

SHORT
COMMUNICATIONS

Chemical Composition of Sediment Load Carried by Rivers

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According to the modern theory of lithogenesis [1], the mobilization of suspended and dissolved materials in drainage basins is the initial stage of the formation of sedimentary rocks. The major portion of chemical elements is transported with river suspensions, including alkaline and calc-alkaline metals, which are highly mobile in the supergene zone.

Nowadays, the total discharge of solid materials from continents is known fairly accurately [2–6], which is not the case for the chemical compositions of suspended and bed loads. The geochemical knowledge of river suspensions is very different for different elements. A large body of analytical data is available for the elements involved in ecological monitoring, for instance, heavy metals. Many other elements are characterized by a few determinations scattered over various publications. The most recent comprehensive compilations of the chemical compositions of suspended matter of the world's rivers were published by Volkov [7], Gordeev [8], and Martin and Meybeck [9] already more than 20 years ago. Since then, the amount of raw data has expanded significantly, and the accuracy and sensitivity of analytical methods have improved. Recently, we presented a new compilation of the compositions of suspended and bed loads in the world's rivers, which was based on the data from about 500 Russian and foreign publications, and estimated the average abundances of 72 elements [10]. This paper gives a summary of these results with short geochemical comments.¹

The average concentrations of chemical elements reported in [10] for the suspended and bed loads of the world's rivers can be compared with the corresponding data on the compositions of the main types of sedimentary rocks, clays and shales, sands and sandstones, and the upper part of the continental crust as a whole (Table 1). As could be expected, the compositions of finely dispersed river suspensions approach the compositions of clay rocks, whereas the alluvium consisting of coarser frac-

tions is chemically more similar to sands and sandstones.

Human activity impacts almost the whole land surface and obviously influences to a varying extent the abundances of chemical elements in suspended and bed loads. The quantitative estimation of the contribution of anthropogenic sources is a difficult problem. However, some of the most technophile elements show anomalously high contents in industrial regions both in suspended loads and in bottom sediments (Table 2). Interestingly, after the cessation or strong reduction of contaminant input, such anthropogenic geochemical anomalies vanish rather rapidly (within several decades) under the influence of natural processes [13].

Compared with bottom sediments, the suspended materials are spatially much more homogeneous. This provides a possibility to evaluate the geographic variations in their composition. This is most clearly exemplified by major elements, whose contents are almost independent of economic activity. Using the data of [2, 5], all rivers can be grouped with respect to their predominant location in particular climatic zones. This allows us to calculate the average compositions of river suspensions for various physiographic zones (Table 3).

The content of SiO₂ decreases from cold to warmer areas (beyond mountainous regions) and is approximately equal in humid and arid climates. This is accompanied by a nonlinear increase in Al₂O₃ content, especially intense in the regions with the lowest SiO₂ contents (Fig. 1) confined to the zone of extensive laterization in the tropical belt.

The minimum Fe₂O₃ contents were observed in the suspended matter of rivers from the temperate zone, and higher values are characteristic of rivers draining the tundra–taiga and tropical zones. It should be pointed out that these differences are conspicuous in regions with a humid climate and are almost imperceptible in regions of low precipitation.

In contrast to Fe₂O₃, the suspended matter of rivers from the temperate zone is strongly enriched in CaO and MgO, whereas the rivers of the tundra–taiga and tropical zones are depleted in these components. The magnitude of the difference is also higher in regions with a humid climate. The maximum contents of CaO

¹ Depending on the type of distribution (normal or lognormal), average concentrations were calculated as arithmetic or geometric means. The weighted average concentrations of major elements and carbon were calculated from the compositions of suspended materials from various continents. The complete raw data set and references were reported elsewhere [10].

Table 1. Average contents of chemical elements in suspended and bed loads, soils, sandy and clayey sedimentary rocks, and the bulk composition of the upper continental crust, ppm (C, Na, Mg, Al, Si, S, K, Ca, and Fe in %)*

Element	Suspended load [10]	Bed load [10]	Soils [11]	Sands and sandstones [12]	Clays and shales [12]	Upper continental crust [12]
Li	35	20	25	25	46	30
Be	1.7	1.5	0.3	1.4	2.8	2.1
B	59	25	20	26	110	34
C _{org}	2.0	1.4				
C _{inorg}	4.0	0.40	2.0	0.93	1.4	0.81
N	1750	1300	2000	120	580	100
F	700	200	200	330	610	510
Na	0.82	0.79	0.5	1.39	1.02	2.07
Mg	1.44	0.57	0.5	1.12	1.65	1.77
Al	8.63	4.30	7.10	5.96	8.86	7.6
Si	25.60	35.00	33.0	31.42	26.88	28.32
P	1000	800	800	620	790	610
S	0.12	0.02	0.07	0.19	0.36	0.14
K	2.15	1.10	1.4	1.76	2.73	2.23
Ca	2.60	1.70	1.5	2.83	2.21	3.89
Sc	14	10	7	5.4	15	15
Ti	3900	3100	5000	3500	5100	3410
V	120	50	90	75	120	120
Cr	85	50	70	55	76	150
Mn	1150	500	1000	600	970	670
Fe	5.03	2.50	4.0	3.21	4.71	4.06
Co	19	15	8	13	19	17
Ni	50	25	50	32	47	62
Cu	45	20	30	31	36	39
Zn	130	60	90	57	52	78
Ga	20	10	20	10	16	19
Ge	1.4	0.5	1	1.1	2	1.3
As	14	6	6	7.2	9.3	6.5
Se	1.5	0.3	0.4	0.1	0.36	0.16
Br	9	6	10	48	57	11
Rb	77	50	150	80	130	110
Sr	150	150	250	220	240	270
Y	25	20	40	29	31	26
Zr	150	250	400	230	190	160
Nb	13	20	10	6.4	11	12
Mo	1.8	1.5	1.2	1.5	1.6	1.5
Ru	–	0.0003	–	–	–	–
Rh	–	0.0001	–	–	–	–
Pd	–	0.0006	–	–	–	–
Ag	0.3	0.05	0.05	0.019	0.2	0.13
Cd	0.5	0.4	0.35	0.74	1.0	0.3
In	0.2	0.1	1	0.03	0.063	0.19
Sn	2.9	4	4	2.8	3.5	3.8

Table 1. (Contd.)

Element	Suspended load [10]	Bed load [10]	Soils [11]	Sands and sandstones [12]	Clays and shales [12]	Upper continental crust [12]
Sb	1.4	2	1	2.6	1.0	1.2
Te	7?	–	–	–	0.01	0.003
I	4.8	3	5	1.0	1.2	0.68
Cs	5.2	4	4	6.7	10	4
Ba	500	290	500	370	460	510
La	32	38	40	20	48	32
Ce	68	75	50	39	75	63
Pr	7.7	8	7	4.3	10	8.7
Nd	29	30	35	16	36	29
Sm	5.8	6	4.5	3.8	8	5.7
Eu	1.4	1.5	1	0.84	1.2	1.3
Gd	5.6	6	4	2.8	5.8	6.2
Tb	0.79	1	0.7	0.7	0.83	0.89
Dy	4.5	5	5	2.9	4.4	4.8
Ho	0.90	1	0.6	1.9	0.7	1.6
Er	2.6	3	2	2.3	1.9	2.7
Tm	0.38	0.5	0.6	1.7	0.6	0.49
Yb	2.5	3	3	1.8	2.5	2.5
Lu	0.40	0.4	0.4	0.83	0.39	0.51
Hf	4.4	6	6	4.5	5.0	4.5
Ta	0.88	2	2	1	1.4	1.4
W	1.4	5	1.5	1.6	2.6	2.5
Re	0.0019	0.002	–	–	–	0.0004**
Os	0.0001	0.00005	–	–	–	0.0001**
Ir	5.2×10^{-5}	0.0001	–	–	–	3×10^{-6} ?**
Pt	–	0.001	–	–	–	–
Au	0.044?	0.01	0.001–0.02	0.0083	0.0065	0.0061
Hg	0.077	0.05	0.06	0.049	0.089	0.072
Tl	0.56	1	0.2	0.8	1.3	0.77
Pb	25	15	35***	14	14	17
Bi	0.3	0.2	0.3	0.2	0.38	0.33
Ra	8×10^{-7}	1×10^{-6}	8×10^{-7}	–	–	6×10^{-7} **
Th	10	10	9	7.8	10	9.3
U	2.4	3	2	2.3	4.5	2.5

Notes: * Recalculated to air dry sample, assuming that the loss on ignition is 11%, and the total of major components is 99% of the mass of the annealed sample.

** Earth's crust [11].

*** Preindustrial background is 12 ppm [11].

Table 2. Average contents of selected technophile elements in the river suspensions and bottom sediments of rivers in areas with low and high anthropogenic influence (geometric mean values) [10]

Element	Suspended matter of the world's rivers		Bottom sediments of rivers	
	Background regions	Regions with high anthropogenic influence	Background regions	Regions with high anthropogenic influence
Cr	85	150	50	140
Ni	50	65	25	40
Cu	45	95	20	70
Zn	130	350	60	260
Cd	0.5	2.7	0.4	2.5
Hg	0.077	1.0	0.05	0.7
Pb	25	95	15	80

Table 3. Average compositions of river suspensions from various climatic zones, wt % [10]

Climatic zone	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O
<i>Plains, uplands, and low mountains</i>							
Tundra and taiga, <i>N</i> = 42	68.30 ± 5.76	13.84 ± 2.87	8.96 ± 4.31	2.30 ± 1.00	2.73 ± 2.02	1.47 ± 0.72	2.40 ± 0.86
Humid climate of temperate zone, <i>N</i> = 18	62.46 ± 4.66	15.96 ± 3.39	8.66 ± 2.39	2.43 ± 0.98	6.58 ± 6.06	1.24 ± 0.81	2.68 ± 0.78
Dry climate of temperate zone, <i>N</i> = 5	63.71 ± 8.90	14.42 ± 3.45	5.08 ± 1.87	2.90 ± 0.70	10.10 ± 4.14	1.49 ± 0.71	2.30 ± 0.29
Humid climate of tropical zone, <i>N</i> = 15	59.76 ± 3.68	23.33 ± 4.89	9.95 ± 1.90	1.90 ± 0.80	1.34 ± 0.87	0.77 ± 0.50	2.95 ± 1.05
Dry climate of tropical zone, <i>N</i> = 8	58.68 ± 5.51	25.39 ± 8.10	9.24 ± 1.86	2.08 ± 1.32	1.80 ± 2.07	0.99 ± 1.14	1.83 ± 1.10
<i>Mountainous regions</i>							
Humid climate, <i>N</i> = 5	59.82 ± 4.80	16.58 ± 3.63	9.18 ± 4.99	2.33 ± 0.72	7.45 ± 4.40	1.67 ± 0.34	2.97 ± 0.73
Dry climate, <i>N</i> = 33	63.60 ± 4.78	14.19 ± 1.55	4.70 ± 1.40	2.70 ± 1.15	9.84 ± 5.53	2.25 ± 0.62	2.68 ± 0.52

Note: *N* is the number of rivers used for calculations.

and MgO are related to the presence of considerable amounts of carbonates. It is difficult to explain why carbonates are more intensely accumulated in the rivers of the dry temperate zone than in the rivers of moderately humid tropical regions. The resolution of this question requires a more detailed discussion; however, one circumstance that is often overlooked should be noted. The duration of suspended matter formation and transportation by rivers is much longer than the travel time of river water along the whole flow path. Therefore, the observed composition of suspended matter may not correspond to present-day conditions and reflect to a larger degree past environments.

The content of Na₂O in the suspended load of rivers decreases from polar to tropical regions, irrespective of the humidity of regional climate. These variations

reflect an increase in the mobility of sodium, which is not accumulated in weathered products.

A similar tendency was observed for K₂O only in low-humidity environments, whereas the concentrations of K₂O increase in a humid climate. Potassium shows a moderate mobility during weathering and is accumulated in clay minerals. Perhaps, plants play an important role in this process because they extract K from soils and release it in a concentrated form with organic detritus, the ash components of which directly participate in the formation of secondary clay minerals. At a given average annual temperature, regions with a more humid climate show higher bioproductivity, which, according to the above considerations, must be favorable for the accumulation of potassium in weathered products.

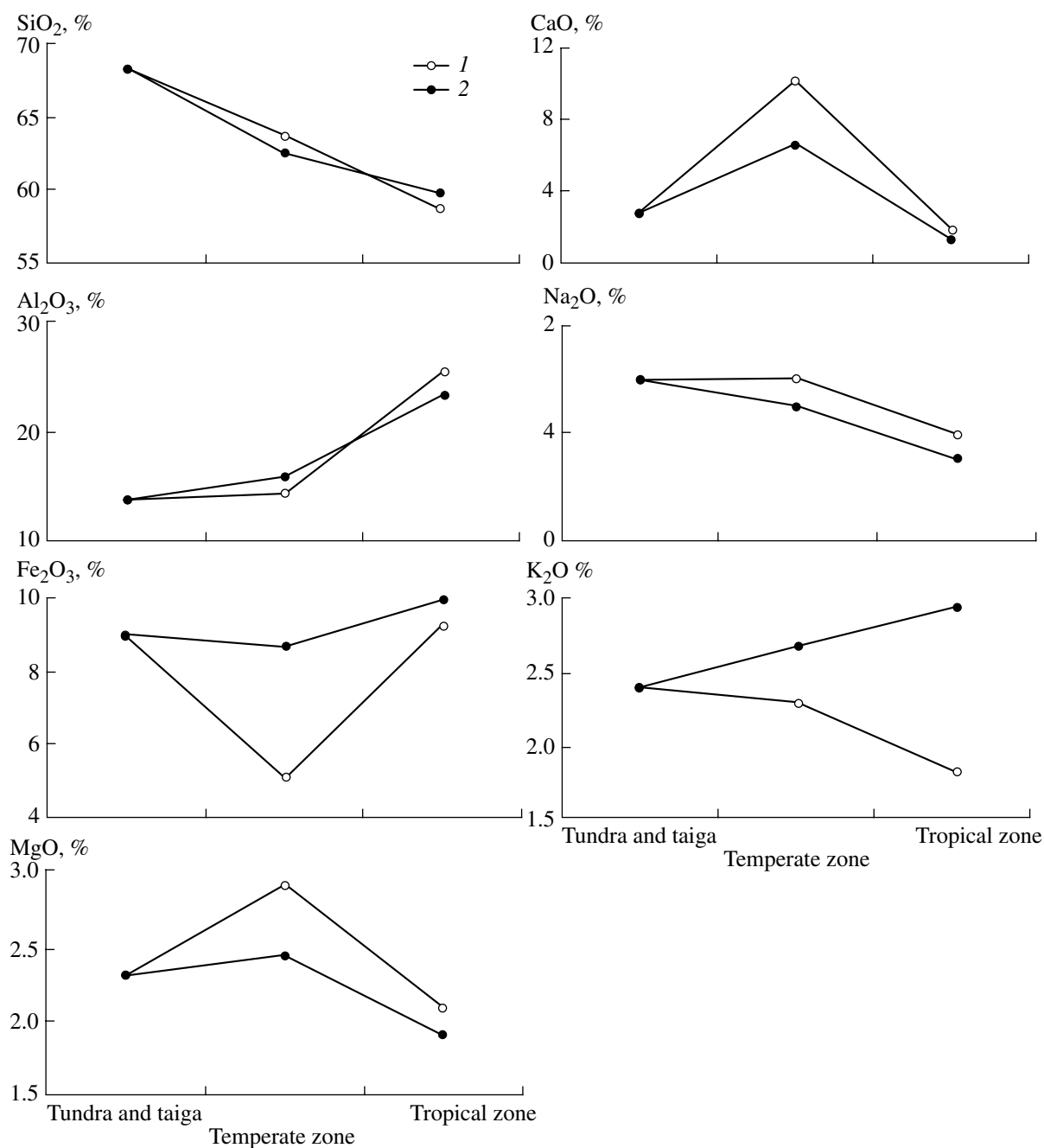


Fig. 1. Contents of major elements in the suspensions of rivers from various physiographic zones: (1) areas with an arid climate and (2) areas with a humid climate.

Several parameters were proposed as indicators of the extent of weathering. One of them is the $\text{Al}_2\text{O}_3/\text{Na}_2\text{O}$ ratio. Both these components occur mainly in the silicate part of source rocks but show strongly different migration properties: aluminum is an inert component, whereas sodium is among the most mobile elements. It is obvious that the $\text{Al}_2\text{O}_3/\text{Na}_2\text{O}$ ratio must increase with increasing degree of weathering of the lithogenic basis of drainage basins. Another indicator is the $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio,

which also includes components of the silicate fraction with different migration properties. As the mobility of Si is higher than that of Al, this ratio must decrease with increasing extent of weathering. Indeed, as can be seen in Fig. 2, the lowest degree of weathering of suspended matter is observed in the rivers of the tundra and taiga zones, and the maximum degree is characteristic of the tropical zone. The rivers of the temperate zone occupy an intermediate position closer to the taiga and tundra zones.

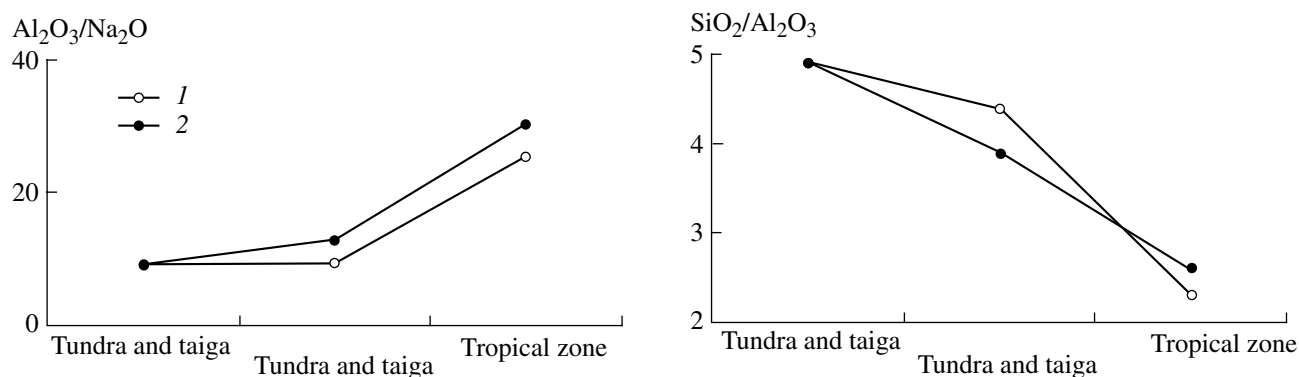


Fig. 2. Ratios Al_2O_3/Na_2O and SiO_2/Al_2O_3 in the suspensions of rivers from various physiographic zones: (1) areas with an arid climate and (2) areas with a humid climate.

It is clear that any adequate geochemical estimate of the global discharge of solid materials must be based on weighted average values, but this requirement is currently very difficult to meet because of the paucity of relevant data. Nonetheless, weighted average values

can be calculated, as a first approximation, for particular continents from the flux of suspended matter in the largest rivers with a correction for the unaccounted for part of the total flux. The necessary data on the suspended load of large rivers are given in Table 4. Since

Table 4. Discharge of suspended matter by the large rivers [4, 5, 14, 15] for which the chemical composition of suspensions was reported

River	Discharge of suspended matter		River	Discharge of suspended matter	
	10^6 t/yr	%		10^6 t/yr	%
<i>North America</i>			Loire	8	4.1
Mackenzie	82	12.5	Garonne	6	3.1
St. Laurent	5	0.8	Rhone	56	29.0
Hudson	36	5.5	Danube	68	35.2
Colorado	135	20.5	Don	5	2.6
Mississippi	399	60.7	Volga	14	7.3
Total	657	100.0	Kuban	8	4.1
<i>South America</i>			Rioni	10	5.2
Orinoco	210	13.5	N. Dvina	4	2.1
Caroni	48	3.1	Mezen'	1	0.5
Amazon	1198	76.7	Pechora	9	4.7
Parana	92	5.9	Total	193	100.0
Rio Negro	13	0.8	<i>Asia</i>		
Total	1561	100.0	Ob	16	0.5
<i>Africa</i>			Yenisei	13	0.4
Nile	120	37.4	Lena	20	0.6
Senegal	24	7.5	Yana	3	0.1
Niger	40	12.5	Khatanga	5	0.2
Congo	48	15.0	Huang Ho	1100	35.4
Orange	89	27.7	Yangtze	481	15.5
Total	321	100.1	Mekong	160	5.1
<i>Europe</i>			Indus	250	8.0
Rhine	3	1.6	Ganges (Brahmaputra)	1060	34.1
Seine	1	0.5	Total	3108	99.9

Table 5. Chemical composition of suspended matter transported from various continents

Continent	Discharge of suspended matter [16]		Content, wt %							
	10 ⁶ t/yr	%	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O	Total
North America	1080	7.0	71.14	14.22	5.92	1.92	3.23	1.05	2.53	100.01
South America	1238	8.0	60.00	23.19	9.67	1.95	1.33	1.12	2.75	100.01
Africa	1043	6.7	62.02	20.31	8.82	2.61	2.75	1.55	1.96	100.02
Europe	580	3.7	61.21	13.99	7.60	2.84	10.02	1.64	2.70	100.00
Asia	9137	59.1	62.28	17.20	7.77	3.11	5.11	1.37	3.16	100.00
Oceania	2231	14.4	59.76	23.33	9.95	1.90	1.34	0.77	2.95	100.00
Australia	165	1.1	58.68	25.39	9.24	2.08	1.80	0.99	1.83	100.01
All land regions	15474	100.0	62.26	18.53	8.19	2.70	4.12	1.26	2.94	100.00

no data are available for Australia and Oceania, the compositions of the suspended loads of these areas were taken to be identical to the compositions of suspended matter from the rivers of arid and humid tropical zones, respectively (Table 3). Then, assuming that the weighted average composition of suspended matter of large rivers from a given continent closely approaches the composition of the sediment load and using the known values of the latter for all continents, the global average chemical composition of suspended matter can be obtained for all land areas (Table 5).

Table 6 presents the results of calculations and earlier estimates for the average chemical composition of suspended matter in the world's rivers compared with the average composition of clay rocks in the sedimentary cover of the continental crust. This comparison reveals only minor differences between the average compositions of clay rocks and suspended matter of the world's rivers, and the best agreement was obtained using our estimates. The maximum differences were observed for K₂O (-12.5%) and CaO (-9.4%), which can be explained by the migration of these components

Table 6. Comparison of the compositions of suspended matter and clayey sediments of the continental crust, wt % (difference in % relative is shown in parentheses)

Component	Suspended matter			Clays and shales [19]
	[17]	[18]	This study	
SiO ₂	63.37 (+2.2)	64.49 (+4.03)	62.26 (+0.4)	61.99
Al ₂ O ₃	18.10 (-0.4)	18.24 (+0.4)	18.53 (+1.9)	18.17
Fe ₂ O ₃	8.42 (+6.6)	7.90 (0.0)	8.19 (+3.4)	7.90
MgO	2.39 (-15.5)	1.95 (-31.1)	2.70 (-4.2)	2.83
CaO	4.07 (-10.9)	3.68 (-19.5)	4.12 (-9.4)	4.57
Na ₂ O	1.56 (+32.2)	1.03 (-12.7)	1.26 (+6.8)	1.18
K ₂ O	2.09 (-37.8)	2.71 (-19.35)	2.94 (-12.5)	3.36

Table 7. Comparison of the average contents of major components in the suspended materials and bottom sediments of the world's rivers (recalculated to oxide totals of 100%)

Component	Suspended matter of world's rivers	Bottom sediments of world's rivers	Enrichment factor of bottom sediments, %
SiO ₂	62.26	81.14	23.3
Al ₂ O ₃	18.53	8.80	-110.6
Fe ₂ O ₃	8.19	3.87	-111.6
MgO	2.70	1.03	-162.1
CaO	4.12	2.58	-59.7
Na ₂ O	1.26	1.15	-9.7
K ₂ O	2.94	1.44	-104.2
Total	100.00	100.01	

into bottom sediments from seawater during the formation of biogenic (chemogenic) carbonates and diagenetic silicates, respectively.

Thus, the major-element chemical composition of suspended matter in the world's rivers changes regularly from one climatic zone to another but is in general similar to the average composition of clay rocks of the

continental crust. This fact can be considered as indirect evidence that the present-day conditions of sedimentary rock formation are not strongly different from the conditions averaged over Phanerozoic time, which comprises most of the sedimentary rocks occurring in the continental crust.

The bed load carried by traction accounts for 10–30% of the continental discharge of solid materials [20–22] and is enriched compared with the suspended load in silica and depleted in other major elements (Table 7). This feature is explained by the fact that quartz shows the highest mechanical and chemical resistance in the supergene zone among main rock-forming minerals. Under given climatic conditions, grain-size composition is probably the main control on the chemical composition of both suspended and traction-transported materials. This conclusion is supported by the results of Supatashvili [23] on the rivers of Georgia.

The chemical composition of river-transported solid materials calculated for various proportions of suspended and bed loads is significantly different from the average composition of the upper continental crust but is fairly similar to the composition of clayey and sandy sedimentary rocks mixed in the proportion 2 : 1, which corresponds to their abundances in the continental crust (Table 8). The relative enrichment of sandy–clayey sedimentary rocks in sodium, magnesium, and potassium has probably a secondary origin and is explained by the fact that these rocks were mostly deposited in marine environments with high concentrations of dissolved compounds of alkaline and calc-alkaline elements.

Table 8. Major-component compositions of solid materials transported by rivers and of the upper continental crust, wt %

Component	Percentage of traction load in the total discharge of solid materials			Upper continental crust [12]	2 : 1 mixture of clayey and sandy rocks of the continental crust [19]
	10	20	30		
SiO ₂	64.15	66.04	67.92	64.74	66.11
Al ₂ O ₃	17.56	16.58	15.61	14.25	16.22
Fe ₂ O ₃	7.76	7.33	6.89	6.20	6.54
MgO	2.53	2.37	2.20	3.14	2.65
CaO	3.97	3.81	3.66	5.82	3.66
Na ₂ O	1.25	1.24	1.23	2.98	1.66
K ₂ O	2.79	2.64	2.49	2.87	3.14
Total	100.01	100.01	100.00	100.00	99.98

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