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Climatic control on eastern Andean denudation rates (Central Cordillera from Ecuador to Bolivia)

E. Pepin*, J.L. Guyot, E. Armijos, H. Bazan, P. Fraizy, J.S. Moquet, L. Noriega, W. Lavado, R. Pombosa, P. Vauchel

IRD Lima, UMR 234 GET, Université Paul Sabatier, Toulouse, France

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A B S T R A C T

The suspended sediment yield and associated current denudation rates of eight large catchments located along the eastern range of the central Andes have been determined. The catchments have been chosen as mountainous and mainly denudational basins to avoid sediment sinks that could bias our analysis. Discharge data and suspended sediment concentrations measured at each catchment outlet have been combined to produce average annual sediment fluxes and thus yields and current denudation rates over time spans of 2–43 years. Denudation rates range between 0.25 and 1.20 mm yr^{-1} with a north to south gradient. Maximum values are observed in Bolivian catchments. A correlation analysis has been carried out to determine the main controlling factors of current denudation rates at the catchments spatial scale. Climatic, topographic and lithologic parameters have been studied. Our results suggest that denudation rate is mainly controlled by the climate and especially its variability. A strong negative correlation between mean average runoff and denudation rate is detectable whereas topography and lithology are playing no significant role. A multiple regression analysis is suggesting that large Andean catchment denudation rate could be efficiently estimated by the variability of the climate. Combining both slope and lithologic secondary parameters improves the estimation. Finally, the important effect of climate variability on erosion and sediment transport seems to be enhanced by the potential protection of the vegetation cover that is directly controlled by the climate regime.

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1. Introduction

Specific suspended sediment yield can be defined as the total mass of sediment transported as suspended load by the river at the outlet of its drainage basin. It is expressed per unit of catchment area and per unit of time (t km^{-2} $year^{-1}$). The ratio between sediment yield and sediment density is providing the catchment mean denudation rate (mm yr^{-1}). Sediment yield (and thus denudation rate) is rather representative to mechanical erosion in contrast with solute fluxes linked to the chemical erosion.

For instance, previous contribution have attempted to link global pattern of sediment yields to climatic factors (Hicks et al., 1996; Dadson et al., 2004; Dosseto et al., 2006; Pepin et al., 2010), topographic parameters like slope, relief and basin area (Milliman and Meade, 1983; Pinet and Souriau, 1988; Milliman and Syvitski, 1992; Aalto et al., 2006; Syvitski and Milliman, 2007); vegetation (Verstraeten and Poesen, 2001; Vanacker et al., 2007); or natural stochastic variation in water discharge and sediment supply (Fuller et al., 2003). Finally, correlation between sediment yield and external parameters have been tested using multiple regression models (Summerfield and Hulton, 1994; Hovius et al., 1998; Restrepo et al., 2006; Restrepo and Syvitski, 2006; Aalto et al., 2006). Indeed, relationships found between denudation rate and external factors from around the world have been divergent especially according to spatial and temporal scale of study. In the Andes, for instance, Aalto et al. (2006) found strong relationships between current sediment yield, slope and lithology in Bolivian catchments. In their review of tropical rivers, Latrubesse et al. (2007) plotted the relationship between sediment yield and average water discharge for orogenic continental rivers of South America. Restrepo et al. (2006); Restrepo and Syvitski (2006) suggested strong correlation between sediment yield and mean annual runoff in the Magdalena catchment. Pepin et al. (2010) highlighted a significant correlation between runoff, mean slope and suspended sediment yield studying western Andean catchments located along Chile. The effect of vegetation cover on current denudation rate has been demonstrated in Ecuadorian catchments by Vanacker et al. (2007); Molina et al. (2008) and in Argentinean

* Corresponding author.
E-mail address: emilie.pepin@geosci1.net (E. Pepin).

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areas by Braud et al. (2001). Focusing on larger time-scales, Safran et al. (2005) highlighted correlation between millennial-scale erosion rate and channel steepness (i.e. channel gradient corrected for drainage area) of contiguous catchments from Bolivia. Still focusing on Bolivia basins, Insel et al. (2010) suggested no significant correlation between long term denudation rates and relief, slope, drainage basin size or present-day latitudinal variations in precipitation. Finally, Wittman et al. (2009) presented long-term denudation rates from the Andes to the floodplain of two Bolivian basins.

We focus for the first time on eight large catchments extending along the Andean range and covering an area of ~6,74,000 km^2 from Ecuador to the south of Bolivia. These catchments are large enough to provide first order trends of suspended sediment yields and runoffs representative of the Andean Cordillera range between 0 and 22°S. The current mean denudation rate has been thus determined along the Eastern side of the Cordillera as well as the mean current runoff and its seasonal variability. Several topographic parameters as well as lithologic and vegetation cover indexes have also been computed. This database allows to specify the main controlling factors of the current denudation rate at a large spatial scale. Our results assess the role of climate-driven erosion and especially they provide evidence for the predominant control of the seasonal variability of rainfall and its effects on denudation rates.

2. Studied area, datasets and methods

8 mountainous catchments located on the eastern side of the Andes, from Ecuador to the south of Bolivia; between latitudes 00.00′ S and 22.55′ S and longitudes 79.37′ W and 63.11′ W (Fig. 1, Table 1) have been studied. Their outlets correspond to hydrological stations located at the fringes of the mountain range, so that 97% of the studied area is located above an altitude of 400 *m* that we arbitrarily defined as the Andes boundary. This mountainous nature prevents significant sediment sinks and attests the catchments to be purely denudational basins. Therefore, our catchment set is suitable for a mesoscale erosional processes study. Moreover, the erosive behavior of the studied area is considerable. For instance, the seven catchments of our set included in the Amazonian basin, are known to account for only 11% of its total surface area but to product the quasi totality of the Amazonian suspended sediment (Meade et al., 1985; Guyot, 1993; Goulding, 2003; Filizola, 2003).

2.1. Topographic and lithologic parameters

Various parameters, presented in the following paragraphs, allow a detailed topographic characterization of the studied area (see Table 1).

Because of the mesoscale setting of the catchments studied, the SRTM topographic database for South America appears accurate enough to perform the basin-scale morphometric analysis as its absolute vertical uncertainty is estimated to be near 6 m (Farr et al., 2007) and its spatial resolution is around 90 m in the area of study. Various topographic parameters known as potentially important for erosion control have been computed for each catchment using semi-automatic procedures from ARGIS software. Slope and drained surface (directly related to the transport laws) are very commonly used (Whipple and Tucker, 1999) and has already been

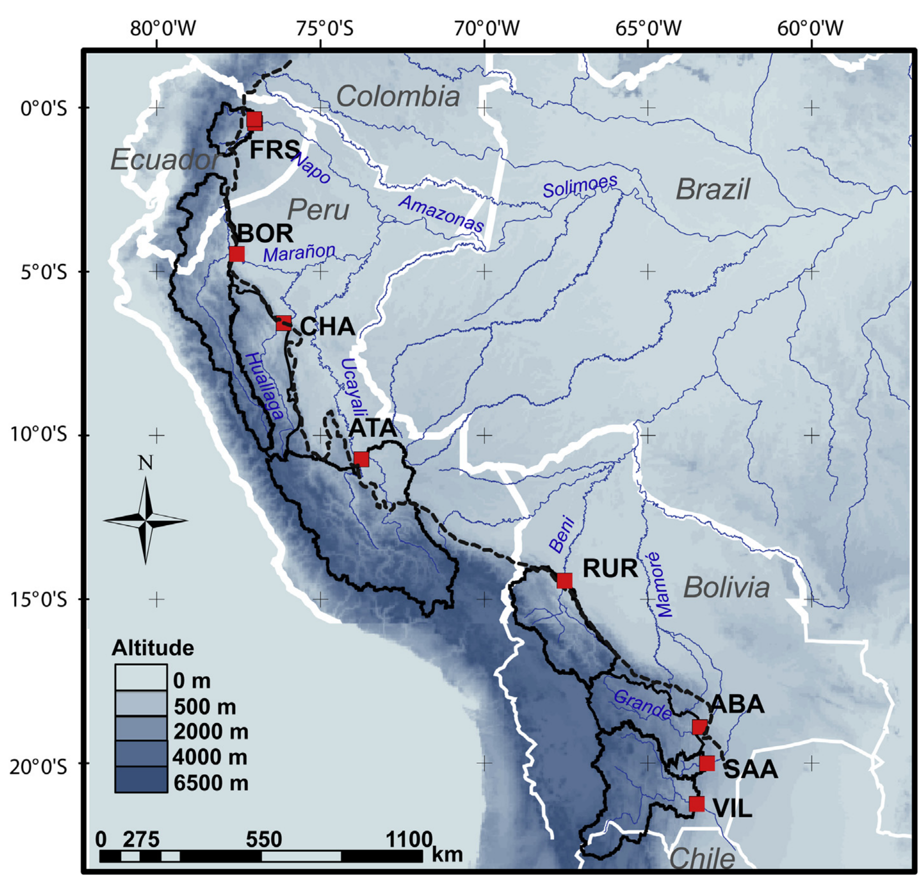

Fig. 1. Definition of the basins studied. See Table 1 for the names, slopes and surfaces. Catchment outlets are defined by hydrological stations (red square) where water discharge and suspended sediment concentrations are measured. Dashed line indicates the altitude of 400 *m* taken as the Andes boundary. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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