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Sediment transport in the Rio Grande, an Andean river of the Bolivian Amazon drainage basin

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Abstract The Rio Grande is one of the main Andean tributaries of the Rio Mamore, a tributary of the Rio Madeira which is the main southern affluent of the Amazon. The use of historical (1969-1990) and unpublished data on sediment transport from 15 Andean gauging stations, made it possible to assess the very strong temporal variability of river sediment-transport. Most of the sediment transport occurs during the three months of high water, which may represent up to 90% of the annual load. An exceptional flow registered on the Rio Pirai during March 1983, supplied a sediment yield 20 times higher than the annual mean value of the 18 previous years. The measured sediment transport rate varies from 190 to 11 600 t km^{-2} year^{-1}. Sedimentation is observed along these Andean rivers, which may represent up to 50% of the total sediment load.

INTRODUCTION

The Amazon, the most important river in the world, brings to the Atlantic ocean an estimated sediment load of 1200 × 10^6 t year^{-1} (Meade *et al.*, 1979, 1985), for a mean discharge of 209 000 m^3 s^{-1} (Molinier *et al.*, in press). The main part of the sediment transport comes from the two Andean tributaries, the Rio Marañón-Solimões and the Rio Madeira, with sources in the Peruvian and Bolivian Andes respectively. Until now, knowledge of the sediment yield of the Andean rivers was largely confined to their confluence with the Amazon in Brazil (Gibbs, 1967; Richey *et al.*, 1986; Ferreira *et al.*, 1988).

The recent results of the PHICAB (Climatological and Hydrological Program of Amazonian drainage basin of Bolivia, ORSTOM-SENAMHI-UMSA) in Bolivian Amazonia made it possible to estimate with accuracy the contribution of the upper Rio Madeira drainage basin (Roche & Fernandez, 1988; Guyot *et al.*, 1988, 1989, 1993; Bourges *et al.*, 1990).

Data, collected at the SEARPI (Channel Water Service of the Pirai River) and at the SENAMHI (National Meteorology and Hydrology Service of Bolivia) have made it possible to evaluate suspended sediment yields at 14 gauging stations of the Rio Grande Andean basin, as well as at one station of the Rio Parapety, which drains the Izozog swamps (Fig. 1). The following results may be different from those previously published (Guyot *et al.*, 1989), because the discharge data of some gauging stations have been completed and corrected (Table 1).

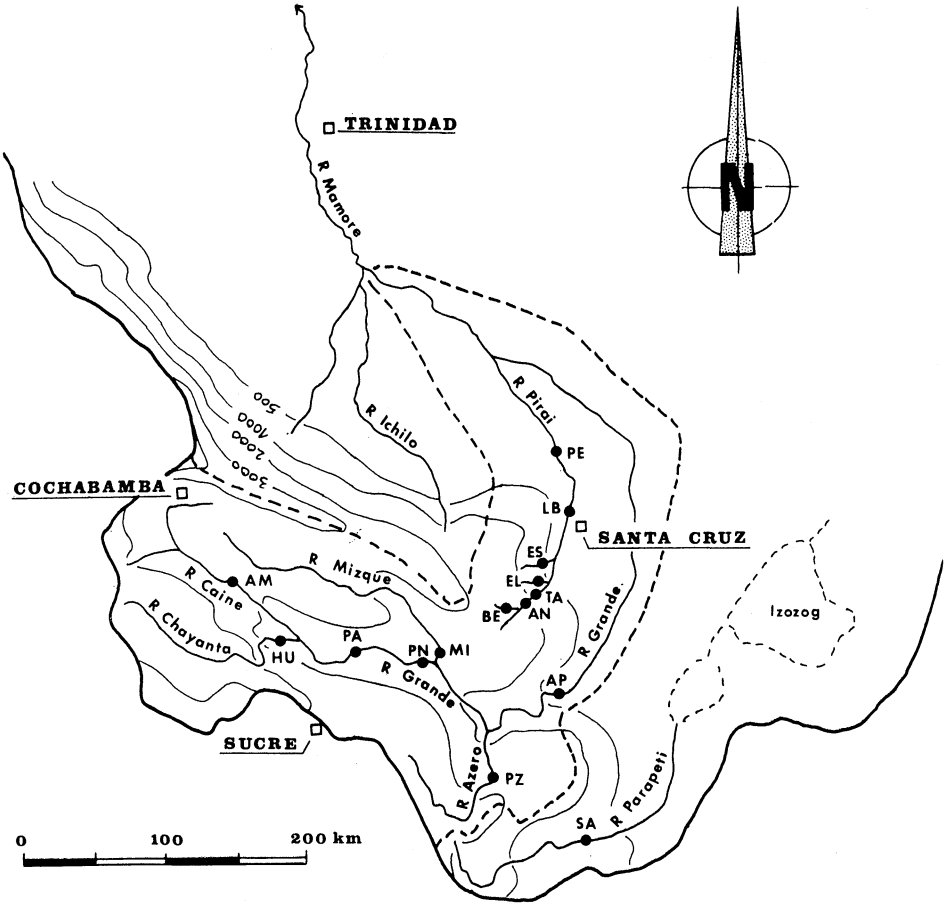

Fig. 1 Map of the Rio Grande drainage basin showing gauging stations (See Table 1 for station code).

THE DRAINAGE BASIN

The Rio Grande joins the Rio Ichilo to form the Rio Mamore, whose discharge represents 48% of the upper Rio Madeira water yield. At its confluence with the Rio Ichilo, the Rio Grande drains a 102 600 km^2 basin, 70% of which is located in the Bolivian Andes Eastern Cordillera.

Topography is highly variable with almost 5000 m high summits in the Cochabamba and Chayanta Cordilleras (Tunari), down to an altitude of 160 m at the Rio Ichilo confluence. The drainage basin is divided into a steep mountainous zone and a subhorizontal Amazonian flood plain.

Like the topography, the Rio Grande basin is climatically very diverse. Upstream of Abapo, the Rio Grande basin, as well as the Rio Parapety basin, is subject to a semiarid climate with rainfalls ranging from 450 to 1000 mm year^{-1}. In contrast, the Amazonian plain of the Rio Grande basin receives 1420 mm year^{-1} (Roche *et al.*, 1992). The mean annual rainfall of the Rio Pirai drainage basin ranges from 800 to 1300

Table 1 Gauging station characteristics, Rio Pirai and Rio Grande drainage basin, Bolivia.

Code	Gauging station	Altitude (m)	Drainage area (km^2)	Period	Service	Mean annual discharge ($m^3 s^{-1}$)
BER	Rio Pirai at Bermejo	900	480	1977-1983	SEARPI	4.2
ANG	Rio Pirai at Angostura	650	1 420	1976-1985	SEARPI	10.0
TAR	Rio Pirai at Taruma	600	1 590	1976-1983	SEARPI	7.6
ELV	Rio Elvira at Elvira	650	64	1977-1983	SEARPI	0.5
ESP	Rio Espejos at Espejos	550	203	1977-1983	SEARPI	2.6
LBE	Rio Pirai at La Belgica	350	2 880	1977-1982	SEARPI	13.0
PEI	Rio Pirai at Puente Eisenhover	280	4 160	1977-1982	SEARPI	20.1
AMO	Rio Caine at Angosto Molineros	1850	9 200	1971-1974	SENAMHI	65.6
HUA	Rio Chayanta at Huayrapata	1600	11 200	1976-1982	SENAMHI	112
PAR	Rio Grande at Puente Arce	1500	23 700	1969-1974	SENAMHI	127
PNA	Rio Grande at Puesto Nava	950	31 200	1971-1975	SENAMHI	251
MIZ	Rio Mizque at Puesto Nava	950	10 800	1971-1975	SENAMHI	69.6
PAZ	Rio Azero at Puente Azero	1080	4 360	1975-1982	SENAMHI	32.7
ABA	Rio Grande at Abapo	450	59 800	1976-1990	SENAMHI	334
SAN	Rio Parapety at San Antonio	550	7 500	1976-1983	SENAMHI	90.9

mm $year^{-1}$ (Carvajal, 1988). Most of the rainfall (70 to 80%) occurs during the four months from December to March (Garcia, 1985; Herbas, 1987).

Vegetation is nonexistent to a short cover at high altitudes, and wet tropical forest in the northern basins of the Cordillera (Rio Pirai). Between these two zones savannah vegetation exists. The Andean part of the drainage basin consists mostly of Palaeozoic detrital series, with some Mesozoic strata. The Amazonian flood plain is totally occupied by Quaternary and Plio-Quaternary sediments.

SEASONAL VARIABILITY

Under a similar precipitation regime, hydrological systems show the same discharge distribution in the whole drainage basin, with a high water period from December to April. The three months of maximum high water (January, February and March) contribute between 44% (Espejos) and 56% (La Belgica) of the annual flow in the Rio Pirai drainage basin. In the Rio Grande basin, under semiarid climatic conditions, these values range from 63% (Abapo) to 75% (Puesto Nava).

For the Rio Pirai at Angostura (1420 km^2), the seasonal variability of daily discharge is great with the water yields consisting of a succession of short flash floods (Fig. 2(a)), which can occur even during the dry season. The Rj factor (max. daily

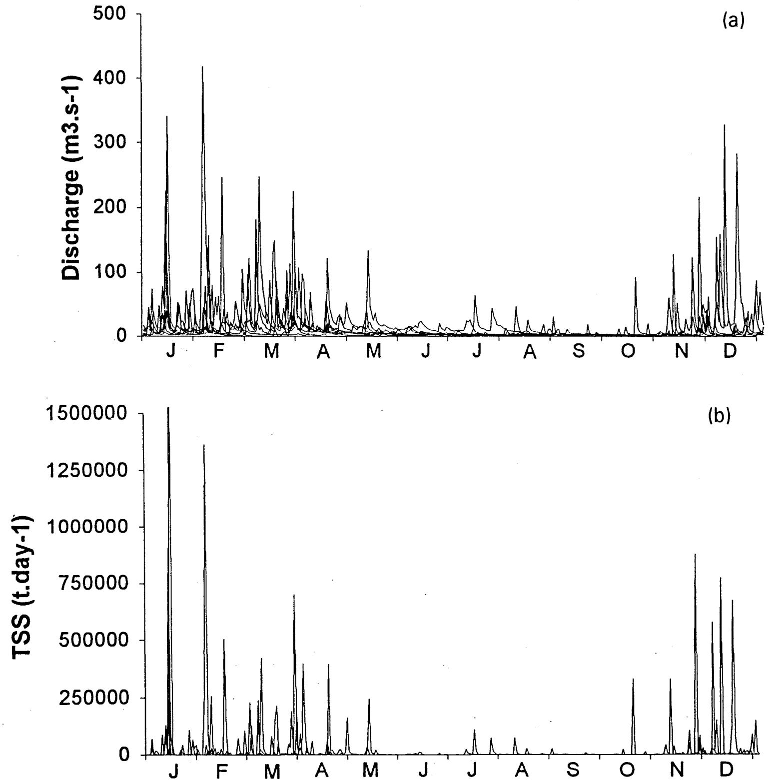

Fig. 2 Seasonal variations of discharge (a) and suspended sediment load (b) of the Rio Pirai at Angostura (1976-1985 period).

value/min. daily value) is 1400 for this station. For the Rio Grande at Puesto Nava (31 200 km^2) this value is 260, and the seasonal variability is characterized by the Andean tropical annual flood (from January to March) and a very noticeable low water period from June to October (Fig. 3(a)).

Like discharge, suspended sediment transport is strongly temporal, and the three months of January, February and March yield between 57% (Puente Eisenhover) and 74% (Taruma) of the annual sediment discharge in the Rio Pirai. Some exceptional floods of a few days observed on the Rio Pirai (Fig. 2(b)) are responsible for 54% (Angostura) to 81% (Espejos) of the annual sediment export (Molina, 1986; Benavidez, 1988). In the Rio Grande (Fig. 3(b)), the suspended sediment discharge is concentrated in the rainy season, and the three months of high water are responsible for 75% (Abapo) to 90% (Huayrapata) of the annual sediment yield.

Rj factors for suspended sediment yields are 16×10^5 and 7×10^5 for the Rio Pirai at Angostura and the Rio Grande at Puesto Nava respectively. The daily variability of discharge and suspended sediment is greater in the Rio Pirai basin than in the Rio Grande basin, but the monthly variability is greater in the Rio Grande basin.

The total suspended sediment (TSS)-discharge relationship (Fig. 4) shows a great dispersion (factor 1000), and does not permit the use of rating curves for suspended sediment yield estimation. Because of the strong seasonal variability, daily sampling is necessary to estimate the sediment yield in the Bolivian Andes. In the case of the Rio

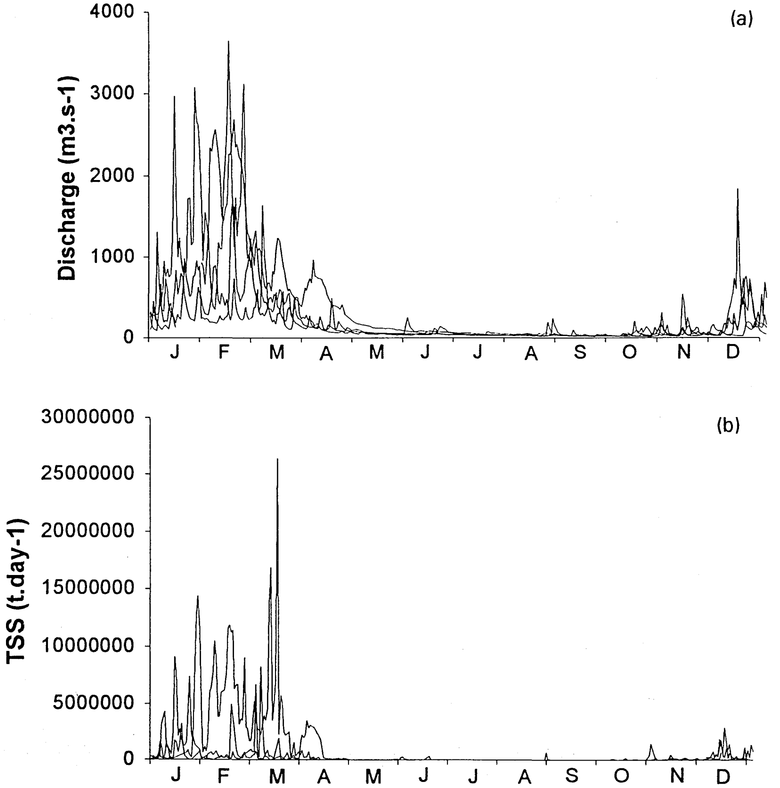

Fig. 3 Seasonal variations of discharge (a) and suspended sediment load TSS (b) of the Rio Grande at Puesto Nava (1971-1975 period).

Pirai, the sediment yield calculation with sampling frequency of three, five and 15 days produce yield deviations of 19%, 60% and 157% respectively.

INTERANNUAL VARIABILITY

An interannual variability must be considered in addition to the seasonal variability. In March 1983, an exceptional flood of the Rio Pirai produced a catastrophic event in the Santa Cruz area (GTZ, 1985). During this year, the sediment load was 20 times greater than in the previous 18 years (Fig. 5). Since 1983 the mean value has doubled.

REGIONAL VARIABILITY

Runoff varies from 5 l s^{-1} km^{-2} (Puente Eisenhover) to 13 l s^{-1} km^{-2} (Espejos) in the Rio Pirai basin, and from 6 l s^{-1} km^{-2} (Abapo) to 10 l s^{-1} km^{-2} (Huayrapata) in the Rio Grande basin, depending on the rainfall regime. The two neighbouring gauging stations of Angostura and Taruma on the Rio Pirai have very different discharge values because of different periods of observation. The Angostura station data are strongly influenced by the exceptional floods of 1983 and 1984 (Tables 1 and 2).

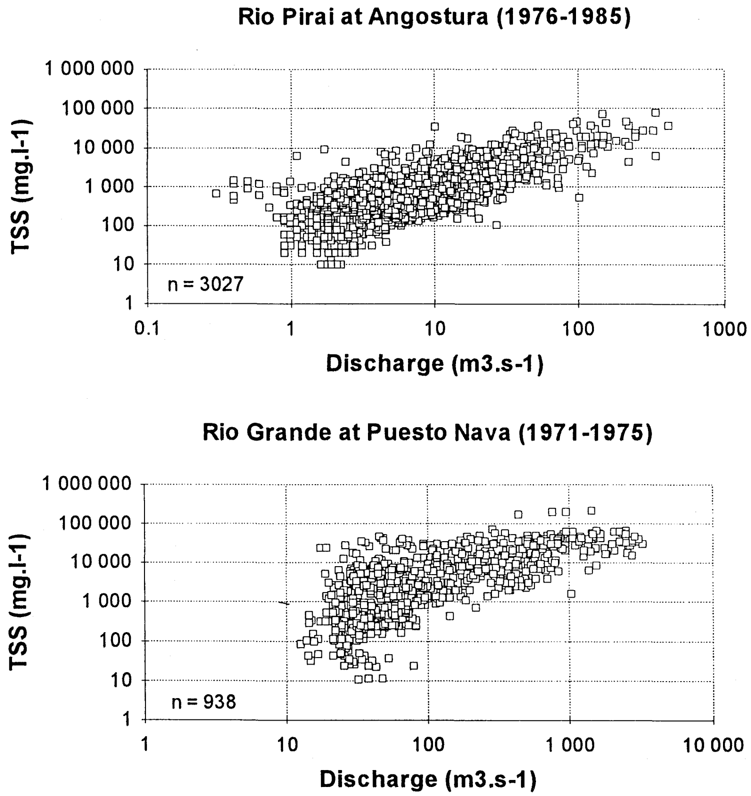

Fig. 4 Suspended sediment *vs.* discharge for the Rio Pirai at Angostura (1976-1985) and the Rio Grande at Puesto Nava (1971-1975).

Mean annual suspended sediment concentrations vary from 470 to 2220 mg l^{-1} in the Rio Pirai basin, and from 1210 to 17 900 mg l^{-1} in the Rio Grande basin. Maximum daily concentrations of 76 300 mg l^{-1} and 279 700 mg l^{-1} are registered in the Rio Pirai at Angostura (15 January 1985) and in the Rio Caine at Angosto Molineros (20 January 1973) respectively.

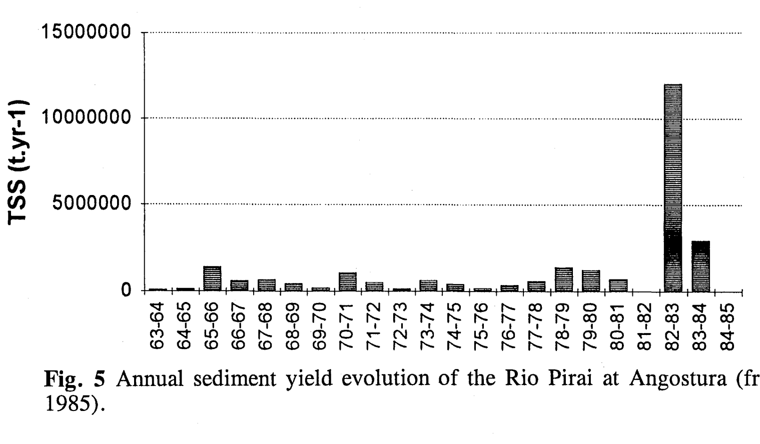

Fig. 5 Annual sediment yield evolution of the Rio Pirai at Angostura (from GTZ, 1985).

Table 2 Suspended sediment transport results, Rio Pirai and Rio Grande drainage basin, Bolivia.

Code	Gauging station	No. of samples	Suspended sediment: Concentration TSS ($mg\ l^{-1}$)	Annual rate TSS ($10^6\ t\ year^{-1}$)	Annual rate per unit area TSS ($t\ km^{-2}\ year^{-1}$)
BER	Rio Pirai at Bermejo	2220	1 000	0.60	1 250
ANG	Rio Pirai at Angostura	3027	1 400	3.0	2 080
TAR	Rio Pirai at Taruma	2264	1 230	1.3	840
ELV	Rio Elvira at Elvira	2162	470	0.03	460
ESP	Rio Espejos at Espejos	2186	1 170	0.42	2 070
LBE	Rio Pirai at La Belgica	1684	2 220	2.3	790
PEI	Rio Pirai at Puente Eisenhover	3900	560	1.1	260
AMO	Rio Caine at Angosto Molineros	580	17 890	106	11 600
HUA	Rio Chayanta at Huayrapata	282	4 100	24	2 110
PAR	Rio Grande at Puente Arce	868	17 670	136	5 730
PNA	Rio Grande at Puesto Nava	938	9 710	203	6 520
MIZ	Rio Mizque at Puesto Nava	897	4 990	26	2 440
PAZ	Rio Azero at Puente Azero	557	1 210	2.1	480
ABA	Rio Grande at Abapo	851	8 410	136	2 280
SAN	Rio Parapety at San Antonio	642	4 270	19	2 590

The mean annual sediment transport rate varies from 260 to 2080 t km^{-2} $year^{-1}$ in the Rio Pirai basin, and from 480 to 11 600 t km^{-2} $year^{-1}$ in the Rio Grande basin (Table 2). The maximum transport rates are observed in the upper part of the Rio Grande drainage basin, where slopes are greater, the vegetal cover reduced and the rainy season shorter.

These sediment transport rates cannot be directly associated to the rate of erosion, because of sedimentation (Fig. 6). In the Rio Pirai basin, considering only the common period 1977-1981, the upstream-downstream transport rate shows a progressive increase in the Andes, and then a decrease after La Belgica station. A suspended sediment yield loss of 50% occurs in the Amazonian flood plain, just downstream from the Andean piedmont. In the Rio Grande drainage basin, the same phenomenon is observed, but sedimentation accounts for $>30\%$ of the sediment yield of the Andes.

Extrapolating the results of the two main piedmont gauging stations (Taruma & Abapo), which monitor 86% of the Andean part of the Rio Grande drainage basin, the total suspended sediment yield from the Andes is estimated to be 162×10^6 t $year^{-1}$, corresponding to a mean sediment transport rate of 2300 t km^{-2} $year^{-1}$.

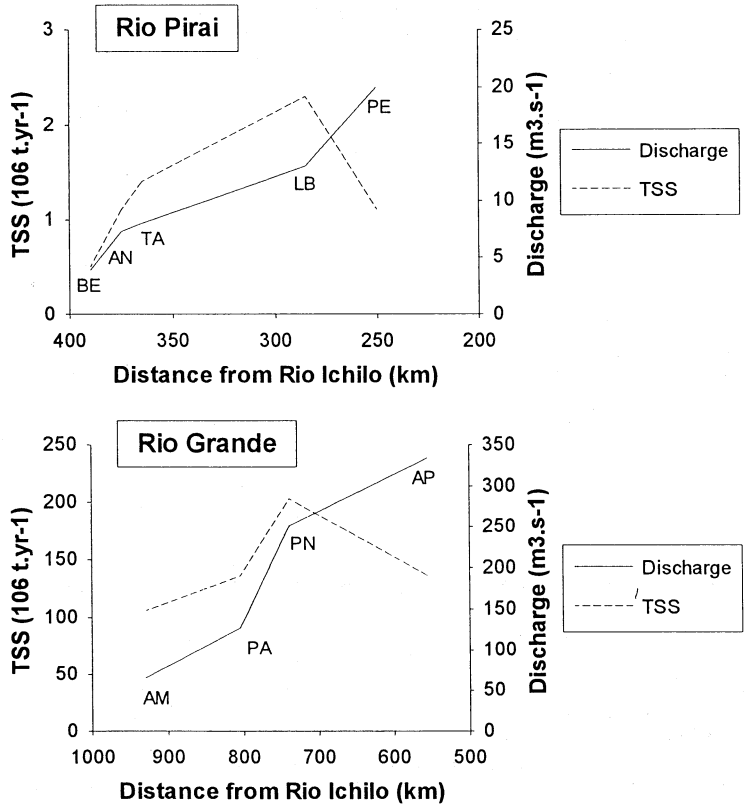

Fig. 6 Discharge and suspended sediment yield evolution along the Rio Pirai (1977-1981) and the Rio Grande (See Table 1 for station code).

CONCLUSION

From these results based on frequent sampling, it is possible to estimate the suspended sediment yields in an Andean basin of 71 000 km^2. The measured loads are highly variable in time, both seasonally and interannually. This variability also depends on whether daily data or monthly data are used.

The difficulty of estimating sediment yield from discharge measurements requires daily water sampling in Andean rivers during high water periods. Sampling has to proceed for at least 10 years in order to take into account high interannual variability. Finally, regional variability is also strong (varying by a factor of 50), making it is very difficult to extrapolate results to the entire drainage basin.

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