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Weathering intensity in lowland river basins: from the Andes to the Amazon mouth

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Abstract

Actively eroding mountains supply un-weathered material into large river basins. It is still not known whether these un-weathered minerals undergo significant chemical weathering during storage in continental alluvial deposits within the surrounding lowland areas. Here we use previously reported weathering and erosion fluxes of rivers from the Amazon Basin to assess this effect. We show that the fraction of total denudation (weathering plus erosion) occurring as dissolved export experiences only a slight increase during transfer through the lowlands. The overall low weathering intensity of Andean sediments throughout the Amazon basin is attributed to the fact that source rocks are recycled meta-sedimentary rocks.

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Keywords: Weathering rates, Erosion rates, Floodplains, Amazon Basin

1. Introduction

Two main weathering regimes have been distinguished from relationships between chemical weathering and physical erosion rates that have been reported over a variety of spatial scales, from soils to large river basins[1-4]. (1) At low denudation rates (*D*, the sum of erosion rate *E* and weathering rate *W*), weathering and denudation rates

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correlate with each other. This regime is one of long residence time of solids in the Critical Zone, in which weathering rates (*W*) are limited by the supply of fresh minerals, hence by *D*, and is therefore called "supply-limited"[3] (broadly similar to a "transport-limited"[5,6] regime[5,6]). (2) At higher *D*, the solid residence time in the Critical Zone shortens and *W* attains a plateau in the *W*-*D* space as it becomes limited by the combination of reaction kinetics[4,7-9] and chemical equilibrium (as runoff is finite)[10]. This "kinetically limited"[4] regime is broadly similar to a "weathering-limited"[5,6] regime. At the river catchment scale, *W* and *D* remain decoupled[8], especially as mass wasting processes in active mountain belts produce un-weathered river sediment, thereby increasing erosion (*E)* and therefore *D,* but not *W*. It is still uncertain whether this decoupling holds true in large rivers systems, a question raised by the observation that river-scale *W* does not exceed soil-scale *W*, even in rivers passing through lowland areas surrounding active mountain belts[8].

This question has remained unanswered to date because most data and concepts relating *W* and *D* are derived from observations made on soil-covered hillslopes or on small rivers draining eroding landscapes. We still know little about the chemical processes that solutes and sediments are subjected to once they are transported by river networks to the oceans through vast lowland areas in which particles are deposited and stored before being re-introduced again into riverine transport. The most striking features of these lowland areas are active floodplains that are made up of an assembly of meandering river channels, associated banks and bars, shallow lakes and seasonally inundated river deposits[11]. Over longer time scales, sediment can also be deposited in "inactive" alluvial formations that are involved in riverine transport again only episodically through channel migration or river avulsion. During their residence in lowland alluvial formations, sediment is left to further react with water and atmospheric gases such as CO_2 and O_2[12-14]. How do these reactions modify the *W*-*D* relationship during transfer of sediments through lowland areas of large river basins? We tentatively answer this question by examining literature data on *W*-*D* across the Amazon Basin, from the Andean outlet to the river mouth.

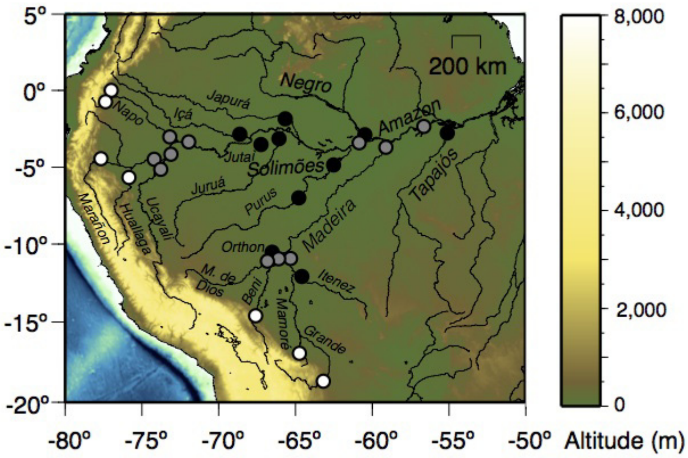

Fig. 1. Map of the Amazon Basin and location of the gauging stations. Open circles represent rivers draining mostly the Andes, black circles rivers draining mostly lowland areas, and grey circles rivers with Andean headwaters but also draining a large lowland area.

2. Source of data, methods, and concepts

The Amazon is the world's largest river in terms of drainage area and water discharge[15], and ranks amongst the first for dissolved and sediment fluxes[16]. This basin also features a geomorphic distribution typical of large rivers draining to passive margins. Headwaters drain the high, tectonically active Andes with altitudes of up to more than 6000 m, and high *E* and *W*. Downstream, the main tributaries flow across a vast foreland and lowland area[17,18]. Gauging stations at which *W* and *E* were measured are located in Fig. 1.

Here we focus on silicate-derived *W*, although carbonate weathering has been reported to occur in the Andean foreland[12,14]. Accurate values of silicate-derived *W* rely on disentangling the contribution of atmospheric inputs, carbonate and evaporite dissolution, and possibly of anthropogenic activities[19]. This was done for the Amazon Basin only in a handful of studies[12,18,20]. Values for *E* were taken from multi-annual time series of sediment gauging performed within the framework of the HyBAm (Hydrology of the Amazon Basin, http://www.ore-hybam.org) program[21-24]. Similar rates were obtained when using denudation rates derived from cosmogenic, *in situ*-produced ^{10}Be [ref. 25], as these two methods usually agree within a factor of 2 [ref. 26]. Total denudation rates *D* were calculated from $D = E + W$. The *W*/*D* ratio can then be calculated. This ratio is a metric for weathering intensity and is analogous to a chemical depletion fraction[27]. This *W/D* ratio is actually independent of discharge and drainage area, unlike *D*, *W*, or *E* taken individually. We acknowledge that the *W/D* ratio might be affected by a downstream change in *E*, as lowland areas can be loci of net sediment deposition / erosion, at least over short time scales[21]. Results are shown in Tab. 1.

W and *D* are commonly plotted against each other as area-normalized fluxes (Fig. 2). From the outlet of a mountain belt to the mouth of a large river, several end-member scenarios can be hypothesized, that result in distinct vectors in the *W-D* space (Fig. 2): (1) as the drainage area becomes larger, if sediment and dissolved fluxes remain the stable, both *W* and *D* decrease at a constant *W/D* ratio; (2) if sediment is trapped in the lowland area[21], *D* decreases but *W* remains constant (if the lowland area supplies sediment *D* can increase); (3) if sediments from the mountain range undergo weathering in the lowlands, *W* increases but *D* remain constant. The two latter scenarios assume that the change in drainage area is small enough such that it is not driving the shift in *D* and *W*.

Tab. 1: Gauging stations locations, characteristics and weathering and denudation rates. For lowland reaches of Andean-fed rivers, the stations at which contributing tributaries are gauged are listed (see section 4)

Basin	River	Location/ Station	Area km^2	Discharge m^3 s^{-1}	*W* t km^2 y^{-1}	Ref.	*E* t km^2 y^{-1}	Ref.	*W/D*	*Contributing stations*
Napo	Napo	FO	12358	1263	73.3	12	631	23	0.10	
Napo	Coca	SEB	5291	449	75.6	12	837	23	0.08	
Marañon	Marañon	BOR	114237	4975	23.2	12	890	24	0.03	
Marañon	Huallaga	CHA	68741	3042	25.8	12	710	24	0.04	
Beni	Beni	RUR	69980	2153	14.5	12	3140	21	0.00	
Mamoré	Mamoré	PVI	7886	532	29.1	12	1150	21	0.02	
Mamoré	Grande	ABA	59311	360	7.6	12	2310	21	0.00	
Jutaí	Solimões	RJut	65000	3000	21.6	20	27	20	0.44	
Içа	Solimões	Riça	150000	6000	25.7	20	133.8	20	0.16	
Juruá	Solimões	RJur	186500	13000	23	20	97.2	20	0.19	
Japurá	Solimões	RJap	331000	27000	20.4	20	87.2	20	0.19	
Purus	Solimões	RPur	358000	106000	20.2	20	76.9	20	0.21	
Purus	Purus	LAB	226552	5552	11.6	12	311.0	22	0.04	
Negro	Negro	RNeg	468000	39000	8.5	20	8.2	20	0.51	
Negro	Negro	Mouth	280000	16070	0.6	18	13.9	22	0.04	
Beni	Orthon	CAR	33485	475	9.8	12	55	21	0.15	
Mamoré	Itenez	VG	354022	1630	1.9	12	5	21	0.28	
Tapajós	Tapajós	Itoba	387000	10780	10	18	11.0	22	0.48	
Napo	Napo	BEL	100035	6489	31.6	12	463	23	0.06	FO,SEB
Marañon	Marañon	SR	357255	16885	19.2	12	470	24	0.04	BOR,CHA
Ucayali	Ucayali	JH	352593	12090	18.9	12	570	24	0.03	ATA
Amazonas	Amazonas	TAM	722089	30148	18.7	12	560	23	0.03	JH,SR
Solimões	Solimões	VGr	990000	52000	91	20	510.7	20	0.15	BEL,TAM
Solimões	Solimões	Manacapuru	2148000	98750	20	18	187.5	22	0.10	BEL,TAM,LAB
Beni	Madre de Dios	MIR	124231	5602	21.7	12	570	21	0.04	
Mamoré	Mamoré	GUA	618220	7916	4.9	12	95.8	21	0.05	ABA,PVI,VG
Beni	Beni	CE	276350	9779	15.6	12	680	21	0.02	RUR+MIR+CAR
Madeira	Madeira	Mouth	1325000	31250	8.9	18	184.4	22	0.05	GUA+CE
Madeira	Madeira	RMad	1306000	34000	16.5	20	225.9	20	0.07	GUA+CE
Amazon	Amazon	Óbidos	4619000	169480	15	18	120.4	22	0.11	Man.,RMad,RNeg
Amazon	Amazon	Obi	4640000	175000	32.2	20	246.9	20	0.12	Man.,RMad,RNeg

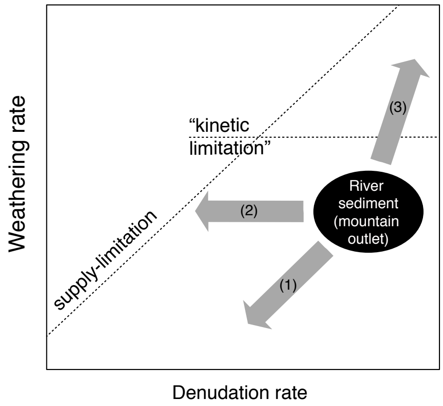

Fig. 1. Conceptual diagram of area-normalized weathering rates *vs.* denudation rates and possible end member scenarios of evolution of those rates from a mountain outlet to a large river mouth. (1) As the drainage area becomes larger both *W* and *D* decrease but the *W/D* ratio remains the same; (2) As sediment is trapped in the lowland area *D* decrease but *W* remains constant; (3) As sediments from the mountain range undergo weathering in the lowlands, *W* increases (up to the supply-limitation, where all soluble elements have been solubilised) but *D* remain constant. Note that the "kinetic-limitation" is represented here as a flat line[8], but other forms of kinetic limitations have been reported[7,9].

3. Results

Rivers of the Amazon Basin can be separated into three groups (Tab. 1). (1) Rivers draining only (or mostly) Andean regions have high *W* and high *D* and low *W/D* ratios, *i.e.* lower than $<10^{-1}$ and down to 10^{-2} (meaning that 1% of the denudational flux occurs as dissolved). (2) Rivers draining only (or mostly) lowland and foreland regions have lower *D*, and relatively high *W/D* ratios (between 10^{-1} and 10^{0}, but actually always lower than 0.5). (3) The last group of rivers drain both the Andes and lowland areas and have intermediate *D* and *W/D* (scattered around 10^{-1}).

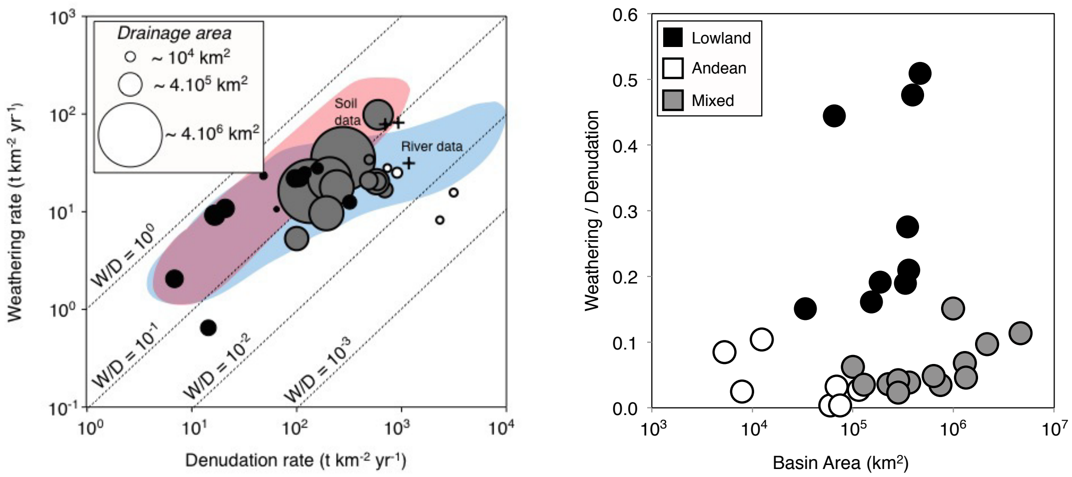

Fig. 3. (left) Weathering rates vs. denudation rates (both area-normalized) for river of the Amazon Basin from the Andean outlet to the mouth (Óbidos). (right) Relationship between W/D ratio and basin area. For both panels, open circles represent rivers draining only the Andes, black circles rivers draining only lowland areas, and grey circles Andean rivers including a large lowland area. In the left panel the size of the symbol scales with drainage area and crosses are Andean river basins with drainage area < 15,000 km^2. The area shaded for "soil data" is from cosmogenic nuclides and chemical depletion fractions and the area shaded for river data is from dissolved and suspended loads[8].

When plotted in the *W-D* space, rivers of the lowland Amazon Basin with Andean headwaters have both lower *D* and *W* than their pure Andean sources (Fig. 3), suggesting that the large increase of drainage influences the two rates (trend (1) in Fig. 1). However, large tributaries also plot on higher *W/D* ratios than pure Andean rivers (trend (2) in Fig. 1, Fig. 3). The smallest of the large tributaries have *W/D* ratios similar to those found in pure Andean basins (Fig. 3).

4. Possible causes for a limited downstream change in weathering intensity

Three hypotheses can be invoked to explain the downstream shift in *W/D* in Fig. 3: (1) contribution of high *W/D* lowland tributaries draining cratonic shield areas (2) contribution of high *W/D* lowland tributaries (Fig. 3) draining large, stable alluvial formations; (3) further weathering of sediments recently derived from mountainous areas during their storage in active floodplains. These two latter hypotheses are not mutually exclusive and actually reflect the same process but on different time scales: weathering of detrital sediments in continental alluvial formations[14]. For each river reach, the role of processes (1) and (2) can be partially corrected for by calculating the *W/D* ratio resulting from the mixture of the *W* and *D* fluxes of all tributaries contributing to this reach (listed in Tab. 1). This number can then be compared to the *W/D* ratio measured at the outlet of the reach, yielding a downstream change in *W/D* (Fig. 4) that ranges from -0.04 (Napo River reach) to +0.04 (Mamoré and Upper Solimões river reaches). This small shift results either from weathering of river sediment in the active floodplain channel or from the contribution of small lowland tributaries or ground water, all not gauged nor sampled. The contribution of these inputs can be assumed to scale with the "un-monitored" drainage area, calculated as the difference between the drainage area at the reach outlet and the sum of the tributary drainage areas. As shown in Fig. 4, the change in *W/D* does not correlate strongly with the "un-monitored" drainage area (nor does it with "un-monitored" discharge, not shown). This observation suggests that the contribution of small lowland tributaries does not control the small downstream change in *W/D*, which is therefore attributed to weathering of sediments in the active floodplain.

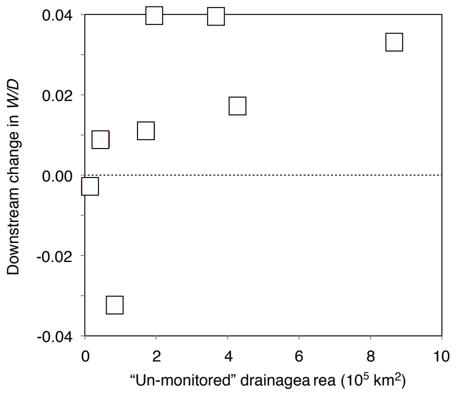

Fig. 4. Change in the *W/D* ratio as a function of the "un-monitored" drainage area. For a given river reach, the number on the Y-axis corresponds to the difference between the *W/D* ratio measured at the outlet and the *W/D* ratio calculated from the discharge-weighted average of the *W* and *D* fluxes of all tributaries (*i.e.* lowland and Andean-derived) contributing to the reach. The number on the X-axis corresponds to the difference between the drainage area at the reach outlet and the combined drainage areas of all tributaries contributing to the reach.

5. Limitation of weathering intensity by the meta-sedimentary source rock

Despite a slight shift in weathering intensity from the Andes to the Amazon mouth, the largest river in the world exports weathering products characterized by *W/D* ratios around 10^{-1}. The only rivers actually reaching *W/D* ratio in the range 0.2-0.5 are pure lowland rivers, most likely because they drain non-eroding settings. If one considers now the Amazon Basin as a whole as a Critical Zone-type reactor, it is surprising that despite fairly long sediment residence times[28,29], the weathering intensity at the Amazon mouth (10%) is far below that of supply-limited soil columns (50%). However, most of the soil data is derived from studies made on granitic rocks, of which up to 50% can be dissolved. By contrast, most continental sediment-producing orogens are made up of meta-sedimentary rocks, which have already lost soluble elements during previous weathering cycles[30,31]. Therefore, low

W/D ratios of denudational fluxes of many mountain ranges might result from the fact that meta-sedimentary source rocks can attain only a low weathering intensity. In support of this explanation we note that rivers of the northern part of the Andes (*e.g*. Napo river), draining a larger proportion of volcanic and andesitic rocks, display higher *W/D* ratios than southern tributaries[31,32]. To summarise, as most river sediment contained in the Earth's largest rivers are derived from meta-sedimentary source rocks, weathering intensity cannot increase significantly with residence time, even if this "Critical Zone" has the size of the Amazon Basin.

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