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Geomorphological of a portion of the Andes and Pre-Andes of San Juan, Argentina

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A detailed geomorphological map is presented for a portion of a poorly investigated mountainous region of the Dry Frontal Andes and Western Pre-Andes of San Juan province around 30°S latitude. This map shows the presence and extension of landforms and geomorphic processes in an area of 2175.9 km^2 and is the result of detailed aerial photograph and remotely sensed data interpretation, including digital elevation models, supported by field survey. The landforms have been distinguished according to morphogenetic criteria, into: (i) glacial landforms; (ii) periglacial landforms; (iii) mass movement landforms; (iv) fluvial landforms: (v) polygenic landforms and (vi) neotectonic landforms. The objective of this map is to provide information on the landforms present in the selected area, allowing it to be used as a baseline for the study of landscape evolution or support guidelines for territorial management and planning.

Keywords: Geomorphological map; GIS; San Juan province; Argentina

1. Introduction

Geomorphological maps are transmitters of information about the form, origin, age and distribution of landforms together with their formative processes, rock type and surface materials (Brunsden, Doornkamp, Fookes, Jones, & Kelly, 1975). Geomorphological maps can emphasize different aspects of landforms: form, origin, age and relations. Dependent on the purpose of the map, these aspects can be depicted by colored area symbols, patterns and line symbols (Van Zuidam, 1985). A great variety of geomorphological mapping systems have been designed over the course of time, however Tricart (1965) insisted that without genetic interpretation these do not constitute geomorphological maps. Geomorphological mapping, based on field surveys and the use of aerial photograph interpretation and remote sensing techniques, have long been used by applied geomorphologists. One of the drivers of the resurgence in geomorphological mapping is technology: the availability of new data sources (e.g. digital elevation models (DEMs)) has allowed new insights and rapid mapping to be performed, organized within the framework of a geographic information system (GIS) (Smith, Paron, & Griffiths, 2011).

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In this paper I present a geomorphological map that's illustrates the entirety of landforms and geomorphic processes observed in a portion of the Frontal Andes and Western Pre-Andes of San Juan province, Argentina (See the associated main map). The resulting maps can provide a basis for urbanism, land use planning and zoning.

2. Study area

The territory of interest covers an area of 2175.9 km^2 and is located in the middle west of Argentina and in the north of San Juan province, Iglesia department, between latitudes 29°39′–30°9′S and longitudes 68°47′-69°41′W, on the northeast side of the Central Frontal Andes and north of Western Pre-Andes. It is characterized by high relief with peaks up to 5000 m a.s.l. (Figure 1).

The population of the Department of Iglesia (Figure 1) is 9099 (2010), with the principal economic resources of the region being mining (ore), agriculture (seeds and vegetables) and tourism. Agricultural activity is located mainly in valley areas, where there is a water supply available from the irrigation network and private wells. Most of the small towns in the Department are situated downstream of river basins from the Frontal Andes (Malimán, Colangüil, Angualasto) or Occidental PreAndes (Buena Esperanza). The villages suffer flash floods and debris flows during the summer period, which has caused material damage and several casualties, primarily to the road that connects the farming communities of Angualasto, Buena Esperanza and Malimán, as well as road 413 which connects the major cities of San Juan to the two major mining projects in Argentina (Pascua Lama and Veladero).

The hillsides rise from 1587 m a.s.l. to 5639 m a.s.l. with average slope angles of 12°. The slopes are very steep in the upper portion (~45°) and are rocky and poorly vegetated. The area is characterized by semi-arid conditions with a dry climate, short summers and severe winters with very low temperatures (−18°C to 0°C), strong winds and a rainy season normally lasting from November to March. Nevertheless, the rainfall regime is irregular, with periods of both rare precipitation and heavy rain. Above 4000 m a.s.l. precipitation is mainly snow and hail; precipitation events are of irregular frequency. The maximum rainfall is recorded in the summer and the largest amount of rainfall measured on one month was 62.3 mm (January 1993).

The valley of Iglesia is a regional tectonic depression limited to the west by the Frontal Andes and to the east by Western Pre-Andes. The Frontal Andes is a mountainous system generally oriented in a north–south direction with peaks up to 5000 m a.s.l. and contains a Paleozoic basement comprising sedimentary, metamorphic and igneous rocks, which was strongly deformed and is intruded by Upper Paleozoic granitoids. An Andean cover lies unconformably over the Paleozoic basement, and is composed of Permo-Triassic and Cenozoic sedimentary, volcanic and volcaniclastic rocks, intruded by Mesozoic and Cenozoic granitoids. This cover was deformed in Cenozoic times, during the Andean Orogenic Cycle (Ramos, 1999).

The Precordillera, an older orographic system with a lower topographical hierarchy, has a general north–south orientation and rises up to 3000 m a.s.l. Lower Ordovician sedimentary rocks are the oldest stratigraphic units, composed of limestones, sandstones and lutites and is observed in the eastern parts of the study area. Devonian conglomerates, sandstones and pelites appear in the area, and Carboniferous marine formations (lutites, wakes and conglomerates) have unconformable contact.

The Pleistocene is represented by glacial, alluvial and colluvial landforms and the Holocene by conglomerates, sands silts and clay occupying the valleys and riverbeds. Data were acquired from geologic map sheets published by the Servicio Geológico Minero Argentino (Argentine Mining Geologic Service) at 1:250,000 scale.

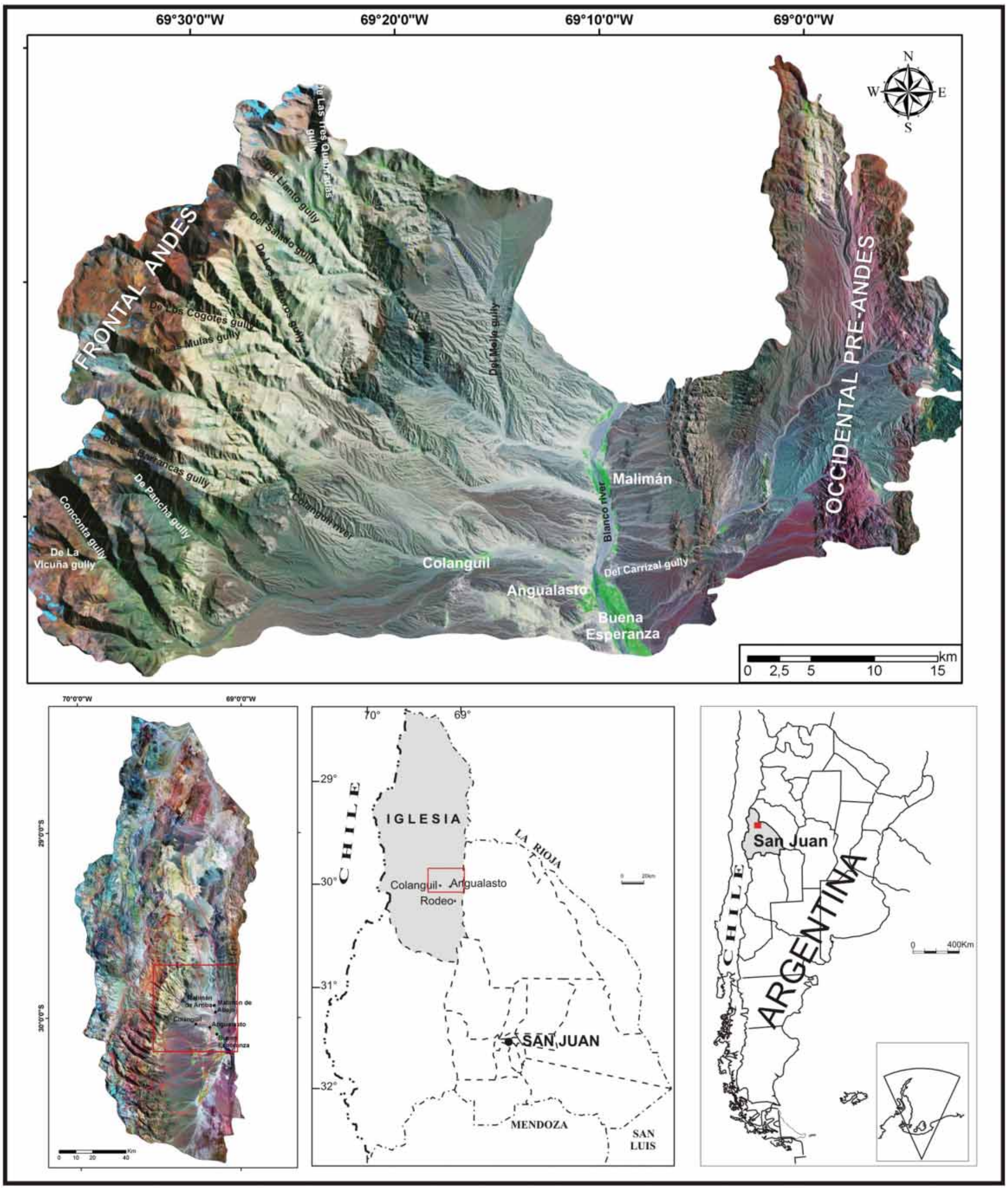

Figure 1. Location of the study area and their location in San Juan province, Argentina.

3. Materials and methods

All recognized landforms were mapped on screen in a GIS environment (in vector format) and later were verified by fieldwork. The subdivision of landforms into active, inactive and fossil (WP/WLI, 1993) was based on morphological criteria. Landforms are classified active where they appear fresh on the imagery at a given date. The common subdivision of rock glaciers into active, inactive and fossil based on morphological criteria (Martin & Whalley, 1987; Wahrhafting & Cox, 1959) was applied in this study.

Table 1. Satellite imagery used in the geomorphological mapping.

Satellite	Date	Path	Row
Landsat 5	1986-04-02	233	80
Landsat 5	1990-04-13	233	81
Landsat 7	2000-11-19	233	80
Landsat 7	2002-03-21	233	81
Landsat Mosaic	1985–1990		
SPOT5	2008-04	56724100804021441472J	

For this research, aerial photographs and digital satellite images (Table 1), were georeferenced to a common coordinate system (GCS_WGS_1984; Datum: D_WGS_1984).

Geologic map sheets published by the Servicio Geológico Minero Argentino (Argentine Mining Geologic Service) at 1:250,000 scale were used to determine lithology.

Altitudes were obtained from 1:100,000 topographic sheets with a 50-m contour interval published by the Instituto Geográfico Militar (Argentine Military Geographic Institute), and from topographical information obtained from the Shuttle Radar Topographic Mission (USGS, 2000). A DEM was interpolated using Natural Neighbor. The final map is presented at a scale of 1:75,000 in order to fit an A0 paper sheet, but its precision relates to the original 1:50,000 scale mapping.

4. Geomorphological setting

Landforms have been grouped, taking into account their main genetic agent, into: (i) glacial landforms; (ii) periglacial landforms; (iii) mass movement landforms; (iv) fluvial landforms; (v) polygenic landforms and (vi) neotectonic landforms.

The landforms of the resulting landscape are related to glacial, periglacial, fluvial and alluvial action, aggradational and degradational processes, as well as to neotectonic activity and climatic changes. The landforms originating from the present glacial environment prevail only at higher altitudes. Even though current glacial activity is limited, in the past it was an active agent in modeling the relief of the region. It is possible to observe erosional landforms and some depositional landforms of glacial origin and small lakes and ponds.

Periglacial landforms have modified an early Pleistocene glacial landscape which occupies lower altitudes. The most representative periglacial landforms are detrital slopes, patterned ground, rock glaciers, solifluction forms, talus cones and asymmetrical valleys, with south facing slopes being steeper than north facing slopes.

Permanent fluvial activity is restricted mostly to the Blanco river that runs N-S and is composed of braided channels, mostly due to the high volume of bedload.

4.1. *Glacial landforms*

Present glacial activity is restricted to higher elevations, above 4650 m a.s.l. At this elevation, it is possible to observe small glaciers (<0.5 km^2) and lateral and end moraines. A total of 10 glaciers were mapped, covering an area of 2.84 km^2, or about 0.13% of the total area.

The main glacial erosional landforms observed appear above 4400 m a.s.l. on the Permo-Triassic volcanic and volcaniclastic rocks. The most representative erosional landforms are cirques, arêtes, horns, U-shaped valleys and, exceptionally, hanging valleys. The best example of cirques appears at the headwater of De la Vicuña gully (Figure 1) with a ∼1500-m wide amphitheater. U-shaped valleys are up to 3 km long, usually less than 500 m wide, and 200–400 m deep. Late Pleistocene till deposits (moraines) have also been observed. In the De la Vicuña valley (above 3400 m a.s.l.), a moraine is located downvalley; , this moraine is 1.6 km long and 78 m thick, has clear, sharp crests. Clasts are largely vo1canic (andesitc, dacite, rhyolitic). In De las Tres Quebradas valleys (above 3200 m a.s.l.) laleral moraines are followed discontinuously downvalley where they are partly covered by colluvial cones and locally eroded by tributaries.

In addition, a large number of perennial snow patches have been observed at the top of main valleys, above 4000 m a.s.l., on south and east facing slopes.

4.2. *Periglacial landforms*

Typical cryogenic processes observed in the study area are: frost-shattering, vertical and horizontal sorting, cryoturbation, solifluction, nivation, permafrost creep and cryodenudation processes on the slopes. These processes create micro- and mesofeatures such as: patterned ground, structures of extrusion, tors, solifluction lobes and terraces, garlands, nivation hollows, detritic slopes, asymmetric valleys, nivodetritic avalanche channels, cryoplanation surfaces, and rock glaciers.

The most common solifluction forms noted in the area are the solifluction lobes, with the shape of protuberances located on the mountain slopes of the main modern fluvial valleys. Thermokarst depressions have been observed in the areas above the non-active and fossil rock glaciers, located topographically beneath the active ones. In the detrital slopes, the rock fragments resulting from gelivation are channeled. The downward movement of this material causes a trenching in the substrate that, at times, becomes the funneling chute for snow and rock avalanches. Talus cones, are very common on andesitic, dacitic and rhyolitic rocks, these are formed by creep, with a sheet-flow drift caused by the downfall of small and sharp rock. Broken material largely originates from the action of intense cryoweathering and the absence of vegetation.

Over 158 rock glaciers were mapped, occupying an area of 10.90 km^2, or about 0.55% of the total area, of these only 23% are tongue-shaped rock glaciers. Active (60%), inactive (30%) and relict (10%) rock glaciers, are widely distributed over the study area. All the rock glaciers mapped occur above 3480 m a.s.l. (active, 3651 m a.s.l.), with this elevation thought to be the minimum necessary elevation for the development of rock glaciers (Esper Angillieri, 2009, 2010). However, the differentiation between inactive and active rock glaciers in this area is only based on the interpretation of aerial photographs and must therefore be considered as preliminary. The location with respect to late Pleistocene moraines clearly indicates that all intact rock glaciers are of post-glacial age; in most cases these can be assigned to the Holocene (Brenning, 2005). Peatlands are common at the foot of a periglacial environment.

The cross-profile of the valleys is markedly asymmetric due to north facing slopes being exposed to direct sunshine. As a result there is more weathering, with stepped features, than those facing south. The latter are colder and steeper and have a greater number of rock glaciers located on them.

4.3. *Mass wasting landforms*

The large accumulation of debris, lithological characteristics, absence of vegetation and occurrence of triggering events, such as frequent precipitation and/or earthquakes, have all favored mass wasting processes. On these accounts, a great number of landforms have been recognized in the study area and include colluvial cones, landslides, debris avalanches, debris flows and areas with solifluction/gelifluction (talus cones, rock glaciers and solifluction lobes) that were mentioned in the previous section.

A total of 346 debris flows were identified covering an area of 42.45 km^2, accounting for 1.95% of the study area (Esper Angillieri, 2011a). Historical records note the following debris flows:

- in 1944 in the Del Carrizal gully (Esper Angillieri, 2007, 2011b), heavy rainfall, steep slopes, narrow gully and the elongated morphology of the main watersheds caused a debris flow with a peak discharge of 600 m^3/s. Thirty-five people died, houses and most of the cattle and crops were destroyed. There are no data about the volume of rainfall, no newspaper records or eyewitnesses.
- in 2007, after heavy rainfall, the road that connects the farming communities of Angualasto, Buena Esperanza and Malimán (Figure 1) was damaged.
- in 2010, as a result of heavy rainfall of 50 mm/h (average annual rainfall $<$44.9 mm), a sizeable debris flow affected the town of Malimán. Several homes were damaged and most of the crops and farm animals were destroyed. The local school and irrigation channels also suffered severe damage (Perucca & Esper Angillieri, 2011).

Although, the study area was affected by slides (6) and debris avalanches (24) of different types and sizes, they do not show evidence of present activity. In general they are eroded and have smooth surfaces and so can be considered relicts because they have been developed under climatic conditions considerably different from those at present (mainly wetter periods).

Other common type of mass wasting include rockfall. Rocks, boulders, and dirt loosened by freezing, weathering, and other forces, simply fall downward, until they hit something that stops their descent. This type of mass wasting occurs on all lithologies.

4.4. *Fluvial landforms*

Alluvial fans are the most common fluvial landform in the study area (identified as a **NA1** to **NA4 on the** geomorphological map)**.** The youngest fan generation (NA-4) has adjusted to the present floodplain and is interpreted as the result of ongoing degradation of the Quaternary slopes. These fans are often developed as telescopic fans cut into inactive and degrading colluvial slopes. These active areas are frequently flooded with modern flash floods and have a poorly developed drainage pattern. Desert varnish or desert pavement have not developed. These areas are found in lower altitudes relative to older levels of fans, which do possess desert varnish and desert pavement, in addition to a much better defined drainage pattern. A lateral convergence of neighboring alluvial fans into a single apron, against a slope, is called a 'bajada', or compound alluvial fan.

All the alluvial fan levels are related to past climatic conditions, colder and more humid than currently. Abundant snowfall and rain during the Pleistocene allowed the deposition of greater amounts of detritus, generating alluvial cover with thickness increasing towards the east. These climatic conditions alternated with arid intervals, similar to present, where vertical erosion of streams prevailed, forming a landscape of stepped levels (Perucca & Martos, 2009).

The modern river system is characterized by a strong seasonal regime with the absence of water during most of the year and summer flooding. The main, permanent flow-type river in the study area is the Blanco river, with the floodplain affected by lateral erosion and sediment accumulation processes. Braided streams and small islands, or bars, are frequent, with significant riverbed load, steep descent and large width-to-depth ratio. The floodplains of tributary rivers are affected by stream incision in the uppermiddle channel sectors, and by accumulation processes in the lower sectors.

In the areas surrounding the town of Angualasto (Figure 1), where softer sedimentary rocks and clay-rich soils outcrop, badlands are frequent.

4.5. *Polygenic landforms*

Erosion surfaces formed by running water in arid or semiarid regions have been identified at the base of the receding mountain front. In the study area up to five different glacis levels have been recognized (**NG1** to **NG5**) based on their assumed age and/or their position/stacking in the landscape. With E−W orientation, these are underlain by bedrock that is typically covered by a thin, discontinuous veneer of soil and alluvium derived from upland areas. These landforms truncate weak materials such as poorly indurated Tertiary sediments (sandstones and pyroclastic rocks), and tend to be veneered by alluvial gravels, indicating the importance of fluvial processes in their creation. The NG1 level has an alluvial cover (greywackes, volcanics and granites clasts) that rarely exceeds 10 m. Lower (younger) glacis tend to have thinner alluvial cover, and the alluvium tends to decrease in thickness toward the distal edge of the piedmont. The alluvium tends to be poorly sorted at the top of the glacis, becoming better sorted downslope. The oldest level (**NG1**) is between 189 and 29 m high from the level of the river channels, while the youngest is 1 to 2 m thick and has a gentle slope to the east.

4.6. *Neotectonic features*

Some thrust faults with recent tectonic activity, have been identified (Bastias & Uliarte, 1991; Siame et al., 1996). These tectonic features, with N-S direction, take place both on the foothills of Frontal Andes and Occidental Pre-Andes.

5. Conclusions

A 1:75,000 geomorphological map of a portion of the Andes and Pre-Andes of San Juan is presented here. The present work constitutes a first approach to the identification and knowledge of the geomorphologic features and processes in a little investigated portion on the Dry Andes and Pre-Andes province, Argentina.

The permanent snowfields and glaciers are located above 4650 m a.s.l. Between 4650 m and 3651 m a.s.l., active rock glaciers are found, mainly on south-facing hillsides. Talus rock glaciers occur on steep hillslopes, whilst in cirques above 4500 m a.s.l. probable active tongue-shaped rock glaciers are found. Below 3500 m a.s.l., the predominant features are formed by fluvial and mass wasting processes. The main valley is characterized by accumulation processes in the river bed, a well-developed floodplain and terraces

The geomorphological map establishes a framework for the interpretation and further analysis of individual landforms at various spatial and temporal scales. Furthermore, active geomorphic processes can be used to produce mass wasting, flood or erosion susceptibility maps, in order to help developers, planners, contractors and engineers for land-use planning.

Software

The map was produced using Esri ArcGIS 9.2.

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