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Geomorphological mapping and landforms characterization of a high valley environment in the Chilean Andes

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ABSTRACT

Despite the wide diversity of landforms, there are only a few geomorphological maps of the Chilean Central Andes. In this study, we present a detailed geomorphological map on a 1:50.000 scale for the Diguillín Valley (Ñuble Region, Chilean Andes), as a result of the interpretation of aerial photographs from the year 2000 provided by Aerophotometric Service of the Chilean Air Force (FACh). To represent the landforms, we used the French model and the morphoclimatic simplifications suggested by the Instituto Geológico Minero de España in 1: 50.000 scale cartography (Joly, 1966; Tricart, 1971). A total of 22 landforms of structural, glacial, gravitational and fluvial origin were identified over an area of 156 km^2. The map shows the spatial distribution of the landforms and provides valuable information for the geomorphological evolution and environmental planning of the study area.

1. Introduction

Geomorphological mapping is a classical technique for representing the spatial distribution of landforms and processes (Peña Monné, 1997; Theler et al., 2010; Alcalá-Reygosa et al., 2016; Campos et al., 2018). Furthermore, a geomorphological map is a valuable document for land and geomorphological risk management as well as baseline data for other sectors of environmental research such as landscape ecology, forestry or soil science (Otto and Smith, 2013).

In Chilean Central Andes, most of the research is focused on glacier fluctuations (e.g. Bown et al., 2008; Le Quesne et al., 2009; Pellicciotti et al., 2014; Malmros et al., 2016; among others), and geomorphological mapping and climate projections of rock glaciers in the dry Andes (27°-33°S) (Brenning, 2005; Azócar and Brenning, 2010). Besides, deglaciation in the semi-arid Andes of Chile (32∘–35∘S) was studied by Caviedes et al. (1972), Herrera (2016), Fernández et al. (2019) and Charrier et al. (2019), based on geomorphological mapping and geochronology.

However, some regions of the zone between Central Andes (35° S) and Patagonia (38° S), such as the Ñuble Region (36° S - 37° S) (Fig. 1), have a lack of detailed geomorphological studies. A few morphological approaches in this region have been carried out such as a description of the geomorphological characteristics of the Andean range between 35° S and 38° S (González and Vergara, 1962), and a geomorphologic evolution of the Rio Laja valley (Thiele et al., 1998). In the Diguillín valley (Fig. 1), Zúñiga et al. (2012) studied the morphology of the Diguillín basin in order to evaluate the hydrological processes. Recently, in the Nevados de Chillán area, Caro (2014) analyzed the morphology of the Glaciar Nuevo, a glacier located on the west slope of the Volcán Nuevo but no glacial evolution studies have been found.

The glacial evolution of the zone between Central Andes and Patagonia can be considered an important factor for the understanding of geomorphological processes and landforms. Further studies in Chachapoal (35° S) (Charrier et al., 2019), laguna del Maule (36° S) (Singer et al., 2000), lago Llanquihue (41° S) (Lowell et al., 1995), río Blanco (45°30′S) (Mardones et al., 2011) among others (Clark et al., 2009; Clapperton, 1994a, 1994b) suggest that these regions were occupied by large glaciers during the Last Glacial Maximum (LGM), a period between

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26.5 ka and 19 ka (Clark et al., 2009), and subsequent deglaciation have triggered intense processes, resulting in a very complex terrain with a great diversity of landforms.

There are few geological studies of the Nevados de Chillán (Dixon et al., 1999; Naranjo et al., 2008) and nearby areas (Ramos and Kay, 2006). However, the paleogeography inherited from pre-Miocene tectonic uplift and pediplain events, the neogene tectonics and paleogeographic evolution of the Andes Mountains in central Chile (González-Ferrán, 1994; Farías et al., 2008, 2010; Rodríguez et al., 2015; Charrier, 2019) can facilitate the understanding of the geology and geomorphology of the study area.

The aim of this study meets the need to establish a more detailed knowledge of the evolution of the Ñuble Region by providing a detailed geomorphological map of the Diguillín Valley (Main map in Appendix A. Supplementary data). This valley presents a great variety of morphologies due to tectonics and climate fluctuations since the last glacial period. Landform assemblages may yield insight information on the timing of glacier fluctuations (Alcalá-Reygosa et al., 2016; Bendle et al., 2017) and tectonics and paleogeographic evolution into past variations (Breuer et al., 2013; Chelli et al., 2015). Also, provide information for the application of glacial inversion methods, land-system analysis (Blende et al., 2017), and dating techniques (Alcalá-Reygosa et al., 2017; Charrier et al., 2019) for new reconstructions. Thus, the map provides support to better understand the geomorphological evolution of the study area and improve the knowledge of the Quaternary glaciations of the Chilean South -Central Andes.

2. Regional setting

The Central Andes of Chile (33°- 36° S) is located in the south of the transition zone between the flat-slab subduction to the north and the normal subduction to the south. It is subdivided into three morphostructural units, parallel to the subduction zone, which have an essentially north-south orientation. These three units are from west to east: Coastal Cordillera, Central Depression and Principal Cordillera. The orientation of the morphostructural units is controlled by the ante-arc zone located between the Peru-Chile trench and the Principal range that comprises an intra-arc or magmatic arc in the Principal Cordillera with active volcanism (Tassara and Yañez, 2003).

The Diguillín Valley, is located in the Principal range (36° 52 ′S - 36° 59′ S/71° 38 ′W - 71° 21′ W) in the Southern Central Andes. This area has a very irregular relief that range, north to south, from 4000–600 m a.s.l. To the NE, the Diguillin Valley border the Nevados de Chillán Volcanic Complex (CVNCh) placed in the Southern Volcanic Zone of Chile. CVNCh is a volcanic complex 6 km long in a N140°E direction (González-Ferrán, 1994; Dixon et al., 1999).

The geology of the Diguillín valley is shown on a map (Fig. 2) based on previous studies (Naranjo et al., 2008; SERNAGEOMIN, 2003) and our field observations. The oldest rocks of the study area appear in the CVNCh which are formed by igneous rocks from the Santa Gertrudis-Bullileo Batolith (Miocene), volcanic - volcanoclastic rocks from the Cura-Mallín Fm. (lower-middle Miocene) and the Cola de Zorro Fm. (Upper Pliocene-Pleistocene) (SERNAGEOMIN, 2003; Naranjo et al., 2008). Overlying the Cura-Mallín and Cola de Zorro formations, there are andesitic lava from the Atacalco Fm. (Middle-Upper Pleistocene) and the Ignimbrita El Castillo (Upper Pleistocene). In some sectors of the valley and slopes, there are semi-solid landslide deposits (Middle Pleistocene-Holocene) and more recent alluvial, laharic and fluvioglacial deposits (Holocene) (SERNAGEOMIN, 2003; Naranjo et al., 2008).

The formation of the Diguillín Valley began during the Oligocene-Miocene as a result of a N–S half-graben sedimentary basins system (Chillán, Lileo and Lonquimay basins) between Chile and Argentina (Radic, 2010). A tectonic inversion of these basins system occurred in the Upper Miocene (Jordan et al., 2001; Burns, 2002; Radic et al., 2002; Radic, 2010; Charrier et al., 2005). These basins are connected by a NW-SE accommodation zone, which also coincides with the extension,

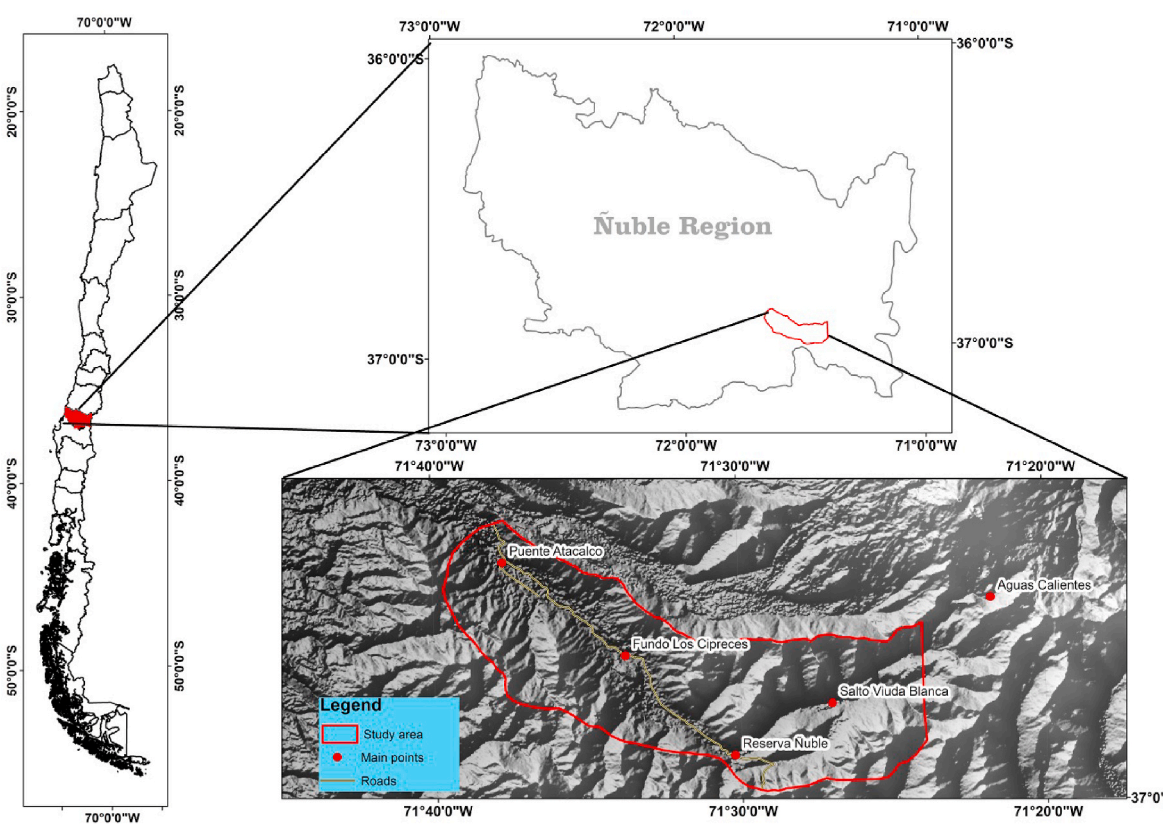

Fig. 1. Slope map of the study area in Ñuble region (lower image) and its location in Chile.

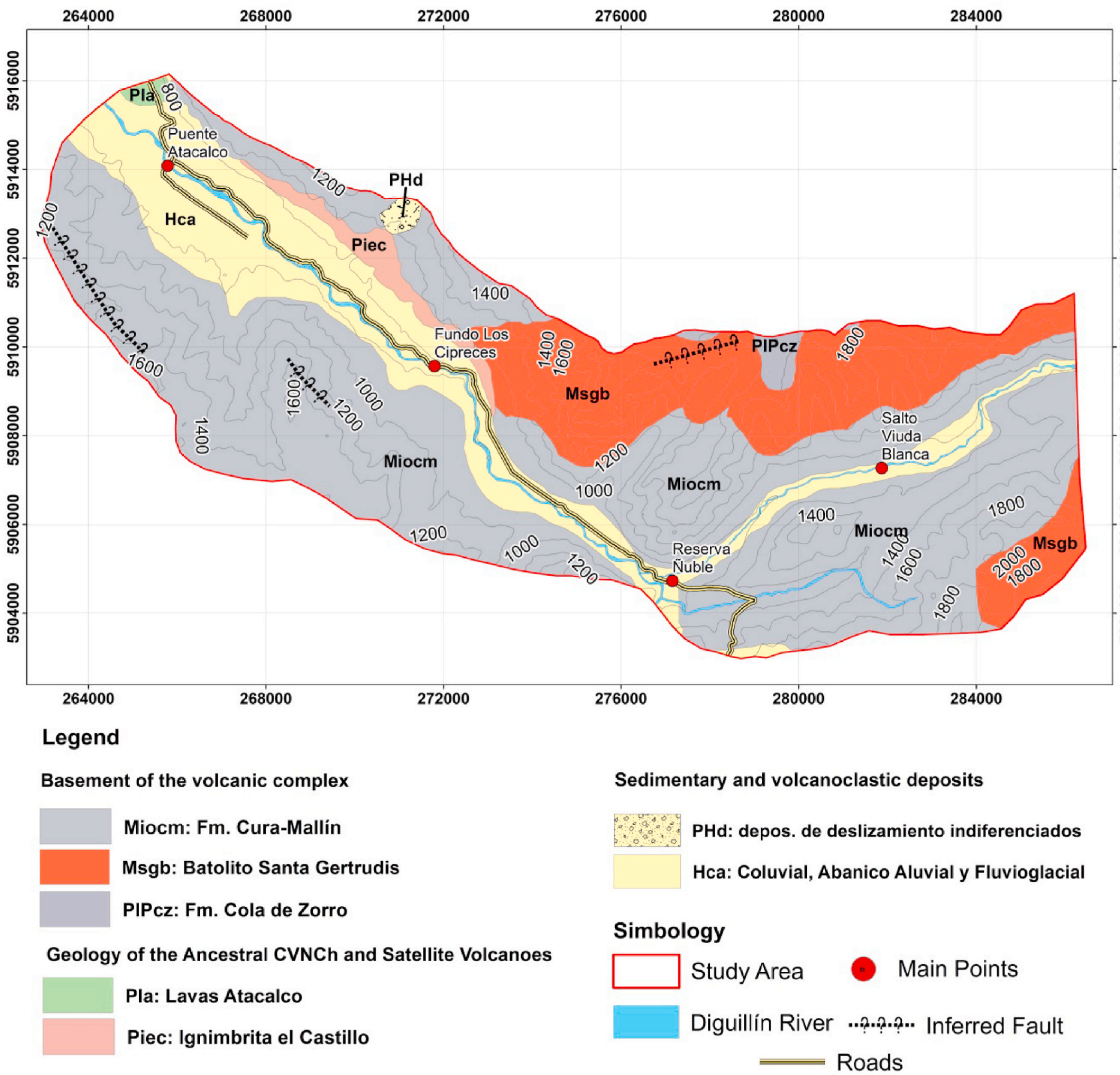

Fig. 2. Geologic map of the Diguillín Valley.

in Chile, of the Cortaderas Alignment (Ramos et al., 2006), determining the direction of the main valleys of the Andes Mountains (Fig. 3). After the last Upper Miocene tectonic events, glacial and fluvial processes affected surface topography changing into the present day valleys.

Some studies located in the northern sector of the central Andes such as the Maipo basin (Herrera et al., 2009; Herrera, 2016), southern Maipo and the Cachapoal catchments (Charrier et al., 2019), show that the main glaciers that descended from the east during the LGM would have deepened the drainage systems. Brüggen (1929) and Lliboutry (1956) considered that Pleistocene glaciers in the Maipo and Cachapoal basisn reached the Central Depression up to altitudes of 750 m a.s.l. and 675 m a.s.l. Respectively. Recent studies in the Maipo catchment (Borde, 1966; Chiu, 1991; Ormeño, 2007; Herrera, 2016) and Cachapoal (Santana, 1967; Charrier et al., 2019) concluded that glaciers only descended at altitudes between 950 m a.s.l. and 1300 m a.s.l., reaching lengths of ~60 km. In the Lontué valley, it is estimated that the glaciers reached altitudes little above the Central Depression (Puratich, 2010).

To the south, Niemeyer and Muñoz (1983) established this glacier advance below 1000 m a.s.l in the Laja Lago. In the Lontué river drainage basin, the ELA reached 2500–2600 m a.s.l. (Puratich, 2010), at least 700 m below the current one, located at 3300 m a.s.l. (Espizua, 2005). According to Lowell et al. (1995), in the LLanquihue area the ELA was located at 1800 m a.s.l during the LGM.

Today the glaciers cover around 2.4 km^2 and they are constrained to the Cerro Blanco Glacier, locally known as Los Nevados, where the Equilibrium-Line Altitude (ELA) places at ~ 2800 m a.s.l. (Zenteno et al., 2004), suggesting an extensive ice cap centered in the CVNCh that advanced with an E-NE direction affecting the High Diguillín and Renegado hydrological basins (Zúñiga et al., 2012).

The climate of the study area is temperate with annual temperature averages of 14 °C, although it experiences significant changes during the year (4–30 °C). Humid air masses that arrive from the Pacific Ocean generate precipitation and temperature changes. The average annual precipitation ranges from 1200 to 2000 mm. According to the Chilean Directorate of Waters, the humid period lasts half of the year, and precipitation in winter could be in form of snow.

3. Methods

The geomorphological map of the Diguillín valley (scale 1:50.000) was produced (Main map in Appendix A. Supplementary data) in order to represent the landforms of the study area. A semi-detailed analysis of four vertical aerial photographs (GEOTEC 1:70.000 Sector10 Concepción, SAF, 2000) from Aerophotometric Service of the Chilean Air Force (FACh) was carried out with stereoscope and Enhanced Compression Wavelet (ECW) obtained from SAS Planet with zoom 20

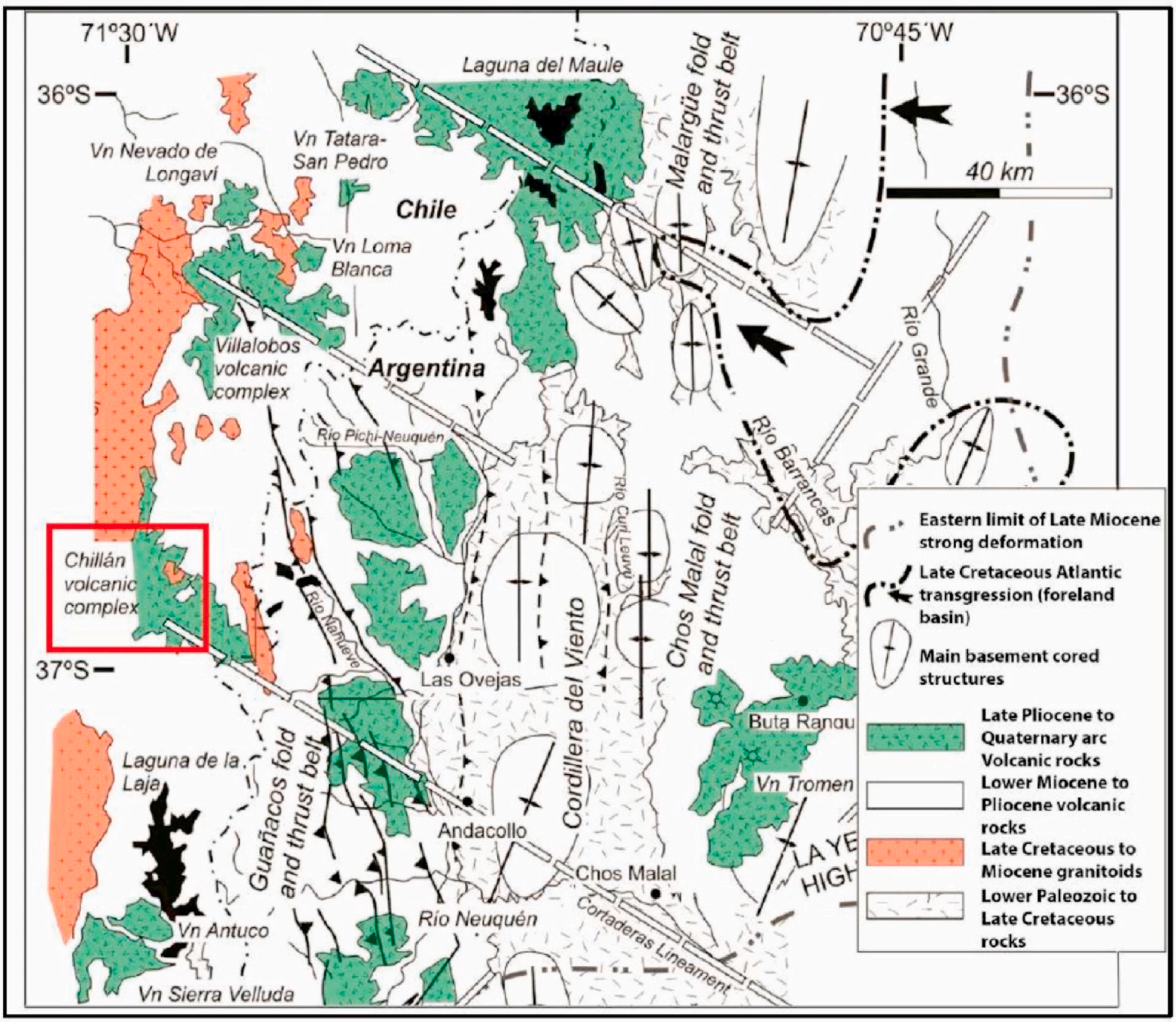

Fig. 3. Study area (red square) in the frame of regional structures features (Modified form MeulleStef, 2017). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

(287 × 180 number of tile) of server ESRI.

To represent the landforms in detail, we used the standard procedures provided by French geomorphological mapping criteria (Joly, 1966; Tricart, 1971) and the morphoclimatic simplifications suggested by the Instituto Geológico Minero de España in 1: 50.000 scale cartography (IGME, 2004). The French model is characterized by a morphogenetic orientation based on the dependence of the relief on climatic conditions. The map is organized through a general legend expressed by two types of elements: geomorphological landforms and recent deposits or surface formations. The geomorphological landforms are represented with a genetically grouped symbology that is identified through a specific color of strong intensity. The recent deposits constitute areas colored in shades of low intensity according to certain colors that also correspond to its genesis.

The map was verified during twelve days of fieldwork in 2018. Lithologic units, stratigraphy of landforms, geological structures and their geometric relationships were establish. Besides, a morphological and stratigraphic analysis of the landforms and deposits were performed which include stratigraphic columns and geological profiles at different scales. Glacial, fluvial and gravitational landforms were identified on the map and correlated using position and morphological characteristics. This information was supplemented with a morpho-structural analysis that were corroborated in the field, and later aided by digital terrain models designed by means of an Alos Palsar digital elevation model. The software used to produce the map was the ESRI ArcGIS 10.3 (ArcMap environment).

4. Results

The geomorphological map of Diguillín valley (Main map in Appendix A. Supplementary data) shows a wide diversity of landforms. In total, 22 types of landforms are mapped along an area of 156 km^2. These landforms have been classified in the following categories: structural, fluvial, gravitational and glacial landforms.

4.1. Structural landforms

The landforms included in the structural relief are related to tectonic activity. We recognize in the study area faults, triangular shaped facets and scarps. The structural alignments control the evolution of Diguillín valley, dividing it in two main sections. A first section extends from Aguas Calientes valley (2.100 m a.s.l.) to Trumao located at Reserva Ñuble (895 m a.s.l.). Here the valley has 12 km long, 300–600 m wide and a N65°E direction. The second section encompass from Reserva Ñuble to Atacalco (620 m a.s.l.) where the valley reaches 16 km long, a maximum wide of 1.8 km and a N48°W direction. A volcanic and igneous relief of 5.5 km long and 700 m a.s.l high is located in the central part of the valley. This structure exerts a barrier effect that changed the direction of the Diguillín river. Other minor valleys separated by watersheds and arêtes are controlled by minor alignments with NNW-SSE, NNE-SSW, N–S and E-W directions.

4.1.1. Faults

Based on the analysis of shielding models and regional alignements, we observed that most of the structural features has a preferential NE-SW direction that coincides with the bottom of the narrow valleys whereas other minor number of structural features with a NW-SE direction coincides with the main valleys. The study area is affected by fault systems parallel to the regional alignments that present N80W–N10E and N70W–N30W directions.

For instance, we identified in fieldwork two faults affecting pyroclastic layers belonging the Cura-Mallín formation. The first one is an oblique reverse fault N10°E/55° NW which exhibits kinematic markers of recrystallization steps and striated features with 41°N rake. The second reverse fault is found in the same area although it has a different direction (N80°W/45°SW). This fault is also characterized by fault gouge between the two rock blocks.

4.1.2. Triangular shaped facets and scarps

In the study area, two well-defined triangular shaped facets areas are distinguished to the west of Atacalco and Los Cipreses with NW-SE direction and 2,5 km 1,65 km long respectively (Fig. 4). Close to it, in the southern slope of Valle las Trancas also triangular shaped facets are evident by scarps being associated with inferred faults with NE-SW direction and 1,5 km long.

4.2. Glacial landforms

Today, there are no glaciers in the summits of the study area but evidence of glacial action is observed in Diguillín valley. Thus, ice masses occupied at least half of the valley in the past maybe during the Last Glacial Maximum or Late Pleistocene cold events. The intensity of glaciation is recorded especially in the upper valley where we found glacial eroded landforms remnants such as cirques, polished and striated bedrock surfaces, arêtes and U-shaped glacial profiles. Glacial deposits are also preserved including erratic boulders, morainic deposits and glacio-fluvial terraces.

4.2.1. Glacial cirques

Glacial cirques were delimited in the catchments of Reserva Ñuble around 1800 m a.s.l., especially in the northern slope where they reach a major size. We mapped 9 glacial cirques with a perimeter between 2 and 4.5 km and slopes ranging from 20° to 45°. Arêtes characterized by a horse-show shape (concave surface) named col acts as limits between glacial cirques. Furthermore, one glacial lake is located in the southern slope of Reserva Ñuble which origin is associated with abrasion and over-deepening.

4.2.2. U-shaped glacial valleys

Glacial erosion has developed a U-shaped morphology in Diguillín valley, a typical configuration of mountain glaciations. U-shaped morphology of Diguillín valley present two directions: (i) one has a N65°E direction that extends from Aguas Calientes valley to El Trumao in Reserva Ñuble where the valley is 12 km long and 300–600 m wide (ii) the second has a N48°W direction from El Trumao to Atacalco. The size of this section of the valley is 16 km long and a maximum wide of 1.8 km. Several cross subsidiary and hanging valleys to Diguillín, ranging mostly NNW-SSE direction and length from 1.5 to 2.5 km, appear to the SW and the S of the study area.

4.2.3. Polished and striated bedrock surfaces

A polished bedrock surface of 10 m long and 3 m wide on andesitic rocks is located 3,7 km to the SE from Atacalco at 690 m a.s.l (Fig. 5). Others polished and striated surfaces are observed around Reserva Ñuble area. The first one, at 885 m a.s.l., is preserved on an andesitic surface of 4 m long with glacial grooves (1 m long and 20 cm wide) and striations that indicate a SW direction of glacier advance. The second is located at 926 m a.s.l., on a polished granodiorite dome. The presence of these eroded glacial morphologies suggest that the ice covered the upper part of the valley sometime in the past.

4.2.4. Morainic deposits

Three types of morainic landforms were also identified in the study area: inner moraines, lateral moraines and erratic boulders. Inner moraine deposits, ~ 5 m high and ~10 m long, are emplaced close to Salto de la Viuda Blanca (1075 m a.s.l.) and El Trumao Reserva Ñuble (922 m a.s.l.). It is compound by striated boulders embedded in a chaotic

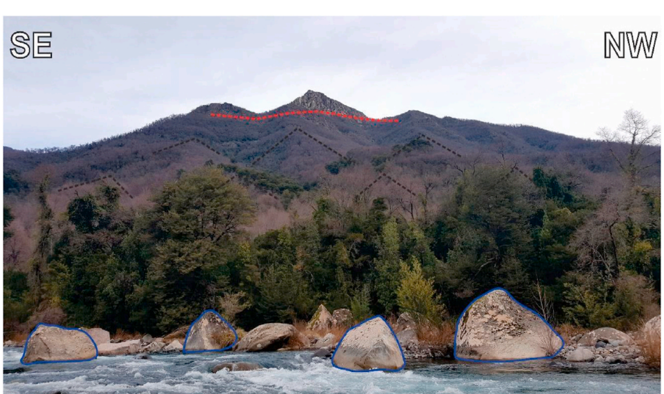

Fig. 4. Southward of the Diguillín valley. A triangular shaped facet (black dashed lines), an inferred fault (red dashed line) and a rockfall deposit (blue lines) are delimitated. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Fig. 5. Polished rock on the southern slope of the Atacalco area. Friction clefts are marked in red color. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

matrix (20%) of medium sand and clay size with subangular to subrounded clasts (80%). The type of rocks are andesites, granodiorites and granites. Their origin is associated with glacier retreat and they are massive debris accumulations which adopt an irregular or regular hummocky landscape. Two lateral moraines are distributed to the NW of Reserva Ñuble (900 and 818 m a.s.l.) (Fig. 6). These deposits consist of isolated single ridges of 4 m high and 20–700 m long compound by a chaotic mixture of angular to rounded clasts (70%) and a clay size matrix (30%). The lithology is mainly formed by granitic, andesitic and pyroclastic rocks. Erratic boulders up to 13 m in maximum length appear on the top of a fluvioglacial deposit located 2,5 km to the SE from Atacalco bridge (697 m a.s.l.) (Fig. 7). Signs of erosion such as plucking and striated features (1.5–4 m long and parallel arrangement) are well-preserved in all the boulders. The size of the boulders ranges between 2 and 13 m and the arrangement of the major axes indicates a NNW direction of advance.

4.2.5. Fluvioglacial terrace system

We delimited an extensive fluvioglacial plain which origin is associated with sediment accumulation that filled the bottom of Diguillín valley forming an extensive plain (Fig. 8). The material was carried by water derived of glacial melting together with fluvial activity. When glaciers disappear, the river incision created a fluvioglacial asimetric terraces system. We performed a detailed analysis of 6 stratigraphic columns in several terraces from el Trumao sector (Reserva Ñuble), to the Atacalco bridge. The biggest terrace (el Trumao) is 100 m wide and 14 m high and it is compound by several layers of a chaotic mixture of heterogeneous conglomerates where subangular to subrounded clasts, from 1 cm to 2.5 m size, represent the 60% of the deposit and fine matrix (sand grains and clay) constitute the 40%. The other terraces, located at different points on the north slope up to the Atacalco bridge, has a similar composition. Their size are smaller except one that present similar dimensions that the one emplaced at el Trumao.

4.3. Gravitational landforms

Gravitational landforms include erosive and accumulative relief caused by the influence of gravity. The processes associated with hillslope dynamics are frequent in the study area due to elevation (average altitude of 1900 m a.s.l.), a mountain climate that experience periodical freeze/thaw cycles and temperature fluctuations being ideal conditions for periglaciation and the presence of steep slopes (20-45°). Thus, wide erosive and depositional features were mapped such as rockfalls, debris flows, landslides, alluvial fans, colluvial deposits, glacis, creep and solifluxion terraces.

4.3.1. Rockfall

Rockfall deposits were delimitated on the northern slope of El Trumao (Reserva Ñuble) and 5,5 km to the SE of Atacalco bridge. These deposits are characterized by the existence of angular pyroclastic and andesitic boulders which sizes ranges between 10 cm and 4 m. They are distributed at the feet of steep slopes (30-45°) that exhibits prominent scarps. It must be noted that the scarps close to Atacalco bridge are associated with triangular shaped facets which implies an active tectonic

Fig. 7. Erratic boulder in the southern slope of the Atacalco bridge, showing striation marks.

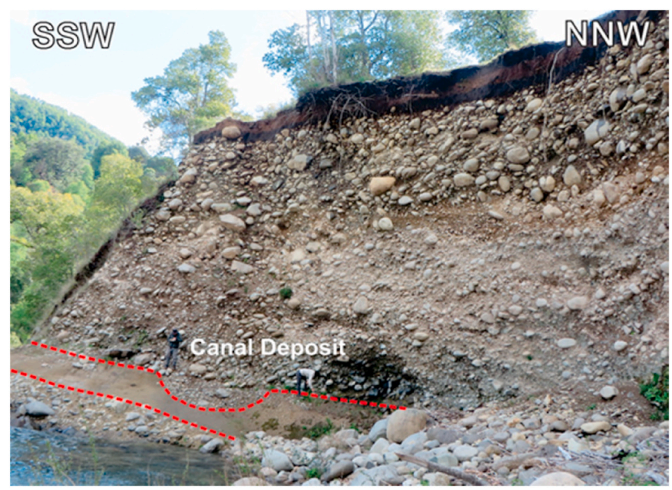

Fig. 8. Fluvioglacial terrace located 3.8 km to the SE of the Atacalco bridge compound by heterogeneous conglomerates layers. In red is pointed out a sedimentary channel structure formed into micro conglomerates and sand deposits. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

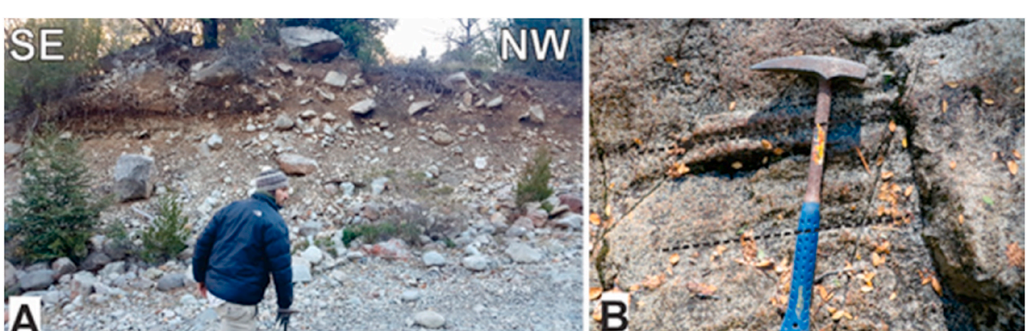

Fig. 6. A) Lateral moraine deposit; B) Boulder striation of the inner moraine.

activity (Fig. 4).

4.3.2. Debris flows

We recognized debris flows distributed along steep slopes (>30°) of Diguillín valley, especially in the meridional and oriental parts, as well as tributary valleys. They show characteristic erosive and sedimentary morphologies such as a semicircular starting head scarp, the channel and the depositional lobes. The channel and the depositional lobes reach a maximum size of 100 m wide and 650 m long.

4.3.3. Landslides

Two landslides have been mapped, both located in a steep slope 4,5 km to the SE from Atacalco bridge. Landslides process mobilize weathered material masses from the slopes to the valleys. The scars appear clearly defined and exhibits a concave shape with a perimeter of 1 km, indicating the mobilized material. By contrast, the deposits are covered by vegetation which means that landslides are not an active process in Diguillín valley.

4.3.4. Alluvial fans

A coalescent alluvial fan system was identified in the southern slope of Atacalco (Fig. 9). Due to the valley is wide and the energy of the debris transport processes decreases downslope, the material is accumulated at the base of the slopes. The delimited alluvial fans have 2 km long and 1 to 1,5 km wide matching with fault zones.

4.3.5. Colluvial deposits

Periglacial activity caused by ice inside the rocks associated with the frequency of freeze-thaw cycles produce colluvial deposits. The periglacial processes affected the andesitic rocks which have joint and fissure networks. Thus, we found colluvial deposits at the feet of the steep slopes around Los Cipreses, characterized by angular to subangular clasts (60%) and a matrix (40%) of clay size. The size of the clasts ranges from 2 cm to 1 m.

4.3.6. Creep and solifluxion

Climate in Diguillín valley is cold in winter and warm in summer, being susceptible to produce freeze/thaw cycles and temperature fluctuations. As a result of this process, we detected the existence of creep and solifluxion lobes on the southern slope of Diguillín valley, 3,6 km to the SE of Atacalco bridge. The evidence of creep process is the basal curvature to the north of trees.

Fig. 9. View of an alluvial fan located on the southern slope of the Atacalco bridge sector.

4.3.7. Glacis and piedemonts

Colluvial glacis (Tricart et al., 1972) were delimited in both slopes (northern and southern) of Atacalco (Fig. 10). They present a maximum slope of 10° and 3–14 km length. To the south, the glacis connect with alluvial fans and colluvial deposits, whereas to the north they contact with fluvial terraces. Piedemonts are formed by colluvial-alluvial sediments originated in the slopes and they have under 20° slope. We found piedemonts to the NE and SW of the study area joining colluvial deposits and alluvial fans with the bottom of the valley (Fig. 11).

4.4. Fluvial landforms

Fluvial process occurs mainly along Diguillín river. The high slope and intense tectonic uplift, that produced several fractures or fault systems, which are key factors to facilitate fluvial processes. Erosion predominates in the upper valley, whereas accumulation and fill are more important downvalley. We mapped two main landforms: terraces and alluvial plain.

4.4.1. Fluvial terraces

An asymmetric and divergent terrace system has been distinguished in the study area. This landform is a consequence of tectonic uplift and fluvial incision after the accumulation of the fluvioglacial and alluvial deposits. We observe 3 levels of terraces in the southern slope of Atacalco, each with a thickness of 2 m. However, the northern slope present 2 levels of terraces although they are thicker (7–14 m the first level) (Fig. 12).

4.4.2. Alluvial plain

The alluvial plain is formed by the solid load of the Diguillín river, mainly formed by gravels. Points bars developed by lateral accumulation of sands and gravels are stabilized by vegetation on the inside bend of the current channel (Fig. 13). Towards the east, alluvial plain disappear upstream giving way to glacis and foothills formed by glacial and outwash deposits and rocky outcrop.

5. Discussion

We obtained a detailed geomorphological map of Diguillín valley (Main map in Appendix A. Supplementary data) where 22 types of landforms are represented, according with their geomorphic environment. Although the absence of dates in the study area do not allow us to perform an absolute chronological reconstruction, we can provide a relative geomorphological evolution based on the analysis of the map and published data.

Fig. 10. Colluvial glacis with wide development between the base of the relief and the fluvial terraces.

Fig. 11. Cross-sectional view of the Diguillin Valley in the Trumao sector, where piedemonts at the base of the relief can be observed.

Fig. 12. Alluvial plain and two fluvial terrace levels (t3 and t4) in the northern and southern banks of the Diguillín river.

Structural alignments (NE-SW) derived of the subduction of the Nazca Plate beneath the South American Plate (Mpodozis and Ramos, 1989) and fault tectonic structures (NW-SE) inherited from the pre-Andean anisotropic basement (Meulle-Stef, 2017) and reactivated during the Tertiary (Melnick et al., 2003, 2006; Ramos et al., 2006) have controlled the origin and development of Diguillín valley. Then, subsequent denudational fluvial processes and progressive tectonic uplift since the upper Miocene tectonic inversion (Jordan et al., 2001; Burns, 2002; Radic, 2010; Radic et al., 2002) produced an intensive erosion on volcanic and intrusive rocks (Miocene to Pleistocene).

Glaciers have also modelled the landscape during the Pleistocene as evidence glacial eroded landforms remnants (cirques, polished and striated bedrock surfaces, arêtes and U-shaped glacial profiles) and deposits (erratic boulders, morrainic deposits and glacio-fluvial terraces). The directions of glacial movement can be inferred by minor alignments parallel to Diguillín valley (NNW-SSE, NNE-SSW).

However, the age of the glaciation remains unknown. The preservation of polished and striated bedrock surfaces as well as erratic boulders and glacial deposits indicates that an ice masses occupied the upper Diguillín valley areas and advanced on its lowest position until 3,7 km SE from Atacalco bridge (690 m asl). This glacial advance likely occurred 21 ka ago when glaciers reached their maximum extent in this part of the Central Andes (Siegert, 2001). To confirm this hypothesis, a dating effort is necessary by means of radiocarbon, *in situ* cosmogenic surface dating or optically stimulated luminescence methods.

Once the glacier retreat, slope activity and fluvial processes were predominant. Sediment supply by ice masses formed glacial and fluvioglacial deposits that have been affected by fluvial erosion. The evidence are fluvial terraces due to the incision of Diguillín river. Furthermore, periodical freeze/thaw cycles, steep slopes (20-45°) and cold climate are ideal conditions for the formation of gravitational landforms such as rockfalls, debris flows, landslides, colluvials deposits, creep and solifluxion terraces. Today some of them are active as rockfalls, debris flows, creep and solifluxion.

6. Conclusions

The 1:50,000 geomorphological map obtained in Diguillín valley clearly provide the distribution and characteristics of structural, fluvial, gravitational, and glacial landforms. This map also represents a consistent base for ongoing research such as dating to better constrain the

Fig. 13. Satellite view of the Diguillín river in the Atacalco bridge sector. The alluvial plain and the point bar are marked in green and yellow, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

geomorphological and paleoclimatic evolution of the study area. It must be noted that our study allowed the identification of glacial abrasion at 690 m asl which suggest a significant glacier advance even more extensive than in other mountains areas of the Chilean Andes. Furthermore, the geomorphological map of Diguillín valley is the first detailed document reported in the Chilean Andes and it could be an important support to carry out similar studies in other mountain areas of the Chilean Andes.

Author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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