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Chemical weathering and atmospheric/soil CO_2 uptake in the Andean and Foreland Amazon basins

Jean-Sébastien Moquet [a,*], Alain Crave [b], Jérôme Viers [a], Patrick Seyler [a], Elisa Armijos [c], Luc Bourrel [a], Eduardo Chavarri [d], Christelle Lagane [a], Alain Laraque [a], Waldo Sven Lavado Casimiro [e], Rodrigo Pombosa [f], Luis Noriega [g], Andrea Vera [f], Jean-Loup Guyot [h]

[a] LMTG/OMP, CNRS/IRD/Université Paul Sabatier, 14 avenue Edouard Belin, 31400 Toulouse, France
[b] Géosciences Rennes (UMR CNRS 6118)/OSUR, Université de Rennes1, Bâtiment 1, Campus de Beaulieu, CS 74205, F-35042 Rennes Cedex, France
[c] LAPA (Laboratório de Potamologia da Amazônia), Av. General Rodrigo Octávio Jordão Ramos, 3000, Campus Universitário, Bloco Arthur Reis, Coroado, Manaus, Brazil
[d] UNALM - FIA, Casilla 18 1209, Lima 18, Peru
[e] SENAMHI, Casilla 11, 1308, Lima 11, Peru
[f] INAMHI Iñaquito N36-14 y Corea, Código 16-310, Quito, Ecuador
[g] SENAMHI Calle Reyes Ortiz no. 41 2do Piso, La Paz, Bolivia
[h] LMTG/OMP, CNRS/IRD/Université Paul Sabatier, CP 7091, Lago Sul, 71619-970 Brasilia (DF), Brazil

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ABSTRACT

This study is a geochemical investigation of the Andean and Foreland basins of the Amazon River at high spatial and time resolution, carried out within the framework of the HYBAM research program (Hydro-geodynamics of the Amazon Basin). Monthly sampling was carried out at 27 gauging stations located in the upper tributaries of the Amazon Basin (from north to south: the Napo, Marañon, Ucayali, Madre de Dios-Beni and Mamore Rivers). The aim of this paper is to estimate the present-day chemical weathering rate (CWR), as well as the flux of CO_2 consumption from total and silicate weathering in the Andes and Foreland Amazon basins, and to discuss their distribution as a function of geomorphic and structural parameters. Based on the forward method, the Napo and other Ecuadorian basins present high silicate weathering rates in comparison with the other basins. We confirm that the Marañon and Ucayali Rivers control the Amazon hydrochemistry due to the presence of salt rocks and carbonates in these basins. The Madre de Dios, Beni and Mamore basins do not contribute much to the Amazon dissolved load. This north to south CWR gradient can be explained by the combination of decreasing weatherable lithology surface and decreasing runoff rates from the north to the south. The foreland part of the basins (or Mountain–Lowland transition) accounts for nearly the same proportion of the Amazon silicate chemical weathering and carbonate chemical weathering fluxes as the Andean part. This result demonstrates the importance of the sediment accumulation areas in the Amazon Basin weathering budget and can be explained by the occurrence of a higher temperature, the deposition of fresh sediments from Andean erosion and a higher sediment residence time than in the upper part of the basin.
With a total CO_2 consumption rate of 744.10^3 moles $km^{-2} year^{-1}$ and a silicate CO_2 consumption rate of 300.10^3 moles $km^{-2} year^{-1}$, the Upper Amazon River (Andes + Foreland part) is the most intense part of the Amazon Basin in terms of atmospheric CO_2 consumption by weathering processes. It is an important CO_2 sink by weathering processes but accounts for only somewhat more than half of the CO_2 consumption by silicate weathering of the Amazon Basin. This result points out the importance of the Lowland part of the basin in the inorganic C silicate budget. The Upper Amazon accounts for 2–4% of the world's silicate CO_2 consumption, which is the same proportion as for the southern and southern-east Himalaya and Tibetan plateau.

1. Introduction

The Earth's surface undergoes a series of complex interactions between the atmosphere, lithosphere, oceans and biosphere, through energy and matter exchanges. Although the main processes involved in these interactions are relatively well known, their quantification and the identification of the spatial and temporal scales remain central questions for the Earth Science community (Bouchez, 2009).

One of key questions involves quantifying the role of weathering in the carbon (C) cycle and its interaction with climate and tectonics at the geological timescale. Carbonates and silicates are the two main rock families consuming atmospheric CO_2 by weathering processes (CO_2 tot). The dissolution of carbonates only affects CO_2 consumption (CO_2 carb) over periods of less than ~100,000 years, which

* Corresponding author at: LMTG/OMP, CNRS/IRD/Université Paul Sabatier, 14 avenue Edouard Belin, 31400 Toulouse, France. Tel.: +33 5 61 33 25 93; fax: +33 5 61 33 25 60.
E-mail address: jean-sebastien.moquet@ird.fr (J.-S. Moquet).

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corresponds to the residence time of carbonates in the oceans. By contrast, the consumption of atmospheric CO_2 by silicate weathering (CO_2 sil) plays a major role in the long-term carbon budget (Dalai et al., 2002; Wu et al., 2005) and can exert control over temperature on the global scale (Ebelmen, 1845; Walker et al., 1981; Berner et al., 1983; Berner and Maasch, 1996). Walker et al. (1981) proposed a negative feedback for weathering processes in terms of atmospheric C and consequently, the global temperature. Conversely, Raymo (1991) and Raymo and Ruddiman (1992) suggest that the formation of mountains increases the intensity of erosion driven by the exposure of fresh rocks to chemical weathering processes, and consequently leads to an increase in atmospheric CO_2 consumption. According to these latter authors, tectonics would consequently play a major role in climate change. In this context, it is fundamental to understand the mechanical and chemical erosion processes in the young mountainous ranges in the world. If the study of reliefs is shown to be important, the effect of other environmental parameters (vegetation, climate, lithology and mechanical erosion rates) could also play an important role in chemical weathering rates (CWR) (Raymo, 1991; Drever, 1994; White and Blum, 1995; Galy and France-Lanord, 1999; Lucas, 2001; Millot et al., 2002; Oliva et al., 2003; Berner, 2004; Viers et al., 2007) and must be constrained (e.g. Berner et al., 1983; Francois and Walker, 1992; Goddéris and François, 1995; Goddéris et al., 2007).

The composition of major elements in river waters allows us to estimate the amount of dissolved matter transported from the continents to the oceans. Through the estimation of dissolved load sources, CO_2 consumption by the acid degradation of continental rocks can be determined, as well as the processes governing the solute phases in rivers (e.g. Meybeck, 1983; Stallard and Edmond, 1983; Négrel et al., 1993; Probst et al., 1994; White and Blum, 1995; Gaillardet et al., 1999; Mortatti and Probst, 2003; Picouet, 1999; Ryu et al., 2008; Noh et al., 2009).

Many studies involving weathering and CO_2 consumption focus on the Himalaya and Tibetan plateau (e.g. Ahmad et al., 1998; Blum et al., 1998; Galy and France-Lanord, 1999; Galy and France-Lanord, 2001; Dalai et al., 2002; France-Lanord et al., 2003; Jacobson and Blum, 2003; Hren et al., 2007; Chakrapani and Saini, 2009; Noh et al., 2009). By contrast, the chemical weathering of the Andes has received much less attention, even though some authors consider this region to be highly active. The Northern Andes have been studied through a description of the hydrochemistry of the Orinoco (Colombia, Venezuela) and Upper Amazon basins (Edmond et al., 1995), and various authors studied weathering and chemical fluxes in the Upper Madeira Basin (Bolivia) (Roche et al., 1986; Guyot et al., 1989; Guyot et al., 1995; Elbaz-Poulichet et al., 1999; Dosseto et al., 2006), while others studied weathering at the scale of the entire Amazon Basin (Gibbs, 1972; Stallard, 1980; Probst et al., 1994; Amiotte Suchet and Probst, 1995; Gaillardet et al., 1997; Mortatti and Probst, 2003; Tardy et al., 2005; Tardy et al., 2009). These authors consider the Andes as the main source of dissolved ions, which are identified as the main sink of CO_2 consumption by weathering processes. However, the Andean basins have been studied only at low resolution in time or/and space. Recently, local-scale studies focus on smaller basins in the Andes (Sobieraj et al., 2002; Boy et al., 2008; Lindell et al., 2010a; Lindell et al., 2010b).

Through a long-term international cooperation effort, during the 1980's the PHICAB research program (Climatology and Hydrology of Bolivian Amazon Basin) and during the 2000's the HyBAm research program (Hydro-geodynamics of the Amazon Basin) recorded daily hydrological data and monthly chemical data (major elements) for 27 gauging stations. On the basis of this large and unique database, the following main questions are addressed in this investigation: i) What is the contribution of each hydrochemical end-member in the Upper Amazon River? ii) What is the present-day weathering rate and flux of atmospheric/soil CO_2 consumption from carbonate and silicate weathering? iii) What is the role of the Foreland zone (Andes–Lowland transition) in the Amazon CWR?

In order to answer these questions, the first section of this paper presents the studied area. The second section reports the material and methods. The third section describes the chemical database from various foci. The coefficients used in the forward method and the working hypothesis are discussed step by step in this part. Finally the main interpretations of the results are discussed in the last part. The step by step calculations details are presented in the Appendix 1.

2. Studied area

2.1. Main geographical features

The studied hydrological basins are located in the northwestern part of South America, between latitudes 0° 47′N and 20° 28′S and longitudes 79° 36′W and 58° 45′W (Fig. 1). The studied area covers a total surface area of 1.9 million km², representing 32% of the entire Amazon Basin area and nearly 28% of the Amazon water discharge (Callède et al., 2010). It extends around 3000 km along the Andes Cordillera.

Five main tributaries of the Amazon drain this area. From north to south these include, the Napo, Marañon and Ucayali tributaries form the Amazonas/Solimoes River and the Madre de Dios, Beni and Mamore tributaries form the Upper Madeira River. The Napo tributaries include the Aguarico, Coca and Jatunyacu Rivers. The Marañon tributaries include the Pastaza, Santiago, El Tigre and Huallaga Rivers. The Pastaza and Santiago Rivers flow through the Ecuadorian Cordillera and join the Marañon River on the north. The El Tigre River drains the northern Foreland area and joins the Marañon River on the north. On the south of the Marañon basin, the Huallaga River drains a large part of the Peruvian central Andes. The Orthon River is a floodplain tributary of the Beni River. The Rio Grande River is an Andean tributary of the Mamore River. The Itenez River drains the southern Bolivian floodplain and a part of the Brazilian Shield. The Purus River is a western Lowland Amazon tributary. The studied basins are located across four countries: Ecuador, Peru, Bolivia and Brazil (Fig. 1).

We divided the studied area into three geomorphic zones (Fig. 1):

- The Andean part consists of high reliefs from 400 m.a.s.l. (meters above sea level) to 6700 m.a.s.l. The biotopes range from mountainous tropical forest to high altitude desert (Dinerstein et al., 1995).
- The Foreland part with an altitude between 400 m.a.s.l. and approximately 120 m.a.s.l. with low reliefs (river slopes between 5 and 25 cm km^{-1}; (Bourrel et al., 2007)), and is covered by inundated tropical forest. This area corresponds to the retro-arc basin in the Cenozoic Andes (Roddaz et al., 2006b).
- The Lowland part, below approximately 120 m.a.s.l., with a very weak slope gradient between 1 and 3 cm km^{-1} (Sioli, 1967), is covered by “terra firme” and inundated tropical forest. Precambrian shields board the Amazon corridor in the north and south.

The Andean and Foreland area is considered as the Upper Amazon part in this study.

Due to the very low population density, the impact of human activity on the dissolved and suspended load of the river was considered to be negligible.

2.2. Geology and lithology

The Andes started to build up during the Late Cretaceous and began to take their present form during the Cenozoic, by the propagation of an orogenic wedge to the east involving pre-orogenic sedimentary and metamorphic rocks and syn-orogenic deposits (Roddaz et al., 2006a,b).

The Andean part is composed of acid to intermediate igneous rocks. Likewise, the meta-igneous rocks fall into this composition