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Geochemistry of fine-grained sediments in the Yangtze River and the implications for provenance and chemical weathering in East Asia

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Abstract

In order to interpret the marine clastic record preserved in the sedimentary basins of the East Asian marginal seas, it is important to understand how sediment transport and chemical weathering affect the composition of sediment enroute to its sink. Here we present a new data set for fine-grained sediment (<63 μm) from the Yangtze River and its major tributaries, which represents a baseline for interpreting sediment in the East China Sea. We demonstrate that there is no significant coherent downstream variation in the major element contents, which are generally more enriched than the average upper continental crust, except for water-soluble elements including Sr, Rb, Na, and K. Nd isotopes show that most of the sediment comes from the eastern and middle Yangtze Craton, as well as the Songpan-Garze Terrane. Chemical weathering varies significantly across the basin with upstream tributary sediments being relatively unweathered compared to those in the lower reaches. However, sediments in the main Yangtze stream show no trend in chemical weathering along its course, with some of the least weathered materials being found closest to the delta. Grain size and the abundance of hydrodynamically sorted heavy minerals affect the bulk geochemistry, especially the rare earth elements (REEs).

Keywords: The Yangtze River; Fine-grained sediments; Geochemistry; Provenance; Chemical weathering

Background

The Yangtze River is the largest river in eastern Asia and supplies sediments to the marginal seas of the Western Pacific, as well as filling sedimentary basins onshore between Tibet and the modern delta (e.g., Clark et al. 2004; Zheng et al. 2013). Understanding what controls the intensity of chemical weathering and the strength of bedrock erosion are important goals if we are to quantify how climate and tectonic activity influence the development of the Earth's surface and the composition of sediments deposited on the surrounding continental margins. If we are to use ancient sediments in the East China Sea to examine past environments in central China or the uplift history of the Tibetan Plateau, then an understanding of where the modern river derives this sediment is fundamental.

The Yangtze River provides a good opportunity to test how climate and tectonic compete with one another to control erosion because this river spans a wide range of landscapes that experience quite different climatic and tectonic forcing (e.g., Chen et al. 2001a, b; Clark et al. 2004). Understanding where sediment is being derived from, what its composition is and how that changes during transport due to abrasion and chemical weathering is essential if the marine sediment archive is to be exploited (e.g., He et al. 2013b).

In theory, the bulk composition of the sediment may provide a way of determining the provenance of this material if there is sufficient diversity in the bedrock compositions. However, sediment compositions may be changed from the original bedrock as a result of transport and chemical weathering. The geochemistry of bedload and suspended sediments has been used by many workers to determine the provenance, weathering, and tectonics of several river basins (e.g., Bhuiyan et al.

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2011; Condie et al. 1992; Shao et al. 2012; Singh 2009, 2010; Taylor and McLennan 1985; Wu et al. 2011; Yang et al. 2004b). However, it is unclear if their interpretations are valid because of disruption to the signal caused by transport processes.

There have been several geochemical studies of Yangtze River sediments, including analysis of the rare earth element (REE) composition (e.g., Yang et al. 2002; Yang et al. 2013; Yang and Wang 2011), major element chemistry (e.g., Chen et al. 2002; Yang et al. 2004a), and the Sr-Nd isotope characteristics (e.g., Meng et al. 2008; Yang et al. 2007). However, there has been little integration of major/trace element chemistry and Sr-Nd isotope composition, especially for sediments finer than 63 μm, which are often considered to be tracers of the average REE composition of the source regions and dominate the volumetric flux to the ocean (e.g., Yang and Wang 2011). These authors argue for a strong link between the REE chemistry of the river sands and that of the dominant sources, which they infer to be in the upper reaches of the river based on the similarity of the REE composition in the Jinshajiang (upper reaches) and delta sands. Yang et al. (2002) also showed that REEs are generally enriched in clay and silt fractions, but depleted in the sand fraction, suggesting that grain size may be crucial control on sediment chemistry, something that has been documented in other SE Asian rivers (e.g., Clift et al. 2008).

In this paper, we examine the bed sediment chemistry of a series of Yangtze River sediments, including the major and trace elements, as well as the Sr-Nd isotope composition of the material finer than 63 μm, collected between the headwaters of the Yangtze on the Tibetan Plateau and the delta in easternmost China to investigate how effective the major and trace element chemistry can be in determining provenance and developing a sediment budget for the river system and thus help constrain its influence on basins in the East China Sea. We also endeavor to see how chemical weathering affects the composition of sediment in the river. It has been suggested that intensified chemical weathering, following the uplift of the Himalayas and Tibetan Plateau, has exerted an important influence in controlling Cenozoic climate since the start of India-Asia collision around 50 Ma (e.g., Berner and Berner 1997; Raymo and Ruddiman 1992). However, this theory is not universally accepted because the potential impact of chemical weathering on climate has yet to be properly quantified. In doing so, we provide a benchmark against which to compare older deposits within the East China Sea and other Chinese sedimentary basins supplied by the Yangtze.

The Yangtze River is influenced by the warm, wet climate of the East Asian monsoon and because it is recognized that warmth and moisture are important for accelerating rates of mineral alteration (e.g., West et al. 2005; White and Blum 1995). We would expect that transport and exposure to a monsoonal climate would result in a coherent increase in chemical weathering and sorting downstream and a decrease in grain size, assuming that most of the sediment load is generated in the upper reaches. No such pattern would emerge if sediment production was strong in other parts of the drainage.

In this study, we assess the effect of transport in controlling the chemical weathering proxies, via its effect on grain size as well as chemical breakdown that occurs during the transport. Degree of alteration can be calculated based on major and trace element compositions. Typically this involves tracking the relative abundance of a water-soluble element compared to an insoluble element in order to assess the degree of alteration (e.g., Nesbitt et al. 1980). We also examine whether chemical weathering and grain size exert important influences on the trace element composition of the fine-grained sediment. If these effects dominate, then it seems unlikely that rare earth element (REE) or other trace element groups can be used as effective provenance tools. Garzanti et al. (2010) have demonstrated that in South Asia the REE character of sediment is strongly controlled by the presence of a small volume of ultra-dense minerals, such as zircon and monazite and that these in turn are subject to hydrodynamic sorting and concentration so that differences between sediments from different rivers may be small compared to differences between different grain size fractions in a single point bar deposit.

Geological setting

The Yangtze River drainage is located from 33° 25′ N 91° 10′ E to 31° 23′ N 121° 58′ E and is more than 6300 km long, with a catchment area of 1.8×10^6 km^2 and an annual average discharge of ~9.6×10^{11} m^3 (e.g., Chen et al. 2001a, b; Ding et al. 2004). The river originates on the Tibetan Plateau at an elevation higher than 5000 m and finally reaches the East China Sea after merging with several large tributaries (Fig. 1). The river catchment can be divided into five broad physiographic provinces, including the northeast Tibetan Plateau, the high mountains of the Longmen Shan and associated ranges, the Sichuan Basin, mixed mountain and basin terrains (broadly referred to as the Three Gorges area), and the eastern lowlands. Generally, the Yangtze River can be divided into three parts: upper, middle, and lower reaches. However, the upstream reaches can further be divided into two segments: the Jinshajiang and the Chuanjiang (Fig. 1). The Yangtze River drainage covers several tectonic units, with the main body of the Yangtze Craton and the Qamdo Block, the Songpan-Garze terrane, the Qinling-Dabie orogenic belts, and the Cathaysia Block forming the primary potential sources (e.g., He et al. 2014). The basement

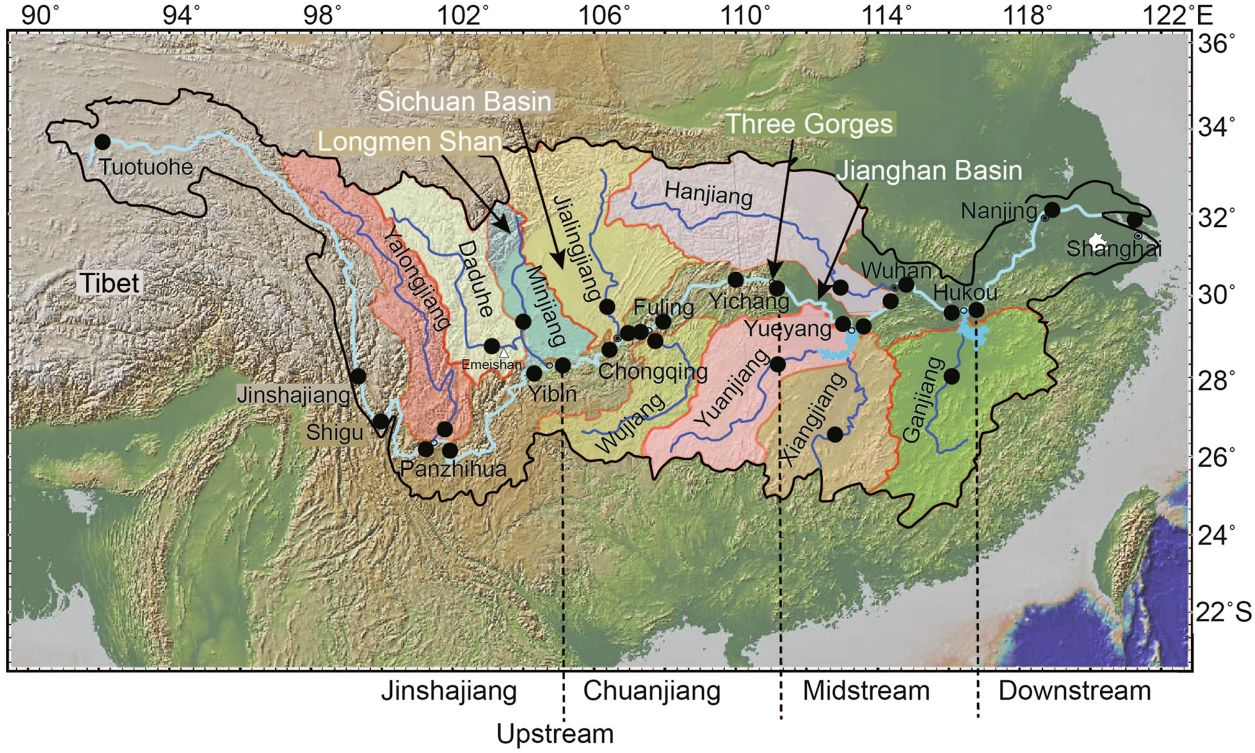

Fig. 1 Shaded topographic map showing the mainstream, major tributaries, and the sample location points within the Yangtze River drainage basin. Topography is from the Shuttle Radar Topography Mission (SRTM) plotted by GeoMapApp (http://www.geomapapp.org) (e.g., Ryan et al. 2009)

sources consists of diverse rock compositions and strata, including widely distributed carbonate rock, continental sandstone, volcanic rocks, and gneiss (e.g., He et al. 2013b).

The Yangtze River catchment is located in the humid, sub-tropical climate zone, dominated by the East Asian monsoon system, with seasonal alternation between the warm and wet summer monsoon, and a cold and dry winter monsoon. There are differences in the intensity of monsoon precipitation between the upper and lower streams. Annual precipitation tends to decrease westward from about 1000 mm in the eastern lowlands to about 700 mm in the Sichuan Basin, but rises to over 1700 mm on the eastern flanks of the central Longmen Shan. West of the Longmen Shan, precipitation decreases across the Tibetan Plateau, from about 600 mm in the middle reaches of the Yalongjiang to about 400 mm at the head of the Jinshajiang (e.g., He et al. 2014; 2013b; Yang et al. 2004b).

Methods

We collected 30 river bed sediment samples along the Yangtze River, including the mainstream and major tributaries. The sampling sites cover the whole drainage, from the head at Tuotuohe to the river mouth (Fig. 1 and Table 1). The samples from the major tributaries were taken just above their confluence with the mainstream in order to characterize what each tributary is contributing to the main stream.

All the sand samples were filtered to <63 μm after removing carbonate and organic materials, using 0.5 mol/L CH_3COOH and H_2O_2 for 24 h. Major element contents in the sediments were measured using the X-ray Fluorescence Spectrometer (ARL-9800) in the Center of Modern Analysis of Nanjing University. The samples were decomposed by pressurized HF-HNO_3 mixture in sealed Teflon beakers to determine the trace element content. Trace elements, including REEs, were determined by ICP-MS (Finnigan MAT Element-II) in the State Key Laboratory for Mineral Deposits Research, Nanjing University. Twenty-seven samples were analyzed for Sr and Nd isotopes (excluding Fuling 1, Xiangjiang, and Yueyang 1), which were dissolved in Teflon beakers with a solution of HF-HNO_3, and then separated by conventional ion-exchange techniques. The isotopic measurements were performed on a Thermo Finnigan Triton Tl Thermal Ionization Mass Spectrometer (TIMS) and Thermo Fisher Scientific Neptune MC-ICP-MS at the State Key Laboratory for Mineral Deposits Research, Nanjing University. Measured Sr and Nd isotopic ratios were normalized using a $^{86}Sr/^{88}Sr$ value of 0.1194 and a $^{146}Nd/^{144}Nd$ value of 0.7219, respectively. Analyses of

Table 1 Sample location of the Yangtze River

No.	Sample	Longitude	Latitude	Date
1	Tuotuohe	91° 5′ 9.20″	34° 17′ 43.30″	05/2009
2	Jinshajiang	99° 22′ 14″	28° 11′ 9″	09/2011
3	Shigu	99° 58′ 52.00″	26° 52′ 14.00″	05/2010
4	Panzhihua 1	101° 29′ 25.80″	26° 35′ 16.20″	03/2009
5	Yalongjiang	101° 49′ 16.20″	26° 46′ 2.40″	03/2009
6	Panzhihua 2	101° 49′ 13.80″	26° 35′ 28.80″	03/2009
7	Yibin 1	103° 45′ 18″	29° 37′ 28″	03/2009
8	Daduhe	103° 45′ 42.00″	29° 33′ 16.00″	03/2009
9	Minjiang 1	103° 45′ 18.00″	29° 37′ 28.00″	03/2009
10	Yibin 2	104° 41′ 26.40″	28° 47′ 0.00″	03/2009
11	Chongqing 1	106° 29′ 22″	29° 23′ 35″	03/2009
12	Jialingjiang	106° 29′ 1.80″	29° 33′ 22.80″	03/2009
13	Chongqing 2	106° 37′ 0.60″	29°37′11.40″	03/2009
14	Fuling 1	107° 21′ 9″	29° 44′ 1″	03/2009
15	Wujiang	107° 23′ 33.80″	29° 36′ 20.80″	03/2009
16	Fuling 2	107° 24′ 37.20″	29° 44′ 8.40″	03/2009
17	Badong	110° 20′ 46″	30° 3′ 3″	05/2009
18	Yichang	111° 18′ 43.70″	30° 39′ 49.50″	05/2009
19	Yueyang 1	112° 55′ 7.60′	29° 32′ 49.50″	05/2009
20	Yuanjiang	111° 41′ 11.20″	29° 1′ 25.90″	05/2009
21	Xiangjiang	112° 56′ 55.20″	28° 8′ 51.60″	05/2009
22	Yueyang 2	113° 11′ 27.30″	29° 29′ 28.50″	05/2009
23	Wuhan 1	114° 14′ 32″	30° 28′ 31″	05/2009
24	Hanjiang	113° 25′ 57.80″	30° 23′ 33.50″	05/2009
25	Wuhan 2	114° 25′ 32.90″	30° 40′ 19.10″	05/2009
26	Jiujiang	115° 54′ 30″	29° 43′ 8″	05/2009
27	Ganjiang	115° 51′ 21.50″	28° 38′ 57.90″	05/2009
28	Hukou	116° 18′ 26.80″	29° 46′ 3.10″	05/2009
29	Nanjing	118° 44′ 40.10″	32° 6′ 47.40″	05/2009
30	Changxing Island	121° 58′ 45.00″	31° 11′ 16.00′	05/2009

standards during the period of analysis are as follows: NBS987 for Sr isotopes ($^{87}Sr/^{86}Sr = 0.710235 \pm 4$) and JNdi-1 for Nd isotopes ($^{143}Nd/^{144}Nd = 0.512120 \pm 3$). The results of the geochemical analyses are provided in Tables 2, 3, 4, 5, and 6.

Results

We use <63 μm fraction sediment major element chemistry to assess the basic characteristics of the fine-grained sediments that we have sampled from the Yangtze River. Discrimination schemes from Herron (1988) show that the sands to silt from the Yangtze cluster between wacke and more iron-rich shales. It is clear that the sediments of the Yangtze are not very geochemically mature because they plot far from the quartz arenite field (Additional file 1: Figure S1). Thus, compared to many sediments in basins worldwide, those from the Yangtze are quite primitive and suggest relatively limited amounts of alteration from the bedrock sources.

We can also assess how the major element compositions compare with one another to assess the processes that control the sediment composition. Figure 2 shows how major elements vary compared to the silica contents, which are largely a reflection of the quartz content of the sediment. These figures show a negative correlation of CaO, Fe_2O_3, and MgO with SiO_2. There is also a rough negative correlation between SiO_2 and TiO_2. However, there is no correlation between the SiO_2 and Al_2O_3 or K_2O concentrations.

There is very little coherent variation downstream between the headwaters and the delta in terms of the major element composition, which may represent the effects of sorting in dominating the sediment composition at any one particular point, masking any general trend that might exist. Some of the samples show either very high or low values at certain points but show no clear evolution downstream. We note that there is a steady increase in MgO from the headwaters as far as Yibin, which is also broadly paralleled by an increase in K_2O from Shigu to Yibin but little else is apparent (Table2).

We examine the REE composition of sediments using a standard, multi-element diagram normalized against chondrite (Fig.3, Tables 3-5). We plot the samples taken from the different segments in the mainstream separately from those samples from the major tributaries. All the sediments show a similar type of pattern, with an enrichment in the light rare earth elements (LREE) and a relatively flat pattern in the heavy REEs (HREE; Gd to Lu). All the samples show a clear relative depletion in Eu, which is typical of the upper continental crust (e.g., Taylor and McLennan 1985). In the following discussion, we quantify the degree of LREE enrichment using the ratio La/Sm, while the relative enrichment in HREEs is represented by Tb/Yb, although the difference is small. None of the samples shows a particularly unique pattern that would show the influence of one particular tributary or source dominating the sediment in any one place.

$^{87}Sr/^{86}Sr$ ratios vary from 0.711549 ± 3 to 0.740534 ± 5, and $^{143}Nd/^{144}Nd$ ratios from 0.511860 ± 3 to 0.512216 ± 3, corresponding to εNd values ranging from −15.2 to −8.2 (Table6). High εNd values, representing to more erosion of primitive, younger crust (e.g., DePaolo and Wasserburg 1976), are found mainly in the samples from the Jinshajiang, which have low $^{87}Sr/^{86}Sr$ ratios. In the tributaries, the Jialingjiang has both low $^{87}Sr/^{86}Sr$ ratios and relatively low εNd values (i.e., old, evolved crust), whereas the Yuanjiang and Ganjiang have higher $^{87}Sr/^{86}Sr$ ratios but lower εNd values (Fig. 4).

Table 2 Major element composition of the sediments in the Yangtze River

		Al_2O_3	CaO	Fe_2O_3	K_2O	MgO	MnO	Na_2O	P_2O_5	TiO_2	SiO_2	CIA
1	Tuotuohe	12.37	12.82	5.69	2.52	2.56	0.10	1.61	0.24	0.81	60.91	60.66
2	Jinshajiang	12.45	10.46	9.08	1.95	4.29	0.11	1.51	0.30	1.88	58.07	63.69
3	Shigu	10.62	8.23	4.89	1.70	2.78	0.07	1.90	0.21	0.85	68.53	56.69
4	Panzhihua 1	12.65	9.58	7.75	2.02	4.34	0.10	1.70	0.26	1.38	59.80	61.92
5	Yalongjiang	15.61	4.44	12.65	2.15	5.19	0.21	1.96	0.34	2.81	54.88	63.95
6	Panzhihua 2	14.63	6.58	9.85	2.06	4.40	0.14	1.70	0.32	2.43	57.78	65.15
7	Yibin 1	12.34	9.64	9.75	2.51	6.80	0.14	1.32	0.30	2.03	55.09	63.59
8	Daduhe	12.96	9.09	7.36	2.55	6.06	0.10	2.20	0.30	1.25	58.24	56.45
9	Minjiang	15.44	4.54	6.57	2.75	3.03	0.08	2.05	0.31	0.86	64.35	61.37
10	Yibin 2	13.15	13.21	7.42	2.75	6.58	0.10	1.32	0.26	1.20	53.65	64.21
11	Chongqing 1	12.87	2.58	15.45	2.05	2.65	0.31	1.63	0.41	2.06	60.47	62.96
12	Jialingjiang	14.71	4.01	6.53	2.65	2.45	0.07	1.66	0.24	0.93	66.62	63.77
13	Chongqing 2	11.87	12.24	7.94	2.21	5.18	0.13	1.64	0.28	1.44	57.14	60.38
14	Fuling 1	12.97	11.46	9.98	2.49	6.21	0.13	1.31	0.32	2.01	52.96	64.97
15	Wujiang	18.06	6.83	8.65	3.24	3.18	0.12	0.53	0.27	1.03	58.14	77.50
16	Fuling 2	13.53	3.05	6.83	2.40	3.20	0.08	1.66	0.22	1.23	67.39	62.63
17	Badong	19.53	1.53	8.16	3.05	1.74	0.12	0.82	0.11	0.91	63.85	76.46
18	Yichang	13.26	20.19	6.42	2.61	4.43	0.10	1.23	0.27	0.84	50.29	65.81
19	Yueyang 1	11.61	6.27	6.96	2.08	3.96	0.09	1.60	0.25	1.59	65.15	60.70
20	Yuanjiang	13.37	0.81	4.80	2.69	1.87	0.06	0.93	0.15	0.88	74.25	69.14
21	Xiangjiang	20.55	0.26	9.27	2.90	1.48	0.11	0.59	0.28	1.08	63.63	80.14
22	Yueyang 2	12.08	3.04	6.58	2.22	3.13	0.08	1.29	0.22	1.34	70.00	64.48
23	Wuhan 1	17.17	3.36	8.36	2.90	3.64	0.10	1.32	0.28	1.29	61.32	69.60
24	Hanjiang	15.90	4.43	8.51	2.61	4.04	0.11	1.98	0.29	1.21	60.74	62.97
25	Wuhan 2	17.05	3.17	8.43	2.90	3.95	0.41	1.45	0.26	1.28	60.93	68.24
26	Jiujiang	14.52	4.31	7.79	2.53	4.00	0.11	1.54	0.24	1.45	63.71	65.01
27	Ganjiang	14.10	0.43	5.09	3.01	0.94	0.06	0.71	0.14	0.90	74.33	71.50
28	Hukou	13.22	9.99	12.45	2.27	8.76	0.24	1.68	0.38	0.99	50.73	62.31
29	Nanjing	10.28	8.15	12.13	1.67	4.32	0.16	1.50	0.45	3.20	58.50	60.35
30	Changxing	12.38	5.67	6.48	2.23	4.03	0.08	1.92	0.28	1.28	65.60	58.60

Discussion

Sedimentary sorting

Because Al_2O_3 or K_2O concentrations are largely controlled by the abundance of micas, clays, and feldspar, particularly potassium feldspar in case of K_2O, the lack of correlation between SiO_2 and Al_2O_3 or K_2O indicates that there is apparently no simple relationship between the amount of quartz in the sand and the abundance of feldspar. On the other hand, Fe_2O_3 and MgO are largely held in mafic, heavy minerals, such as pyroxenes and amphiboles, as well as iron oxides. It is perhaps not surprising that we see a steady decrease in these mafic-related elements as the total amount of quartz increases. These negative correlations therefore represent a dilution trend by quartz. Because the total amount of quartz in the sediment reflects not only the composition of the sources but also the sorting of the sediment as a result of current activity, and the effects of chemical weathering, it seems unlikely that we can use the concentrations of major elements as a provenance proxy, unless the sorting process can be accounted for (e.g., Garzanti et al. 2008). Great care would have to be taken in doing this because this could change both with time during the seasonal flooding and ebb of the river, as well as along the length of the river channel and across the channel with depth. This would be hard to do even in a modern river and seems unlikely to yield any sensible result when applied to older deposits.

The sediment composition is strongly influenced by local sorting of minerals, as a result of current activity both across the channel and in meanders where the current velocity changes rapidly and results in local concentration or

Table 3 Trace element composition of the sediments in the Yangtze River

Samples	Sc	Ti	V	Cr	Co	Ni	Rb	Sr	Y	Zr	Nb
Tuotuohe	5.97	1988.27	46.15	45.25	5.16	16.11	61.20	189.88	13.41	346.04	5.66
Jinshajiang	9.55	6352.46	135.79	115.41	14.83	39.03	42.96	176.50	29.50	1271.48	15.28
Shigu	11.81	5770.17	113.06	84.26	12.28	31.51	48.65	172.28	30.63	655.11	13.56
Panzhihua 1	5.92	8906.07	187.85	206.07	20.68	82.82	59.77	212.66	26.43	491.92	21.58
Yalongjiang	8.26	17752.43	253.91	134.77	34.54	69.61	35.13	182.18	35.18	719.90	27.02
Panzhihua 2	5.28	16150.15	314.23	199.79	29.41	77.42	18.29	198.64	31.17	669.88	24.66
Yibin 1	3.51	13501.08	220.83	170.60	22.26	50.70	85.75	180.15	31.28	967.38	26.93
Daduhe	5.64	8161.48	157.60	125.41	15.81	43.02	52.48	202.43	42.94	1066.66	30.12
Minjiang 1	8.15	5714.67	141.56	79.69	14.21	39.19	21.33	147.92	28.02	444.22	16.05
Yibin 2	5.83	7733.59	178.70	101.48	19.19	49.41	45.90	183.60	23.18	322.45	17.88
Chongqing 1	16.32	13889.48	248.35	97.02	23.88	39.51	48.51	65.61	57.23	1284.19	30.09
Jialingjiang	10.14	6452.94	137.38	124.50	12.88	37.07	28.15	125.75	35.22	1128.31	17.88
Chongqing 2	5.93	8734.99	152.28	132.52	16.62	35.47	40.56	179.38	25.66	955.23	20.40
Fuling 1	21.05	16803.91	267.87	196.23	25.32	62.18	109.89	234.58	39.60	850.64	29.67
Wujiang	10.48	5924.52	155.52	85.13	17.34	46.09	22.87	106.42	25.61	295.34	19.66
Fuling 2	10.03	8031.61	147.71	103.73	15.11	38.30	31.20	98.81	33.30	797.32	20.31
Badong	11.63	5972.17	169.45	90.46	24.38	49.21	51.25	68.88	16.36	267.32	17.52
Yichang	3.97	4981.18	126.59	79.90	15.39	44.86	43.01	264.56	12.68	313.54	13.67
Yueyang 1	17.53	10896.68	195.09	113.91	19.76	48.58	116.77	169.30	33.27	523.93	23.41
Yuanjiang	7.65	5719.15	107.50	66.35	9.80	26.13	46.03	50.75	26.45	592.06	18.02
Xiangjiang	18.38	8477.10	202.11	139.69	18.10	59.31	195.66	73.13	43.33	1149.21	26.60
Yueyang 2	10.27	9020.72	143.59	110.77	15.47	38.21	39.49	98.18	37.90	771.32	23.34
Wuhan 1	10.08	7707.60	171.55	100.17	18.21	48.04	16.97	80.51	27.16	395.24	20.37
Hanjiang	6.32	7223.73	180.99	73.31	22.99	46.94	19.97	133.61	35.09	471.24	20.84
Wuhan 2	7.68	7962.05	182.54	98.35	17.67	47.93	21.65	83.11	27.95	400.50	21.63
Jiujiang	7.96	8957.52	170.59	98.47	18.57	44.53	31.42	102.18	31.77	544.97	22.30
Ganjiang	6.09	5900.86	80.35	48.15	7.68	19.17	105.37	43.86	38.20	971.55	28.74
Hukou	2.65	6043.32	170.45	99.28	44.42	82.55	89.58	157.36	31.77	463.21	16.90
Nanjing	9.04	15785.47	207.20	238.47	14.80	38.31	65.59	207.21	74.69	3366.28	38.35
Changxing	6.29	9014.45	148.76	107.62	15.47	84.35	37.11	172.09	45.52	1147.71	24.68

dilution of heavy minerals, so that some geochemical characteristics are controlled mostly by local hydrodynamic processes rather than by chemical weathering or source composition.

We assess the effect that the presence of heavy minerals has on sediment chemistry by plotting key ratios against one another. Figure 5a shows a plot of Th/Al against Zr/Al. In this case, Al is used as a normalizing element, while Th is hosted in heavy minerals, especially in monazite (e.g., Ni et al. 1995), which is often associated with felsic intrusive rocks. Zr is enriched in zircon, which is also often associated with monazite. This plot (Fig. 5a) shows a positive correlation, suggesting that sediments that are rich in monazite are also rich in zircons, as might be expected from currents concentrating these dense minerals. Figure 5b, c shows the relationship between heavy mineral concentration, as represented by Th/Al, and the relative enrichment in LREE and HREE, as proxied by La/Sm and Tb/Yb. Yang and Wang (2011) argued that the LREEs primarily reside in clay minerals, while Garzanti et al. (2011) showed that monazite and allanite are also very rich in these elements. In contrast, HREEs are generally concentrated in certain heavy minerals, especially xenotime and zircon (e.g., Garzanti et al. 2011). The HREE-enriched heavy minerals significantly influence the REE compositions, reflecting the control of provenance (e.g., Rollinson 2013). We note that there is a poorly positive correlation with LREE and a negative correlation with HREE, which suggests that the LREE chemistry is partly controlled by the presence or absence of key heavy minerals, especially monazite or zircon, which in turn is controlled both by provenance and

Table 4 Trace element composition of the sediments in the Yangtze River

Samples	Cs	Ba	Hf	Ta	Pb	Th	U	La	Ce	Pr	Nd
Tuotuohe	33.48	344.12	9.39	0.51	35.21	9.74	2.28	25.49	50.90	5.67	21.05
Jinshajiang	3.34	431.12	29.43	1.23	26.73	12.66	5.65	39.62	81.95	9.32	34.89
Shigu	3.68	347.83	15.94	1.09	19.72	11.77	3.47	38.55	79.27	8.81	32.55
Panzhihua 1	4.85	464.53	12.16	1.51	27.73	7.19	3.31	37.22	78.54	8.86	33.84
Yalongjiang	4.38	1042.56	16.75	1.93	47.35	12.40	3.90	87.02	140.34	15.22	53.32
Panzhihua 2	4.92	427.76	15.61	1.74	24.87	8.12	3.59	41.38	88.21	10.11	39.01
Yibin 1	5.31	1178.82	21.96	1.73	86.48	8.39	4.57	48.82	100.45	11.07	41.76
Daduhe	2.34	456.18	23.50	2.47	55.73	19.67	10.19	56.79	107.09	12.74	46.46
Minjiang 1	4.65	505.81	11.29	1.29	23.61	10.85	2.83	39.77	80.14	9.20	34.42
Yibin 2	1.03	1074.33	9.07	1.36	60.83	10.32	4.35	39.23	81.41	9.02	34.34
Chongqing 1	4.68	358.44	32.02	2.38	21.65	22.49	7.15	73.90	131.94	16.42	63.03
Jialingjiang	4.96	756.74	25.71	1.36	23.50	16.10	3.43	56.35	105.34	12.82	46.24
Chongqing 2	1.07	800.32	22.42	1.29	44.14	10.31	4.23	45.95	95.25	9.71	36.57
Fuling 1	6.77	1119.80	24.71	2.00	81.77	24.38	6.36	68.01	135.52	15.11	57.24
Wujiang	6.31	566.85	6.87	1.40	36.06	10.05	3.38	35.28	79.81	8.45	31.71
Fuling 2	3.99	329.41	21.61	1.60	20.12	15.81	4.40	50.23	99.98	11.71	44.16
Badong	8.85	420.29	7.04	1.32	34.46	7.24	3.23	27.10	72.31	6.87	25.89
Yichang	1.15	455.99	7.95	0.96	47.99	8.72	4.09	34.53	76.50	7.86	29.80
Yueyang 1	7.11	569.57	14.62	1.62	50.25	17.72	4.65	51.09	107.43	11.85	45.67
Yuanjiang	5.48	512.91	14.43	1.36	28.29	8.50	3.19	31.46	64.23	7.30	27.01
Xiangjiang	24.61	831.80	33.05	2.55	189.50	37.43	10.37	65.80	136.58	14.90	56.00
Yueyang 2	5.77	396.93	22.10	2.01	44.79	19.15	5.26	56.45	113.87	12.55	47.87
Wuhan 1	5.01	383.33	10.30	1.64	46.70	10.44	2.97	41.03	84.44	9.54	35.35
Hanjiang	3.85	554.83	11.40	1.48	30.07	11.14	2.81	43.85	100.37	10.66	40.06
Wuhan 2	5.38	386.41	10.01	1.60	33.08	10.36	2.76	40.01	80.96	9.71	36.72
Jiujiang	4.85	367.64	14.18	1.60	36.52	12.61	3.61	45.72	93.33	10.89	40.93
Ganjiang	11.72	312.62	25.78	3.36	39.18	19.74	5.83	47.33	98.18	11.03	39.11
Hukou	7.17	595.00	11.86	1.26	73.31	9.72	4.38	50.30	126.50	12.16	47.06
Nanjing	3.90	373.04	82.84	3.39	56.16	31.31	12.05	103.11	202.50	23.37	87.56
Changxing	4.47	298.53	29.98	1.93	17.85	19.97	5.80	70.35	132.72	16.03	59.50

current sorting. The HREE is apparently less controlled by heavy mineral abundance, at least as tracked by Th/Al, but variations in HREE enrichments are quite small compared to LREEs. We note that there is no simple trend between the headwaters and the river mouth in these chemical ratios and that local hydrodynamic processes dominate in controlling heavy mineral abundance, consistent with the findings of Garzanti et al. (2008) in Himalayan rivers. Figure 5d demonstrates a negative correlation between the abundance of heavy minerals and enrichment in high-field strength elements (HFSE). Samples in the downstream area tend to be the richest in heavy minerals and these show relatively little HFSE enrichment.

We now investigate the relationship between grain size and bulk sediment chemistry by examining the relationship between SiO_2/Al_2O_3 and REEs and HFSEs (Fig. 6). SiO_2/Al_2O_3 is a proxy for sand/clay because these two elements are preferentially enriched in quartz and clay minerals, respectively. Yang et al. (2002) demonstrated that REEs were more abundant in finer-grained sediment. However, we found little linkages between Si/Al and total REE concentrations. In fact, we noted a slight, but poorly defined positive correlation between more sandy sediment and higher REE contents. This mismatch with the conclusion of Yang et al. (2002) may reflect variation within our more limited range of grain sizes (<63 μm) and higher abundance of monazite, allanite, and to the lesser extent xenotime in the coarser fraction that they considered. However, Fig. 6a shows that there is positive correlation between the degree of LREE enrichment and the presence of quartz within the sediment, with the exception

Table 5 Trace element composition of the sediments in the Yangtze River

Samples	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Tuotuohe	3.79	0.75	3.11	0.41	2.64	0.56	1.68	0.25	1.69	0.28
Jinshajiang	6.62	1.35	6.01	0.86	6.03	1.31	4.00	0.59	3.61	0.65
Shigu	6.27	1.27	5.64	0.79	5.56	1.21	3.46	0.51	3.22	0.52
Panzhihua 1	6.51	1.45	5.89	0.81	5.66	1.18	3.37	0.51	2.92	0.46
Yalongjiang	8.84	1.85	7.59	1.06	6.95	1.45	4.13	0.62	3.74	0.61
Panzhihua 2	7.40	1.64	6.53	0.89	6.14	1.27	3.67	0.53	3.26	0.53
Yibin 1	7.85	1.74	6.83	0.94	6.64	1.43	4.06	0.59	3.73	0.59
Daduhe	9.13	1.60	8.26	1.17	8.39	1.77	5.17	0.76	4.79	0.80
Minjiang 1	6.57	1.33	5.75	0.79	5.32	1.16	3.34	0.50	3.04	0.49
Yibin 2	6.69	1.57	5.62	0.78	5.01	1.08	3.20	0.46	2.82	0.45
Chongqing 1	12.19	2.87	10.76	1.52	10.72	2.40	6.99	1.03	6.62	1.08
Jialingjiang	8.34	1.43	7.18	0.97	6.75	1.44	4.27	0.64	3.94	0.63
Chongqing 2	7.06	1.48	5.94	0.85	5.53	1.23	3.47	0.51	3.08	0.53
Fuling 1	10.82	2.31	7.92	1.10	7.00	1.52	4.69	0.68	4.62	0.75
Wujiang	6.12	1.19	5.33	0.73	4.96	1.06	2.97	0.44	2.71	0.43
Fuling 2	8.57	1.65	7.12	0.96	6.51	1.39	4.13	0.60	4.11	0.68
Badong	5.34	1.07	4.60	0.66	4.58	0.99	2.87	0.41	2.59	0.41
Yichang	5.79	1.23	4.83	0.66	4.39	0.90	2.49	0.34	1.94	0.29
Yueyang 1	8.59	1.76	6.57	0.90	5.99	1.31	3.85	0.58	3.68	0.62
Yuanjiang	5.06	0.95	4.67	0.69	5.15	1.14	3.46	0.52	3.22	0.51
Xiangjiang	10.66	1.67	8.33	1.15	7.90	1.76	5.50	0.85	5.92	0.98
Yueyang 2	8.92	1.62	7.82	1.08	7.46	1.64	4.70	0.74	4.71	0.77
Wuhan 1	6.76	1.43	5.83	0.82	5.64	1.20	3.40	0.51	3.13	0.50
Hanjiang	7.81	1.56	7.00	0.98	6.85	1.43	4.12	0.58	3.63	0.59
Wuhan 2	7.11	1.45	5.99	0.81	5.62	1.19	3.53	0.54	3.21	0.51
Jiujiang	7.87	1.63	6.85	0.94	6.33	1.39	4.02	0.57	3.60	0.57
Ganjiang	7.29	0.78	6.59	1.00	7.42	1.72	5.25	0.83	5.31	0.91
Hukou	9.17	1.93	8.17	1.10	7.42	1.56	4.32	0.60	3.64	0.58
Nanjing	16.26	2.67	14.42	1.99	14.74	3.31	10.04	1.57	9.84	1.68
Changxing	11.13	1.99	9.39	1.28	8.75	1.93	5.60	0.86	5.35	0.89

of the Yalongjiang, which is strongly enriched, but relatively sand-poor. Figure 6b demonstrates that there is an approximate negative correlation between enrichment in HREEs and the abundance of sand, the opposite trend of that seen for the LREEs. Since HREEs are very concentrated in xenotime and to a lesser extent zircon (e.g., Garzanti et al. 2011), our observations would suggest that xenotime is more abundant in the finer sediment. Likewise, enrichment in HFSEs shows a negative correlation with less enrichment associated with sandier sediment (Fig. 6c). We note that there is no clear downstream development in any ratio, which we would expect if transport was dominating this relationship. If the mainstream was experiencing a simple development and most of the sediment was being supplied by a short upstream interval of the river, then it is overwhelmed by the addition of new sediment from the tributaries, or from local sources, during the journey between the headwaters and the river mouth.

REEs' composition is all influenced by sedimentary sorting, while HREEs and HFSE enrichment are less controlled by the abundance of heavy minerals compared to the LREEs, but there is no clear trend from the upstream to downstream along the drainage, indicating that the chemical ratios are more affected by hydrodynamic processes (i.e., sorting) rather than provenance.

Chemical weathering

In order to understand how chemical weathering intensity varies within the Yangtze, we employ several proxies, which have been applied in many situations and which are widely believed to reflect of the alteration of fresh

Table 6 Sr-Nd isotope composition of the sediments in the Yangtze River

No.	Samples	$^{143}Nd/^{144}Nd$	1σ	Epsilon Nd	$^{87}Sr/^{86}Sr$	1σ
1	Tuotuohe	0.512092	5	−10.65	0.73	7
2	Jinshajiang	0.512082	3	−10.85	0.71	11
3	Shigu	0.512090	3	−10.69	0.71	4
4	Panzhihua 1	0.512182	3	−8.9	0.71	4
5	Yalongjiang	0.512216	3	−8.23	0.71	4
6	Panzhihua 2	0.512185	4	−8.84	0.71	3
7	Yibin 1	0.512060	3	−11.28	0.72	8
8	Minjiang 1	0.512042	3	−11.63	0.72	6
9	Daduhe	0.512200	2	−8.54	0.71	3
10	Yibin 2	0.512089	3	−10.71	0.72	4
11	Chongqing 1	0.512038	2	−11.7	0.73	4
12	Jialingjiang	0.511860	3	−15.18	0.71	3
13	Chongqing 2	0.511956	3	−13.3	0.71	3
14	Wujiang	0.512025	3	−11.96	0.72	4
15	Fuling	0.512003	3	−12.39	0.72	5
16	Badong	0.512065	6	−11.18	0.72	2
17	Yichang	0.512038	4	−11.7	0.71	7
18	Yueyang	0.512013	4	−12.19	0.72	7
19	Yuanjiang	0.511916	3	−14.08	0.74	5
20	Wuhan 1	0.512037	4	−11.72	0.72	4
21	Hanjiang	0.512088	2	−10.73	0.72	8
22	Wuhan 2	0.512069	4	−11.1	0.72	6
23	Jiujiang	0.512063	4	−11.22	0.72	5
24	Ganjiang	0.511927	3	−13.87	0.74	4
25	Hukou	0.512087	3	−10.75	0.72	6
26	Nanjing	0.512028	5	−11.9	0.71	10
27	Changxing	0.512048	3	−11.51	0.72	7

rock particles. K_2O/Al_2O_3 is widely interpreted as a proxy for alteration because potassium is a water-soluble element that is released during the breakdown of potassium feldspar and has been applied to the study of sediments on East and Southeast Asian continental margins (e.g., Clift et al. 2008; Hu et al. 2012). In addition, we employ the classic proxy Chemical Index of Alteration (CIA), which also involves these elements, but also takes into account Na and Ca (e.g., Nesbitt and Young 1982). CIA was developed for use in soil profiles, but the proxy has been widely applied to sediments in rivers and in drill cores (e.g., Liu et al. 2007; Wan et al. 2010; Wan et al. 2009). In Fig. 7, we show how these proxies relate to grain size, as proxied by SiO_2/Al_2O_3. In Fig. 7a, we see that K_2O/Al_2O_3 shows a rough negative relationship with SiO_2/Al_2O_3 implying that sandier sediments are generally less altered than mud-rich sediments. Figure 7b shows the same relationship with CIA, although this is generally better correlated, with the exception of two of the tributaries, the Ganjiang and Yuanjiang. As with the other proxies we have examined, there is no clear correlation between the location of the sample within the Yangtze and the degree of alteration or the grain size. We do see however that the grain size is a primary control on the alteration proxy and that unless this can be accounted for the application of weathering proxies to river sediments is of limited use in understanding weathering in the system.

Figure 8 shows the calculated CIA values for the different samples inside a triangular diagram and demonstrates how our river samples compare with other major rivers. We note that the Yangtze plots between sediments from the Pearl River and from the Yellow River, with the Yellow River samples showing lower CIA values, indicating that are less altered. This is perhaps not surprising because the climate of the Yellow River basin is generally colder and drier than the Yangtze, while the Pearl River basin is warmer and wetter, which would favor more chemical alteration if transport times are similar (e.g., West et al. 2005). We note that the Yangtze and the Pearl Rivers have higher CIA and are more altered than sediment from the Ganges and Yellow Rivers. Although the Ganges River lies in a warm and wet environment, it derives its sediment from the tectonically active Himalaya and consequently has relatively unaltered sediments. The low alteration state also reflects rapid transport through the flood plains where most of the chemical weathering occurs (e.g., Lupker et al. 2012).

We further reconstruct the development in chemical weathering in the Yangtze from source to sink using both CIA and K_2O/Al_2O_3 (Fig. 9). It is interesting to note that although there are some similarities, these proxies do not give identical images of the weathering state in the river. The solid line represents the development of alteration state in the mainstream, with individual red squares showing the state of the major tributaries. CIA remains relatively stable through much of the mainstream, although there is one unusual point of very high alteration at Badong. Given its isolation, it is questionable whether this is a very representative data point, although why is not apparent. We also note a rise in the degree of alteration as tracked by CIA between Yueyang and the confluence with the Hanjiang, followed by a steady decrease in alteration from that point to the river mouth (Fig. 9a). The rise could be explained by sediment addition from the Yuanjiang and Xiangjiang, as could the initial decrease downstream from the Hanjiang but the continued fall cannot be caused by influx from other tributaries like the Ganjiang. The trend implies either that we were sampling progressively sandier material downstream (Fig. 9c) or that less altered material is being added to the mainstream from

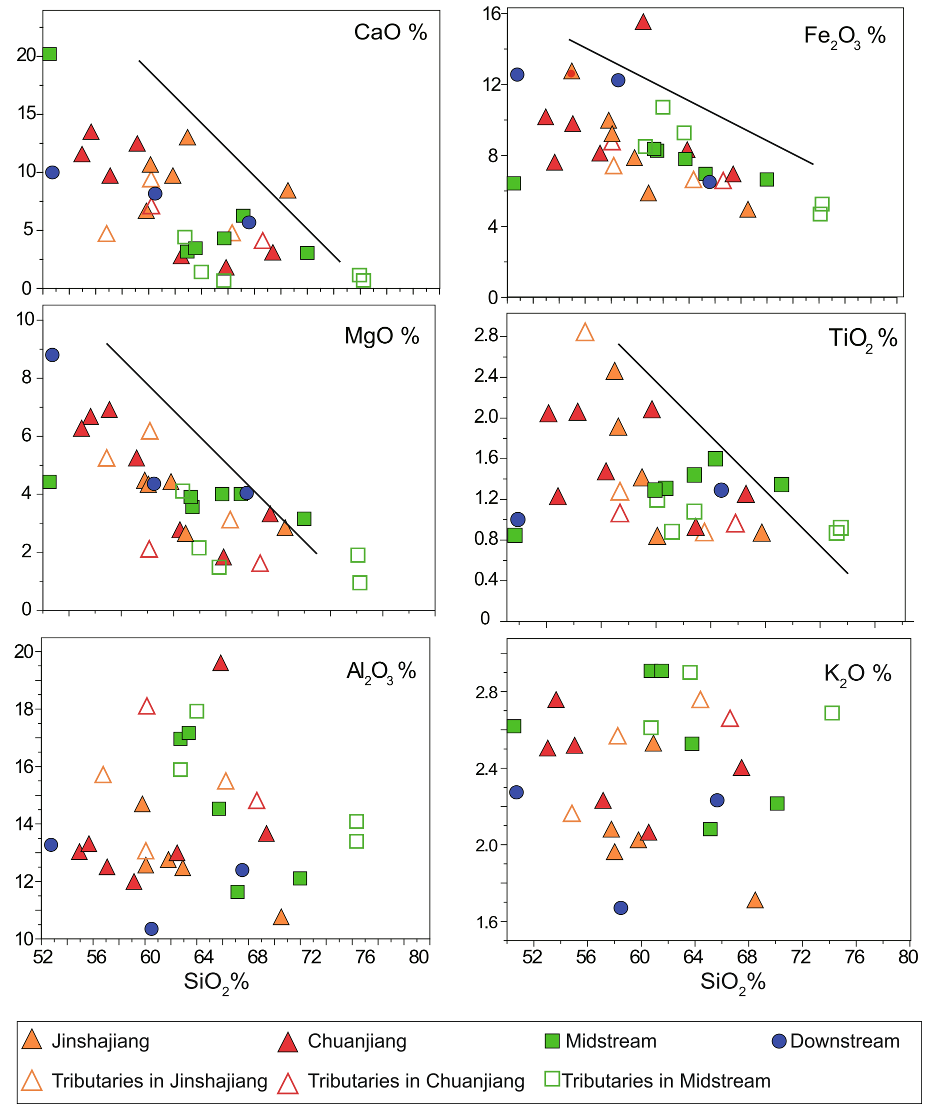

Fig. 2 Plots of major elements versus silica contents. Diagrams showing CaO, Fe_2O_3, MgO, and TiO_2 define negative correlations with SiO_2

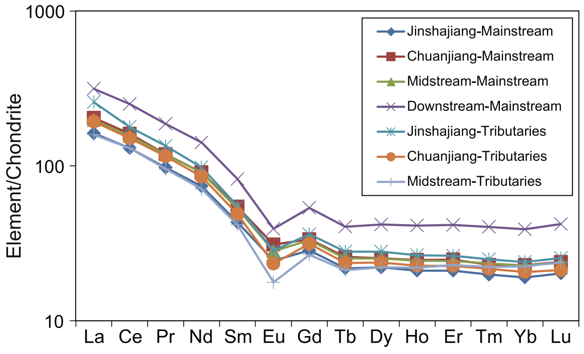

Fig. 3 Chondrite normalized REE pattern of sediments collected from different segments of the Yangtze River. The values are the average of several samples within a segment. Chondrite values from (e.g., Sun and McDonough 1989)

other sources, such as from river terraces. The trend in K_2O/Al_2O_3 (Fig. 9b) is somewhat different in being relatively stable in the lower reaches of the river, reflecting the fact that CIA is also influenced by more mobile Na as well as K. It is interesting to note that according to CIA, most of the river sediment is more altered than the sediment that we find in the river mouth, which is the opposite of what one would expect if transport resulted in more chemical weathering. It is impossible to see how sediment would be become less altered downstream with more transport and without the addition of extra sediment, unless the finer sediments were being progressively less well sampled, perhaps because they are increasingly in suspension and not deposited in the river banks where the sediments were taken. If we consider only K_2O/Al_2O_3, then we can see that the chemical weathering state at the

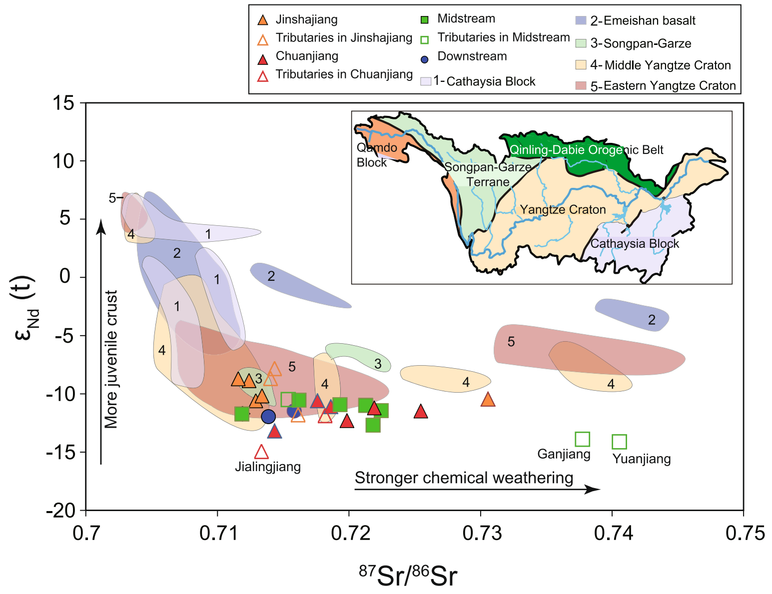

Fig. 4 $^{87}Sr/^{86}Sr$ versus εNd(t) diagram for different geological units within the Yangtze River drainage basin. Data of Eastern Yangtze Craton, Middle Yangtze Craton, Emeishan, and Cathaysia are from GEOROC (*http://georoc.mpch-mainz.gwdg.de/georoc/Start.asp*). The tectonic units map is modified from He et al. (2013a, b). Data from Songpan-Garze are from Cai et al. (2009). Sr-Nd isotopic compositions of sediment from the Yangtze River drainage shows no coherent variation downstream

river mouth is similar to that through much of the mainstream, although the sediments in the uppermost Jinshajiang do seem to be slightly more altered than most of the mainstream, despite the fact that they are close to their source regions. This a little unusual given the cold, dry conditions in the Tibetan Plateau, but higher alteration may reflect slow transport times in the upper reaches, with dilution of sediment downstream by greater supply from fresher sources. There is generally more variability of chemical weathering in the tributaries compared to the

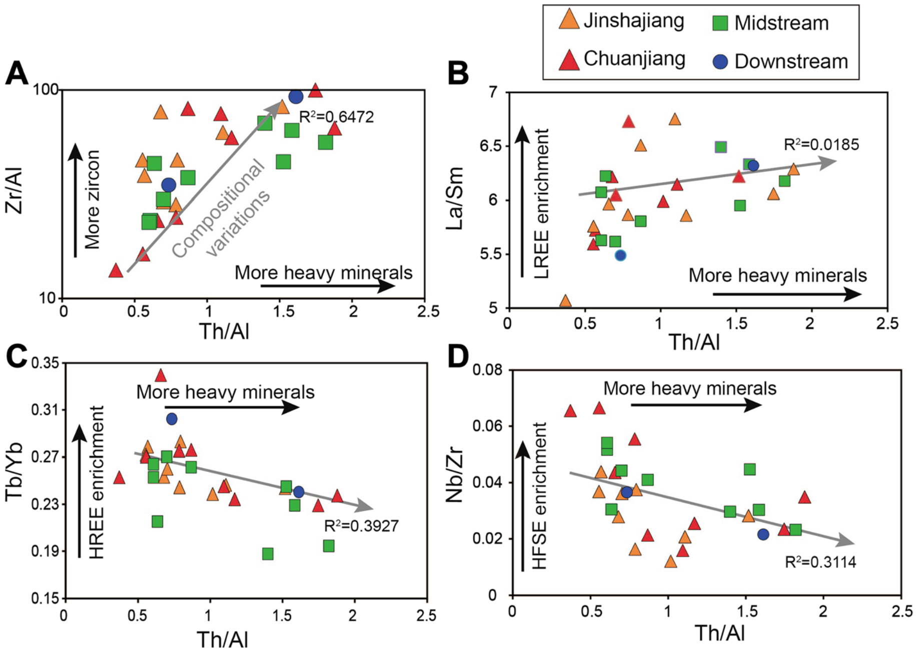

Fig. 5 Variations of trace element ratios of the Yangtze River sediments. **a** Zr/ Al_2O_3 vs. Th/Al, showing enrichment of zircon compared to heavy mineral accumulation. **b** Th/Al vs. La/Sm, indicating the relationship between heavy mineral accumulations and LREE enrichment. **c** Th/Al vs. Tb/Yb, showing heavy mineral accumulations with HREE enrichment. **d** Th/Al vs. Nb/Zr, showing heavy mineral accumulations with HFSE enrichment

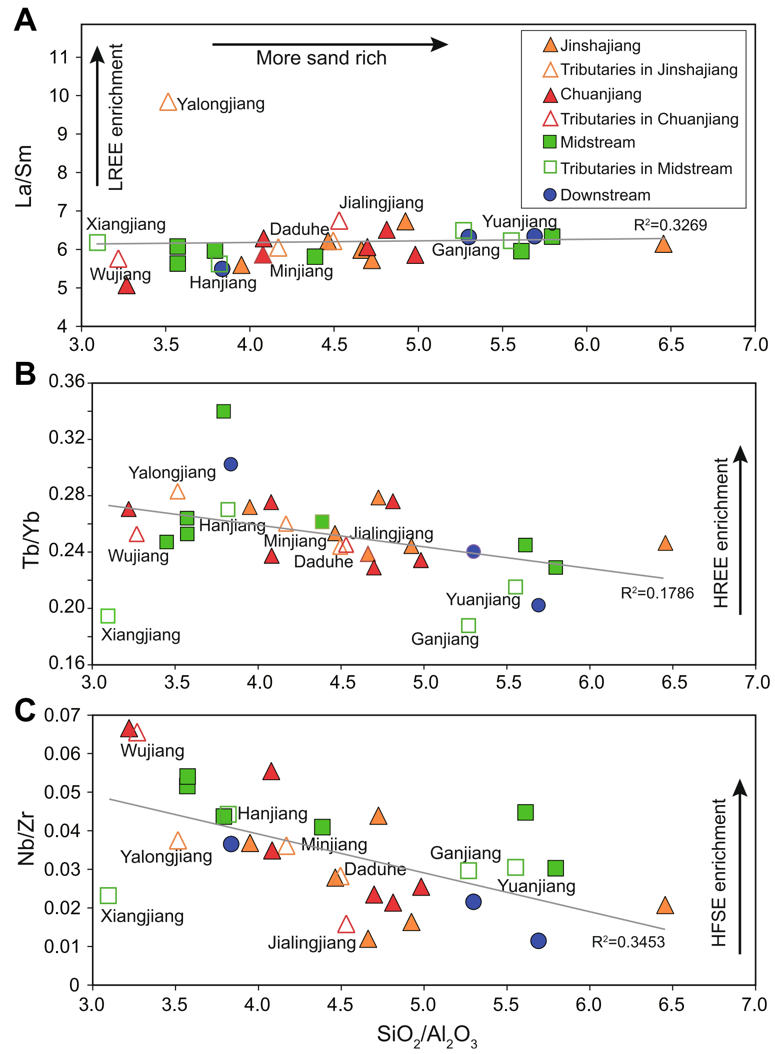

Fig. 6 Plots of SiO_2/Al_2O_3 vs. **a** LREE, **b** HREE, and **c** HFSE, showing the relationship between grain size and REEs

mainstream, especially when considering CIA, and this likely reflects the averaging of sediment within the mainstream and more local heterogeneity within the smaller tributary basins. Nonetheless, it is not clear that transport is having a significant effect on the overall state of weathering in the sands we consider.

We now discuss the effect of chemical weathering on the trace element composition of the sediments. There is no apparent relationship between the degree of chemical alteration and the extent of LREE enrichment. In contrast, Fig. 10 shows that the more altered sediments have higher degrees of enrichment in the HFSEs. Although there are a few exceptions, there is a general positive correlation between CIA and Nb/Zr. There is no link between location within the river basin and the extent of trace element enrichment. This suggests that REE chemistry might be relatively independent of chemical weathering, whereas HFSEs are affected by this process and therefore make relatively poor provenance proxies.

Provenance

We here use Sr-Nd isotopic compositions to understand the source of sediment in the river and the variations in the downstream influx of sediment both from local sources and from the larger tributary basins (Fig. 11). In the upper reaches, εNd values decrease downstream. The upper reaches, including Jinshajiang and Chuanjiang, have higher εNd values, but then decrease, especially from Panzhihua 1 to Chongqing 2, but the mainstream and tributaries in the midstream and downstream segments show lower values, which are not far from the average of εNd values (εNd = −11.4). The εNd values of the river sediments are controlled by the bedrock values of the drainage upstream of the sample point, and the monazite content of the sediments because

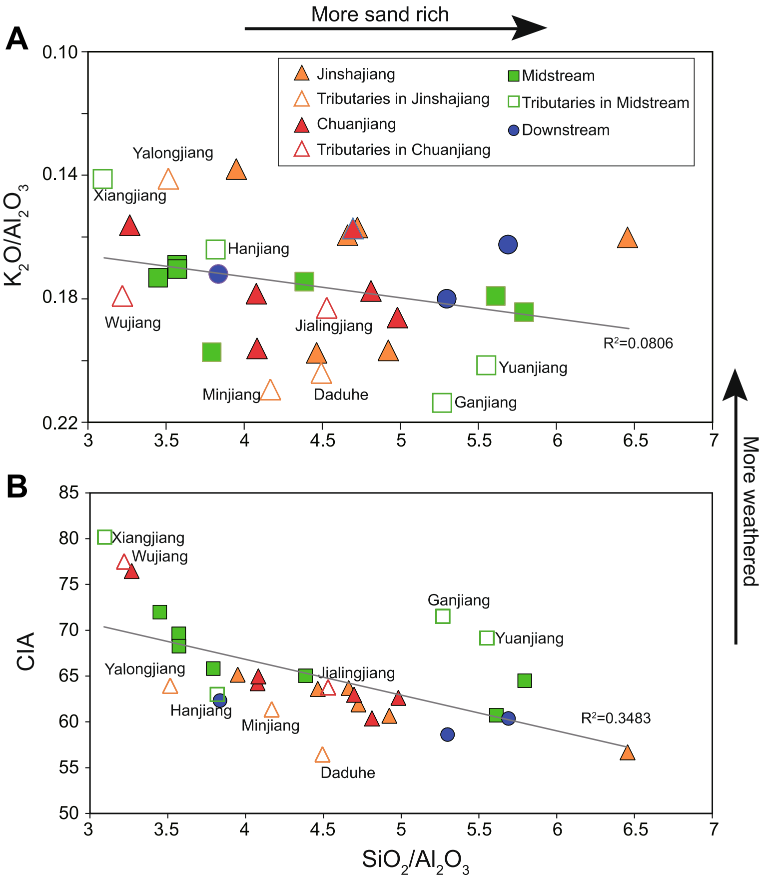

Fig. 7 Plots of SiO_2/Al_2O_3 vs. **a** K_2O/Al_2O_3, **b** CIA, showing links between chemical weathering and grain size for different sections in the Yangtze River

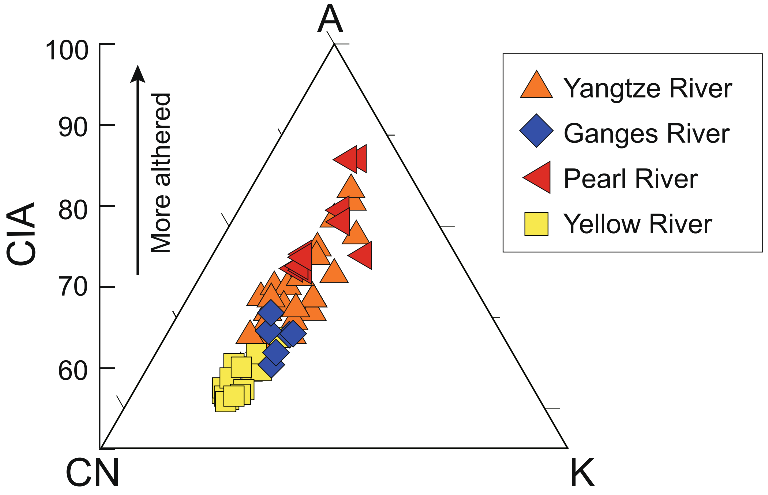

Fig. 8 A-CN-K *triangle plot* showing chemical weathering trends. Samples in the Yangtze River compared with the Ganges (e.g., Singh 2009), Pearl (e.g., Zhang and Wang 2001), and Yellow Rivers (e.g., Li 2003)

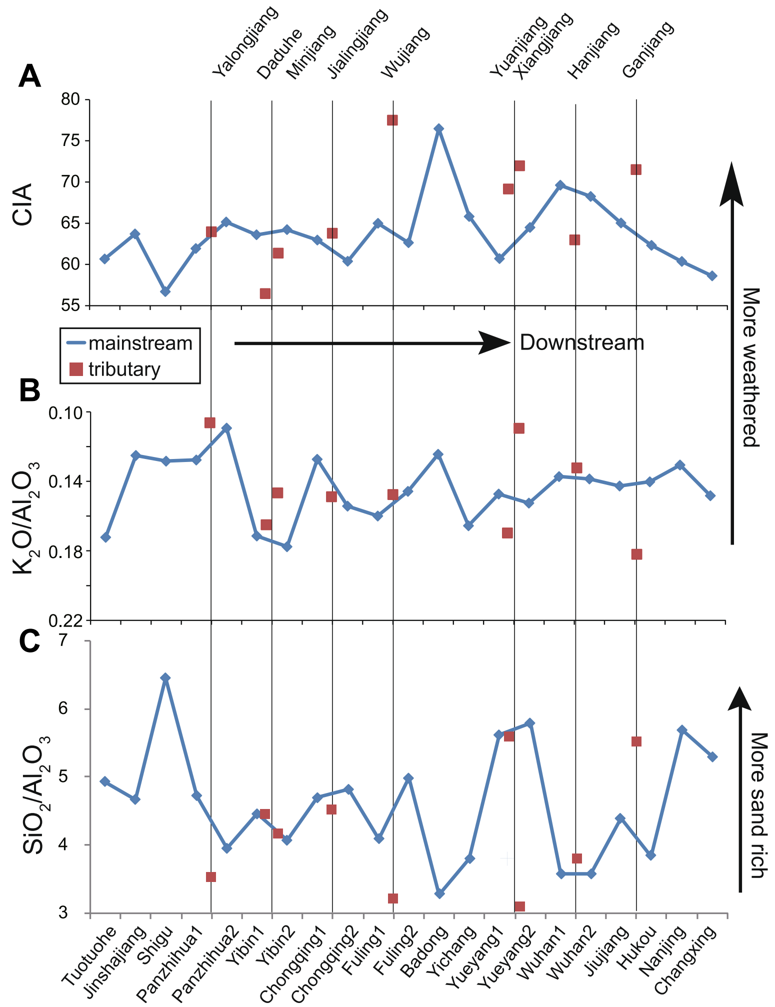

Fig. 9 Downstream variations of **a** CIA and **b** K_2O/Al_2O_3, indicating the evolving chemical weathering change from source to sink. **c** SiO_2/Al_2O_3

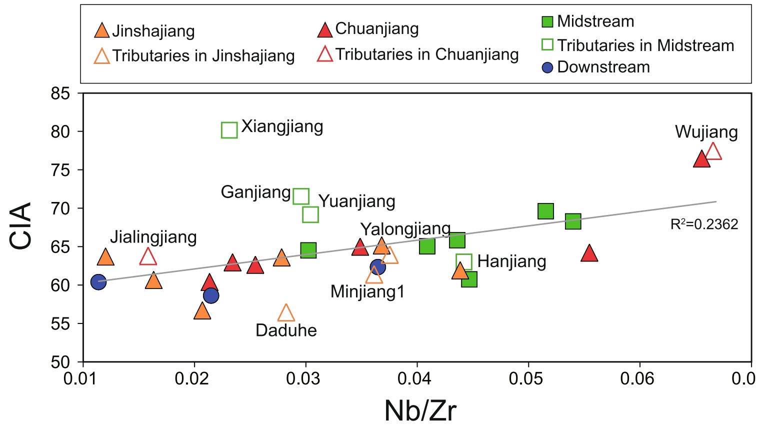

Fig. 10 Diagram showing the relationship between chemical weathering and trace element compositions, CIA vs. Nb/Zr (HFSE enrichment)

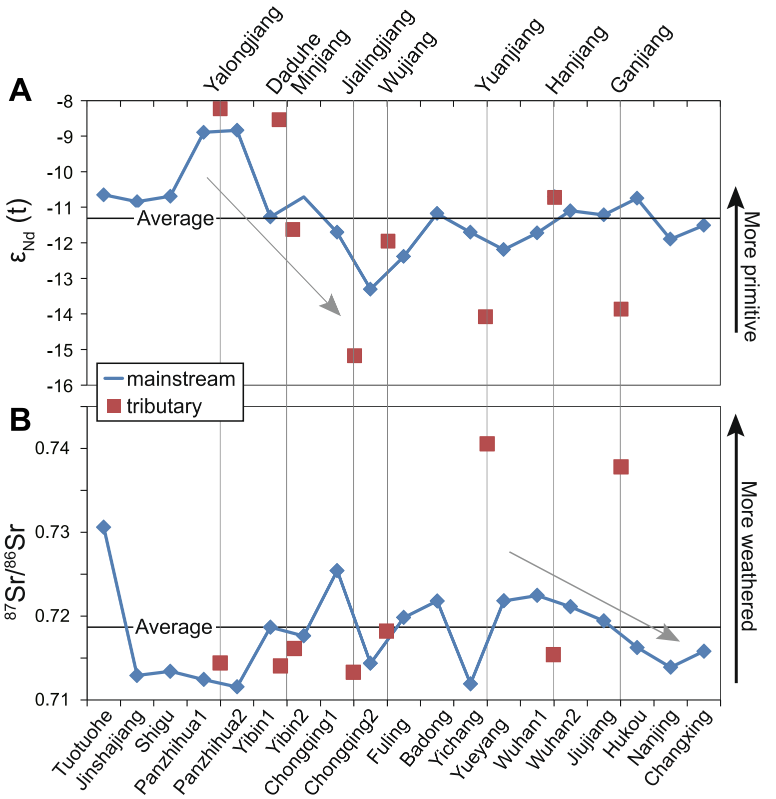

Fig. 11 Downstream variations of Sr-Nd isotopic composition of the mainstream shown as a continuous *blue solid line* and tributaries shown as *red squares*. **a** εNd(t); **b** ^{87}Sr/^{86}Sr

Nd is especially concentrated in this mineral (e.g., Garçon et al. 2014). The Jinshajiang and Chuanjiang segments mainly incise Mesozoic and Cenozoic igneous rocks, as well as a large area of Emeishan basalts, which have high εNd values (e.g., Qi and Zhou 2008; Zhang and Wang 2003). The progressive change in εNd values from Panzhihua 1 to Chongqing 2 implies that the river is picking up a lot of new sediment along that stretch.

The mid-lower reaches mainly drain Quaternary fluvial and lacustrine sediments, together with intermediate-felsic igneous rocks and metamorphic units forming parts of the Yangtze Craton that represents much older crust originally generated at 2.5–2.8 Ga (e.g., He et al. 2013a; Iizuka et al. 2010). The lower εNd values in the downstream compared to the upstream are largely a function of this change in source bedrock and the fact that the river continues to gain sediment as it progresses downstream. Although there are basalts in the middle and lower Yangtze, they have a limited areal extent and do not affect river sediments as significantly as the Emeishan basalts (e.g., Yang et al. 2007). The moderate but steady increase in εNd values from Yueyang to Hukou implies that sediment like and including the Hanjiang must be adding sediment along that stretch and that the Yuanjiang and Ganjiang are not volumetrically significant suppliers. Sr isotope ratios vary substantially from upstream to downstream, which suggests more complex factors influencing their development compared to Nd isotopes, which is consistent with Sr being water mobile and Nd being resistant to change due to alteration. These factors could include grain size, chemical weathering, and seasonal variations, as well as the bedrock Sr isotope compositions (e.g., Goldstein and Jacobsen 1987; Ma and Liu 2001; Mao et al. 2011; Rai and Singh 2007; Tripathy et al. 2011). The ^{87}Sr/^{86}Sr values of the upper mainstream, excluding the very high value at Tuotuohe, are much lower than the midstream and downstream. Values from the tributaries also display the same patterns, with the Yalongjiang, Daduhe, Minjiang, Jialingjiang, and Wujiang having lower ^{87}Sr/^{86}Sr values, whereas the Yuanjiang and Ganjiang are much higher. This pattern reflects erosion of the low ^{87}Sr/^{86}Sr value Emeishan Basalts and younger igneous rocks in the upstream but higher ^{87}Sr/^{86}Sr values in old metamorphic rock sources and more radiogenic Sr isotope silicates in the mid- and lower reaches (Fig. 11).

As discussed above, Sr isotope ratios could vary with grain size. Here we plot ^{87}Sr/^{86}Sr values against the grain size, which is represented by SiO_2/Al_2O_3 (Fig. 12). It is clear that the ^{87}Sr/^{86}Sr values have poor positive correlation with the grain size, a little different from

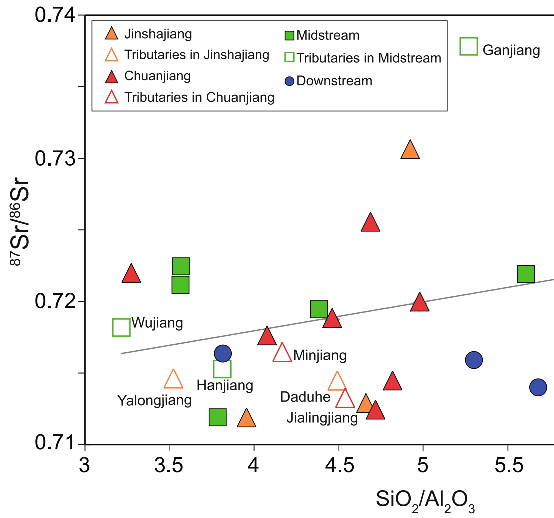

Fig. 12 Diagram showing the relationship between ^{87}Sr/^{86}Sr ratio and grain size

the conclusion made by some other researchers (e.g., Yang et al. 2007). This difference may be attributable to the finer grain size range we used in this study (<63 μm).

Chemical weathering is another factor in controlling the isotopic values in the modern river because unstable feldspar and epidote dominate the sediment Sr budget (e.g., Garçon et al. 2014). The ^{87}Sr/^{86}Sr values in the mid-lower reaches are higher than upstream, consistent with more weathered sediment in the mid-downstream of the Yangtze since alteration tends to drive ^{87}Sr/^{86}Sr to higher values (e.g., Derry and France-Lanord 1996). Like the CIA, the ^{87}Sr/^{86}Sr values imply decreasing alteration in the sediment from Yueyang to the river mouth, although some of this trend is driven by the provenance change implied by the Nd data between Yueyang and Hukou. From Fig. 11a, we can also deduce that the tributaries of the Daduhe, Minjiang, Jialingjiang, and Hanjiang contribute more sediment to the mainstream than the Yuangjiang and Ganjiang because the bulk composition of the river changes substantially downstream of each confluence towards the value of the tributary.

We summarize the Sr-Nd isotope compositions of different units in the Yangtze River drainage (Fig. 4). It is obvious that the Jinshajiang samples match bedrock compositions from the Songpan-Garze Terrane and that the samples in the Chuanjiang are consistent with strong erosion from the middle Yangtze Craton, while the samples from the mid-lower reaches fall between the two and could also reflect additional erosion from the eastern Yangtze Craton. The data are consistent with the Songpan-Garze Terrane, and the Eastern and Middle parts of the Yangtze Craton being the main sources of the Yangtze sediments. In contrast to the evidence from heavy minerals and clay mineralogy (e.g., He et al. 2013b; Yang et al. 2009), the isotope geochemistry data shows that the rocks exposed in the western Yangtze Craton, especially the Emeishan Basalts, are not the main sources of <63 μm sediment to the modern river. Not surprisingly, the river sediments have lower εNd values than the magmatic rocks from the Cathaysia Block, which mostly lies to the South within the Pearl River drainage and is not an important source. Moderate exposures of primitive magmatic rocks within the Yangtze Craton do not influence the bulk composition of the river to a significant degree. Our sediment samples have a relatively restricted range of εNd values but a wide range in ^{87}Sr/^{86}Sr values, which we consider to reflect the influence of chemical weathering in changing the original bedrock composition. We particularly note that the Ganjiang and Yuanjiang have very high ^{87}Sr/^{86}Sr values and are located in the middle-lower reaches of the river where chemical weathering might be strong as a result of slow erosion and transport rates in relatively flat topography and because of the warm and wet monsoonal climate, as indicated by their high CIA values.

The relationship between εNd values and REEs are shown in Fig. 13. The HREE (Nb/Zr) have a rough positive trend with εNd values, while LREE (La/Sm) and HFSE (Nb/Zr) have no association with εNd values. LREE and HFSE composition appears to be relatively unrelated to the average crustal age of the source rocks, whereas the degree of enrichment in HREEs increases as the average crustal age of the bedrock increases because εNd values are linked to the average age of original crustal generation and not to the last magmatic event. Yang et al. (2002) argued that the source rock is the primary control on the REE composition in river sediments but this ignores the effect of hydrodynamic sorting. We now refine this conclusion by showing that the HREEs are influenced by the source rock but that the LREEs

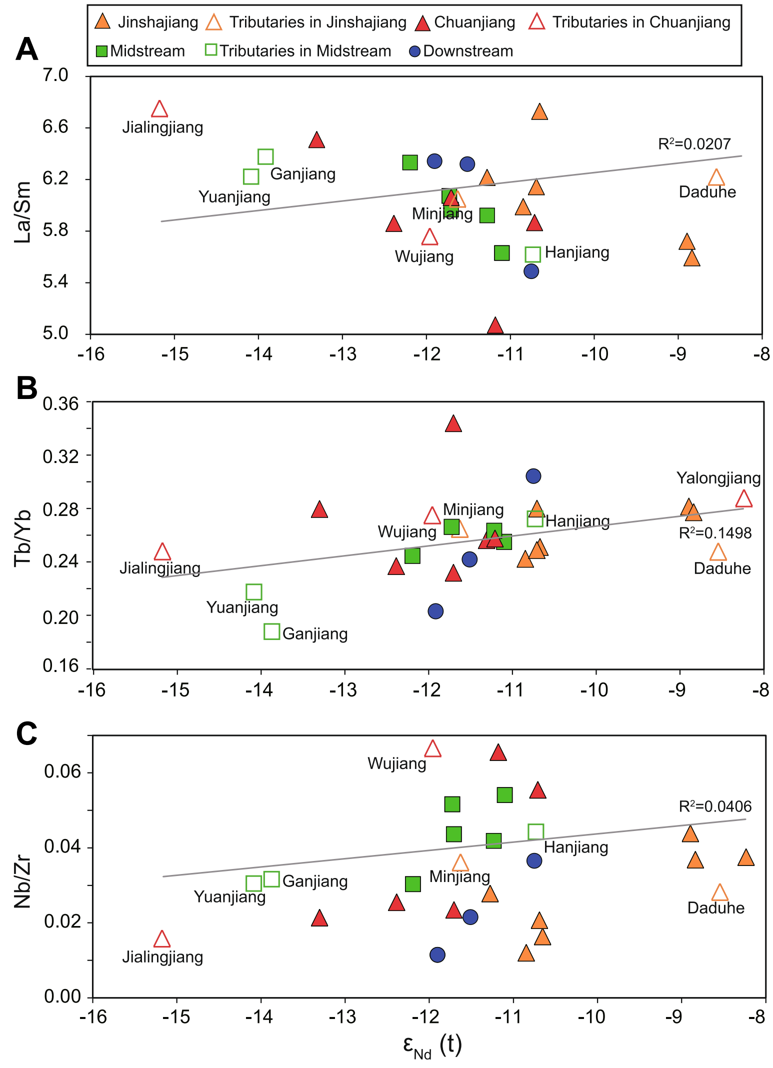

Fig. 13 εNd(t) compared with REEs and HFSEs. **a** La/Sm, **b** La/Yb, and **c** Nb/Zr

and HFSE are not affected. In addition, the fact that many of the tributaries have similar REE chemistries means that the close match between the Jinshajiang and the delta sediments cannot be used to argue that the upper reaches are the dominant source regions.

Yangtze Craton as typical continental crust

We now assess how typical the Yangtze River Basin is of continental crust at the planetary scale by comparing the trace element compositions of sediments in the river with those of average upper continental crust (UCC), as summarized by Rudnick and Fountain (1995). Figure 14a shows the trace elements normalized to the UCC from the mainstream and major tributaries. Both mainstream and tributaries define the same general patterns, with relative Rb and Sr depletion and particularly high Th, U, Zr, Hf, and Ti enrichment. We note that most of the elements lie above the average value of the UCC in both mainstream and tributaries and we suggest that this reflects the fact that the sediments we sample here are more abundant in heavy minerals and clay compared to the average of the UCC because these minerals carry many of the trace elements analyzed here (e.g., Garzanti et al. 2010). The depletions in Rb and Sr are inferred to be the product of intense chemical weathering, because these are soluble elements that have been systematically removed from the sediments during transport, which appears to exceed the provenance influence.

The major element compositions of the average samples normalized to UCC are displayed in Fig. 14b. Although the average sediment has similar SiO_2 and Al_2O_3 contents to the UCC, there is enrichment in Fe_2O_3, MnO, MgO, TiO_2, and P_2O_5, which is consistent with our interpretation that these Yangtze sediments are more concentrated

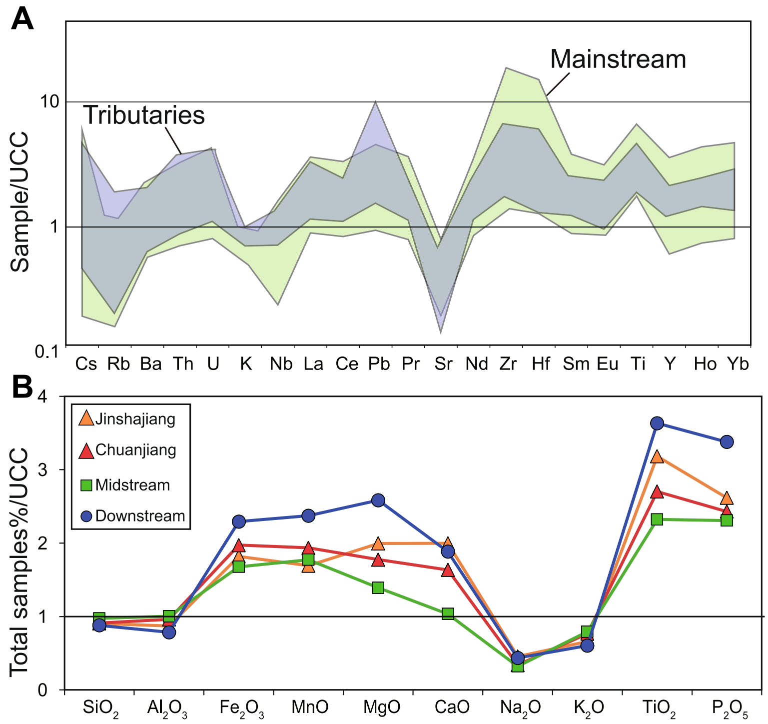

Fig. 14 Trace element normalized to the Upper Continental Crust (UCC) as defined by Rudnick and Fountain (1995). **a** Samples in the mainstream and tributaries; **b** total major element percent of sediments normalized to UCC

in heavy minerals than the average crust. We have no evidence that the Yangtze basin itself is substantially more enriched than might be expected for average crustal values. Depletions in Na_2O and K_2O concentrations are attributed to leaching by chemical weathering, similar to the Rb and Sr noted above. These elements are transported to the ocean in solution (e.g., Yuan et al. 2012). In this study, we only analyze sediment finer than 63 μm, and we inferred that the coarser material may be dominated by quartz, feldspar, and other minerals, which are relatively poor in many trace elements. Our work also did not consider the suspended sediment fraction but only the bedload, which may account for the significant differences between our average compositions and UCC (e.g., Garzanti et al. 2011). This fine-grained bedload sample can be useful for sediment provenance but is not completely representative of the crust being eroded within the basin at the present time.

Conclusions

In this study, we analyzed a series of samples from the mainstream of the Yangtze River, as well as its major tributaries, to see if there were any patterns in the major and trace element chemistry that could be used to constrain provenance and chemical weathering processes within this major river system.

No clear variations in major element chemistry were found between the source and the delta. Within the <63 μm grain size range, we see little linkage between grain size and total REE abundance, while the LREE, HREE, and HFSE show different relationship with the heavy minerals, chemical weathering, and provenance, respectively. Nd isotope data show that the major sources of sediment in the Yangtze appears to be within the lower and middle parts of the Yangtze Craton, as well as in the Songpan-Garze Terrane exposed in Eastern Tibet and Yunnan. There is no simple trend to more chemical weathering downstream in the main river according to the CIA proxy and K/Al values, but the major tributaries do show significant changes.

We conclude that the major and trace element chemistry of the sediments in the Yangtze River can provide important information about the source of the sediment and especially its chemical weathering state, which is crucial for interpreting the marine clastic record of the sedimentary basins in the East China Sea. However, caution needs to be used especially when applying REEs to provenance issues because grain size effects and the sorting of heavy minerals by hydrodynamic processes typically dominate the bulk composition of the sediment. In the East China Sea, this would be especially true because the Yangtze would not be the only source of clastic sediment. Sediment provenance can only be seriously addressed if grain size and sorting issues can be properly corrected for and by using proxies resistant to chemical weathering effects, such as Nd isotopes.

Additional file

Additional file 1: Fig. S1. Compositional maturity plots of sediments in the Yangtze River. Most samples plot in the Wacke and Shale areas, indicating immaturity of the sediments. (PDF 368 kb)

Abbreviations

CIA: Chemical Index of Alteration; HFSE: high-field strength element; HREE: heavy rare earth element; LREE: light rare earth element; REE: rare earth element; UCC: upper continental crust.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

ZHB conceived and designed the study. HMY carried out the experimental study, obtained analytical data, and wrote the manuscript with PC. RT, WWH, and LC collaborated in the sampling collection. All authors read and approved the final manuscript.

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