

## CHEMICAL AND MECHANICAL EROSION RATES IN ICELAND AS DEDUCED FROM RIVER DISSOLVED AND SOLID MATERIAL

PASCALE LOUVAT\*, SIGURDUR REYNIR GISLASON\*\*, and  
CLAUDE JEAN ALLÈGRE\*

**ABSTRACT.** This study investigates dissolved, suspended loads and sands of major Icelandic rivers and determines chemical and mechanical erosion rates as well as rates of CO<sub>2</sub> consumption by the chemical weathering. A steady state model of erosion is used to locally calculate the river suspended load fluxes needed to balance chemical weathering.

The total dissolved solid concentrations range from 20 to 179 mg/kg. The highest concentrations are for spring fed rivers draining young rocks in the vicinity of active volcanoes, and the lowest for direct runoff rivers draining old Tertiary rocks. Total dissolved loads, “corrected” for atmospheric, geothermal, and magmatic inputs are used together with mean annual discharges to estimate low-temperature chemical erosion rates of 16 to 111 t/km<sup>2</sup>/yr. These rates increase with runoff but decrease with the age of the rocks. Icelandic chemical erosion rates are higher than the world average for silicate rocks, reflecting both high reactivity of the basalt and high runoff, but lower than those for other basalt-draining rivers (in Réunion, Java, Azores or Deccan). CO<sub>2</sub> consumption rates associated to chemical denudation range between 0.18 and 2.12 10<sup>6</sup> mol/km<sup>2</sup>/yr with an average value of 0.74 10<sup>6</sup> mol/km<sup>2</sup>/yr, higher than the world average for rivers draining silicate rocks.

Chemical compositions of suspended sediments and sands are similar, showing a very low weathering stage. The elements most soluble during the weathering show slightly lower concentrations in the suspended sediments. River sediment chemical compositions are assumed to reflect a mixture between 3 initially pristine rock end-members: high Mg-basalt, tholeiite and rhyolite. The most insoluble elements (REE and Th) are used to re-define the mean chemical composition of the initially unaltered rocks of each drainage basin.

A mass budget between the unaltered rock of the catchments and the river dissolved and suspended loads (steady state model of erosion) is used to calculate the average annual solid load of the rivers, which range from 650 to 4300 mg/l. For some rivers there is a good agreement between calculated and measured suspended loads but for others the calculated load is much higher than the measured one. The difference stems from groundwater inputs, man-made dams and other sedimentary traps. If the relevancy of the steady state model of erosion can be questioned, the accuracy of sediment load measurements is also questionable. Pros and cons of both methods are argued. The calculated solid loads lead to very high mechanical erosion rates, ranging from 940 to 10200 t/km<sup>2</sup>/yr. Those increase with the glacier cover but decrease with the age of the catchment rocks. Icelandic mechanical erosion rates rank among the maximum reported rates, underscoring the importance of glaciers, tectonics, glassy basaltic rocks and high runoff. In association with low chemical weathering rates, these place Icelandic rivers as an end-member in the observed anti-correlation between mechanical to chemical erosion ratios and temperature for volcanic islands.

### INTRODUCTION

Riverine erosion intensity is controlled by numerous parameters such as lithology, climate through runoff and temperature, relief, tectonics, vegetation, and age of the rocks. As many of these parameters are intrinsically linked to each other, the attempts of building general erosion laws have been quite unfortunate till now. This study takes

\*IPGP, Laboratoire de Géochimie et Cosmochimie, 4 place Jussieu, 75252 Paris Cedex 05, France; louvat@ipgp.jussieu.fr

\*\*Institute of Earth Sciences, Askja, University of Iceland, Sturlugata 7, IS-101 Reykjavik, Iceland.

place in this context of adding new data on basalt riverine erosion thereby contributing to the long-term process of defining global erosion laws. The most influential parameters under debate are reviewed:

Meybeck (1979), Gislason and Eugster (1987a), Bluth and Kump (1994), Taylor and others (1999), Stefánsson and Gislason (2001) and Wolff-Boenisch and others (2006) gave an order of increasing susceptibility to chemical weathering for many rocks. They have shown that basalts are among the most easily weathered silicate rocks and that basaltic glass weathers faster than crystalline basalt. An increased weathering rate with increased temperature was demonstrated in the studies of Velbel (1993), White and Blum (1995), Louvat (ms, 1997) and White and others (1999). Dessert and others (2001, 2003), based on the previous riverine basalt weathering studies in Massif Central, Parana, Iceland, Réunion, Sao Miguel, Java and Deccan suggested an Arrhenius-type relationship between the CO<sub>2</sub> consumption during basalt weathering and both runoff and temperature. A simple relationship between weathering rate and temperature for granitoids was clearly excluded by Millot and others (2002).

The effect of temperature and runoff on weathering rates have been addressed earlier in the studies of the negative feed-back effect of silicate rocks weathering on the Earth's CO<sub>2</sub> budget and thus climate (for example Walker and others, 1981; Berner and others, 1983; Berner, 1994; Berner and Berner, 1996 and 1997; Berner and Caldeira, 1997; Brady and Carroll, 1994; Brady and Gislason, 1997). The key to this feedback is the atmosphere greenhouse effect. High global temperature and greater rainfall on the continents, caused by higher atmospheric CO<sub>2</sub> concentration, brings about enhanced atmospheric CO<sub>2</sub> removal caused by faster silicate weathering. On the basis of their studies of the chemistry of major rivers Edmond and others (1995), Edmond and Huh (1997) and Huh and Edmond (1999) concluded that there was no clear climatic effect on weathering rates on the present Earth. In place of climate-weathering feedback, Edmond and others (1995), Bickle (1996), and more recently Huh (2003) assumed that increase in global CO<sub>2</sub> degassing is eventually matched by increase in CO<sub>2</sub> uptake via enhanced weathering accompanying mountain uplift. This has been disputed by Berner and Caldeira (1997) and Berner and Berner (1997).

In their study of silicate weathering by the world's largest rivers and weathering of volcanic islands, Gaillardet and others (1999a) concluded that weathering of silicate rocks is consistent with a positive action of temperature but that temperature is not the over-riding parameter. Runoff and mechanical denudation are more important. Pinet and Souriau (1988) and Milliman and Syvitski (1992), in a worldwide investigation of continental erosion, emphasized the influence of relief and other geomorphologic parameters, and precipitation on mechanical and chemical erosion rates. Milliman and Syvitski (1992) showed the importance on the global seaward sediment flux budgets of small mountainous rivers in active tectonic areas.

Moreover, Dessert and others (2003) estimated that volcanic rocks were responsible for 30 percent of the global CO<sub>2</sub> consumption rate due to silicate rock weathering. Dissolved element fluxes from rivers draining volcanic rocks to the ocean are also enormous and in particular those from the high runoff volcanic islands. Based on hydrologic budgets and water geochemistry Rad and others (2007) have demonstrated that these fluxes are even bigger if subsurface waters are taken into account. Surface plus subsurface volcanic island fluxes could for example be sufficient to fill in the actual imbalance of seawater Sr mass budget (Louvat and others, 2005). Volcanic rocks weathering has also been included in a revised version of Berner's GEOCARBSULF model for the evolution of the carbon cycle over Phanerozoic time, using the oceanic strontium isotope record (Berner, 2005).

The influence of vegetation as enhancing the weathering of silicate rocks has been demonstrated by many authors (Schwartzman and Volk, 1989; Berner, 1992, 1997;

Drever, 1994; Gislason and others, 1996; Berner and Cochran, 1998; Moulton and others, 2000).

Aging of rocks slows down chemical weathering as shown by Cochran and Berner (1996), Taylor and Blum (1995), Gislason and others (1996).

In order to better constrain the influence of each parameter at constant lithology, a systematic study of riverine erosion on volcanic islands has been undertaken on Réunion and Sao Miguel, Azores (Louvat and Allègre, 1997 and 1998), following the more global studies of large rivers by the same group (Négre and others, 1993; Gaillardet and others, 1995; Dupré and others, 1996; Allègre and others, 1996; Gaillardet and others, 1997). This approach is based on the geochemical study of the dissolved, suspended and sandy loads of the rivers. First, the dissolved load was corrected for all the concentrations, which do not arise from the weathering of the silicate rocks. Secondly, the mean chemical composition of the rocks before their weathering was defined by comparing the chemical compositions of the suspended loads to those of local rocks. Finally, a mass budget between the elemental concentrations in the initially unweathered rocks and the dissolved and suspended loads of the river waters was assessed using a steady state model of erosion. This allowed estimation of the chemical and mechanical erosion rates. The similar previous studies of riverine erosion on Réunion and Sao Miguel islands showed that hot spot basalts constitute an extreme end-member characterized by high erosion rates and high rates of CO<sub>2</sub> consumption (Louvat and Allègre, 1997 and 1998).

Iceland provides an opportunity of studying basalt weathering in a cold oceanic climate. Comparison of its erosion rates with other similar studies in temperate and tropical climates may provide refinement of the mechanisms by which climatic parameters affect weathering (the results of the present study have already been included in the definition of a general law of atmospheric CO<sub>2</sub> consumption during basalt weathering by Dessert and others, 2001 and 2003). The influence of glaciers and age of the rocks is also a concern in Iceland. Numerous studies have been made on Icelandic rivers and on the chemical weathering of basalt in Iceland (for example Gislason and Arnórsson, 1993; Gislason and others, 1996; Moulton and others, 2000; Stefánsson and Gislason, 2001; Stefánsdóttir and Gislason, 2005; Gislason and others, 2006; Vigier and others, 2006; Gannoun and others, 2006; Pogge von Strandmann and others, 2006; Sigfússon and others, 2008). This study complements earlier work on Icelandic rivers by adding new data on the geochemistry of the suspended and sandy loads and by assessing the mechanical erosion rates via the steady state model of erosion. Because the National Energy Authority of Iceland has continuously surveyed Icelandic rivers since the 1950's, the steady state model of erosion can be tested by comparing the calculated concentrations of suspended sediments to the concentrations measured in the rivers.

#### GENERAL SETTINGS OF ICELAND

The volcanic island of Iceland is situated on the North Atlantic mid-oceanic ridge, just below the Arctic Circle. Its surface area is of 103000 km<sup>2</sup>, 510 km from East to West and 350 km from North to South. Glaciers, the largest in Europe, occupy 12 percent of this surface; the biggest is Vatnajökull in the SE area (fig. 1). Maximum altitude reaches 2119 m at Hvannadalshnjúkur in the SE. The central area of the island, which is also the most recent and active area, consists of a wide plateau with a mean altitude of 500 to 700 m. Some mountains and glaciers protrude from this plateau at 1500 to 2000 m. Except for the southern part, the coastal area is cut out by deep fjords, which extend inland as large valleys.

Iceland is formed from volcanic rocks mainly basaltic and tholeiitic in composition (80–85%), the remaining (15–20%) being acidic intrusions and sediments (Jóhannesson and Saemundsson, 1989). As a result of the ocean floor spreading, the

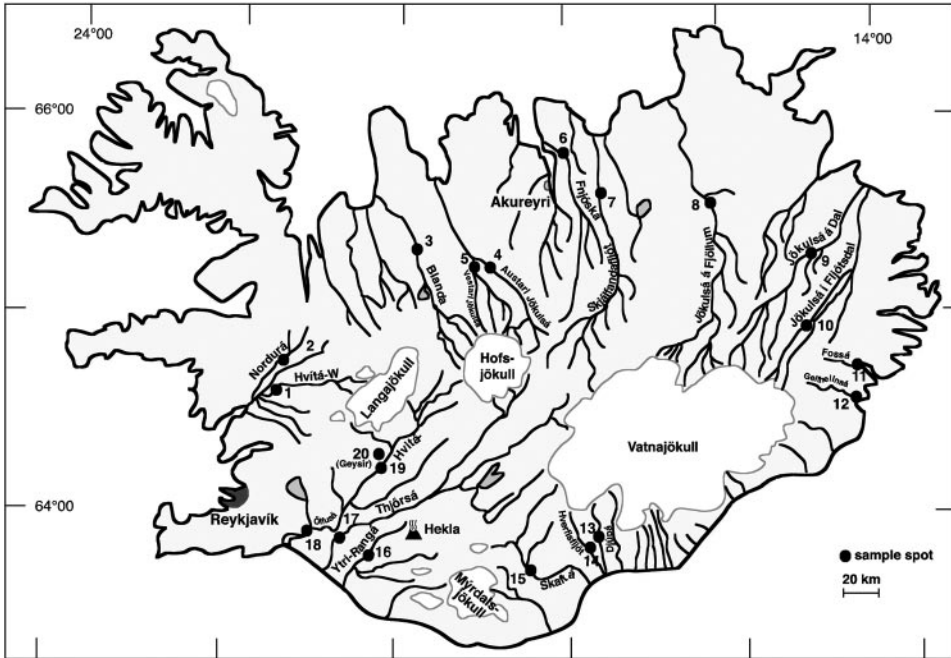


Fig. 1. Schematic map of Iceland showing the main rivers, glaciers and lakes and the location of the samples.

age of the rocks increases perpendicularly to the active volcanic Rift zones, eastward and westward. The oldest rocks that have been recognized are 12 to 16 My old (Moorbath and others, 1968; Hardarson and others, 1997).

The climate in Iceland is of oceanic boreal type, with cool summers and relatively mild winters. It is influenced by the polar stream from Greenland off the northern and eastern coasts, and by the Gulf Stream off the southern and western coasts. Annual mean temperature in the lowlands and costal areas is 4°C, varying from -5°C to 0°C during the winter, and from 5°C to 10°C during the summer (Einarsson, 1991). The alternating incursion of cold and dry air from the North and of warm and humid air from the Atlantic makes this island a permanent zone of conflicting air masses and precipitation is therefore significant, ranging from 400 to 4000 mm/yr. The highest precipitation occurs on the glacier areas (also at high altitudes) and on the southern and eastern parts of the island.

With such high precipitations, rivers are present everywhere in Iceland, except in the central Rift zones where the permeability of the youngest volcanic rocks is too high and no surface streams can be seen. Rivers are of four types: glacier-fed, spring-fed, lake-fed, and direct runoff (plus all possible combinations of these types). Glacier-fed rivers are the largest in terms of length and discharge; their waters are dark and turbid, carrying large quantities of suspended material. In contrast, the other rivers have clear waters. Chemical compositions and discharges for the spring-fed rivers are almost constant through time whereas they are much more variable for glacier-fed and direct runoff rivers (for example Gislason and others, 1996). Glacial rivers begin their swelling in June and summer floods carry huge quantities of materials (for example Lawler, 1991). There are many geothermal springs in Iceland, and two types of geothermal fields can be distinguished: low-temperature fields (temperature of the

groundwater lower than 175°C) are located on the Plio-Pleistocene and Tertiary areas, and high temperature fields (up to 300°C at depth) are in the active Rift zones. High temperature geothermal fields are expressed at the surface as thermal springs, geysers, mud pools, solfataras and fumaroles. When they join rivers, thermal springs may noticeably modify the chemical compositions of the river waters (for example Gislason and others, 1996). Magmatic degassing and percolation through the cold groundwater systems may also be a source of dissolved load for spring-fed rivers in active areas.

#### SAMPLING AND ANALYSIS

Nineteen rivers were sampled around Iceland (fig. 1) during late May 1996, at the beginning of the river swelling period. The aim was to sample most of the major Icelandic rivers but also to have samples representative of the different types of rivers (glacier-fed, spring-fed and direct-runoff). For the largest rivers we sampled both water and suspended material, and for most of the samples we also collected riverbank sands. In most cases, sampling was undertaken with a bucket and a rope, thrown from a bridge in the middle of the stream. When this was not possible, samples were taken from one of the riverbanks. All samples are surface samples. River water samples were filtered at the end of each sampling day with Sartorius 0.2 µm cellulose acetate filters, on a Teflon Sartorius filter holder (147 mm of diameter); filtered samples were transferred into acid-washed polypropylene bottles and acidified with distilled nitric acid, except one aliquot which was kept unacidified for anion analysis. Filtrated samples for nutrient analysis were refrigerated at the end of each day in the field, and kept frozen until analyses were carried out. This was done to prevent organic growth or decay. When rivers were carrying sufficient quantities of suspended material (Jokulsá á Fjöllum, Jokulsá á Dal, Hverfisfljót), sampling the suspended material was simply done by settling in the buckets; this material was then transferred into a polypropylene bottle. When suspended material was not very abundant (mainly in non glacier-fed rivers), the riverine particles were concentrated from 45 to 60 liters of river water by tangential filtration on 0.2 µm filtering cartridges: filtered clean water was discarded, and the more and more dirty water was kept and represents the fraction larger than 0.2 µm. Suspended loads, collected either by settling or by tangential filtration, were then centrifuged in the laboratory and dried at 80°C. Sand samples were also dried at 80°C.

In the following, what is called the 'suspended' load, or 'particulate' load, is the material coarser than 0.2 µm, and the 'dissolved' load is what passed through the 0.2 µm pores of the Sartorius filter.

*Dissolved Load.*—Temperature, pH, and alkalinity were measured in the field. The end point of the alkalinity titration was defined by Gran's plots. Anions (Cl, NO<sub>3</sub><sup>-</sup>, SO<sub>4</sub><sup>2-</sup>, F, Br) and major cations (Na<sup>+</sup>, Ca<sup>2+</sup>, Mg<sup>2+</sup>, K<sup>+</sup>) were measured by HPLC Dionex 300, with a precision greater than 5 percent. Dissolved SiO<sub>2</sub> concentrations were measured by colorimetry, and dissolved iron was analyzed on a Thermo Jarrel Ash ICP-AES. The dissolved inorganic nutrient concentrations (NH<sub>4</sub><sup>+</sup>, NO<sub>3</sub><sup>-</sup>, NO<sub>2</sub><sup>-</sup>, and PO<sub>4</sub><sup>3-</sup>) were determined colorimetrically with an Alkem auto analyzer. Trace element concentrations for Li, B, Sr, Ba, Rb, Al, Fe, Mn, V, Sc, Cr, Co, Cu, Zn and Mo were determined by ICP-MS (VG PlasmaQuad II+), using indium as internal standard. The accuracy of the analysis was assessed by running the SLRS-3 riverine standard every ten samples (table 1). The total dissolved solids (TDS) are calculated from the analyzed concentrations by the following equation:

$$\text{TDS (mg/l)} = \text{SiO}_2 + \text{HCO}_3 + \text{Cl} + \text{SO}_4 + \text{Na} + \text{Ca} + \text{Mg} + \text{K}.$$

*Solid load.*—Sands and suspended loads were finely crushed and dissolved by an acid attack (HF, HNO<sub>3</sub>, HClO<sub>4</sub>) prior to their analysis. These solutions were then

TABLE 1  
*Chemical compositions of the dissolved loads: major elements and nutrients*

sample river	Type	Disch. m <sup>3</sup> /s	T(°C)	pH/T(°C)	TDS mg/l	SiO <sub>2</sub> µmol/l	HCO <sub>3</sub> µmol/l	Cl µmol/l	Na µmol/l	Ca µmol/l	Mg µmol/l	K µmol/l	SO <sub>4</sub> µmol/l	NH <sub>4</sub> nmol/l	PO <sub>4</sub> nmol/l	NO <sub>3</sub> nmol/l	NO <sub>2</sub> nmol/l	$\Delta\Sigma$ %
ISL1	Hvítá-W	78.2	6.0	8.62/16.5	51	206	350	114	290	78	42	11	17	380	550	1050	26	7
ISL2	Nordurá	23.5	7.9	7.64/16.6	42	135	288	138	217	78	51	7	17	1640	50	1400	20	4
ISL3	Blanda	38.7	8.3	7.67/16.8	53	164	413	109	255	92	79	14	23	370	80	360	21	7
ISL4	Austari Jökulsá	46.1	4.9	7.15/4.9	37	171	275	43	189	61	24	8	8	220	360	390	37	8
ISL5	Vestari Jökulsá	19.0	6.4	7.75/6.4	78	263	675	82	320	116	132	23	15	<200	770	<150	24	5
ISL6	Fmjóská	32.8	8.5	7.65/8.5	55	260	413	64	211	106	50	7	9	210	300	<150	<20	6
ISL7	Skjálfandafliót	139.0	8.2	7.67/13.0	58	214	463	45	289	91	60	10	29	240	590	<150	<20	5
ISL8	Jökulsá á Fjöllum	176.0	7.7	7.95/7.7	89	246	763	59	505	121	80	14	62	250	1390	380	22	-4
ISL9	Jökulsá á Dal	189.0	5.4	7.15/5.4	39	128	338	32	132	92	53	7	8	310	150	1010	29	10
ISL10	Jökulsá í Fjótisdal	85.5	4.3	7.30/4.3	43	110	375	43	107	137	58	7	27	<200	<50	<150	25	6
ISL11	Fossá	26.5	4.7	6.30/4.7	20	82	93	94	104	38	30	3	9	350	<50	2040	36	16
ISL12	Geithellnaá	18.0	8.1	7.15/8.1	35	128	200	140	170	81	48	5	16	270	<50	3400	46	14
ISL13	Djúpá	28.0	6.4	7.00/6.4	38	157	243	95	203	65	35	6	18	<200	320	<150	<20	8
ISL14	Hverfisfljót	25.2	7.8	7.35/7.8	56	174	363	132	309	111	52	10	55	330	700	1730	41	5
ISL15	Skafá	103.0	7.8	7.50/7.8	70	228	475	107	322	140	82	11	77	<200	590	210	41	4
ISL16	Ytri-Rangá	45.3	6.4	8.10/6.4	179	331	1475	306	1038	301	242	37	151	240	1650	910	46	2
ISL17	Thjórsá	460.0	8.1	7.45/8.1	60	192	438	95	339	97	58	12	50	<200	570	<150	34	3
ISL18	Öfúsa	412.0	8.4	7.75/8.4	62	199	463	152	348	101	60	15	22	8120	140	550	54	3
ISL19	Hvítá-S	136.0	6.6	7.50/6.6	53	199	388	76	278	84	49	12	30	230	360	<150	44	5
ISL20	(Geysir)		72	9.21/20.0	1202	8100	3500	3880	9500	76	1	581	1126	400	<50	1800	25	2

See text for analytical methods and calculation of TDS.  $\Delta\Sigma/\Sigma$  represents the charge balance of the dissolved loads. For Geysir, data in italic are from Arnósson and others, 1983.

TABLE 1 (continued)  
Chemical compositions of the dissolved loads: trace elements

sample	river	F	Br	B	Li	Sr	Rb	Ba	Al	Fe	Mn	V	Sc	Cr	Co	Cu	Zn	Mo
		nmol/l	nmol/l	nmol/l	nmol/l	nmol/l	nmol/l	nmol/l	nmol/l	nmol/l	nmol/l	nmol/l	nmol/l	nmol/l	nmol/l	nmol/l	nmol/l	nmol/l
ISL 1	Hvítá-W	3140	150	120	51	34	4.6	0.33	1530	<150	9	410	51	14.6	<0.2	3.2	3.64	1.2
ISL 2	Nordurá	480	210	190	8	45	2.4	0.43	<200	190	11	10	31	<5	<0.2	3.8	<3.0	1.0
ISL 3	Blanda	3490	220	160	66	58	4.7	1.96	210	<150	538	50	39	<5	1.2	9.1	6.51	2.4
ISL 4	Austari Jökulsá	2950	130	<100	30	15	2.7	0.18	1230	340	13	210	38	7.2	0.2	4.1	4.99	1.2
ISL 5	Vestari Jökulsá	6040	<100	230	219	52	8.1	0.60	290	<150	7	430	76	7.7	<0.2	3.3	<3.0	2.4
ISL 6	Fnjöská	1350	<100	<100	11	19	2.6	0.15	<200	260	12	140	75	<5	<0.2	2.2	<3.0	<1.0
ISL 7	Skjálfandafjót	3620	<100	190	138	34	3.3	0.22	840	280	15	380	56	<5	<0.2	4.2	3.78	1.6
ISL 8	Jökulsá á Fjöllum	7270	120	970	249	40	3.9	1.07	700	<150	13	420	66	6.0	<0.2	3.0	3.42	4.9
ISL 9	Jökulsá á Dal	820	<100	<100	21	26	1.7	0.14	280	<150	35	60	31	<5	<0.2	7.4	4.07	<1.0
ISL 10	Jökulsá í Fjótisdal	940	<100	<100	36	54	1.8	0.11	<200	<150	77	15	25	<5	0.3	4.1	<3.0	1.5
ISL 11	Fossá	<500	130	<100	1	20	0.6	0.46	<200	<150	12	10	16	<5	<0.2	3.4	8.82	<1.0
ISL 12	Getthellnaá	1810	180	<100	4	34	1.1	0.63	<200	400	7	15	26	<5	<0.2	3.1	8.52	<1.0
ISL 13	Djúpá	1810	120	<100	62	19	1.4	0.25	630	<150	9	110	33	<5	<0.2	2.5	3.61	<1.0
ISL 14	Hverfisfljót	3920	210	1000	1283	45	2.9	0.17	690	<150	55	160	39	<5	0.2	2.7	<3.0	2.2
ISL 15	Skaffá	5760	130	490	132	85	2.5	0.23	360	<150	32	180	50	<5	0.2	4.6	3.19	2.0
ISL 16	Ytri-Rangá	31700	410	1450	1047	334	9.9	1.57	240	690	111	390	103	7.2	0.6	6.2	8.60	19.3
ISL 17	Thjórsá	7200	110	590	196	51	3.5	0.25	390	<150	24	160	45	<5	<0.2	3.6	<3.0	2.8
ISL 18	Ölfusá	2860	240	310	91	55	6.6	0.75	460	600	68	210	50	12.0	0.3	3.5	<3.0	1.4
ISL 19	Hvítá-S	3790	100	180	110	40	4.0	0.53	490	<150	22	170	48	5.9	<0.2	2.5	<3.0	2.3
ISL 20	(Geysir)	530000	4990	74600	86819	105	1550		6110	<150	13	140	2700	32.7	<0.2	<1.0	<3.0	156

diluted to the concentration of 20 mg/l. Na, K, Ca and Mg concentrations were determined by HPLC Dionex 300. The trace elements Sr, Rb, Ba, Li, Cs, transition metals, REE, Pb, U and Th were analyzed by ICP-MS (VG PlasmaQuad II+), with indium as internal standard. BR and BE-N rock standards (basalts) were dissolved and analyzed under the same conditions as the suspended load and sand samples (table 2).

#### RIVER DISSOLVED LOADS

##### *Chemical Compositions*

*Major elements and nutrients.*—The chemical compositions of the river waters of this study are shown in table 1. Temperatures of Icelandic river waters during the sampling ranged between 4.3 and 8.4°C. Their pH is high, from 6.30 to 8.62, the higher pH (pH > 8) being that of the spring-fed type river Ytri-Rangá (Isl16) and of the spring and glacier fed river Hvíta-W (Isl1). The Fossá River (Isl11) has a low pH of 6.3 and all its major element concentrations are the lowest of all the sampled rivers. This river is a direct-runoff river, with a small and steep catchment, relatively old rocks, and dominating snowmelt at the time of sampling. Its low element concentrations and pH reflect short residence time of the water in the catchment and limited water-rock interaction. The mean pH of Icelandic precipitation is 5.4 (Gislason and others, 1996). With one exception, the total dissolved solids (TDS) concentrations of the sampled rivers range between 20 and 89 mg/l. The Ytri-Rangá River (Isl16) has a much higher TDS concentration of 178 mg/l, due to admixture of volcanic gases. The TDS concentrations are globally lower than those of other rivers draining basaltic terrains: 65 to 350 mg/l for Réunion rivers (Louvat and Allègre, 1997), 50 to 140 mg/l for rivers on Sao Miguel island (Azores archipelago, Louvat and Allègre, 1998), 63 to 166 mg/l for the Brazilian Parana Basin (Benedetti and others, 1994), 40 to 134 mg/l for the French Massif Central (Meybeck, 1986). The dissolved silica concentration varies between 82 and 331  $\mu\text{mol/l}$ , and the total dissolved inorganic carbon expressed as  $\text{HCO}_3^-$  concentrations are 220 to 800  $\mu\text{mol/l}$  (excluding the 1500  $\mu\text{mol/l}$  for the Ytri-Rangá River and 93  $\mu\text{mol/l}$  for the Fossá River). For all the rivers dissolved  $\text{SiO}_2$  and  $\text{HCO}_3^-$  represent 60 to 75 percent of the TDS concentrations.

After  $\text{HCO}_3^-$ , the most concentrated anions are chloride and sulphate. The concentrations of both these anions are very variable from one river to the other. Excluding the Ytri-Rangá River (Isl16),  $\text{Cl}^-$  varies from 32 to 152  $\mu\text{mol/l}$  and  $\text{SO}_4^{2-}$  from 8 to 77  $\mu\text{mol/l}$ . The Cl distribution in Icelandic rivers is dominated by the sea salt inputs and is thus correlated to the distance to the ocean. The relative abundance of  $\text{Cl}^-$  and  $\text{SO}_4^{2-}$  is also variable, the  $\text{SO}_4^{2-}/\text{Cl}^-$  molar concentration ratio ranges between 0.10 and 1.05. This variability of the concentration and relative abundance with respect to chloride is also observed for fluoride; its concentration ranges between 500 and 3200 nmol/l and the  $\text{F}^-/\text{Cl}^-$  ratio between 0.003 and 0.124, whereas for bromide the  $\text{Br}^-/\text{Cl}^-$  ratio is always close to 0.0015, close to the concentration ratio of oceanic type rain (oceanic ratio: 0.0035). Bromide concentrations range between 100 and 410 nmol/l. The various  $\text{SO}_4^{2-}/\text{Cl}^-$  and  $\text{F}^-/\text{Cl}^-$  ratios reflect various degrees of water-rock interaction since S and F are easily leached out of the basaltic rocks (Gislason and others, 1996; Gislason and Torssander, 2006). The constant  $\text{Br}^-/\text{Cl}^-$  ratio in the Icelandic river waters suggests that the source of these constituents is the seawater component in Icelandic precipitation.

The concentrations of the nutrients  $\text{NH}_4^+$ ,  $\text{PO}_4^{3-}$ ,  $\text{NO}_3^-$ ,  $\text{NO}_2^-$ , and their ratios vary considerably from one river to the other. The  $\text{NH}_4^+$  concentration is highest in river Olfusá and Nordurá, 8120 and 1640 nmol/l respectively, but lowest in some of the glacier fed rivers (<200 nmol/l). The  $\text{PO}_4^{3-}$  concentration is highest in the river Ytri-Rangá and Jökulsá á Fjöllum but lowest (50 nmol/l) in the direct runoff rivers. The  $\text{NO}_3^-$  concentration is highest in the direct runoff rivers Fossá and Geithellnaá, 2040



and 3400 nmol/l respectively, but these are the rivers with the lowest amount of total dissolved solids (table 1). The source of  $\text{PO}_4^{3-}$  in the river water is primarily from rocks but for  $\text{NH}_4^+$  and  $\text{NO}_3^-$  the source is rain and atmospheric  $\text{N}_2$ . The nutrients are recycled through the biomass during the annual cycle and even during daily cycle: their concentrations are the highest in the winter and in the summer during the night, when there is a lack of light for photosynthesis; they are the lowest in mid summer and in the middle of the day when light and temperature are favorable for the growth of organic matter (Gislason, 1997). Thus the nutrient concentrations in rivers depend on the state of the biomass in the catchment area and therefore on the time of sampling.

For direct runoff rivers in Iceland,  $\text{PO}_4^{3-}$  tends to be the rate-determining nutrient for the growth of organic matter, but conversely  $\text{NO}_3^-$  and  $\text{NH}_4^+$  are the rate-determining nutrients in glacier fed rivers (Gislason and others, 1996; Gislason, 1997). It is thus possible that the lack  $\text{PO}_4^{3-}$  limits the consumption of  $\text{NO}_3^-$  and  $\text{NH}_4^+$  by the biomass in the direct runoff rivers Nordurá, Fossá and Geithellnaá (table 1).

Of the major cationic species, sodium has the highest concentrations: 104 to 505  $\mu\text{mol/l}$  (and 1040  $\mu\text{mol/l}$  for the Ytri-Rangá River). Calcium and magnesium have the same range of concentrations, respectively, 38 to 140  $\mu\text{mol/l}$  and 24 to 132  $\mu\text{mol/l}$ , and these are 310 and 186  $\mu\text{mol/l}$  for the Ytri-Rangá River. Calcium is almost always more abundant than magnesium, the Ca/Mg ratio being between 0.9 and 2.5, with an average ratio of 1.7. Concentrations of potassium are very low, in comparison to those of the other major cations, ranging from 3 to 37  $\mu\text{mol/l}$ .

Taking into account the  $\text{HCO}_3^-$ ,  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{NO}_3^-$ ,  $\text{F}^-$  and  $\text{Br}^-$  anionic species and the  $\text{Na}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ , and  $\text{K}^+$  cationic species, the electro-neutrality of the waters is verified within a 10 percent confidence level with the exception of the most dilute direct runoff rivers, Fossá and Geithellnaá, for which the charge balance is 16 and 14 percent respectively (fig. 1, table 1).

*Trace elements.*—As for the major elements, the concentrations of Sr and Rb in the Ytri-Rangá River (Isl16) (resp. 334 and 9.9 nmol/l) are higher than in the other rivers (15 to 85 nmol/l, and 0.6 to 8.1 nmol/l). This is not the case for aluminium (200 to 1515 nmol/l), the highest concentrations being those of the Hvitá-W River (Isl1, 1515 nmol/l) and Austari Jökulsá River (Isl4, 1087 nmol/l), and the lowest those of the direct-runoff rivers (Isl2, Isl6, Isl11, Isl12). The barium concentrations range between 0.11 and 1.96 nmol/l. The lithium and boron concentrations are highly variable: respectively, from 10 to 1283 nmol/l and from 100 to 1451 nmol/l. The Vestari Jökulsá, Jökulsá á Fjöllum, Hverfisfljót, Skaftá, Ytri-Rangá and Thjórsá Rivers (Isl5, Isl8, Isl14, Isl15, Isl16, and Isl17) have the highest boron and lithium concentrations. They also have the highest sulphate concentrations and are among the richest in  $\text{HCO}_3^-$ . The most obvious common point between these five rivers is that they drain areas very close to the active volcanic zones, and thus the high concentrations observed may be due to high reactivity of the young rocks, magma degassing and/or input from geothermal springs.

Most of the Icelandic rivers have very low metal concentrations and for many of these metals (Fe, Cr, Co, Cu, Zn and Mo) concentrations are at the detection levels of the methods they were measured with. However, these data represent a first estimate of metal concentrations in Icelandic river waters and give thus valuable information even if not very precise. For Fe, Cr, Co, Cu, Zn, Mo and Sc there are not much concentration variations between rivers. For Mn and V, concentrations vary more and seem to be lowest for the direct runoff rivers. The Ytri-Rangá river (Isl16) is among the richest rivers for Fe, Mn, V, Sc, Co, Cu, Zn and Mo. However, it seems unlikely to explain these higher concentrations in Ytri-Rangá river by geothermal inputs because we do not observe similar enriched concentrations for the other rivers where geothermal inputs are supposed to occur. For Mn, Co and Cu, the highest concentrations are for the

TABLE 2  
*Chemical compositions of the suspended loads in ppm (mg/kg)*

(ppm)	P-Is11 Hvítá-W	P-Is13 Blánda	P-Is14 Aust. Jökulsá	P-Is17 Skjálfanda.	P-Is18 Jök. á Fröllum	P-Is19 Jök. á Dal	P-Is10 Jök. í Fljótsdal	P-Is14 Hverfisflöt	P-Is15 Skarhá	P-Is17 Thörsá	P-Is19 Hvítá-S	BR	BR/std	BE-N	BE-N/std
Ca	67090	36000	78020	52240	75850	75370	53240	72260	69810	61300	43170	96220	98630	101200	99130
Mg	36620	15770	42720	24990	35510	36220	23220	34200	33550	30090	20710	78450	80080	80320	79290
Na	18600	11190	16930	12120	22000	18710	21060	23010	20300	21290	17160	25050	25510	27350	26600
K	4290	5170	4030	1600	4740	4380	9140	5700	3980	7390	7940	14520	15400	15390	15290
Sr	175	140	175	114	222	216	324	230	204	261	175	1310	1320	1340	1370
Ba	102	150	80	39	92	85	193	115	81	188	228	1070	1050	1040	1025
Rb	10.6	15.5	8.4	4.4	8.5	4.8	18.1	11.6	7.6	17.0	20.1	47.0	47.0	45.8	47.0
Li	5.41	5.56	4.01	3.17	5.03	4.70	7.75	6.15	5.07	8.57	7.84	11.2	13.0	15.0	12.0
Sc	29.7	21.4	33.5	24.4	35.2	36.9	27.0	33.9	33.5	27.0	26.7	19.5	25.0	18.7	22.0
V	317	354	279	223	385	409	312	400	398	304	340	344	340	355	360
Cr	238	125	226	89	80	120	69	87	78	104	93	344	380	355	330
Co	36.9	41.6	39.4	26.7	39.2	39.7	29.5	39.2	37.7	34.3	33.9	48.5	52.0	51.6	61.0
Ni	121	81	100	41	47	56	36	48	43	52	43	231	260	237	267
Cu	440	175	111	77	104	109	98	105	99	115	99	79	72	70	72
Zn	293	279	108	74	127	130	135	139	126	160	152	120	130	115	120
Y	26.7	29.3	27.0	19.0	35.7	33.9	40.0	38.3	35.2	45.6	50.1	28.9	30.0	29.5	30.0
Zr	267	325	212	171	183	317	414	356	271	423	457	273	250	260	265
Nb	30.2	30.9	20.2	12.2	13.3	24.9	34.1	32.0	14.9	30.9	62.2	108.0	98.0	102.1	100.0
Ta	1.20	3.67	2.28	1.39	1.55	2.67	1.16	3.78	1.50	2.36	6.63	3.98	6.20	5.05	5.50
Mo	1.60	3.20	0.75	0.57	0.66	0.65	0.49	1.19	1.06	1.78	1.68	2.20	2.40	2.33	2.50
Sn	15.4	11.6	1.6	0.7	1.0	1.4	1.8	1.9	0.9	1.8	1.5	1.9	2.5	1.0	1.0
Pb	11.7	24.0	2.0	3.2	1.6	3.5	3.0	1.8	1.5	3.8	5.1	4.8	8.0	4.3	4.0
Th	1.65	2.34	0.96	0.46	1.04	0.94	1.72	1.50	0.98	2.63	3.04	9.49	11.00	9.91	11.00
U	0.51	0.77	0.29	0.16	0.35	0.33	0.52	0.40	0.31	0.72	0.92	2.04	2.50	2.15	2.40
La	14.5	18.4	9.6	5.7	13.6	11.7	21.8	16.1	12.7	25.2	29.9	81.7	82.0	84.4	82.0
Ce	31.4	38.9	22.3	13.9	32.3	28.2	50.8	37.9	30.5	56.9	66.6	151.1	151.0	150.6	152.0
Pr	3.92	4.94	2.78	1.90	6.55	4.34	6.55	5.23	4.39	7.38	8.42	17.4	17.4	18.2	18.2
Nd	17.4	20.9	12.7	9.2	20.6	18.2	30.2	24.8	20.3	32.7	35.9	65.0	65.0	72.1	70.0
Sm	4.29	5.18	3.71	2.59	5.63	5.15	7.50	6.49	5.56	8.03	8.86	13.1	12.0	11.8	12.0
Eu	1.42	1.47	1.19	0.93	1.95	2.43	2.65	2.28	1.88	2.49	2.65	3.42	3.70	3.62	3.60
Gd	4.69	5.55	4.35	3.11	6.27	6.18	7.78	7.28	6.41	8.49	8.97	10.3	10.0	10.5	10.0
Tb	0.76	0.81	0.69	0.48	0.96	0.92	1.16	1.07	1.05	1.30	1.42	1.29	1.30	1.30	1.30
Dy	4.89	5.18	4.57	3.26	6.06	6.14	7.63	7.23	6.74	8.13	8.90	6.55	6.20	6.92	6.40
Ho	0.99	1.04	0.92	0.67	1.25	1.22	1.43	1.40	1.28	1.65	1.77	1.01	1.07	1.07	1.07
Er	2.46	2.91	2.61	1.88	3.52	3.21	3.99	3.75	3.67	4.51	4.79	2.54	2.40	2.60	2.50
Tm	0.33	0.37	0.26	0.26	0.43	0.43	0.50	0.53	0.49	0.61	0.69	0.26	0.27	0.29	0.36
Yb	2.33	2.75	2.44	1.82	3.13	3.14	3.54	3.36	3.24	4.11	4.49	1.92	1.90	1.79	1.80
Lu	0.37	0.42	0.38	0.28	0.48	0.45	0.49	0.52	0.45	0.59	0.66	0.26	0.25	0.26	0.24

Mean measured concentrations and certified concentrations for the BR and BE-N rock standards are also given to assess the validity of the analyses.

TABLE 2 (continued)  
Chemical composition of the sands in ppm (mg/kg)

(ppm)	S-ls1 Hvita-V	S-ls13 Blanda	S-ls14 Aust. Jökulsá	S-ls15 Vest. Jökulsá	S-ls18 Jök. á Fjöllum	S-ls19 Jökulsá á Dal	S-ls10 Jök. í Fljótsdal	S-ls11 Fossá	S-ls12 Geithellmá	S-ls13 Djúmá	S-ls14 Hverfisfjöt	S-ls15 Skafiá	S-ls16 Ytri-Rangá	S-ls19 Hvita-S
Cu	77690	55880	82790	79600	80030	79080	59500	67550	57340	63870	71330	74440	65770	56980
Mg	47420	28250	50550	38890	37940	41220	24980	32340	26410	30540	36130	35850	32770	27110
Na	17650	26420	17520	18950	20010	19370	19450	20350	20260	24580	22170	22190	24210	2310
K	4180	17700	2410	3780	3340	3780	8610	5470	7480	9020	5170	4110	7520	9570
Sr	177	191	157	185	213	205	300	213	324	246	211	219	325	217
Ba	101	148	51	90	80	74	175	117	163	175	99	87	179	223
Rb	9.8	13.7	4.3	8.8	8.2	6.9	16.7	8.6	14.7	18.3	9.3	8.9	14.7	21.1
Li	4.74	7.39	3.11	4.56	4.45	3.57	5.90	5.80	5.68	5.66	5.30	4.77	5.80	6.79
Sc	31.6	28.5	34.9	35.6	35.8	37.6	34.4	33.5	28.3	26.0	29.2	31.5	28.5	26.7
V	308	344	305	360	401	505	327	344	301	298	365	429	320	298
Cr	263	103	239	196	108	150	81	84	72	73	85	90	79	99
Co	42.1	38.5	44.4	39.8	42.5	43.6	26.5	37.1	32.7	32.8	37.7	41.0	35.9	31.9
Ni	133	52	120	77	59	71	36	48	39	53	49	51	56	49
Cu	113	147	117	113	117	118	77	117	93	84	98	110	97	88
Zn	104	128	92	112	125	142	114	134	133	121	118	142	157	145
Y	28.1	38.4	22.4	32.7	34.7	38.5	38.5	33.3	33.3	38.8	33.7	35.4	38.2	45.1
Zr	227	394	188	274	212	262	231	167	401	380	344	317	193	250
Nb	25.1	39.0	15.2	24.9	16.9	15.2	21.3	13.2	28.7	34.3	19.9	18.7	21.9	33.9
Ta	2.74	4.68	1.97	2.83	0.63	0.93	1.36	2.00	1.91	2.33	0.83	0.99	1.10	0.88
Mo	0.69	0.85	0.44	0.77	0.62	0.84	0.86	0.31	0.96	1.36	0.72	0.90	1.46	1.42
Sn	1.7	2.1	0.8	1.2	1.9	1.9	2.0	0.7	1.9	2.3	1.7	1.5	2.0	2.0
Pb	1.6	9.0	1.1	2.5	1.9	1.5	2.4	2.3	3.1	2.2	6.8	2.3	3.7	3.6
Th	1.28	1.96	0.77	1.17	0.96	0.87	1.08	1.24	1.43	1.98	1.70	1.40	1.92	2.38
U	0.36	0.56	0.19	0.32	0.30	0.17	0.31	0.34	0.41	0.57	0.47	0.37	0.55	0.69
La	12.0	18.8	11.0	12.2	11.1	11.9	15.1	15.9	16.5	20.0	16.4	14.0	21.8	24.9
Ce	26.2	44.3	24.5	28.6	28.5	27.5	36.2	37.8	39.2	45.6	38.5	34.2	50.5	56.2
Pr	3.56	5.72	3.12	3.93	4.06	3.77	4.66	5.11	5.18	5.69	5.28	4.90	6.32	6.94
Nd	16.3	25.7	13.7	18.3	19.3	19.1	22.0	23.7	23.9	25.9	24.5	22.8	29.5	31.7
Sm	4.09	6.72	3.62	4.85	4.85	5.03	5.49	6.07	6.10	6.41	6.08	5.84	6.75	7.31
Eu	1.35	2.13	1.22	1.64	1.73	1.82	2.04	2.29	2.23	2.29	2.14	2.09	2.63	2.99
Gd	4.60	7.29	4.18	5.92	5.91	6.07	6.50	7.18	6.94	7.26	7.04	6.85	7.86	8.28
Tb	0.75	1.05	0.68	0.91	0.92	0.97	1.00	1.08	1.06	1.15	1.11	1.08	1.19	1.23
Dy	5.14	7.04	4.39	6.30	5.99	5.91	6.24	6.81	6.65	6.92	6.99	6.86	7.45	8.07
Ho	1.00	1.45	0.91	1.18	1.16	1.25	1.30	1.36	1.30	1.39	1.41	1.37	1.45	1.58
Er	2.75	3.93	2.50	3.46	3.20	3.36	3.48	3.59	3.55	3.85	3.77	3.67	3.92	4.39
Tm	0.38	0.55	0.34	0.45	0.43	0.43	0.46	0.49	0.46	0.51	0.53	0.50	0.52	0.59
Yb	2.66	3.69	2.36	3.15	3.01	3.08	3.18	3.21	3.09	3.49	3.35	3.37	3.60	4.14
Lu	0.40	0.58	0.35	0.47	0.45	0.45	0.46	0.48	0.46	0.50	0.53	0.52	0.52	0.60

Blanda river (Isl3). No systematic trends similar to that for major elements can be observed to explain these trace metal concentrations. Their concentrations are most likely controlled by adsorption/desorption and/or precipitation rather than dissolution of rocks, as is the case for many of the major elements. For V and Sc we observe a positive correlation between the concentrations of these two elements in the rivers and also between these two concentrations and the pH of the rivers: the higher the pH, the higher the concentrations. Thus, concentrations of V and Sc are higher for spring-fed type rivers. For the other trace metal elements such relations with pH are less obvious.

Understanding of the trace metal concentrations in river waters usually requires the understanding of both the possible sources of these elements and of the transfers between dissolved and solid phases. In the case of Icelandic rivers, the potential sources are the same as for the major elements (rainwater, weathering, geothermal inputs and magmatic degassing), but they are much more difficult to characterize because their concentrations in these trace elements are much more variable. Trace metal concentrations of rainwater often reflect a large-scale atmospheric circulation and the pollution effects from industrialized areas are much more visible for such trace elements than for major elements. Rainwater trace element concentrations could also be highly influenced by volcanic emissions. For the three other sources, the behavior of these metal elements (except Al and Fe) during water-rock interaction is also poorly understood.

*Comparison with other data, temporal variability of the chemical compositions.*—For some of the samples (Isl1, Isl2, Isl3, Isl4, Isl5, Isl7, Isl17, Isl18 and Isl19), the concentrations of the major species can be compared with the previous studies of Gislason and Arnórsson (1993) on the same rivers. Some of them were sampled at the same location, allowing direct comparison: Hvíta-W (Isl1) and Nordurá (Isl2) in August 1990, Blanda (Isl3) and Austari Jökulsá (Isl4) in February 1990, and the rivers Ölfusá (Isl18) and Thjórsá (Isl17) in September 1990.

For the Hvíta-W and Ölfusá rivers (Isl1 and Isl18) both sets of data are very close. For the Austari Jökulsá (Isl4) and Hvíta-S (Isl19) rivers, the present analyses are quite different from those of Gislason and Arnórsson (1993). For the Nordurá, Blanda and Thjórsá rivers (Isl2, Isl3 and Isl17), there is some consistency between the two sets of chemical compositions, but the samples of the present study are more diluted. For these rivers, there seems to be an overall dilution factor of between 1.3 and 1.7. Since the discharges of the Blanda and Thjórsá rivers in June 1996 (respectively, 14.75 m<sup>3</sup>/s and 425 m<sup>3</sup>/s) were higher than those of Gislason and Arnórsson (1993) in February, July and September 1990, the present dilution factor could be explained by the dominant effect of glacier melting in June, providing more diluted waters to the rivers. This glacier melting effect cannot account for the Nordurá river, which is a direct runoff river, but the discharge of June 1997 (23.5 m<sup>3</sup>/s) is nevertheless much higher than that of August 1990 (4.95 m<sup>3</sup>/s).

The Ytri-Rangá (Isl16) has also been extensively studied (Gislason and others, 1992; Flaathen and Gislason, 2006), by continuous monitoring of its chemical composition during the Hekla volcano 1991 eruption. Gislason and others (1992) noticed pre-eruption fluxes of carbon and sulphur to the river, due to the degassing of the magmatic chamber. Such fluxes make the waters more reactive, causing an intense water-rock interaction, and thus increasing alkalinity and TDS concentration of the river waters. The high concentrations for all the major elements we analyzed for this river are thus not so surprising, because of magmatic degassing fluxes, even in a non-eruptive period. pH, F<sup>-</sup> and CO<sub>2</sub> concentrations are in agreement with those given by Gislason and others (1992) and Flaathen and Gislason (2006) during non-eruptive period.

The chemical compositions and hydrologic parameters of the present study can be compared to the annual variations and annual means of the Ytri-Rangá, Thjórsá, Ölfusá and Hvitá rivers (fig. 1; Isl16, Isl17, Isl18, Isl19) from Gislason and others (1997). This paper presents a monitoring of the geochemical compositions of many rivers in SW-Iceland, based on a monthly sampling from October 1996 to September 1997. The annual variation from 1996 to 1997 in discharge, concentration of total suspended sediments, concentrations of total dissolved solids, alkalinity and the concentrations of Cl, Na, Ca and Sr is shown in figure 2, for each of these four rivers. Each diagram represents monthly measurements of one parameter normalized to its annual average. Normalized measured value for the present study is also shown as well as the actual concentrations (fig. 2).

Discharge variation during the annual hydrological cycle depends on the type of the river (spring-fed, direct runoff or glacier-fed). For spring-fed rivers (for example Ytri-Rangá, Isl16) discharges are constant through time whereas glacier-fed rivers have important floods during summer (glacier melting) and discharges of direct runoff rivers vary with precipitations. Most of the other concentration variations are related to the discharge variations: total suspended sediment concentrations are higher for higher discharges and most of the dissolved concentrations are lower when discharges are higher (global dilution). Chlorine is an exception, with higher concentrations for higher discharge, and this reflects that chlorine mainly arises from sea salts. It is obvious from the diagrams in figure 2 that the concentrations of most dissolved species and of total dissolved solids are much less variable through the annual hydrologic cycle than are the concentrations of suspended sediments. For the four rivers represented in figure 2 (Isl16, Isl17, Isl18 and Isl19), discharges and concentrations measured in this study are very close to the annual means for 1996–97 (ratios between 0.8 and 1.2). Differences between the annual mean and this study values are always lower than 10 percent for the Ytri-Rangá and Ölfusá rivers (Isl16 and Isl18), these rivers are also the ones which show less variability in their discharge and dissolved concentrations through the annual hydrological cycle. Differences are larger for the Thjórsá and Hvitá-S rivers (Isl17 and Isl19), in particular for species such as chlorine and alkalinity, but values for the present study are always close to the June 96 values.

A discussion about nutrient concentration variations through the annual hydrological cycle can be found in Gislason and others (1996).

#### *Atmospheric, Geothermal and Magmatic Inputs to the Rivers*

Among the numerous sources river dissolved chemical compositions may arise from, the well preserved environment of Iceland and the careful sampling upstream from cultivated fields and roads allow us to neglect direct anthropogenic contaminations. In this paper we focus at deciphering atmospheric inputs (mainly sea salt derived rains), low-temperature chemical weathering, high-temperature chemical weathering (geothermal) and magmatic inputs. In the original purpose of this study, only low-temperature weathering rates were ultimately taken into account in order to compare them to other basalt chemical weathering rates world-wide and infer weathering laws according to geomorphologic and climatic parameters (Louvat, ms, 1997). For each river the concentrations arising from precipitation, geothermal or magmatic inputs are thus subtracted from the river water concentrations.

From the previous description of the chemical compositions of the river waters, geothermal and magmatic inputs are obvious for Ytri-Rangá and Jökulsá á Fjöllum rivers (Isl16 and Isl8), but must also be considered for the Vestari Jökulsá, Hverfisfljót, Skaftá and Thjórsá rivers (Isl5, Isl14, Isl15 and Isl17). All these rivers have in common most if not all the following characteristics: high concentrations of  $\text{SO}_4$ ,  $\text{HCO}_3$ , Na, F, B and Li compared to the other Icelandic rivers we sampled. More than chemical

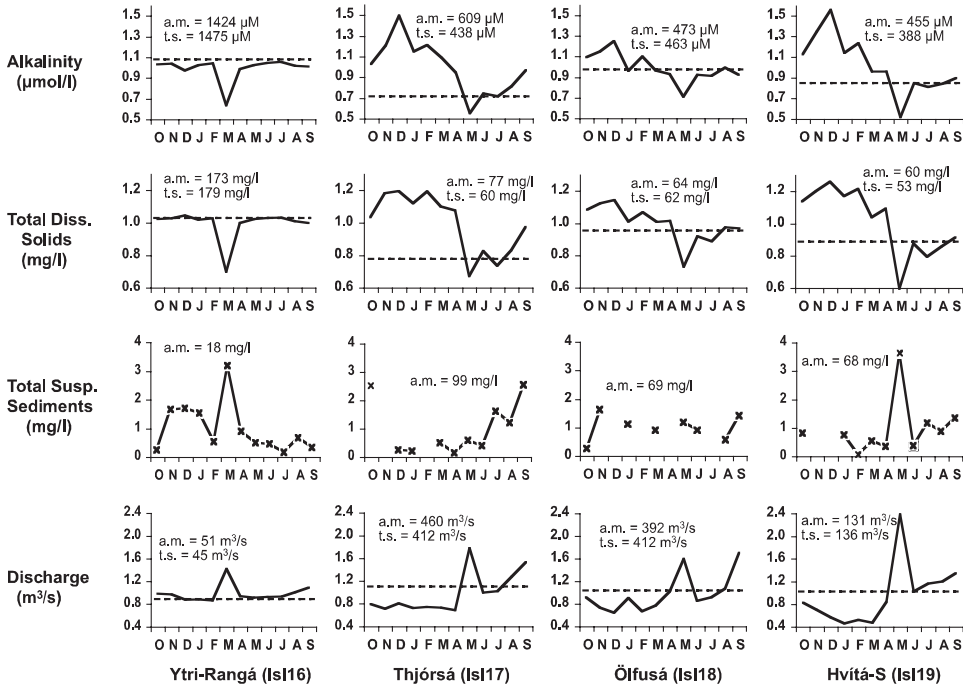


Fig. 2. Annual variations of the discharge, total suspended sediments (TSS), total dissolved solids (TDS) and alkalinity for four Icelandic rivers (data from Gislason and others, 1997). Data for each parameter are normalized to the annual mean. The dotted lines represent normalized values from the present study. The annual means (a.m.) and values for this study (t.s.) are also given.

evidences there are also geographic arguments: these rivers all are situated in areas where geothermal fields have been recognized, either in the form of hot thermo-mineral springs (for Isl8, Isl14, Isl15 and Isl17) or magmatic degassing in active volcanic areas (Ytri-Rangá –Isl16– near Hekla volcano, and Vestari Jökulsá –Isl5– draining the fissure swarm north of the caldeira within the Hofsjökull glacier, fig. 1).

The study of Arnórsson and Andrésdóttir (1995) of the concentrations of boron and chlorine in the thermal and non-thermal waters of Iceland showed that the contribution of rain water with oceanic concentration ratios, and of leaching of the rocks could be determined by the Cl/B ratio, since the most evolved geothermal waters have Cl/B ratios similar to those of the basaltic rocks. In a similar way we can determine, for rivers where geothermal inputs must be considered, the proportion of chlorine arising from rain ( $\alpha$ ) and from geothermal inputs ( $1 - \alpha$ ):

$$\left(\frac{B}{Cl}\right)_{river} = \alpha \left(\frac{B}{Cl}\right)_{rain} + (1 - \alpha) \left(\frac{B}{Cl}\right)_{rock} \quad (1)$$

where  $\left(\frac{B}{Cl}\right)_{rain}$  and  $\left(\frac{B}{Cl}\right)_{rock}$  are the inverses of the Cl/B ratios of Arnórsson and Andrésdóttir (1995), namely 1/1330 for rain and 1/30 for rocks. This equation can also be written:

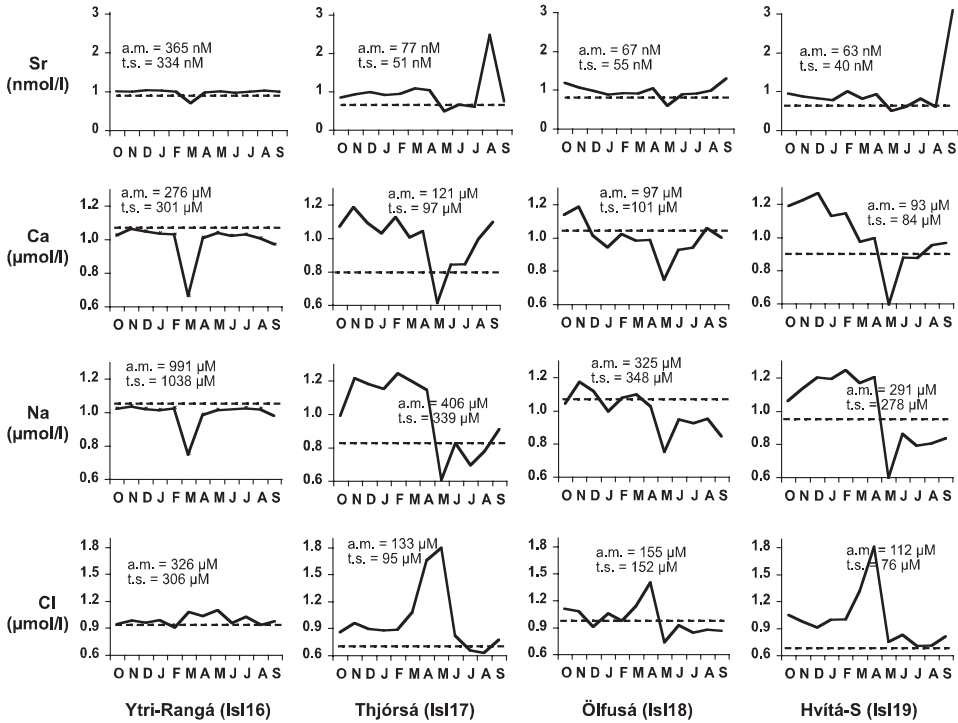


Fig. 2 (continued). Annual variations of Cl, Na, Ca and Sr concentrations for four Icelandic rivers (data from Gíslason and others, 1997). Data for each parameter are normalized to the annual mean. The dotted lines represent normalized values from the present study. The annual means (a.m.) and values for this study (t.s.) are also given.

$$\% (Cl)_{rain} = \frac{\left(\frac{B}{Cl}\right)_{river} - \left(\frac{B}{Cl}\right)_{rock}}{\left(\frac{B}{Cl}\right)_{rain} - \left(\frac{B}{Cl}\right)_{rock}} \times 100 \quad (2)$$

In the river waters we sampled, the Cl/B ratio ranges from 60 to 1150 and is thus intermediate between the Cl/B ratios of oceanic rain (1330) and rocks (30) given by Arnórsson and Andrésdóttir (1995). The lowest Cl/B ratios are those of the six previous rivers (Isl5, Isl8, Isl14, Isl15, Isl16, Isl17), for which we want to make geothermal input corrections. For the other rivers, the Cl/B ratio is not as high as the oceanic ratio (maximum value is 975 for the Hvitá-W river, Isl1) and this means that some of the boron arises from basalt weathering. The average boron concentration of the river waters not concerned by geothermal inputs is 180 nmol/l, in agreement with the previous estimation of boron concentration in Icelandic surface waters by Arnórsson and Andrésdóttir (1995).

The proportions of Cl arising from precipitations, calculated by equation 2 are: 94 percent for the Vestari Jökulsá River (Isl5), 51 percent for the Jökulsá á Fjöllum River (Isl8), 79 percent for the Hverfisfljót River (Isl14), 88 percent for the Skaftá River (Isl15), 88 percent for the Ytri-Rangá River (Isl16) and 83 percent for the Thjórsá River (Isl17). For these six rivers, the remaining chlorine arises from geothermal and magmatic inputs. For the other rivers, all the chlorine arises from precipitations.

TABLE 3

*Chlorine normalized concentration ratios of the different end-members used for the precipitation and geothermal spring input corrections of the river dissolved loads*

	Seawater (GERM. 1997)	mean Thermal Spring (1)	Geysir (this study)	Hekla (Gislason. 1998)
SiO <sub>2</sub> /Cl	0.00019	3.0		0.66
HCO <sub>3</sub> /Cl	0.0041	1.1	0.90	4.1
Na/Cl	0.88	4.2	2.4	3.4
Ca/Cl	0.019	0.11	0.020	0.96
Mg/Cl	0.097	0.0027	0.00025	1.1
K/Cl	0.019	0.078	0.15	0.074
SO <sub>4</sub> /Cl	0.051	0.61	0.29	0.64
F/Cl	0.00013	0.15	0.14	0.080
B/Cl	0.00076	0.025	0.019	0.0053
Li/Cl	4.8E-05		0.022	
Sr/Cl	0.00017		2.7E-05	0.0015
Rb/Cl	2.7E-06		0.0004	
Ba/Cl	1.6E-07			

(1) Data from Arnórsson and others, 1983.

A description of the chemistry of precipitation in Iceland can be found in Gislason and others (1996), Gislason and Eugster (1987b), Gislason (1990) and Gislason and Torssander (2006). The mean pH of the precipitation in Iceland is 5.4 with a standard deviation of 0.46. Chlorine concentrations range between 7.6 and 3300  $\mu\text{mol/l}$  with a median value of 163  $\mu\text{mol/l}$ . This is relatively high since most of the samples are from low elevation close to the coast. The dissolved solid concentrations decrease inland and with increased elevation. The concentrations in snow is somewhat higher than in rain, because of the larger size of the snow flakes compared to rain drops, and thus their ability to catch more aerosols when falling. The Na/Cl, K/Cl, Mg/Cl, and Sr/Cl molar concentration ratios of the rain are very close to the oceanic ratios (table 3), indicating a marine source for these elements. The concentrations of calcium, sulphate, nitrate and ammonia are higher than would be predicted by an unfractionated marine contribution, and other sources must be involved (local basaltic dust, fractionation of the sea-spray, burning of fossil fuel, magmatic gases, biogenic inputs or farming activities).

Knowing for most dissolved chemical species the chlorine normalized concentration ratios of the precipitations in Iceland (oceanic ratios), the river chemical compositions stemming from the precipitation inputs can be corrected for (table 4). The total dissolved inorganic carbon concentrations depicted as HCO<sub>3</sub> concentrations, are corrected from the total dissolved inorganic carbon concentration of an ideal rainwater in equilibrium with the atmospheric CO<sub>2</sub> (1.66 mg/l as HCO<sub>3</sub> or 27  $\mu\text{mol/l}$ , Gislason and others, 1996). SiO<sub>2</sub> concentration is very low in precipitations, thus all the SiO<sub>2</sub> of the rivers is considered to stem from water-rock interaction. The Br/Cl ratios of the sampled rivers are very close to the oceanic ratios: bromide is therefore derived from seawater via precipitations.

Thermo-mineral springs of Iceland have a large range of chemical compositions (for example Arnórsson and others, 1983; Arnórsson and Andrésdóttir, 1995). The



TABLE 4  
River dissolved load chemical compositions after correction of the precipitation and geothermal/magmatic inputs

sample	river	After precipitation input correction											TDS	TDSbas							
		HCO <sub>3</sub> <sup>-</sup>	Cl <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	F <sup>-</sup>	Na <sup>+</sup>	K <sup>+</sup>	Mg <sup>2+</sup>	Ca <sup>2+</sup>	B	Li	Rb			Sr	Ba	TDS	TDSbas			
		μmol/l	μmol/l	μmol/l	μmol/l	μmol/l	μmol/l	μmol/l	μmol/l	μmol/l	μmol/l	μmol/l	μmol/l	μmol/l	μmol/l	μmol/l	μmol/l	μmol/l	μmol/l	mg/l	mg/l
ISL1	Hvítá-W	323	0	11.5	3.1	190	8.5	31	75	33	46	4.3	14	0.31	42	22					
ISL2	Nordurá	261	0	10.0	0.5	95	4.7	38	75	84	2	2.0	21	0.41	31	15					
ISL3	Blanda	386	0	17.4	3.5	159	12.3	69	90	77	61	4.4	39	1.95	44	21					
ISL4	Austari Jökulsá	248	0	5.4	2.9	150	7.2	20	60	20	28	2.6	8	0.18	33	17					
ISL5	Vestari Jökulsá	648	5	11.1	6.0	253	22.1	125	114	171	216	7.9	39	0.59	71	31					
ISL6	Fjujósá	386	0	5.7	1.3	154	6.1	44	105	91	156	3.2	8	0.14	49	25					
ISL7	Skjálfandafljót	436	0	27.2	3.6	250	9.3	56	91	136	135	3.2	27	0.21	53	27					
ISL8	Jökulsá á Fjöllum	736	29	60.1	7.3	478	13.7	77	121	947	247	3.8	35	1.07	85	40					
ISL9	Jökulsá á Dal	311	0	6.3	0.8	104	6.3	50	91	136	19	1.6	20	0.13	35	16					
ISL10	Jökulsá í Fjötsdal	348	0	25.3	0.9	69	6.2	54	136	18	34	1.7	47	0.11	39	18					
ISL11	Fossá	66	0	4.7	0.0	22	1.3	21	36	78	0.3	0.3	4	0.44	12	8					
ISL12	Geithellnaá	173	0	9.2	0.0	46	1.9	35	78	63	57	1.1	3	0.23	30	17					
ISL13	Djúpa	216	0	13.6	1.8	119	4.2	26	63	921	1278	2.6	27	0.15	47	27					
ISL14	Hverfisfljót	336	28	50.1	3.9	217	8.3	42	109	418	127	2.3	69	0.21	62	34					
ISL15	Skafhá	448	13	72.1	5.7	239	9.4	73	138	1245	1034	9.2	288	1.53	160	71					
ISL16	Ytri-Rangá	1448	37	137.8	31.7	801	31.5	216	296	95	530	3.3	37	0.23	53	28					
ISL17	Thjórsá	411	16	46.5	7.2	270	10.8	50	98	194	84	6.2	29	0.73	50	24					
ISL18	Ólfusá	436	0	14.5	2.8	214	12.3	45	82	122	107	3.8	27	0.52	46	24					
ISL19	Hvítá-S	361	0	26.3	3.8	211	10.7	41	82	122	107	3.8	27	0.52	46	24					

sample	river	After precipitation and geothermal/magmatic input correction											TDS	TDSbas								
		SiO <sub>2</sub>	HCO <sub>3</sub> <sup>-</sup>	Cl <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	F <sup>-</sup>	Na <sup>+</sup>	K <sup>+</sup>	Mg <sup>2+</sup>	Ca <sup>2+</sup>	B	Li			Rb	Sr	TDS	TDSbas				
		μmol/l	μmol/l	μmol/l	μmol/l	μmol/l	μmol/l	μmol/l	μmol/l	μmol/l	μmol/l	μmol/l	μmol/l	μmol/l	μmol/l	μmol/l	μmol/l	μmol/l	μmol/l	μmol/l	mg/l	mg/l
ISL5	Vestari Jökulsá	260	628	0	8.0	5.6	236	22	119	110	52	150	7.9	39	68	30						
ISL8	Jökulsá á Fjöllum	159	705	0	42.7	2.8	356	11	77	118	261	150	3.8	34	72	29						
ISL14	Hverfisfljót	91	306	0	33.4	-0.4	99	6	42	106	257	150	2.6	27	35	16						
ISL15	Skafhá	189	434	0	64.3	3.7	184	8	73	136	105	127	2.3	69	56	29						
ISL16	Ytri-Rangá	307	1298	0	114.3	28.7	678	29	174	261	365	150	9.2	289	140	61						
ISL17	Thjórsá	144	394	0	36.7	4.7	201	10	50	93	140	150	3.3	37	46	22						

Only elements for which the correction was applied are presented. TDS is calculated with the same concentrations as in table 1 (see text), whereas TDS<sub>bas</sub> represents the TDS due to basalt weathering only, without HCO<sub>3</sub> concentrations.

salinity ranges between 150 mg/l and 32 permil (for comparison, the salinity of sea-water is close to 35‰). Chloride is the dominant anion in the saline waters (percolation of seawater into the geothermal systems) whereas sulphate, bicarbonate and chloride are all important in the more dilute geothermal waters at elevation above 200 m (Arnórsson and others, 1983). Sodium is the dominant cation, before calcium and potassium. Magnesium is a trace element in most geothermal waters. Sulphate concentrations are high in all springs. The chemical composition of the geothermal waters appears to be mainly controlled by temperature and salinity (Arnórsson and others, 1983). The percolation of seawater is evident for most of the geothermal waters situated near the coasts and at present elevation lower than 200 m.

Chemical composition of geothermal waters arising from magmatic degassing through the groundwaters are more poorly known. Gases issued from subaerial volcanism are mainly composed of H<sub>2</sub>O, CO<sub>2</sub>, SO<sub>2</sub>, HCl, H<sub>2</sub>, HF, H<sub>2</sub>S (Sigvaldason and Elíasson, 1968; Oskarsson, 1980; Le Cloarec and Marty, 1990; Oppenheimer, 2004; Moune and others, 2006), and these major components carry other volatile species such as metals (Al, Hg, Se, As, Zn, Cu, Au, Cd, Sb, Bi) in the form of halides, sulphides and fluorides (Oskarsson, 1980; Le Cloarec and Marty, 1990; Frogner and others, 2001; Moune and others, 2006). The chemical composition of the volcanic gases is very variable both between volcanoes, and eruptive periods (Oppenheimer, 2004). Such variations can be explained both by the physical behavior of the erupting magma or by its chemical composition. How such gases percolate through a hydrologic system and how the chemical signature would be modified are unanswered questions. Magmatic gases acidify the groundwaters, increasing their reactivity towards rocks and the dissolution processes during water-rock interaction, and thus the total dissolved solids concentrations. Compared to the thermo-mineral springs, inputs resulting from magmatic degassing are characterized by lower temperature of water-rock interaction and their chemical compositions are somewhat different from those of the thermo-mineral springs (table 3); lower pH, much higher Mg concentration, and lower silica concentrations. For many other dissolved species, concentrations of waters issued from magmatic gas percolation and concentrations of thermo-mineral springs are similar: high concentrations of CO<sub>2</sub>, SO<sub>4</sub>, Na, B, F *et cetera*. It is however very difficult to give typical average chemical compositions for both end-members because of their large diversity, which reflects mixing between those two kinds of waters, but also mixing with surface waters and groundwaters, intensity of the water-rock interaction and its temperature.

The geothermal and magmatic inputs to the six rivers: Isl5, Isl8, Isl14, Isl15, Isl16, Isl17 are corrected for precipitation inputs using the average ratios in table 3.

For thermal spring input corrections (Isl8, Isl14, Isl15 and Isl17), the average concentrations of Arnórsson and others (1983) for the spring waters with Cl/B ratios lower than 100 (springs with highest water-rock interaction degrees; table 3) is used. For the elements not measured by Arnórsson and others (1983), we used measurements of the present study for the Geysir geothermal spring (tables 1 and 3).

For magmatic degassing input corrections (Isl5 and Isl16), the study of Gislason and others (2006) is used. This study includes data for the concentrations and isotopic compositions of dissolved constituents in precipitations, springs, and river waters in the vicinity of the Hekla volcano, prior to, during and after the January 1991 eruption. From this database, we calculated the mean X/Cl molar concentration ratios of the samples with the highest CO<sub>2</sub> concentrations (table 3). For elements not analyzed by Gislason and others (2006), we use Geysir X/Cl molar concentration ratios (tables 1 and 3).

For Rb and Li the above described correction results in negative concentrations for some rivers underscoring the uncertainty of the chosen end-members. The Rb/Cl

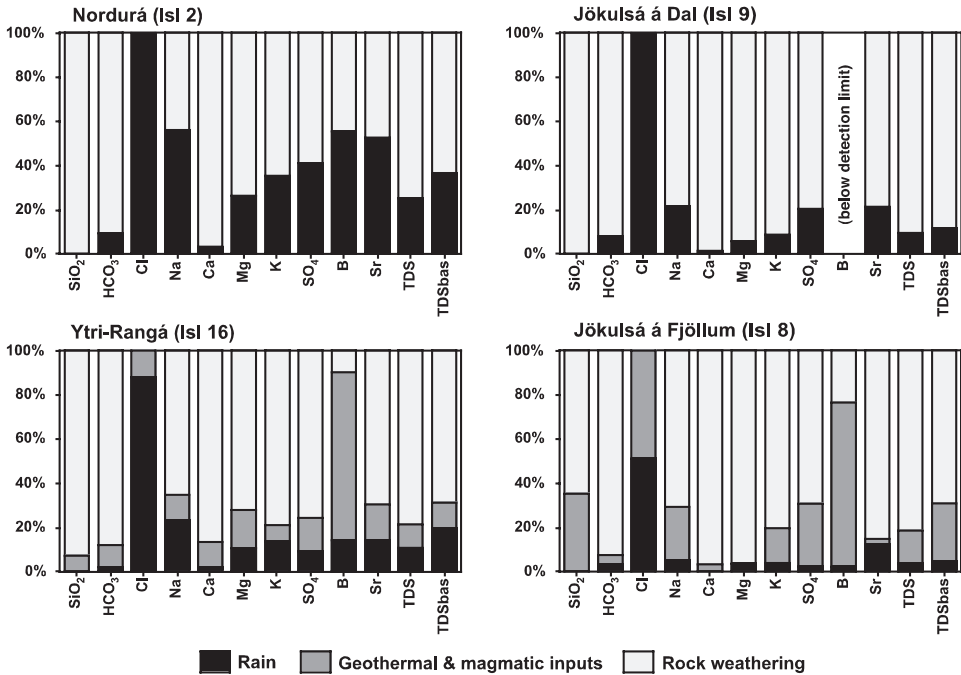


Fig. 3. Proportions of rain, geothermal and rock weathering inputs to the dissolved loads of four characteristic Icelandic rivers: the direct-runoff Nordurá (Isl2) river, the glacial river Jökulsá á Dal (Isl9), the spring-fed river with magmatic degassing Ytri-Rangá (Isl16) and the glacial river with geothermal spring inflows Jökulsá á Fjöllum (Isl8).

and Li/Cl of the Geysir spring (table 4) are too high and cannot be representative of an average chemical composition of Icelandic thermo-mineral springs. Since the Rb concentrations of the six rivers concerned with geothermal inputs are not really higher than the concentrations in the other rivers, we will consider that the geothermal inputs are negligible for Rb. No corrections are made for Ba, as we do not have Ba concentrations of geothermal springs from literature nor from the present study. For Li, we can consider that there is a limit concentration of Li arising from rock weathering above which Li is coming from geothermal sources. Highest Li concentration among the rivers not affected by geothermal inputs is 135 nmol/l (for Skjálfandalfjót river, Isl7) and we thus choose the limit concentration to be 150 nmol/l. For F, correction of geothermal inputs for the Hverfisfljót river (Isl14) is a little too strong and the F/Cl chosen for this correction (from data in Arnórsson and others, 1983) cannot be representative for all the Icelandic thermo-mineral springs.

Chemical compositions of the rivers corrected for precipitation, geothermal and magmatic inputs are given in table 4. Proportions of rain, geothermal, magmatic and rock weathering inputs in the dissolved loads of four representative rivers (Nordurá, Jökulsá á Dal, Jökulsá á Fjöllum and Ytri-Rangá) are shown in figure 3.

Precipitation corrections represent 4 to 39 percent of the total dissolved solid concentrations. As expected, corrections are the strongest for the direct runoff rivers Isl2, Isl11, Isl12 (figs. 1 and 3), with precipitation inputs representing more than 25 percent of the TDS. Precipitation inputs are larger for small direct runoff rivers catching runoff close to the ocean, such as Fossá (Isl11) and Geithellnaá (Isl12), than for bigger direct runoff rivers such as Nordurá (Isl2), glacial rivers such as Jökulsá á Dal (Isl9) and the spring-fed river Ytri-Rangá (Isl16) draining catchments at higher

elevation and further away from the ocean than the small direct runoff rivers (fig. 1). For the glacial fed rivers precipitation inputs represent globally less than 15 percent of the TDS concentrations. For each element precipitation corrections are very variable from one river to the other. Among the major and trace elements for which precipitation correction has been applied,  $\text{SiO}_2$ , Ca and F (and to a lesser extent  $\text{HCO}_3$ ) show negligible or very low precipitation inputs. They are much more important for Cl (average 94%), Sr (average 40%), Na (average 33%), B (average 28%),  $\text{SO}_4$  (average 23%), K (average 20%), and Mg (average 16%).

Geothermal and magmatic corrections represent 3 to 22 percent of the initial TDS concentrations of six of the rivers. Highest corrections are for the Hverfisfljót river (Isl14) and lowest are for the Vestari Jökulsá river (Isl5). Corrections of geothermal and magmatic inputs are particularly important for species such as B,  $\text{SO}_4$ , Na, Cl and  $\text{SiO}_2$ . For  $\text{HCO}_3$ , Ca, Mg and Sr the corrections are overall negligible except when they concern magmatic degassing inputs (Vestari Jökulsá and Ytri-Rangá rivers, Isl5 and Isl16, fig. 3).

After these corrections of precipitation, geothermal and magmatic inputs (table 5), the chemical compositions of the river waters appear more homogeneous and their variations smaller. Ytri-Rangá river (Isl16) remains very much more concentrated than the others for many elements, and the five other rivers for which we made geothermal input corrections also remain among the most enriched in many dissolved species.

In the following, we consider that the remaining concentrations in the river waters, after the subtraction of the precipitation and geothermal/magmatic inputs, all arise from low-temperature volcanic rock weathering within the drainage basins. The total dissolved solid concentrations then calculated ( $\text{TDS}_{\text{bas}}$  of table 4) will be used later to determine the chemical denudation rates for each river basin.

#### RIVER SUSPENDED SEDIMENTS AND SANDS

The chemical composition of river suspended material is given in table 2. Chemical compositions of the river suspended sediments and sands are likely to resemble a mixing of all the chemical compositions of the rocks of their drainage basin, as they represent the weathering material of the whole drainage basin. In order to understand and describe the chemical compositions of these sediment samples, it is thus necessary to compare them to the chemical compositions of the volcanic rocks of Iceland.

The paper of Hardarson and others (1997) on the geochemistry of the magmatic processes in Iceland presents average chemical compositions of basalts for the Tertiary, Pliocene-Pleistocene, and neovolcanic areas. A simple comparison of the chemical compositions of our sediment and sand samples to these data, in terms of concentrations of the major and trace elements, showed us that the average basaltic rock chemical compositions of Hardarson and others (1997) and their classification of the basaltic rocks according to five geological areas were not sufficient for a good geochemical description of our samples. A more precise distinction among the different types of volcanic rocks in Iceland is needed.

#### *The Volcanic Rocks of Iceland*

On the geological map of Iceland (Jóhannesson and Saemundsson, 1989), rocks are classified according to their age (older than 3.1 my, between 0.7 and 3.1 my, younger than 0.7 my, and younger than 10000 y) and their  $\text{SiO}_2$  content. It appears that basic and intermediate rocks are dominant (80–85%), the remaining rocks being sediments (about 10%) and acidic rocks. Among the abundant literature on geochemical studies of Icelandic volcanic rocks, we have compiled the geochemical data (major elements, trace elements, and rare-earth elements) of Bailey and Noe-Nygaard (1976), Schilling, and others (1978), Sigurdsson and others (1978), Wood (1978), Wood and

TABLE 5

*Chemical compositions of the 3 rock end-members chosen to describe the Icelandic volcanic rocks (in % for the major elements and in ppm -mg/kg- for the trace elements)*

FM (%)	High-Mg basalts <60	Tholeiites 70-80	Rhyolites >90
SiO <sub>2</sub>	47.81 ± 0.94	49.46 ± 2.06	71.88 ± 1.56
TiO <sub>2</sub>	1.24 ± 0.41	3.16 ± 0.76	0.26 ± 0.06
Al <sub>2</sub> O <sub>3</sub>	15.06 ± 0.75	13.21 ± 0.63	13.89 ± 1.10
Fe <sub>2</sub> O <sub>3</sub>	4.87 ± 4.33	3.16 ± 1.76	1.02 ± 0.28
FeO	8.85 ± 1.07	11.62 ± 1.91	1.90 ± 0.36
MnO	0.18 ± 0.02	0.25 ± 0.03	0.09 ± 0.02
CaO	12.26 ± 0.86	9.42 ± 1.76	0.84 ± 0.34
MgO	9.87 ± 1.82	5.21 ± 0.86	0.19 ± 0.11
Na <sub>2</sub> O	1.87 ± 0.25	2.86 ± 0.35	5.30 ± 0.42
K <sub>2</sub> O	0.12 ± 0.08	0.61 ± 0.31	4.12 ± 0.35
P <sub>2</sub> O <sub>5</sub>	0.11 ± 0.05	0.39 ± 0.14	0.02 ± 0.01
Sr	153 ± 59	254 ± 72	59 ± 35
Rb	2.6 ± 1.7	11.6 ± 8.0	107.9 ± 14.8
Ba	43 ± 26	183 ± 91	434 ± 161
Sc	40.3 ± 4.7	40.4 ± 7.6	1.9 ± 1.0
Co	54 ± 7	49 ± 8	»
Cr	413 ± 185	70 ± 40	»
Cu	124 ± 16	162 ± 96	12 ± 3
Ni	179 ± 90	37 ± 22	»
Zn	77 ± 13	129 ± 17	152 ± 57
Nb	6.5 ± 3.6	26.0 ± 11.3	126.2 ± 35.5
Ta	0.64 ± 0.29	1.94 ± 0.93	8.94 ± 2.44
Y	22 ± 6	46 ± 15	100 ± 28
La	4.2 ± 2.5	20.4 ± 9.6	102.4 ± 21.0
Ce	11 ± 6	51 ± 18	202 ± 40
Nd	8.4 ± 4.0	35.8 ± 10.3	88.8 ± 14.3
Sm	2.58 ± 1.06	9.41 ± 2.11	17.89 ± 3.39
Eu	0.96 ± 0.34	2.73 ± 0.82	2.23 ± 0.79
Gd	3.28 ± 0.77	8.40 ± 2.23	18.20 ± 3.11
Tb	0.56 ± 0.16	1.40 ± 0.47	3.03 ± 0.84
Tm	0.41 ± 0.11	0.71 ± 0.26	1.38 ± 0.28
Yb	2.28 ± 1.18	4.43 ± 1.13	8.85 ± 1.89
Lu	0.38 ± 0.30	0.64 ± 0.19	1.32 ± 0.28
Th	0.49 ± 0.35	2.06 ± 1.28	17.76 ± 3.80

Data are gathered from Bailey and Noe-Nygaard (1976), Schilling and others (1978), Sigurdsson and others (1978), Wood (1978), Wood and others (1979), Macdonald and others (1990), and Nicholson and Latin (1992).

others (1979), Macdonald and others (1990), and Nicholson and Latin (1992), gathering studies on both recent and old volcanic areas around Iceland. Petrologic studies reveal the presence of continuous magmatic series, from high-Mg basalts to

tholeiites and rhyolites. Thus, the chemical composition of Icelandic rocks shows a wide variability, which appears to be determined by the compatibility of the elements during magmatic differentiation and by the percentage of mantle melt during crustal melting.

In order to describe more easily the behavior of the different elements during these processes and to compare their abundances in the different types of Icelandic volcanic rocks, we use the FM differentiation index, as used by Wood (1978), which is based on the abundance of  $\text{FeO}_T$  (total Fe expressed as FeO), MnO, and MgO:

$$FM = \frac{\text{FeO}_T + \text{MnO}}{\text{FeO}_T + \text{MnO} + \text{MgO}} \times 100 \quad (3)$$

During differentiation processes, the concentration of compatible elements in the extracted rocks decreases whereas that of incompatible elements increases. Concentration of MgO thus decreases with increasing FM value (fig. 4A). According to the classification given by Wood (1978), high-Mg basalts have FM lower than 65 percent, low-magnesia basalts and ferro-basalts (also classified as tholeiites by Carmichael, 1964) have FM between 66 and 77 percent, basaltic andesites and icelandites have FM between 78 and 92 percent, and rhyolites have FM higher than 92 percent (with  $\text{SiO}_2$  higher than 68%). Figure 4 represents elemental concentration versus FM for some characteristic elements, depicting their behavior during the differentiation processes. All rare earth elements, except Eu, behave like Nd, regularly increasing with increasing FM (fig. 4B); so does yttrium. The Eu concentration increases from 0.5 to 5 ppm for a FM value reaching 85 percent, and then decreases to 2 ppm (fig. 4C) for higher FM. This Eu anomaly in the rhyolites is due to the absence of plagioclase, Eu being preferentially present in this mineral (Eu<sup>2+</sup> substitutes for Ca<sup>2+</sup>). The transitional trace metals (Cr, Co, Cu, Ni) are compatible and their concentrations decrease during differentiation (fig. 4D), they are present in negligible amounts in rhyolites. Na, K and Rb are incompatible (fig. 4E), their concentrations are very much higher in rhyolites, and the increase for FM > 85 percent is stronger in the case of K and Rb than for Na. Calcium and scandium follow the behavior of magnesium (fig. 4A). Strontium behaves more like europium, being also easily incorporated in plagioclases; its concentration increases for FM < 85 percent and is very low in rhyolites (fig. 4F).

Given the behavior of the different compatible and incompatible elements, we can consider that there is continuity in the magmatic series for a differentiation FM index up to 85 percent and then another trend towards the rhyolites. Thus, we have chosen to represent the variability of the chemical composition of the volcanic rocks of Iceland by defining three end-members, which will enable us also to compare and understand the chemical compositions of our sand and suspended sediment samples. These end-members are defined according to the FM parameter: the first corresponds to the high-Mg basalts, with FM between 40 and 60 percent; the second represents tholeiites (a little more differentiated than those of Wood, 1978) with FM values between 70 and 80 percent; and the third end-member has a rhyolitic composition with FM higher than 90 percent. The average chemical composition of each end-member ( $\pm$  the standard deviation) is given in table 5. These mean concentrations are calculated from the compilation of the geochemical data of Bailey and Noe-Nygaard (1976), Schilling and others (1978), Sigurdsson and others (1978), Wood (1978), Wood and others (1979), Macdonald and others (1990), and Nicholson and Latin (1992).

#### *REE and Extended REE Patterns of the Suspended Sediments and Sands*

As rare earth elements (except Eu) have a more constant behavior, both during differentiation (incompatibility) and alteration (low solubility) processes, their abun-

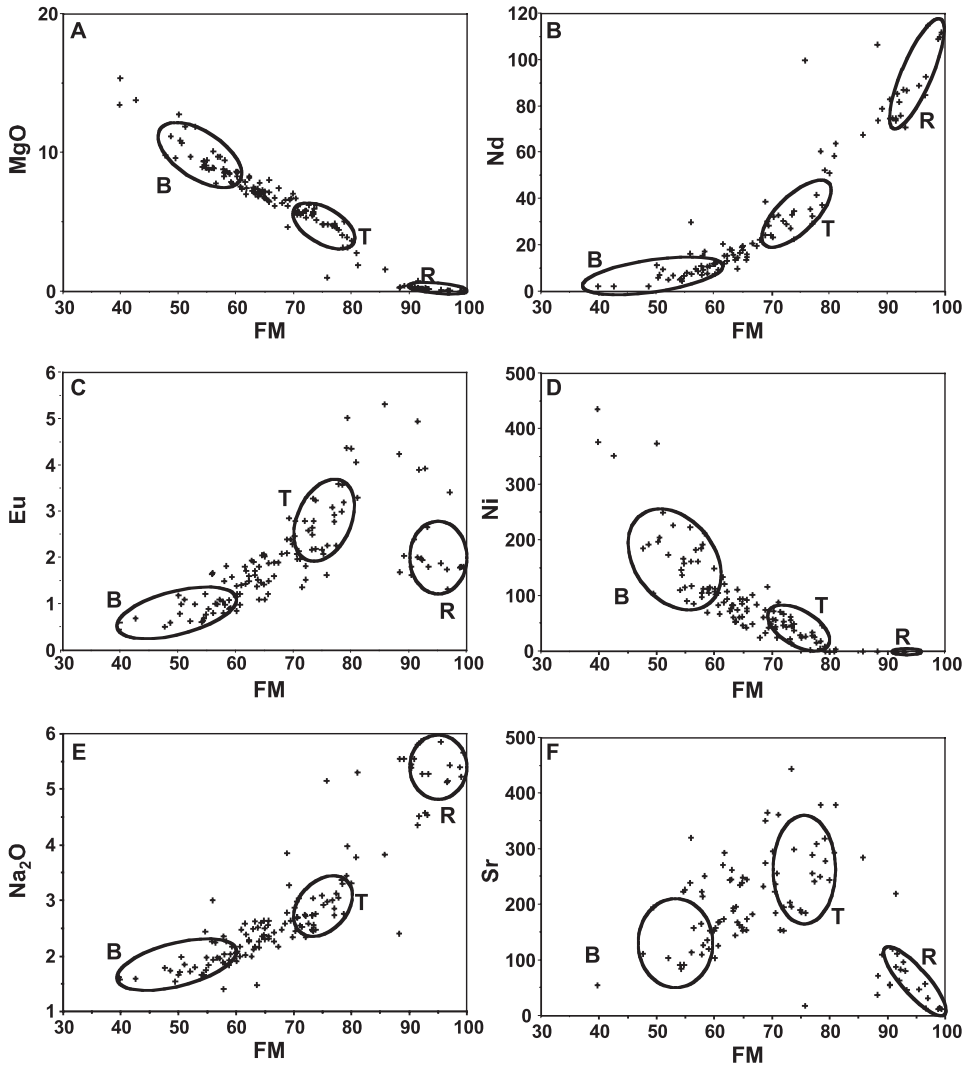


Fig. 4. Correlation diagrams between element concentrations (MgO and Na<sub>2</sub>O in % and others in ppm) and differentiation rating FM (see text) of many Icelandic rocks (data from Bailey and Noe-Nygaard (1976); Schilling and others (1978); Sigurdsson and others (1978); Wood (1978); Wood and others (1979); Macdonald and others (1990); Nicholson and Latin (1992)). These correlations show the characteristic behavior of these elements during magmatic differentiation. High-Mg basalts (B: FM 40 to 60%), tholeiites (T: FM 70 to 80 %) and rhyolites (R: FM >90%) and their corresponding ellipsoids represent the data areas chosen for the definition of these three rock end-members.

dances in the river sand and suspended load samples can be compared with those in the three Icelandic rock end-members previously defined, in order to estimate the average composition of the rocks before weathering. Figure 5 represents the rare earth element patterns, normalized to the primitive mantle (Hofmann, 1988), for sand and suspended load samples and for the three types of rocks (high-Mg basalts, tholeiites, rhyolites). Even if the logarithmic scale smoothes down the potential anomalies, it is obvious that all the sands have very similar patterns, which are intermediate between those of the high-Mg basalts and tholeiites. The rhyolitic pattern is characterized by a

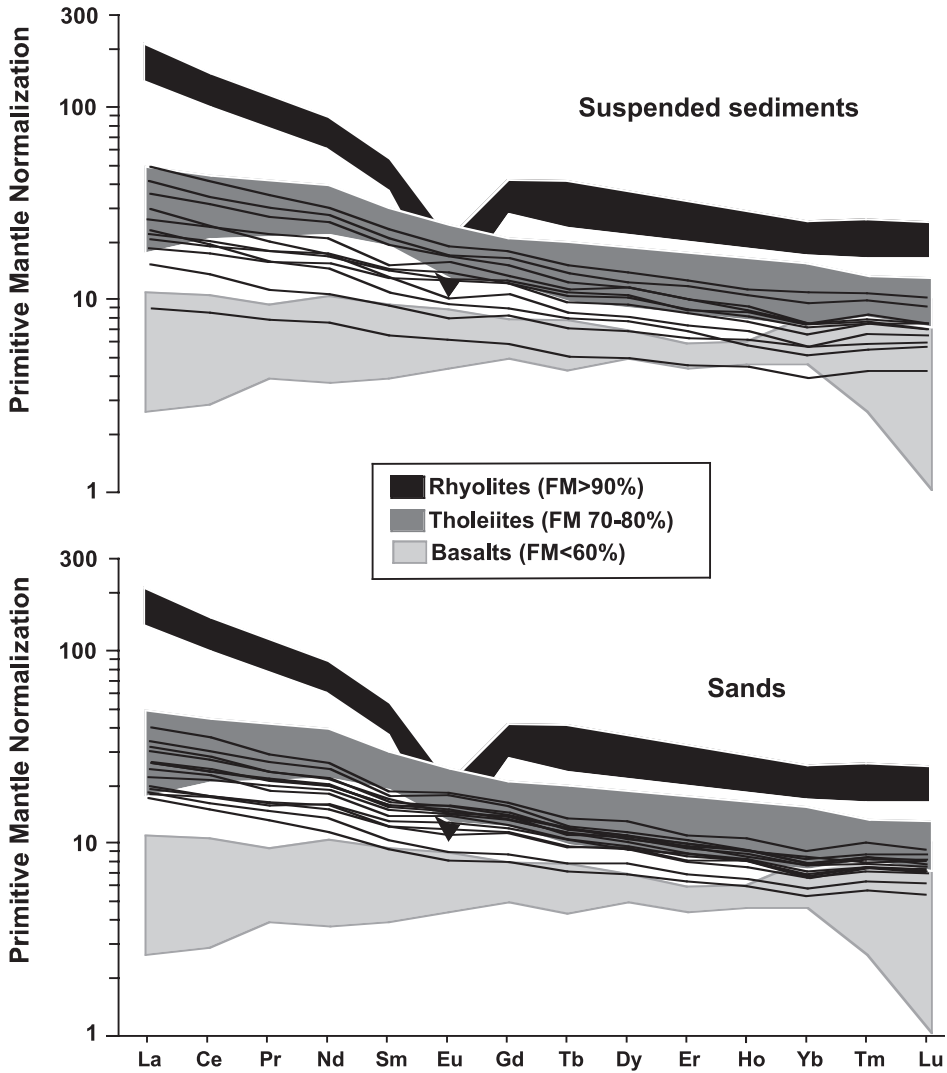


Fig. 5. Rare Earth Elements patterns for the riverine suspended load and sand samples and for the volcanic rocks of Iceland (data sources as in fig. 3). Concentrations are normalized to those of the Primitive mantle (Hofmann, 1988). Volcanic rocks are classified according to their differentiation rating.

significant europium negative anomaly, which is not observed in the sand patterns. Nevertheless, we cannot, on the basis of this simple criterion, exclude that a small quantity of rhyolite-like material may be present in the sands. The slope of the sand patterns more closely resembles that of the tholeiitic pattern than that of the Mg-basalts. For the suspended load samples, the REE abundances are a little more dispersed than the sands, with both lower and higher concentrations than the sands. Such a wider dispersion for the suspended loads could be explained by a dilution effect due to the presence of organic matter within the suspended loads (for example, small amounts of vegetation). However, this dilution effect could also apply for the sand samples, concentrations in the sediments being then either lower or higher than those



in the sands. The concentrations of the non-mobile elements (such as the REE and Th) in the alteration products should be higher than in the initially unaltered rock (or mixing of rocks), because of the partial removal of the most mobile elements (mainly alkaline and alkaline-earth elements and silica) during the weathering. Such reasoning does not take into account the eventual redeposition of silica from over-saturated river waters as was observed in the sands from the Congo and Amazon Rivers (Gaillardet and others, 1995 and 1997; and Dupré and others, 1996) and possible dilution by organic matter. In spite of the dispersion in the REE concentrations of the suspended loads, their patterns still are intermediate between the Mg-basaltic and tholeiitic trends. Here again, as no significant Eu negative anomaly can be seen, the contribution of a rhyolite type end-member is small but cannot be dismissed by these patterns.

Figure 6 shows the extended REE patterns for the suspended loads, the sands, and the three volcanic rocks end-members, these patterns take now into consideration the whole set of elements analyzed for (REE plus alkalines and alkaline-earths, Pb, Th, U, Ta, Y, Cu, Sc, Co, Cr, Ni). In this figure, the concentrations are normalized to primitive mantle (Hofmann, 1988) and the order of the elements is defined by that of the decreasing pattern of the average chemical composition of all Icelandic volcanic rocks compiled. In figure 6, the three types of Icelandic volcanic rocks previously defined have very different patterns. The rhyolite pattern is globally depleted in the most compatible elements (Cu to Ni) and enriched in the most incompatible elements (Rb to Nd) compared to the patterns for basalt and tholeiite, and it has many irregularities: a large depletion in Sr, and smaller depletions in Pb, Ba, Na and Eu. The tholeiite pattern is also slightly depleted in compatible elements and enriched in incompatible elements compared to the high-Mg basalts and presents also irregularities: small depletions in Sr and Na. Sand and suspended load samples have extended REE patterns that are overall intermediate between those of the high-Mg basalts and tholeiites. As for the REE patterns of figure 5, the extended REE patterns of the suspended loads have a more pronounced variability than the sand patterns. Both series of patterns present depletions in Sr and Na; they are larger for the suspended loads than for the sands. Some of the suspended load patterns show enrichments in metallic elements such as Pb, Ta, Nb, and Cu. Some of the sand patterns also show these enrichments in metallic elements but these are smaller. The suspended sediments are more finely grained than the sands. They have encountered more extensive mechanical weathering and probably more chemical weathering since the reactive surface area for water-rock interaction (per unit mass of rock) is much greater for the suspended sediments.

#### *Differences Between Suspended Sediment and Sand Chemical Compositions*

The chemical compositions of the suspended sediments normalized to those of the sands in each river are shown in figure 7. The order of the elements is the same as in figure 6. Excluding the Cu-anomaly for the Hvítá-W river (Isl1), chemical compositions of the suspended sediments and of the sands are very similar, their concentration ratios are between 0.3 and 2, and are very close to 1 for most of the elements and rivers. The patterns of sand normalized sediments for the Hvítá-W, Blanda, Jökulsá í Fljótssdal, and Hvítá-S rivers (Isl1, Isl3, Isl10 and Isl19) are the most irregular but show many similarities. They all present a globally decreasing pattern, suspended sediment over sand concentration ratios decreasing from the most incompatible elements (U, Th. . .) towards the compatible elements (Tm, Lu. . .). All these patterns present depletions in elements such as Rb, Ba, K, Sr, Na, Ca and Mg, and sometimes enrichments in metallic elements. These common trends could be explained in many ways. Depletions in the suspended sediments of the elements which are the most soluble during the weathering processes may reflect that sands are globally less weathered than suspended sediments, due to differences in grain sizes (reactive surface area available for

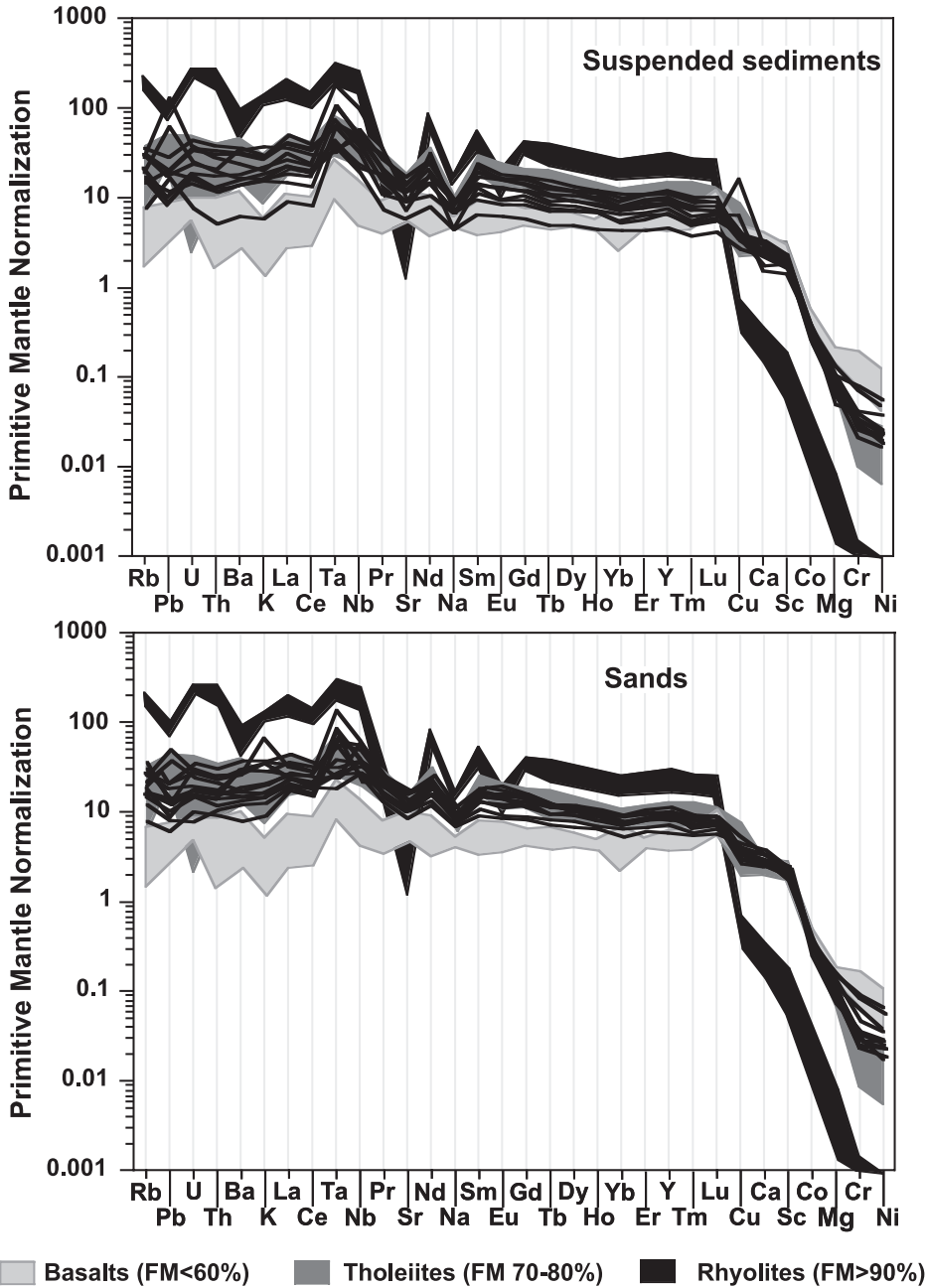


Fig. 6. Extended REE patterns for the riverine suspended load and sand samples and for the volcanic rocks of Iceland (ref. as in fig. 3). Concentrations are normalized to those of the Primitive mantle (Hofmann, 1988). Volcanic rocks are classified according to their differentiation index. The order of the elements is chosen in order to have a decreasing pattern for the average chemical composition of all the considered volcanic rocks (data sources as in fig. 3).

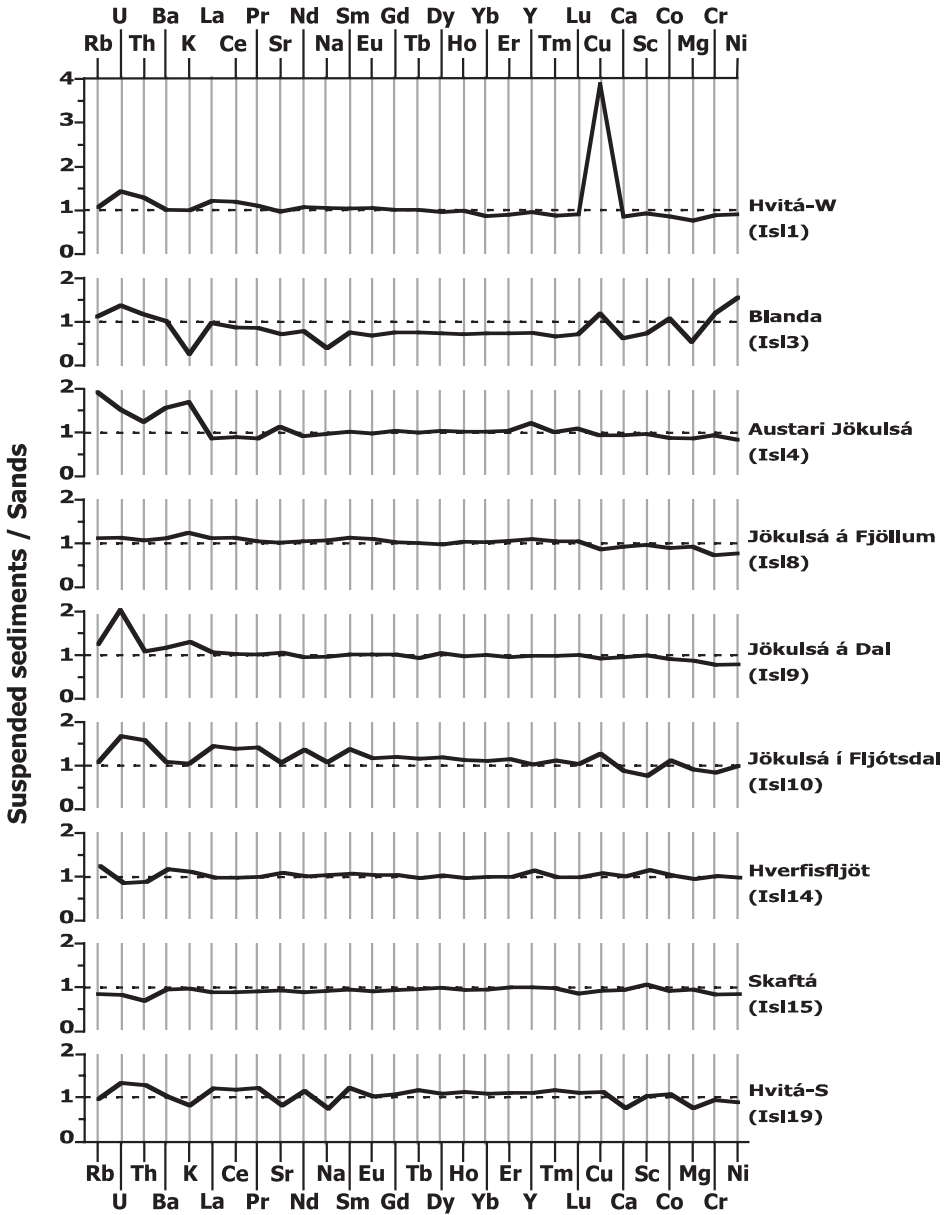


Fig. 7. Extended REE patterns of suspended sediments normalized to their corresponding sands. The order of the elements is the same as in figure 5.

water-rock interaction), but also in mineralogy (both for the less-weathered primary minerals and for the neo-formed secondary minerals). The globally decreasing trend of the patterns may express that sands and suspended sediments, even when coming from the same drainage basin, represent different proportions of the various kinds of rocks of this drainage basin. Reasons for such differences may be again the size or mineralogical fractionation between suspended sediments and sands during the weathering and trans-

port processes, but other causes such as the mobilization of fine sediments by the winds could be involved. Together with the globally decreasing trends, the strong depletions in Ba and Sr relative to Na and K for the Jökulsá í Fljótsdal and Hvitá-S rivers (Isl10 and Isl19) could reflect a slightly more important proportion of differentiated rocks in the suspended sediments than in the sands. The metallic element enrichments of the suspended sediments compared to sands may be due to the much larger specific surface areas of the suspended sediments resulting in more metal adsorption when normalized to the rock mass. These metals could have either an atmospheric or volcanic source. More studies would be needed to better constrain the behavior of these elements in the Icelandic rivers.

In the following, our discussion will focus more on the suspended sediments than on the sands. By assimilating the chemical composition of the sands to those of the sediments, it is assumed that there are insignificant differences between the sediments and the sands, and that the suspended sediments already sample the sandy phase, because of the turbulent flow of the Icelandic rivers.

#### *Local Basalt Chemical Composition for Each Drainage Basin*

In order to quantify the weathering of the volcanic rocks, looking at the depletions of the most soluble elements (mainly alkalines, alkaline-earths, and silica) in the river suspended sediments, the mean chemical composition of the rocks of the drainage basins, before weathering, has to be known as precisely as possible. The most insoluble elements, such as REE and Th, which are not removed during weathering, can be used to reconstruct the chemical composition of the initially unaltered rocks of the drainage basins. This reconstruction is performed in the same way as for the study of riverine erosion in Sao Miguel, Azores (Louvat and Allègre, 1998). Because the suspended sediments of the rivers represent a mixture of all the rocks drained in the river basin, we consider a mixing between all the possible rocks encountered, which can be represented by a mixture of the three rock end-members previously defined: high-Mg basalts, intermediate rocks (tholeiites), and rhyolites (table 5).

For a given element (X) (insoluble or not) in a unit mass of pristine rock, the following mass balance between its concentrations in the local rock, high-Mg basalts, tholeiites and rhyolites can be written:

$$[X]_{local\ rock} = \alpha \times [X]_{basalts} + \beta \times [X]_{tholeiites} + (1 - \alpha - \beta) \times [X]_{rhyolites} \quad (4)$$

where  $\alpha$  and  $\beta$  are the mass fractions of, respectively, high-Mg basalts (end-member 1) and tholeiites (end-member 2) in the mixing.

The absolute concentrations of the most insoluble elements in the suspended loads may be lower than those of the initially unweathered local rocks because of a possible dilution by organic matter, of hydration or formation of secondary minerals. They may also be slightly higher because of the removal of the most soluble elements during weathering. Thus the concentration ratio of an “insoluble element” between the suspended load and the local rock (hereafter designed as  $R_{insol}$ ) may be different from 1. However, concentration ratio of two insoluble elements in the suspended loads is equal to the corresponding ratio in the local rocks before weathering. For all insoluble elements, we define a suspended load versus local rock ratio (the calculation is made with Ce, Gd, La, Y, Nd, Sm, Tb, Th and Sc):

$$R_{insol} = \frac{[X]_{suspended\ load}}{[X]_{local\ rock}} = \frac{[X]_{suspended\ load}}{\alpha \times [X]_{basalts} + \beta \times [X]_{tholeiites} + (1 - \alpha - \beta) \times [X]_{rhyolites}} \quad (5)$$

For the most soluble elements such as Na, Ca, Mg, Na, Sr, Rb and Ba, a depletion ratio  $R_{sol(Y)}^p$  can be defined. It is the ratio of the concentration of a soluble element in the suspended load,  $[Y]_{suspended\ load}$  to the concentration this element would have in the

suspended load if it were insoluble,  $[Y]_{suspended\ load}^{\circ}$ . In other words,  $[Y]_{suspended\ load}^{\circ}$  is equal to  $[X]_{suspended\ load}$  in equation 5, but for a soluble element.

$$R_{sol(Y)}^{\circ} = \frac{[Y]_{suspended\ load}}{[Y]_{suspended\ load}^{\circ}} = \frac{1}{R_{insol}} \times \frac{[Y]_{suspended\ load}}{\alpha \times [Y]_{basalts} + \beta \times [Y]_{tholeiites} + (1 - \alpha - \beta) \times [Y]_{rhyolites}} \quad (6)$$

With equations 5 and 6, for the most soluble and most insoluble elements, the proportions ( $\alpha$ ,  $\beta$  and  $1 - \alpha - \beta$ ) of each rock end-member (basalts, tholeiites, and rhyolites) in the local unweathered rock of each drainage basin, and the  $R_{insol}$  and  $R_{sol(Y)}^{\circ}$  ratios can be determined. As in the case of Réunion and Sao Miguel (Louvat and Allègre, 1997 and 1998), an inverse method is used. In its formalism (introduced in geochemistry by Minster and others, 1977), data and unknowns are all *a priori* more or less known parameters (with *a priori* errors). Given these parameters and their uncertainties, the idea is simply to find the best set of parameters (the *a posteriori* parameters), among these that verify the model equations. Technically, an optimization program is used to compute the *a posteriori* set of parameters by minimization of the distances between the *a priori* set of parameters and the solution, and by propagation of the errors (Allègre and others, 1983a and 1983b).

With the inverse resolution method, the definition of the *a priori* parameters and their errors is the determining step. For the suspended load concentrations, the *a priori* values are those measured and their *a priori* errors are taken as 10 percent of the values. For the three rock end-members (defined by the FM differentiation index), we use mean values and standard deviations previously defined (table 3). For  $\alpha$  and  $\beta$ , as the rhyolitic proportion in the mixing may always be lower than 20 percent (according to the geologic map), we chose an *a priori* value of  $0.45 \pm 0.45$  (thus  $1 - \alpha - \beta$  is  $0.1 \pm 0.1$ ). The insoluble suspended load/local rock ratio  $R_{insol}$  should be close to 1 ( $1.0 \pm 0.2$ ). The soluble element depletion ratios  $R_{sol(Y)}^{\circ}$  have then values between 0 and 1 ( $0.5 \pm 0.5$ ), but Na will be much more depleted than Ba for example, so this parameter needs adjustment for each element (typically  $0.9 \pm 0.1$  for Ba).

The *a posteriori* values of  $\alpha$ ,  $\beta$ , ( $1 - \alpha - \beta$ ),  $R_{insol}$ ,  $R_{sol(Y)}^{\circ}$  and the calculated chemical concentrations of the local rocks for each drainage basin are given in table 6.

The proportion of rhyolitic type rocks is lower than 5 percent in most of the drainage basins. It reaches 10 percent for the Thjórsá River and 17 percent for the Hvitá-S River (Isl19). These proportions are slightly higher than those from the geological map of Iceland. Part of the catchments are covered with glaciers, thus the composition of the rocks under the glaciers is unknown. The proportion of high-Mg basaltic rocks is dominant for the Hvitá-W, Austari Jökulsá and Skjálfandalfjót Rivers (Isl1, Isl4 and Isl7; fig. 1), whereas tholeiites are dominant for the Blanda, Jökulsá í Fljótsdal, Thjórsá and Hvitá-S Rivers (Isl3, Isl10, Isl17 and Isl19). For the other rivers, Jökulsá á Fjöllum, Jökulsá á Dal, Hverfisfljót and Skaftá Rivers (Isl8, Isl9, Isl14, and Isl15), high-Mg basalts and tholeiites occur in similar proportions.

#### STEADY STATE MODEL OF EROSION

##### *Determination of the Suspended Load Concentrations*

Erosion acts through two complementary processes. By the water-rock interaction of chemical erosion, the minerals and rocks incongruently dissolve, depleting the rocks of the most soluble elements. By the crushing action (enhanced by temperature differences and frost) and transportation of the mechanical erosion, fragments of rocks become increasingly more finely grained and are washed out of the drainage basin. Weathering, disorganizes the crystalline lattice, weakens the rocks and makes them more breakable, thus enhancing the mechanical erosion. In return, mechanical

TABLE 6  
*Results of the inverse resolution of the steady state model of erosion*

	Hvítá-W	Blanda	Aust. Jökulsá	Skjálfandafhljót	Jök. á Fjöllum	Jökulsá Dal	Jök. í Fjótisdal	Hverfisfljót	Skafhá	Thjórsá	Hvítá-S
	Isl1	Isl3	Isl4	Isl7	Isl8	Isl9	Isl10	Isl14	Isl15	Isl17	Isl19
Proportions of the three rock end-members in the local rock of each drainage basin											
(Mg-basalt) $\alpha$	0.60 $\pm$ 0.10	0.03 $\pm$ 0.05	0.72 $\pm$ 0.06	0.79 $\pm$ 0.08	0.51 $\pm$ 0.06	0.53 $\pm$ 0.10	0.04 $\pm$ 0.04	0.39 $\pm$ 0.07	0.41 $\pm$ 0.06	0.16 $\pm$ 0.08	0.07 $\pm$ 0.11
(Tholeiite) $\beta$	0.35 $\pm$ 0.12	0.92 $\pm$ 0.06	0.27 $\pm$ 0.06	0.21 $\pm$ 0.08	0.46 $\pm$ 0.07	0.45 $\pm$ 0.12	0.92 $\pm$ 0.06	0.57 $\pm$ 0.08	0.57 $\pm$ 0.07	0.75 $\pm$ 0.10	0.77 $\pm$ 0.14
(Rhyolite) $1-\alpha-\beta$	0.05 $\pm$ 0.03	0.06 $\pm$ 0.04	0.01 $\pm$ 0.01	0.01 $\pm$ 0.01	0.03 $\pm$ 0.02	0.02 $\pm$ 0.03	0.04 $\pm$ 0.04	0.05 $\pm$ 0.03	0.02 $\pm$ 0.02	0.10 $\pm$ 0.04	0.17 $\pm$ 0.06
Chemical composition of the local rock of each drainage basin											
Ba	113 $\pm$ 44	209 $\pm$ 37	86 $\pm$ 34	59 $\pm$ 29	93 $\pm$ 41	92 $\pm$ 40	197 $\pm$ 34	120 $\pm$ 41	90 $\pm$ 35	192 $\pm$ 47	248 $\pm$ 60
Ca	76488 $\pm$ 9473	56037 $\pm$ 7211	82313 $\pm$ 8877	81148 $\pm$ 8386	75932 $\pm$ 9711	79044 $\pm$ 9897	63896 $\pm$ 8145	73918 $\pm$ 9548	76205 $\pm$ 9787	65306 $\pm$ 8524	53660 $\pm$ 7881
K	5025 $\pm$ 1910	6649 $\pm$ 1606	4376 $\pm$ 1715	2587 $\pm$ 1582	4820 $\pm$ 1728	4735 $\pm$ 1770	9745 $\pm$ 1733	5888 $\pm$ 1705	4429 $\pm$ 1438	7828 $\pm$ 2008	9531 $\pm$ 2548
Mg	42761 $\pm$ 6778	25080 $\pm$ 3502	47652 $\pm$ 6442	40536 $\pm$ 5794	38004 $\pm$ 6583	40785 $\pm$ 6935	26841 $\pm$ 3790	36980 $\pm$ 6563	38576 $\pm$ 6781	32078 $\pm$ 5238	25322 $\pm$ 4519
Na	20908 $\pm$ 2592	27382 $\pm$ 2813	18325 $\pm$ 2323	18819 $\pm$ 2225	21136 $\pm$ 2656	19511 $\pm$ 2585	23624 $\pm$ 2590	21761 $\pm$ 2696	21259 $\pm$ 2651	24137 $\pm$ 2733	25312 $\pm$ 2860
Rb	12.1 $\pm$ 7.0	15.5 $\pm$ 5.4	9.1 $\pm$ 6.1	6.7 $\pm$ 5.9	9.5 $\pm$ 6.0	9.1 $\pm$ 6.3	18.9 $\pm$ 5.1	12.0 $\pm$ 5.8	8.4 $\pm$ 4.8	17.7 $\pm$ 7.1	23.2 $\pm$ 9.7
Sr	194 $\pm$ 57	250 $\pm$ 36	187 $\pm$ 49	172 $\pm$ 42	217 $\pm$ 59	225 $\pm$ 60	327 $\pm$ 45	232 $\pm$ 56	221 $\pm$ 56	263 $\pm$ 47	201 $\pm$ 41
Ce	35.0 $\pm$ 14.4	55.4 $\pm$ 11.7	23.9 $\pm$ 12.4	20.6 $\pm$ 11.8	32.4 $\pm$ 12.9	30.1 $\pm$ 12.7	52.8 $\pm$ 10.9	39.2 $\pm$ 12.6	33.3 $\pm$ 10.8	58.8 $\pm$ 15.1	75.3 $\pm$ 19.7
Gd	5.30 $\pm$ 1.55	7.94 $\pm$ 1.25	4.72 $\pm$ 1.45	4.66 $\pm$ 1.40	6.28 $\pm$ 1.50	6.56 $\pm$ 1.54	9.69 $\pm$ 4.40	7.50 $\pm$ 1.51	6.98 $\pm$ 1.41	8.79 $\pm$ 1.57	10.16 $\pm$ 1.88
La	16.1 $\pm$ 7.4	26.1 $\pm$ 5.8	10.2 $\pm$ 6.3	8.5 $\pm$ 5.9	13.6 $\pm$ 6.5	12.4 $\pm$ 6.5	8.1 $\pm$ 4.8	16.6 $\pm$ 6.3	13.9 $\pm$ 5.4	26.0 $\pm$ 7.5	33.7 $\pm$ 9.9
Y	30.2 $\pm$ 8.7	41.9 $\pm$ 7.3	29.1 $\pm$ 7.7	28.3 $\pm$ 7.2	35.6 $\pm$ 8.4	35.9 $\pm$ 8.2	41.7 $\pm$ 7.0	39.4 $\pm$ 8.3	38.2 $\pm$ 7.6	47.1 $\pm$ 9.5	56.3 $\pm$ 12.2
Nd	19.7 $\pm$ 7.4	30.0 $\pm$ 5.3	13.8 $\pm$ 6.7	13.9 $\pm$ 6.3	20.7 $\pm$ 6.9	19.6 $\pm$ 6.8	31.5 $\pm$ 5.3	25.7 $\pm$ 6.6	22.3 $\pm$ 6.1	34.0 $\pm$ 6.9	40.8 $\pm$ 8.2
Sm	4.88 $\pm$ 1.62	7.50 $\pm$ 1.21	4.05 $\pm$ 1.42	3.90 $\pm$ 1.32	5.69 $\pm$ 1.56	5.54 $\pm$ 1.57	7.90 $\pm$ 1.23	6.76 $\pm$ 1.54	6.13 $\pm$ 1.44	8.40 $\pm$ 1.56	10.09 $\pm$ 1.88
Th	1.84 $\pm$ 1.50	3.32 $\pm$ 1.00	1.03 $\pm$ 1.29	0.68 $\pm$ 1.20	1.04 $\pm$ 1.31	1.00 $\pm$ 1.16	1.78 $\pm$ 0.87	1.55 $\pm$ 1.07	1.07 $\pm$ 0.86	2.72 $\pm$ 1.35	3.44 $\pm$ 1.90
Sc	34.56 $\pm$ 5.96	30.98 $\pm$ 4.07	37.21 $\pm$ 5.66	37.51 $\pm$ 5.32	35.99 $\pm$ 6.07	39.13 $\pm$ 6.31	28.77 $\pm$ 3.99	35.60 $\pm$ 5.73	37.05 $\pm$ 6.02	28.76 $\pm$ 4.29	30.53 $\pm$ 4.38

$\alpha$ ,  $\beta$  and  $(1-\alpha-\beta)$  are the 3 rock end-members (basalts, tholeiites and few rhyolites) proportions in the local rock composition of each drainage basin; chemical composition of the local rock of each drainage basin (in ppm), used for the steady state model of erosion.

TABLE 6  
(continued)

	Hvítá-W	Blanda	Aust. Jökulsá	Skjálfandafjót	Jök. á Fjöllum	Jökulsá Dal	Jök i Fljótsdal	Hverfisfljót	Skaftá	Tíjörða	Hvítá-S
	Isl1	Isl3	Isl4	Isl7	Isl8	Isl9	Isl10	Isl14	Isl15	Isl17	Isl19
Ratios of suspended sediments vs local rock for insoluble and soluble elements											
R <sub>ins</sub>	0.899 ± 0.058	0.705 ± 0.055	0.932 ± 0.053	0.669 ± 0.046	1.006 ± 0.057	0.942 ± 0.055	0.964 ± 0.083	0.972 ± 0.049	0.921 ± 0.055	0.969 ± 0.055	0.886 ± 0.057
R <sup>o</sup> <sub>sol</sub> (Na)	0.807 ± 0.034	0.842 ± 0.048	0.885 ± 0.033	0.814 ± 0.043	0.866 ± 0.031	0.939 ± 0.015	0.891 ± 0.037	0.963 ± 0.015	0.921 ± 0.024	0.851 ± 0.036	0.741 ± 0.045
R <sup>o</sup> <sub>sol</sub> (Ca)	0.963 ± 0.008	0.924 ± 0.026	0.982 ± 0.006	0.972 ± 0.008	0.981 ± 0.005	0.977 ± 0.006	0.863 ± 0.048	0.986 ± 0.006	0.974 ± 0.008	0.960 ± 0.012	0.916 ± 0.019
R <sup>o</sup> <sub>sol</sub> (Sr)	0.994 ± 0.001	0.983 ± 0.006	0.998 ± 0.001	0.991 ± 0.002	0.996 ± 0.001	0.996 ± 0.001	0.980 ± 0.008	0.998 ± 0.001	0.990 ± 0.003	0.991 ± 0.003	0.984 ± 0.004
R <sup>o</sup> <sub>sol</sub> (Ba)	1.000 ± 0.000	0.998 ± 0.001	1.000 ± 0.000	1.000 ± 0.000	1.000 ± 0.000	1.000 ± 0.000	1.000 ± 0.000	1.000 ± 0.000	1.000 ± 0.000	1.000 ± 0.000	1.000 ± 0.000
R <sup>o</sup> <sub>sol</sub> (Rb)	0.971 ± 0.007	0.971 ± 0.010	0.985 ± 0.005	0.975 ± 0.007	0.993 ± 0.002	0.992 ± 0.002	0.988 ± 0.005	0.997 ± 0.001	0.993 ± 0.002	0.991 ± 0.003	0.981 ± 0.005
R <sup>o</sup> <sub>sol</sub> (K)	0.938 ± 0.014	0.914 ± 0.029	0.961 ± 0.013	0.913 ± 0.023	0.976 ± 0.007	0.974 ± 0.007	0.961 ± 0.015	0.993 ± 0.003	0.976 ± 0.008	0.971 ± 0.009	0.940 ± 0.014
R <sup>o</sup> <sub>sol</sub> (Mg)	0.984 ± 0.004	0.921 ± 0.026	0.994 ± 0.002	0.979 ± 0.006	0.985 ± 0.004	0.985 ± 0.004	0.921 ± 0.029	0.993 ± 0.003	0.984 ± 0.005	0.974 ± 0.008	0.946 ± 0.013
Results of the computation for the steady-state model of erosion											
I	0.19 ± 0.03	0.16 ± 0.05	0.12 ± 0.03	0.19 ± 0.04	0.13 ± 0.03	0.06 ± 0.02	0.11 ± 0.04	0.04 ± 0.02	0.08 ± 0.02	0.15 ± 0.04	0.26 ± 0.05
P (mg/l)	1190 ± 230	1200 ± 410	1760 ± 540	2410 ± 610	3220 ± 790	2150 ± 560	650 ± 240	4310 ± 1810	3070 ± 960	1490 ± 400	830 ± 180
TSS meas (mg/l)	90	270	700	275	2210	1560	710	6200	1200	140	100
Period	1965-95	1981-95	1974-95	1981-95	1962-2002	1963-2002	1966-1997	1985-95	1984-95	1962-66	1968-75
( <i>lab meas.</i> )	(124)	(80)	(26)	(67)	(377)	(326)	(305)	(143)	(109)	(23)	(79)

R<sub>ins</sub> and R<sup>o</sup><sub>sol</sub>(X) are suspended load vs local rock ratios for the soluble and insoluble elements; P is the calculated concentration of suspended material carried by the rivers (in mg/l); TSSmeas are discharge-weighted averages of the total suspended sediment concentration measured over many years by the Hydrologic Survey of the National Energy Authority of Iceland (references in text).

erosion, by producing finer -but also fresher- material, increases the reactive surface areas in contact with the water, and thus the chemical weathering. This mutual interaction between chemical and mechanical reactions is the key of erosion processes. The resulting erosion products are transported by the river waters, in the form of dissolved and suspended material.

The steady state model of erosion assumes that there is a quantitative equilibrium between the chemical and mechanical erosions at the scale of a drainage basin. All the most soluble elements, which have left the rocks and minerals during the chemical weathering, end up in the dissolved species of the river waters. The crushed and altered rocks, depleted in these soluble elements, will leave the drainage basin as suspended material. There may be a delay between the removal of the dissolved load and that of the suspended load, but on a sufficiently long period of time (typically an average annual hydrologic cycle, but maybe more), a quantitative balance is achieved.

The steady state between chemical and mechanical erosion has been debated by several authors over the three last decades (for example Trimble, 1977; Martin and Meybeck, 1979; Murnane and Stallard, 1990; Stallard, 1995). Following Gaillardet and others (1995 and 1997) and Louvat and Allègre (1997 and 1998), the present study proposes a conservative mass budget between the initially unweathered rocks of the drainage basin and the resulting weathering products (dissolved load, suspended load and sands). This mass budget, considers that a given mass of fresh rock undergoes, during a sufficiently long time, the combined effects of mechanical and chemical erosions, which results in the production of dissolved material and residual altered material (suspended loads and sands) with a conservation of the initial mass. Knowing the mass of water that has been in contact with the fresh rock (namely the river discharge), the soluble element concentrations of the dissolved phase (corrected from the precipitation and geothermal spring inputs), and their depletions in the suspended phase (the weathered solid residue), it is possible to recalculate the mass of suspended matter that is necessary to counterbalance the dissolved load mass of a river water. Furthermore, by summing these two masses, the mass of rock that has been weathered can also be determined, and therefore the total erosion rates.

As the concentrations of suspended material are highly variable during an annual hydrologic cycle, mostly depending on episodic events like major floods or soil movements, field-measurements are hardly likely to give a reliable average (for example Lawler, 1991; Gislason and others, 2006). Dissolved solid concentrations generally vary to a lesser extent: in Iceland, suspended material concentrations vary by up to four or five orders of magnitude whereas dissolved solid concentration vary by one to two orders of magnitude (for example Pálsson and Vigfusson, 1996a; Gislason and others, 2006; fig. 2). Thus the steady-state model of erosion may be a useful way to determine average suspended material concentrations, representative of the erosion processes over the whole hydrologic cycle of the rivers, in particular for hydrologic systems with highly variable regimes.

In Iceland, the river discharges and suspended and dissolved load concentrations are regularly measured (and since 1964 for some of the rivers) by the Hydrology Division of the National Energy Authority (Pálsson and Vigfusson, 1996a, 1996b, 1998 and 1999; Gudmundsson, 1993; Gudmundsson and Jónsson, 1994; Tómasson and others, 1996; Gudmundsdóttir and Jónsson, 1997). Using these studies we are able to test the steady state model of erosion, comparing the measured and calculated fluxes of the transported suspended solids (and assessing the limits of both methods of determination).

#### *Calculation of the Suspended Sediment Loads*

Detailed derivation and discussion of the steady-state mass budget can be found in Louvat and Allègre (1997 and 1998). The sands in the steady-state model of erosion



can be neglected since their soluble element depletions are comparable to those of the suspended sediments. This simplification in the model considers that all solid weathering material is transported under a suspended sediment form and implies that the determined suspended sediment concentrations are somehow low values, since the sands are similarly or less weathered than suspended sediments.

For the suspended load concentration calculations, we can write the following mass-budget equations:

for any Y soluble element (Ca, Mg, Na, Sr, Rb and Ba):

$$\frac{[Y]_{local\ rock}}{[Na]_{local\ rock}} = \lambda \frac{[Y]_{dissolved\ load}}{[Na]_{dissolved\ load}} + (1 - \lambda) \frac{[Y]_{suspended\ load}}{[Na]_{suspended\ load}}$$

for any X insoluble element (Ce, Gd, La, Y, Nd, Sm, Tb, Th and Sc), the concentration in the dissolved load is negligible, thus:

$$\frac{[X]_{local\ rock}}{[Na]_{local\ rock}} = (1 - \lambda) \frac{[X]_{suspended\ load}}{[Na]_{suspended\ load}} \quad (8)$$

$\lambda$  represents the proportion of Na from the local (unweathered) rock, which ends up in the dissolved load after weathering.  $\lambda$  allows us to calculate  $P$ , the concentration of total suspended solids (TSS) in the river (in mass per volume of water):

$$P = \frac{(1 - \lambda) [Na]_{dissolved\ load}}{\lambda [Na]_{suspended\ load}} \quad (9)$$

As for the determination of the chemical composition of the local rocks, we obtain an over-determined system, the number of equations and parameters being much greater than the number of unknowns ( $\lambda$  and  $P$ ), and we resolve it by an inverse method. The *a priori* local rocks concentrations are those previously determined (local pristine basalt chemical composition) and are reported in table 6. The *a priori* suspended loads concentrations are the measured concentrations, and their *a priori* errors are taken as 10 percent of the values. For the dissolved load, the *a priori* values are the concentrations given in table 5 (converted to ppm); the *a priori* errors are also taken as 10 percent of the values.  $\lambda$  ranges between 0 and 1 ( $0.5 \pm 0.5$ ).

The *a posteriori* values of  $\lambda$  and calculated values of  $P$  are reported in table 6.

The calculated suspended load concentrations ( $P$ ) for the eleven sampled glacier fed rivers range between 650 and 4300 mg/l (tables 6 and 7 and figs. 8A and 8B). The highest concentrations of suspended sediments ( $> 3000$  mg/l) are for the Hverfisfljót, Jökulsá á Fjöllum, and Skaftá Rivers (Isl14, Isl8 and Isl15), all three turbulent glacier-fed rivers. The lowest concentrations ( $< 1000$  mg/l) are for the Hvitá-S and Jökulsá í Fljótssdal Rivers (Isl19 and Isl10). Hvitá-S drains a lake, which acts as a sediment trap. The calculated concentration of suspended solids increases from western Iceland, reaching a maximum in the glacier rivers in central Iceland, and then decreasing again towards East.

#### *Comparison of the Calculated and Measured Suspended Sediment Loads*

It is now interesting to compare our calculated sediment loads with those measured by the Division of Natural Resources of the National Energy Authority (Pálsson and Vigfusson, 1996a, 1996b, 1998 and 1999; Gudmundsson, 1993; Gudmundsson and Jónsson, 1994; Tómasson and others, 1996; Gudmundsdóttir and Jónsson, 1997). We have recalculated pluri-annual discharge weighted averages of riverine sediment loads from the Icelandic National Energy Authority database. These are given in table 6 (TSS<sub>meas</sub> in mg/l). These data suffer from a lack of dense measure-

TABLE 7  
*Hydrologic characteristics and erosion rates (chemical, mechanical and consumption of CO<sub>2</sub>) of the Icelandic rivers under study*

sample	river	area km <sup>2</sup>	period of measur.	average an. disch. km <sup>3</sup> /yr	runoff mm/yr	TSS mes mg/l	TSS calc. mg/l	TDS <sub>bas</sub> mg/l	chemical erosion t/km <sup>2</sup> /yr	mechanical erosion t/km <sup>2</sup> /yr	denud. rate mm/kyr	atm. CO <sub>2</sub> cons. 10 <sup>6</sup> mol/km <sup>2</sup> /yr	(Ca+Mg) 10 <sup>6</sup> mol/km <sup>2</sup> /yr	age 10 <sup>6</sup> y	glaciers % of area
ISL1	Hvíta-W	1658	1952 - 1997	2.64	1590	60	1190±230	22.0	35	1893±366	771	0.45	0.15	5.0	22
ISL2	Nordurá	507	1971 - 1994	0.73	1446			15.4	22			0.58	0.25	7.0	0
ISL3	Blanda	1730	1950 - 1997	1.36	784	350 *	1200±410	20.9	16	941±321	383	0.36	0.15	3.0	14
ISL4	Austari Jökulsá	1090	1973 - 1996	1.24	1134	350	1760±540	17.4	20	1996±612	806	0.60	0.19	1.5	10
ISL5	Vestari Jökulsá	846	1972 - 1997	0.67	797			30.0	24			0.40	0.15	1.5	11
ISL6	Friðská	1132	1976 - 1983	1.25	1103			25.2	28			0.47	0.18	6.0	0
ISL7	Skjálfandafjöt	3293	1950 - 1995	2.66	806	120	2410±610	26.5	21	1943±492	786	0.46	0.15	1.5	3
ISL8	Jökulsá á Fjöllum	5174	1971 - 1991	5.17	1000	1500	3220±790	28.9	29	3219±790	1299	0.59	0.16	0.2	28
ISL9	Jökulsá á Dal	3308	1964 - 1994	4.48	1354	1200	2150±560	15.8	21	2911±758	1173	0.67	0.30	3.0	43
ISL10	Jökulsá í Fljótsdal	542	1963 - 1994	0.90	1665	400	650±240	17.7	29	1082±400	445	0.61	0.33	3.0	27
ISL11	Fossá	113	1969 - 1996	0.26	2278			7.9	18			0.18	0.16	8.5	0
ISL12	Gerthellnaá	187	1971 - 1993	0.56	2973			13.7	41			0.48	0.32	7.0	5
ISL13	Djúpá	227	1969 - 1997	0.81	3582			16.8	60			0.48	0.20	1.5	56
ISL14	Hverfisfjöt	559	1982 - 1996	1.32	2364	1500	4310±1810	16.5	39	10190±4279	4091	1.96	0.93	0.5	27
ISL15	Skaftá	1344	1952 - 1997	3.56	2651	1000	3070±960	29.3	78	8138±2545	3286	0.78	0.37	1.0	34
ISL16	Ytri-Rangá	890	1961 - 1996	1.63	1832			60.8	111			2.12	0.67	0.5	0
ISL17	Thjórsá	7343	1948 - 1996	11.57	1576	± 300	1490±400	22.1	35	2348±630	953	0.80	0.29	1.0	14
ISL18	Ölfusá	5760	1951 - 1997	12.55	2179			23.8	52			1.16	0.38	0.5	11
ISL19	Hvíta-S	2409	1950 - 1996	3.43	1422	± 100	830±180	24.1	34	1180±256	486	0.96	0.33	0.5	25

TDS<sub>bas</sub> is the concentration of total dissolved solids arising from basalt weathering (without HCO<sub>3</sub><sup>-</sup>). TSS is the calculated concentration of suspended sediments (the errors come from the inverse resolution). (Ca+Mg) corresponds to the rate of CO<sub>2</sub> consumption, which will precipitate Ca- and Mg-carbonates in the ocean in the long term. "age" is the approximate age of the drainage basins estimated from tectonic and geologic maps (Johannesson and Saemundsson, 1998; Johannesson, 1998). \* before dam (hydropower plant was erected in 1989).

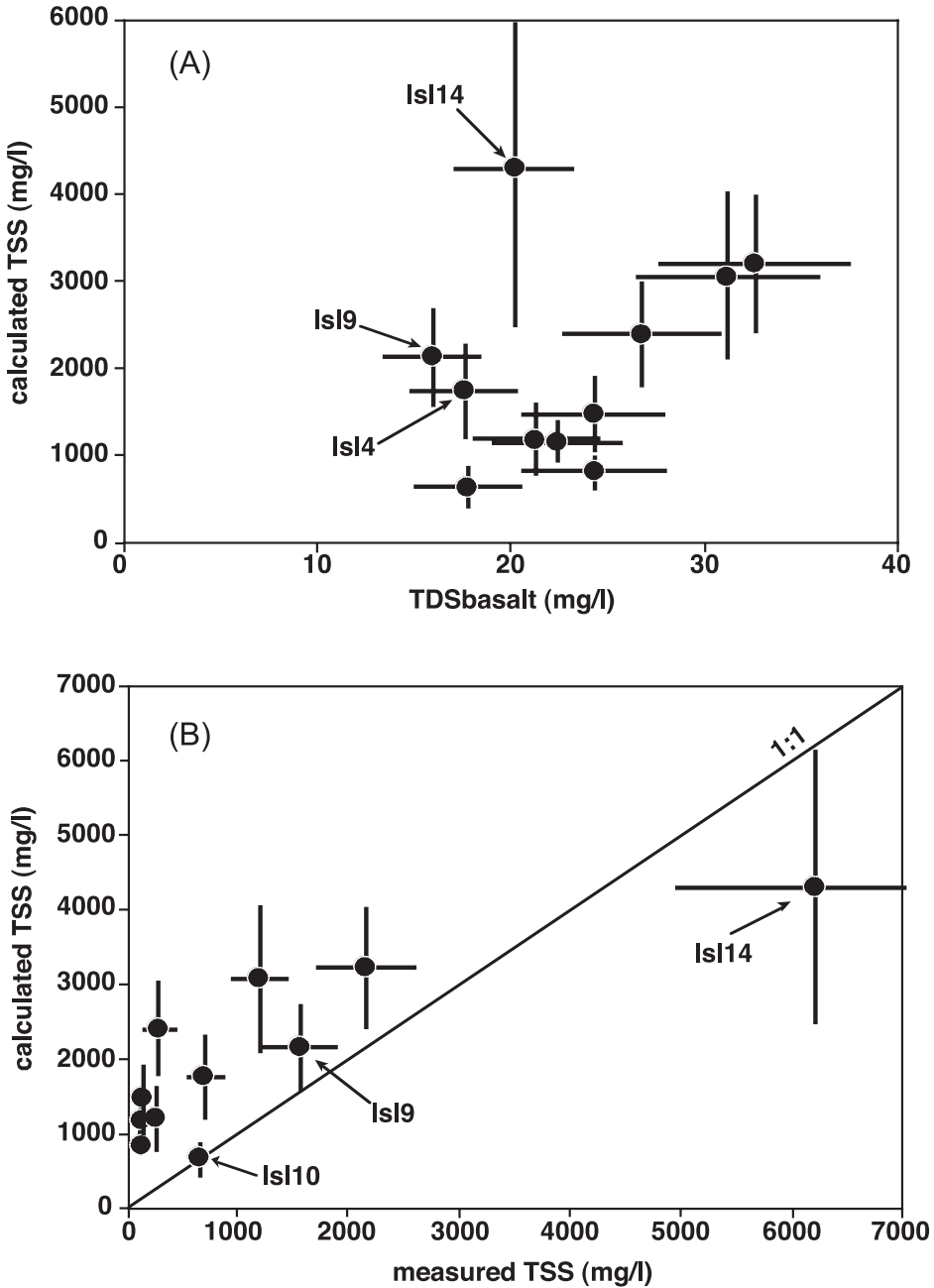


Fig. 8. Correlation diagrams between the calculated concentrations of suspended sediments and (A) the concentrations of total dissolved solids arising from basalt weathering, and (B) the measured concentrations of suspended sediments (Palsson and Vigfusson, 1996) (see table 6).

ments over the annual cycle of the river. Indeed, river suspended sediment loads vary over up to 4 orders of magnitude (for example from 1mg/l to 35000 mg/l for Hverfisfljót glacier river, Isl14) and the frequency of measurement greatly influence

the average determination. A good example of this difficulty and variability is for the Hverfisfljót river (Isl14) for which annual discharge weighted TSS averages are estimated to respectively 710, 650, 1000, 1600, 1200, 1300, 2400, 1200, 1000, 5100 and 16800 mg/l for years 1985 (10 data), 1986 (n=9), 1987 (n=10), 1988 (n=6), 1989 (n=7), 1990 (n=9), 1991 (n=17), 1992 (n=6), 1993 (n=6), 1994 during which this river was particularly well surveyed (n=52), and 1995 (n=12). The pluri-annual (1985–1995) average of 6200 mg/l we give for this river in table 6, is thus strongly influenced by the more frequent measurements of years 1994 and 1995. Other measurements show huge TSS concentration variations during the same day, discharge and TSS being higher at the end of the day, when more ice has melted. So correct measurements of TSS are only possible with continuous monitoring, which in turn is not possible on every river.

Calculated and measured sediment loads are compared in figure 8.

All suspended sediment concentrations calculated via the steady state model of erosion are higher than the measured averages concentrations (table 6), except for Hverfisfljót glacier fed river (Isl14). There is agreement between measured and calculated steady state sediment loads within the error intervals for Rivers Jökulsá á Dal (Isl9), Jökulsá í Fljótsdal (Isl10) and Hverfisfljót (Isl14). For many of the other rivers the calculated steady state sediment loads appear to be 1.5 to 10 times the measured loads (fig. 8 and table 6). Calculated sediment loads for the rivers Hvitá-W (Isl1), Skjálfafljót (Isl7) and Thjórsá (Isl17) are much higher than the measured ones. There is a strong groundwater component in these rivers, especially Hvitá-W (Isl1) and Skjálfafljót (Isl7) (Rist, 1990). There is also a significant spring water addition to the rivers Thjórsá (Isl17), Skaftá (Isl15), Hverfisfljót (Isl14) and Jökulsá á Fjöllum (Isl8) (Rist, 1990). Spring waters and groundwaters have higher dissolved solid concentrations than direct runoff river waters and they do not carry suspended solids. This additional TDS could lead to an overestimation of the steady state suspended solid concentrations. Man made dams and reservoirs in Rivers Blanda (Isl3) and Thjórsá (Isl17), and lake in Hvitá-S (Isl19) act as sedimentary traps.

Comparing the calculated and measured suspended sediment loads is not easy because both sets of data have been acquired by two very different methods, each with its good and bad sides. The direct measurement of riverine suspended sediment loads appears *a priori* more reliable than an indirect estimation but the non-linearity and temporal irregularities of the river suspended sediment loads render the direct measurement very difficult.

An ideal good direct measurement of the suspended sediment loads would require a continuous measurement, which is practically impossible for most rivers. Automated measurement methods are also difficult to put in place because of the spatial variation of the sediment concentration along a cross-section of a river. Thus, in most cases, and in particular in Iceland, suspended sediment loads are measured punctually by hydrologic surveyors. For an ideal river with a regular hydrologic cycle, punctual measurements would be sufficient to re-estimate the suspended sediment load carried by the rivers. But such rivers are scarce. For most rivers the maximum sediment transport occurs during short-lived flood events, which are easily missed by regular punctual measurements (for example, Lawler, 1991). The measurement accuracy depends upon its frequency compared to the frequency of the flood events, glacial surges *et cetera*. Statistically, if the measurement frequency is high enough, one must be able to re-evaluate a sediment load close to the real value, once having measurements from many cycles. If the sampling frequency is too low, then the sediment load estimation is inevitably lower than the true value. Thus, we can assert that the present estimations of the mean measured sediment loads for Icelandic rivers are too low.

The geochemical method for the indirect estimation of suspended sediment loads used in this paper asks additional questions. One is the validity of the steady state of erosion itself as it assumes that the dissolved and solid loads of the rivers are contemporary. This is probably not the case as the dissolved species arising from the rock chemical weathering are certainly more mobile and more quickly carried out by the river waters than are the solids remnants of the rock chemical weathering. Which time scale should then be considered for the steady state model of erosion? We think there is no general answer to that question. For each drainage basin with its particular rocks, climatic and geomorphologic conditions, the residence time of the dissolved and solid loads will be different. For the worldwide largest drainage basins, there are evidences that the sediment weathering degree is not compatible with the dissolved load derived from silicate rock weathering. The solid loads of these big rivers are much more weathered than what their dissolved load would allow to estimate through the steady state model of erosion, and reflect that at least part of these river sediments have undergone many weathering/sedimentation cycles (for example Gaillardet and others, 1999a). In the case of smaller drainage basins (for example on Réunion Island or in Azores, Louvat and Allègre, 1997 and 1998), the steep geomorphology and the torrential hydrologic regime imply short residence time of the sediments and no sedimentation processes. The steady state model of erosion may then be considered realistic for such small basins in a present-day time scale. In the case of Iceland, although the intermediate size of the basins and their morphology allow some sedimentation areas (braided rivers, lakes, dams), the highly contrasted hydrologic regime (long low-water levels in the autumn and winter times, repeated short-lived floods in late spring and summer) should be sufficient to flush out the sediments in a relatively short time. The only evidence for such a short residence time in our Icelandic geochemical data is that the suspended sediment loads are very poorly weathered compared to the pristine basaltic rocks. Another argument in favor of a present-day steady state of erosion in Iceland is that for all the previously studied big rivers for which there was obviously a discrepancy between the sediment weathering state and the dissolved loads, the calculated suspended loads were much lower than the measured ones (Gaillardet and others, 1999b). This is the opposite in Iceland.

Vigier and others (2006) have determined weathering timescales and mechanical erosion rates for some Icelandic rivers, using U series disequilibria. They conclude that weathering timescales are short in Iceland (3000 yr in average) and, comparing their results for mechanical erosion rates with the measured ones, deduce that the weathering operates in near steady-state conditions. The TSS they calculate for Hvitá-S and Jökulsá á Fjöllum with Th/U disequilibria, respectively 160 and 680 mg/l, are five times lower than our estimates with major and trace elements. Given the erosion timescales for these two rivers (2000 yr), this discrepancy may reflect an increased present-day erosion rate due to glacier melting. Globally the two methods of determination (U-series mass budgets in one hand and major and trace element mass budgets in the other hand) concern different time scales and processes. U-series disequilibria are tracing isotopic fractionation occurring as soon as the system is not closed anymore (through alpha recoil for example), but not necessarily in relation to the chemical weathering and water leaching. The correlation between ( $^{234}\text{U}/^{238}\text{U}$ ) activity ratios and mechanical erosion rates for Icelandic rivers shown by Vigier and others (2006) could illustrate this; the very high mechanical erosion rates due to glaciers are likely to increase the physical aperture of the isotopic systems but without real chemical weathering (very low chemical weathering rates). On the other hand we think that the mass-budgets on major and trace elements refer to partial dissolution of the rocks, only due to the chemical weathering processes and most likely occurring on shorter time scales, during the soil formation and maturation, but also during sediment transport.

A second question posed by this geochemical estimation is the use of a single sample. Assuming that this single sample gives global information about the sediment loads cycle does not imply that dissolved and suspended loads do not vary through time, but that their simultaneous variations annihilate each other through the mass balances of the steady-state model of erosion. As previously stated, the dissolved load concentrations of the rivers vary in a much lesser extent than the suspended load concentrations. Among the suspended load concentration variations, we may consider both the grain size and geochemical variations. The grain size of the transported sediments is very dependent upon the river discharge: for a stronger discharge and higher flow velocity, coarser sediments can be transported. However, how will the grain size vary with the discharge? No general relation has been depicted for these rivers at this stage. The chemical composition of the sediments is dependent upon their grain size; the smaller particles are more weathered than the bigger ones, just because of their larger water-rock exchange surface areas. The chemical composition of the sediments and their global weathering state is thus also variable through time. Sediments of Icelandic rivers show a globally low alteration state compared to the pristine basaltic rocks they stem from, and the large error bars for the local basalt composition used to calculate sediment loads via the steady state model of erosion probably cover the temporal geochemical variation range of the sediments. Calculated sediment loads are therefore also given with large error bars (fig. 8 and table 6). An investigation of the temporal variability of the sediment load geochemical, mineralogical and grain size compositions has been undertaken for some NE Icelandic rivers (Eiríksdóttir and others, 2008). In this study, rivers were sampled 6 to 10 times a year and the TSS concentrations are calculated through a steady-state model of erosion and compared to the measured ones.

In the steady state determination of the sediment loads we have neglected the sand contribution to solid material transport, considering that the entire solid load was under a suspended sediment form. As the sand grains, because of their larger size and thus smaller reactive surface, are potentially less weathered than are the suspended sediments, neglecting the sand amounts to potentially underestimate the river solid loads, our calculated TSS represent low values. However, we sampled the suspended sediments in the most turbulent parts of the river at each sampling spot so that our suspended sediment samples also integrate coarse material, similar to the river bottom or beach sands.

Independently of the inherent failures of each estimation method, some natural phenomena and man-made changes may induce discrepancies between calculated and measured sediment loads, as they modify the amount or the quality of the river sediments. Sedimentary traps such as lakes or dams will induce lower measured sediment loads. A number of hydroelectric power plants and reservoirs have been built in the Thjórsá River (Isl17) since the 1960's, and one tributary has recently been diverted to Hvítá-S River (Isl19). A power plant and several reservoirs were built in River Blanda (Isl3) in 1989. Wind erosion will either add or remove sediments from the catchments, thus modifying the effective sediment loads and eventually the river sediment chemical composition. Glacier surges provide large amounts of sediments, often with different mineralogical and grain size properties compared to the previous river sediments.

The steady state model of erosion is a useful tool for estimating river sediment loads and mechanical erosion rates in rivers with high temporal variability of the sediment discharge, which is hard to measure directly.

#### EROSION RATES AND CO<sub>2</sub> CONSUMPTION BY THE WEATHERING

From the dissolved load concentrations corrected for atmospheric, geothermal and magmatic inputs, from the calculated concentrations of suspended sediments

transported by the rivers, and from the bicarbonate concentrations of the river waters, we deduce respectively chemical erosion rates, mechanical erosion rates and rates of CO<sub>2</sub> consumption by the chemical weathering. Erosion rates are weighted by the river average annual discharge (Division of Natural Resources of the National Energy Authority of Iceland) and are normalized to the drainage basin surface area.

Drainage basin characteristics and erosion rates are given in table 7 and represented in figure 9.

#### *Low-temperature Chemical Erosion Rates*

The low-temperature chemical erosion rates for Icelandic rivers range between 16 and 111 t/km<sup>2</sup>/yr. The Ytri-Rangá river (Isl16) has the highest chemical erosion rate. Its TDS<sub>bas</sub> is also the highest, about twice the most elevated value for the other Icelandic rivers, even after the corrections for magmatic degassing inputs. This is due to the particular settings of this river in a very active volcanic area (Hekla volcano), rendering the water-rock interactions very much more efficient (young rocks, acidic waters). Excluding this highest value, chemical erosion rates of the Icelandic rivers under study are between 16 and 78 t/km<sup>2</sup>/yr. Such rates are high if we compare them to the world-wide average of 24 t/km<sup>2</sup>/yr (and the silicate rock weathering part accounts only for 26% of it, Gaillardet and others, 1999a), but they are about 2 times lower than those determined on Réunion island (60–170 t/km<sup>2</sup>/yr, Louvat and Allègre, 1997). They are in the same range of magnitude as those determined for Sao Miguel island (Azores) (25–50 t/km<sup>2</sup>/yr, Louvat and Allègre, 1998) or Deccan Traps (21–63 t/km<sup>2</sup>/yr, Dessert and others, 2001), and a little bit higher than for Kamchatka (1–40 t/km<sup>2</sup>/yr, Dessert and others, 2008). The rivers that have the highest rates (> 40 t/km<sup>2</sup>/yr) are all situated in the southern and southwestern part of Iceland (rivers Isl13, Isl14, Isl15, Isl16, Isl17, Isl18, and Isl19; table 7 and fig. 1). For the rivers of Southwest Iceland, we can compare these erosion rates to those determined by Gislason and others (1996). For the Nordurá, Thjórsá, Ölfusá and Hvítá-S rivers (Isl2, Isl17, Isl18 and Isl19) the chemical erosion rates of the present study are considerably lower than those determined by Gislason and others (1996). However, the average runoffs at the time of sampling used by these authors to calculate the chemical erosion rates are higher than the annual average runoffs used in the present study (Hydrology Department of the Icelandic National Energy Authority). The present study underestimates somewhat the annual average dissolved fluxes for the rivers that had much higher discharge, at the time of sampling, than the annual average (Thjórsá and Hvítá-S; tables 1 and 7). At higher discharge the dissolved concentrations are lower than the annual average concentrations (dilution effect). However, when the chemical erosion rates of Gislason and others (1996) are re-calculated with the present annual average runoffs, then both sets of chemical erosion rates become compatible.

The chemical erosion rates are globally correlated to runoff and to the age of the rocks (fig. 9) as noted by Gislason and others (1996). Where runoffs are higher, the chemical erosion rates are generally higher (exception must be made of the Ytri-Rangá river –Isl16–, which has a too high chemical erosion rate in this correlation). Chemical erosion rates tend also to be higher for young drainage basins than for old ones. Older rocks have less glassy basalt, which alters faster than crystalline basalts (Gislason and Eugster, 1987a; Stefánsson and Gislason, 2001; Wolff-Boenisch and others, 2006) and are already more weathered than younger ones.

We also report here the total (high plus low- temperature) chemical weathering rates calculated from rain input corrected TDS of table 4. They range from 16 to 130 t/km<sup>2</sup>/yr, with a discharge weighted average for Icelandic rivers of 45 t/km<sup>2</sup>/yr (was 40 t/km<sup>2</sup>/yr for low-temperature weathering only). This increase on geothermal and magmatic impacted rivers is 5 percent (Isl5) to 60 percent (Isl14), and demonstrates the potentially crucial impact of geothermal and magmatic

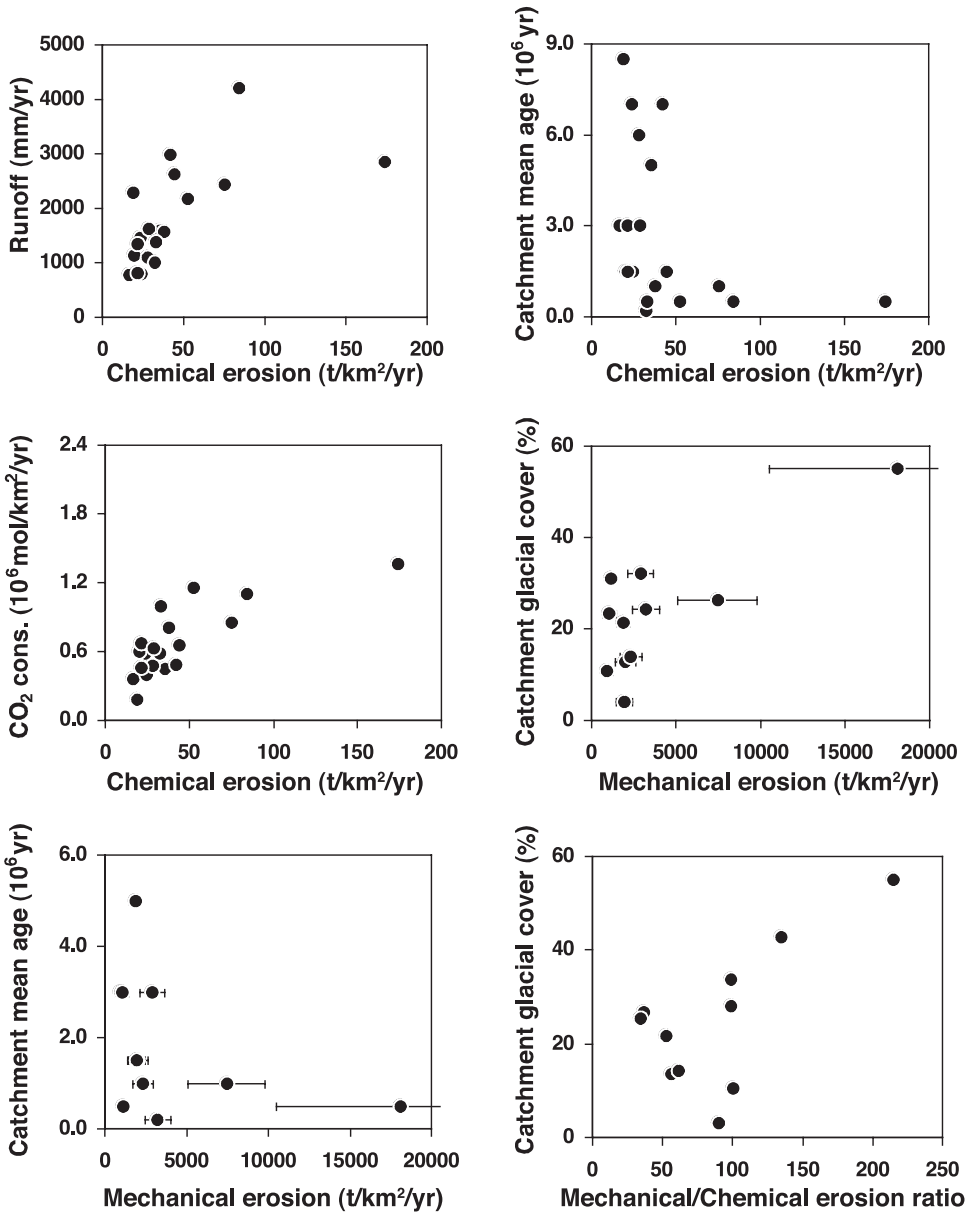


Fig. 9. Correlation diagrams between chemical and mechanical erosion rates, atmospheric CO<sub>2</sub> consumption by the weathering, and climatic and morphological parameters.

derived weathering on the dissolved material fluxes exported to the ocean (Rad and others, 2007).

#### Atmospheric CO<sub>2</sub> Consumption Rates

Rate of CO<sub>2</sub> consumption by the chemical weathering (calculated from corrected HCO<sub>3</sub> concentrations) varies between 0.18 and 2.12 10<sup>6</sup> mol/km<sup>2</sup>/yr, and shows a very good correlation with the chemical erosion rates (fig. 9), illustrating the role of CO<sub>2</sub> as



a driving parameter of chemical weathering. With an average of  $0.74 \cdot 10^6$  mol/km<sup>2</sup>/yr these rates of CO<sub>2</sub> consumption are globally higher than the world-wide average of  $0.3 \cdot 10^6$  mol/km<sup>2</sup>/yr defined by Berner and Berner (1996), among which 50 percent are due to silicate weathering (Gaillardet and others, 1999a). The Icelandic rates are much higher than the  $0.11 \cdot 10^6$  mol/km<sup>2</sup>/yr CO<sub>2</sub> consumption rates of the Central Siberian basalts under permafrost conditions (Pokrovsky and others, 2005), or than those of the Kamchatka Peninsula (average  $0.4 \cdot 10^6$  mol/km<sup>2</sup>/yr, Dessert and others, 2008), but considerably lower than the ones of the tropical Reunion volcanic island ( $1.3\text{--}4.4 \cdot 10^6$  mol/km<sup>2</sup>/yr, Louvat and Allègre, 1997) and similar to those for Deccan Traps ( $0.6\text{--}2.5 \cdot 10^6$  mol/km<sup>2</sup>/yr, Dessert and others, 2001). The highest rate in Iceland is again for the Ytri-Rangá river (Isl16). The rate of volcanic CO<sub>2</sub> degassing in Iceland has been estimated as 0.27 to  $0.49 \cdot 10^6$  mol/km<sup>2</sup>/yr (Gislason and others, 1996) and thus most of our CO<sub>2</sub> consumption rates are higher, except for the small Fossá river, Isl11,  $0.16 \cdot 10^6$  mol/km<sup>2</sup>/yr draining old rocks. However, the net consumption of CO<sub>2</sub> on a longer time scale is lower, as only the CO<sub>2</sub>, which precipitates Ca and Mg, carbonates in the ocean will actually be consumed. The long-term CO<sub>2</sub> consumption rate by chemical weathering is thus estimated from concentrations of Ca and Mg in the river waters (table 7). For most of the rivers, this rate ( $0.15$  to  $0.93 \cdot 10^6$  mol/km<sup>2</sup>/yr) is lower than the volcanic CO<sub>2</sub> degassing flux, or in the same order of magnitude. Only for two rivers (the Ytri-Rangá and Hverfisfljót rivers, Isl16 and Isl14) is this rate higher than the highest volcanic CO<sub>2</sub> degassing rate. From the present study, we estimated the average long term CO<sub>2</sub> consumption rate by chemical weathering for Iceland to be  $0.28 \cdot 10^6$  mol/km<sup>2</sup>/yr (when weighted by the catchment surface areas). Thus there is more CO<sub>2</sub> injected from Icelandic volcanoes to the atmosphere than removed from the atmosphere by the riverine chemical weathering in Iceland. Nevertheless, the average long-term rate of CO<sub>2</sub> consumption by the chemical weathering in Iceland and the lowest estimation of Icelandic volcanic CO<sub>2</sub> degassing are equivalent.

#### *Mechanical Erosion Rates*

The mechanical erosion rates for the rivers under study range between 940 and 10200 t/km<sup>2</sup>/yr. The very high rate is that of the Hverfisfljót river (fig. 1; Isl14) which has both the highest suspended sediment load and the highest runoff among all the studied rivers. Excluding this river, the range of variation of mechanical erosion rates is 940 to 8100 t/km<sup>2</sup>/yr. With such high rates, the mechanical versus chemical erosion ratios are also high (34 to 215). These mechanical erosion rates are very much higher than the worldwide average of 230 t/km<sup>2</sup>/yr estimated by Milliman and Syvitski (1992). But they are in the same order of magnitude as those determined for Réunion island (Louvat and Allègre, 1997) and are 2 to 100 times higher than those determined for Sao Miguel, Azores (Louvat and Allègre, 1998). Icelandic rivers finally rank among the maximum reported values of mean annual specific yields, together with the rivers of New Zealand, New Guinea or Java (Walling and Webb, 1996).

There is a global correlation between the mechanical erosion rate and the glacial cover of the drainage basins (percentage of glaciers in the drainage basins), which underlines the importance of glaciers upon the river sediment transport in Iceland. The presence of sands of glacier origin all over the south and southeast part of Iceland is impressive. The potential mass of sediments concerned has been estimated recently: during the 1996 volcanic eruption under the Vatnajökull Glacier the suspended sediment load had reached 180 million tons in only 42 hours (Stefánsdóttir and Gislason, 2005), all the sediments accumulated beneath the glacier and down-slope have been flushed at the same time. The fate of such an enormous mass of sediments (crushed altered basalt) at sea and its impact on the global chemistry of the ocean still needs to be addressed.

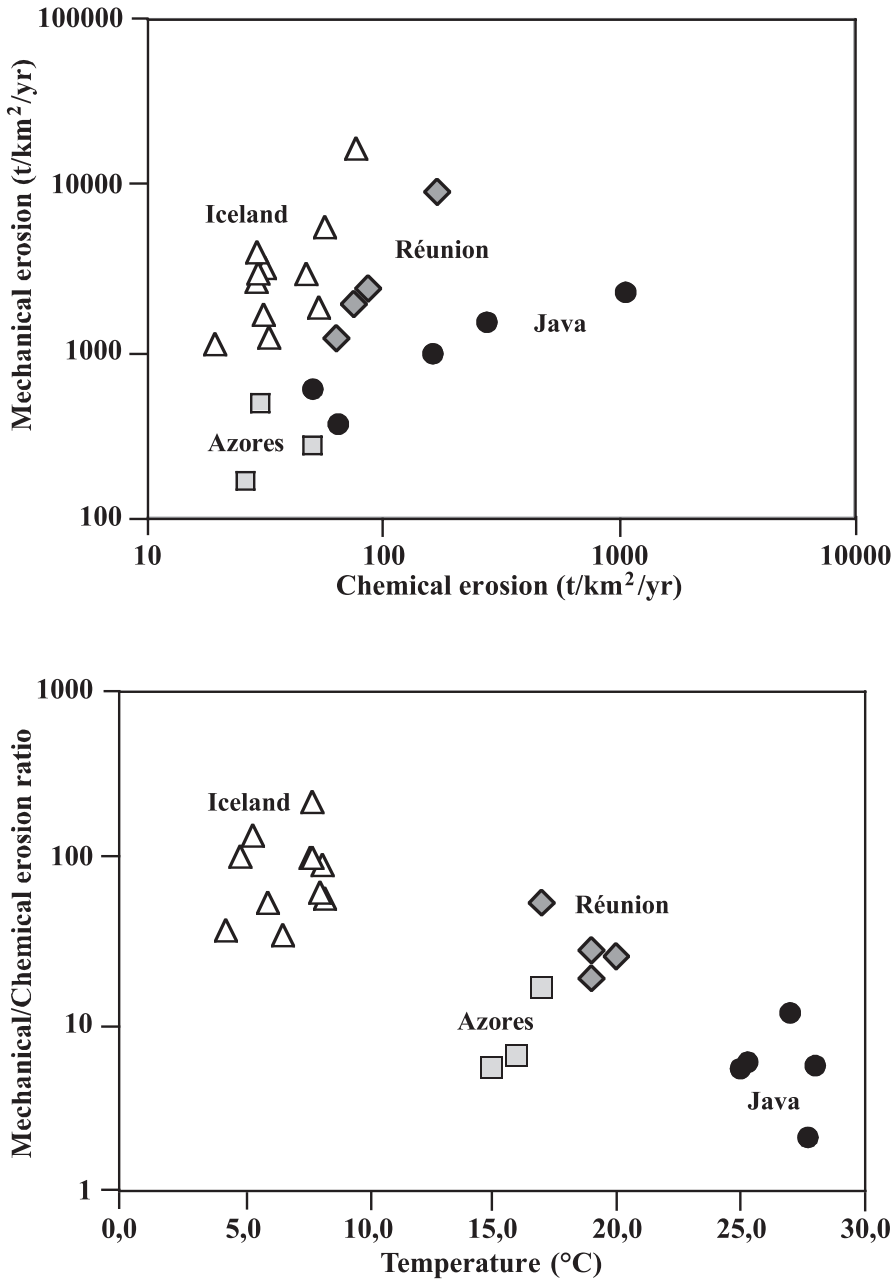


Fig. 10. Correlation diagrams between chemical and mechanical erosion rates and between mechanical to chemical erosion ratios and temperature (of the river at the sampling time) for four volcanic islands (Iceland, Réunion, Sao Miguel in Azores and Java) studied within the same steady-state model of erosion systematics (Louvat, 1997). The mechanical erosion rates represented here are all calculated through this model.

#### *Coupling Chemical and Mechanical Erosion Rates*

In figure 10 are gathered chemical and mechanical erosion rates estimated for the volcanic islands of Iceland (this study), Réunion (Louvat and Allègre, 1997), Sao

Miguel in Azores (Louvat and Allègre, 1998) and Java (Louvat, ms, 1997). All mechanical erosion rates reported in the figure are estimated from the steady-state model of erosion, in a similar manner as in this paper for Icelandic rivers.

We do observe a general trend of increased chemical weathering for higher mechanical erosion, as already stated by Gaillardet and others (1999a) for the silicate part of the 60 worldwide major rivers and by Millot and others (2002) for granitoid watersheds and basaltic basins. However, it would be ambitious to try to define a power law among these rates. The main difference between this figure 10 and the correlations expressed in the previous papers is that individual values for each river are reported here instead of an average for each island. With such a representation, there seems to be not one but many correlations between chemical and mechanical erosion rates. For each volcanic island we could define a power law type relationship between chemical and mechanical erosion rates. This is not totally true for Sao Miguel (Azores archipelago), but the geochemical study of the dissolved and suspended loads for these rivers has shown that three groups had to be determined, according to the more or less differentiated type of the volcanic rocks they were draining (Louvat and Allègre, 1998).

In the second diagram of figure 10 are represented the mechanical to chemical erosion ratios versus the temperature of each river at the time of sampling. In agreement with the previous diagram where each island showed a singular relationship between chemical and mechanical erosion rates, the mechanical to chemical erosion ratios are different from one island to the other and are anti-correlated to the local temperatures of the rivers. Icelandic rivers have the highest mechanical to chemical erosion ratio (35 to 215) reflecting both high mechanical erosion rates, due to glacier cover and high runoff, and a relatively low chemical denudation rate for basaltic catchments because of the low temperatures. On the other end of the trend, Java has low mechanical to chemical erosion ratios (2 to 12), which reflect the particularly high chemical weathering rates under hot humid climate, and the low mechanical erosion rates related to the geomorphology of this island with very steep slopes on the volcanoes but also large sedimentation plains. Réunion and Sao Miguel (Azores) rivers plot between these two end-members, with still relatively high mechanical to chemical erosion ratios for Réunion (20 to 55) and medium values for Sao Miguel (6 to 17). This correlation between mechanical to chemical erosion ratio and temperature is similar to that reported by Dessert and others (2001) linking the rate of CO<sub>2</sub> consumption to runoff and temperature. Another similar correlation can be drawn between chemical weathering rate and temperature.

#### CONCLUSION

This study of riverine erosion in Iceland complements the database of chemical composition of dissolved and suspended material transported by the World Rivers. The study uses the systematics of the steady state model of erosion developed by Négrel and others (1993) and Gaillardet and others (1995 and 1997) for the study of erosion rates on the Congo and Amazon basins, which has been refined for the erosion study of volcanic islands by Louvat and Allègre (1997 and 1998). It has been used in other studies compiling data on basalt weathering in the aim of defining general laws (Dessert and others, 2001 and 2003).

By the means of characteristic molar concentration ratios in the dissolved yields, we have determined the proportions of rain, thermal springs and magmatic gases, and basalt weathering contributing to the river water chemical compositions. Using the steady state model of erosion, it was then possible to establish a mass budget between the unweathered basaltic rocks and the chemical weathering products (dissolved material and residual solids), which allows us to calculate the concentrations of suspended sediments transported by the rivers. By comparing these calculated concen-

trations with the measured concentrations, we have validated the hypothesis of the steady state model of erosion in the case of rivers for which there are no sediment traps and limited groundwater component. We suggest that the steady state model of erosion is a viable way to estimate the mean sediment loads, which are transported by a river, and that this method is a nice addition to costly direct measurements. Icelandic river sediment loads are huge because of the glaciers and the glassy nature of the young rocks. The influences of these easily weatherable and fine-grained basalt river suspended sediments on the global seawater geochemical budgets are certainly not negligible (for example, Gislason and others, 2006).

The comparison of Icelandic chemical and mechanical erosion rates and rates of CO<sub>2</sub> consumption by the chemical weathering with the world-wide averages and with previous studies of basalt weathering allows us to reassert that basaltic lithologies are highly erodeable, even under cold climate. In Iceland, glaciers and the glassy lithologies are the source of high mechanical erosion rates, bringing fine material easily transportable by the rivers, and increasing the water discharges. The chemical erosion rates for Icelandic rivers are comparable to those from Azores or Kamchatka but much lower than in Réunion (Louvat and Allègre, 1997 and 1998; Dessert and others, 2008) reflecting the influence of temperature and runoff on weathering. Icelandic rivers drain rocks of quite homogeneous lithology but of various ages and young rocks are more easily weathered than old ones.

Gathering data from four volcanic islands (Iceland, Réunion, Sao Miguel in Azores and Java) in different climatic, geomorphologic and tectonic contexts, and for which the same systematic of steady-state of erosion was applied, we observe that there is no general correlation between chemical and mechanical erosion rates at the scale of these four islands. However a correlation can be described for each island, leading to distinct mechanical to chemical erosion ratios. These are related to the temperature: the higher the temperature, the lower the mechanical to chemical erosion ratio. The highest mechanical to chemical erosion ratios for Icelandic rivers clearly are due to very high mechanical erosion rates and low chemical weathering rates. More mechanical erosion rate data for volcanic islands and basaltic catchments are needed to refine this promising relationship.

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