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Equilibrium landscapes of the western Andean mountain front (10°s-33°s): Long-term responses to along-strike changes in climate

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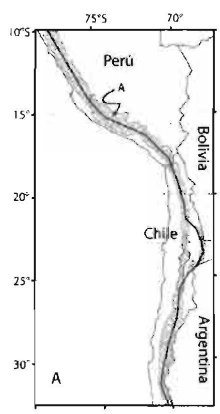
INTRODUCTION

Mountain front landscapes are the result of the interactions between surface processes and tectonic processes. We examine the western mountain front of the central Andes (Figure 1) in an effort to measure the evolution of distinct mountain front landscapes that are the consequence of along-strike and altitudinal changes in climate from Mediterranean to hyper-arid. The geomorphology of the western mountain front of the Andes between 10°S and 33°S shows marked contrasts along its more than 3000 km N-S trend and a strong correlation between atmospheric circulation and geomorphology. We isolate and examine the geomorphology of the mountain front using 90 meter Shuttle Radar Topography Mission (SRTM) topography and its derivatives combined with a 10' precipitation grid from New et al. [2002] to describe the evolution of the landscape. The latitudinal changes in landscapes are developed on the large-scale, tectonic landform of the western Andean mountain front— which in the context of this study, we consider to be reasonably uniform along-strike. The entire study area flanks the highest parts of the Andes and much of the study area forms the western edge of the ~4000 m high Altiplano-Puna Plateau.



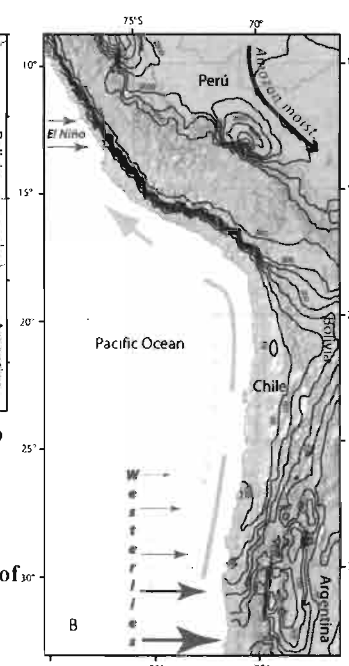


Figure 1. A. Map showing the western Andean mountain front (stippled area) and the location of the profile in figure 3 (line A). B. Shaded relief from SRTM30 DEM with overlay of annual precipitation contours. Contour intervals are 50 mm up to 300 mm/yr and then increase to 500 mm increments. Major atmospheric and oceanic elements are labeled in their approx. locations.

PRECIPITATION AND EROSIONAL STYLE

How moisture interacts with the mountain front dictates the efficiency as well as the type of erosional system that will dominate the landscape. Between 10° and 33°S, we observe both 'top-down' and 'side-cutting" erosional systems (figure 2). The 'top-down' erosional system is the result of moisture derived from the east (Amazon Basin derived) falling at high elevations on the peaks of the western edge of the Altiplano plateau, where there is no comparable moisture source from the west (2B). The "top-down" erosional style that occurs between 15°S to 26°S is dominated by a canyon and pediment morphology. In contrast, the more typical 'side-cutting' erosional system occurs where moisture is incident on the mountain front slope (2C). South of 26°S where the mountain front is purely "side-cutting" in nature the landscape is everywhere dissected by well developed fluvial valleys. North of 15°S a hybrid situation exists where (westerly ENSO and easterly Amazon derived moisture) act on the mountain front slope (2A). The landscape in this hybrid segment more closely resembles the dissected 'side-cutting' landscapes south of 26°.

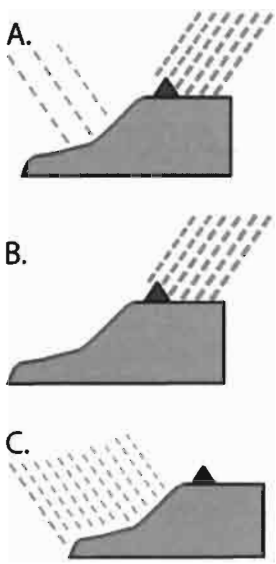


Figure 2. Block diagram illustrating the different erosional styles relative to how precipitation interacts with the mountain front. A. Hybrid side-cutting and top down, B. top-down and C. side-cutting

METHODS

We rely heavily on remotely sensed topographic data (90 m SRTM) along with GIS based geologic maps (1:1,000,000) and a 30-year global compilation of average precipitation with 10' resolution [New et al, 2002]. The location of the mountain front was defined using the slope of the average topography (a 21x21 km moving window average). We consider the mountain front to be the region between the Western Cordillera and the Pacific Ocean (or the central depression) with average slope between 2 and 5 degrees. This is the background, long wavelength 'tectonic' slope upon which the climatic changes are superimposed. In the along-strike profile of the full resolution data (90 m), a minimum in slope occurs in the region between 22°-25°S. North and south of this point relief and slope values increase (Figure 3).

TECTONIC CONTROLS ON THE WESTERN MOUNTAIN FRONT

The western mountain front of the central Andes between 10°S and 33°S is a remarkably regular topographic feature that lies entirely along the Andean forearc and connects lower elevations to the western Andean Cordillera (Figure 1). West of the western mountain front lie the longitudinal valleys, and the Coastal Cordilleras, where present, of Peru and Chile. A sharp coastal cliff, up to 1000 m in places, creates an abrupt boundary between the Pacific Ocean and the Coastal Cordilleras. Most of the study area is bordered to the east by the Altiplano-Puna Plateau and the volcanoes of the western Cordillera. The Altiplano-Puna Plateau is the dominant physiographic feature of the central Andes with an average elevation of ~4000 m.s.l. A broad, low relief, landscape characterizes the Altiplano (15-22.5°S), while a slightly higher average elevation and rugged basin and range topography best describe the physiography of the Puna Region (22.5-27°S).

From the perspective of of the entire Andean mountain belt, our study area also spans several transitions in the geometry of the subducted Nazca plate (the 'slab'). North of 15°S is a 'flat-slab' region, between 15°S and 26°S a zone of steep slab dip, and from 26°-32°S the slab gradually shallows into the Pampean flat-slab segment of the Nazca plate [*Cahill and Isacks*, 1992]. However, below the western side of the Andes (forearc), the geometry of the down-going slab varies little along-strike. In both the Peruvian and Pampean flat-slab regions, flattening of the slab occurs around 100 km depth, east of the forearc [*Cahill and Isacks*, 1992]. Thus tectonic effects on the western Andean mountain front topography that might be caused by these subducted plate segments must be indirect. The most significant tectonic events of what is now the western Andean mountain front since early Miocene would have been the eastward migration of the magmatic arc in jumps [*Kay and Mpodozis*, 2002; *Kay, et al.*, 1999], possibly related to subduction erosion [*von Huene and Scholl*, 1991].

CLIMATIC VARIABLITY

The modern climate of South America is controlled by a combination of ocean and atmospheric circulation and their interactions with the topographic features of the modern topography [*Aceituno*, 1997; *Garreaud, et al.*, 2003; *Lenters and Cook*, 1995] (Figure 1B). The western slope has several dramatic changes in climate N-S as well as an elevation effect. The northernmost part of the study area in central Peru is dominated by an arid climate with a superimposed ENSO effect, its aridity punctuated by approximately decadal wet years during El Niño events in which rainfall increases dramatically on this portion of the western mountain front. The southwestern coast of Peru has a much weaker El Niño influence on its climate, and grades into the hyper-arid conditions of the Atacama Desert [*Johnson*, 1976]. The lack of significant accumulations of nitrate in Peru [*Noller*, 1993] suggest long-term persistence of wetter conditions compared to those in Chile [*Bohlke, et al.*, 1997]. The Atacama Desert in northern Chile hyper-arid, with strongly seasonal, but minor (100-200 mm/yr), precipitation occurring at elevations >3500 m [*Miller*, 1976]. South of 26°S, the westerlies become the dominant moisture bearing air mass. The westerly flow strengthens to the south, and with it winter season moisture content increases such that at 33°S average rainfall is 400 mm/yr on the mountain front and 250 mm/yr near the coast with wintertime precipitation increases during the La Niña phase of ENSO. Further south, the Chilean Patagonian Andes locally receive >4000 mm of rainfall per year [*Hoffmann*, 1975]. Several lines of evidence point to the long-term stability of many of these climate controls [*Houston and Hartley*, 2003].

RELATIONSHIP BETWEEN PRECIPITATION AND MOUNTAIN FRONT SLOPE

A remarkably strong correlation between slope (as measured on a 90 m grid) and precipitation (10 min. grid) is seen in the 60 km x 60 km along-strike swath profile (line A in figure 1) and illustrated in figure 3. In general, both slope and precipitation are at their greatest values in the northern and southern extremes of the study area, whereas the mountain front of the central, very dry Atacama Desert is characterized by very low slopes. This relationship remains consistent across a wide range of rock ages and lithologic contrasts and therefore demonstrates a robust linkage between precipitation and slope in this landscape. The slope curve is anomalously irregular between 900 and 1500 km (figure 3); the maxima mark the deep canyons of southern Peru and northern Chile. There is also a modest maximum in precipitation around 2000 km, which corresponds to the region east of Salar de Atacama. The maximum may exist because the along strike profile traverses an area of generally higher elevations, but also may be exaggerated by errors in the New et al. [2002] grid, which are a factor of 2-5 times higher than the 20 year station averages reported in Houston and Hartley [2003].

The most intriguing departure from a closely coupled latitudinal trend in slope and precipitation occurs at 2400 km (~26°S) where the average slope measured by the swath ramps from values near 7° to values exceeding 25° over <200 km distance, whereas precipitation increases only modestly (factor of 3) over the same distance. For both slope and precipitation, the rate of change for the area south of 2400 km is much greater than the northern part of the profile. One plausible explanation of the rapid change in average slope values is that the location is fixed by the position of the northern extent of westerly air masses. However, if the position of the precipitation boundary has been variable through time, the slope boundary would most likely not be as abrupt as that seen in the data. An alternative explanation could be tectonic in nature since this slope boundary is located at the northern end of where the subducted Nazca Plate begins to acquire a 'flat-slab' geometry. A third alternative, that the precipitation increase forces the geomorphic processes across a threshold, cannot be ruled out. However, the absence of a similar effect along the precipitation gradient north of the Atacama desert would require that the forcing factor not be simply the precipitation quantity, but something coupled to seasonality, frequency, or location (top down versus side-cutting).

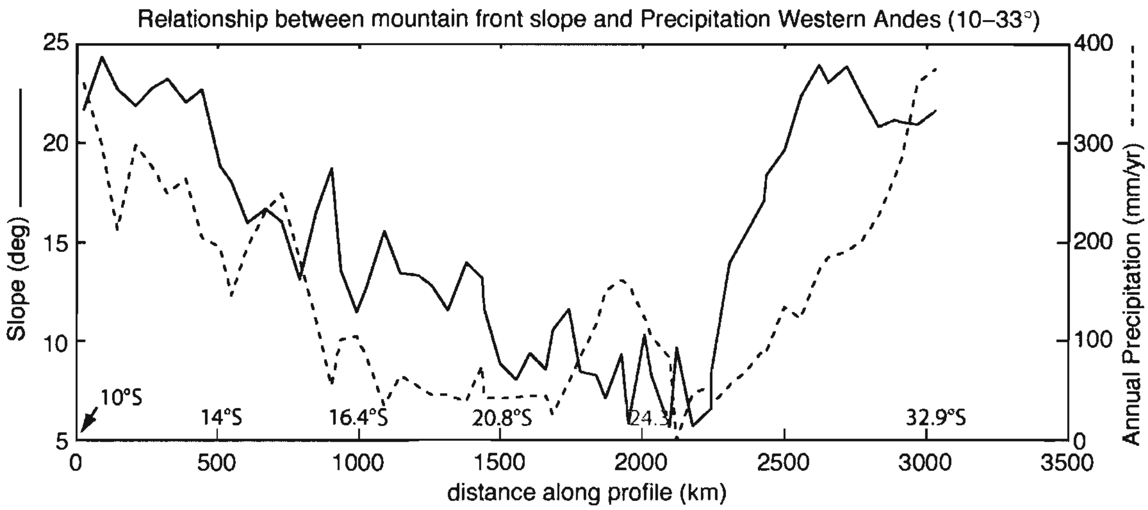


Figure 3. Strike swath profile along western Andes (line in figure 1A) showing average mountain front slope measured from a 90 m slope grid and average annual precipitation from the 10' grid. The maximum dimension of the swath window is 60x60 km, or the width of the mountain front at a given distance in the profile line.

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