Hyatt, O.M.; Tovar, D.S. 2009. Catastrophic landslides, glacier behavior and moraine formation-a view from an active plate margin. Quaternary Science Reviews 28: 1085-1096.

Stone, J.O. 2000. Air pressure and cosmogenic isotope production. Journal of Geophysical Research-Solid Earth 105: 23753-23759.

Tapia, F. 2015. Evolución tectónica y configuración actual de los Andes centrales del sur (34°45'-35°30'S). Tesis de Doctorado (Inédito), Universidad de Chile, Departamento de Geología: 165 p.

Thiele, R. 1980. Geología de la Hoja Santiago, Región Metropolitana. Escala 1:250.000. Carta Geológica de Chile 39. Instituto de Investigaciones Geológicas: 51 p. Santiago.

Thornton, R.M.; Ward, D. 2017. Glacial history of S Cordón de Puntas Negras, Chile, 24.3° S using *in situ* cosmogenic ^{36}Cl. *In* Geological Society of America Joint 52nd and 51st Annual Section Meeting, paper No. 31-3. Pittsburgh, Pennsylvania.

Valero-Garcés, B.L.; Jenny, B.; Rondanelli, M.; Delgado-Huertas, A.; Burns, S.J.; Veit, H.; Moreno, A. 2005. Palaeohydrology of Laguna de Tagua Tagua (34°30' S) and moisture fluctuations in Central Chile for the last 46,000 yr. Journal of Quaternary Science 20: 625-641.

Vargas, G.; Klinger, Y.; Rockwell, T.K.;Forman, S.L.; Rebolledo, S.; Baize, S.; Lacassin, R.; Armijo, R. 2014. Probing large intraplate earthquakes at the west flank of the Andes. Geology 42 (12): 1083-1086. doi:10.1130/G35741.1

Vergara, M. 1969. Rocas volcánicas y sedimentario-volcánicas, Mesozoicas y Cenozoicas, en la latitud 34°30'S, Chile. Universidad de Chile, Departamento de Geología, Publicación 32: 36 p.

Vergara, M.; Levi, B.; Villarroel, R. 1993. Geothermal-type alteration in a burial metamorphosed volcanic pile, central Chile. Journal of Metamorphic Geology 11: 449-454.

Vergara, M.; López-Escobar, L.; Palma, J.L.; Hickey-Vargas, R.; Roeschmann, C. 2004. Late Tertiary episodes in the area of the city of Santiago de Chile: new geochronological and geochemical data. Journal of South American Earth Sciences 17: 227-238.

Walker, M.J.C.; Berkelhammer, M.; Björck, S.; Cwynar, L.C.; Fisher, D.A.; Long, A.J.; Lowe, J.J.; Newnham, R.M.; Rasmussen, S.O.; Weiss, H. 2012. Formal subdivision of the Holocene Series/Epoch: a Discussion Paper by a Working Group of INTIMATE (Integration of ice-core, marine and terrestrial records) and the Subcommission on Quaternary Stratigraphy (International Commission on Stratigraphy). Journal of Quaternary Science 27 (7): 649-659.

Zech, R.; Kull, C.; Veit, H. 2006. Late Quaternary glacial history in the Encierro Valley, northern Chile (29°S), deduced from ^{10}Be surface exposure dating. Palaeogeography, Palaeoclimatology, Palaeoecology 234 (2-4): 277-286.

Zech R.; Kull C.; Veit, H. 2007. Exposure dating of Late Glacial and pre-LGM moraines in the Cordillera Dona Rosa, northern Chile (~31° S). Climate of the Past 3: 1-14.

Zech, R.; May, J.; Kull, C.; Ilgner, J.; Kubik, P.; Veit, H. 2008. Timing of the late Quaternary glaciation in the Andes from 15º to 40º S. Journal of the Quaternary Science 23 (6-7): 635 647.

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