

Strontium isotopic compositions of dissolved and suspended loads from the main channel of the Yangtze River

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Abstract

The concentrations of Sr and ⁸⁷Sr/⁸⁶Sr isotopic ratios have been measured in the dissolved loads from the main channel of the Yangtze River. The result shows that the Yangtze River mainstream water has considerably higher Sr concentration (202–330 μg kg⁻¹) and slightly lower ⁸⁷Sr/⁸⁶Sr ratio (0.7098–0.7108) than the global average runoff values of dissolved Sr (78 μg kg⁻¹) and ⁸⁷Sr/⁸⁶Sr ratio (0.7119). The ⁸⁷Sr/⁸⁶Sr values of 0.7098–0.7108 in river waters result from the intense weathering of carbonate and evaporate rocks that enriched in the Yangtze River drainage basin. The calculated result based on the end-member mixing model shows that about 91% of total dissolved Sr are derived from the weathering of carbonate and evaporate rocks and the other 9% derived from the weathering of silicate rock. The Yangtze River transports about 1.86 × 10¹¹ g yr⁻¹ (2.12 × 10⁹ mol yr⁻¹) of dissolved Sr annually to the East China Sea, with an average ⁸⁷Sr/⁸⁶Sr of 0.7108. The calculated “⁸⁷Sr_{excess} flux” of the Yangtze River is about 2.12 × 10⁷ mol yr⁻¹, indicating the important impact on seawater Sr isotope evolution. The measured ⁸⁷Sr/⁸⁶Sr ratios of suspended particulate matters in the Yangtze River water ranging from 0.7178 to 0.7252, are about 0.015 higher than that of corresponding dissolved loads, reflecting more important contribution of silicate particles in suspended particulate matters and preferential dissolution of carbonate rocks during basin weathering. © 2007 Elsevier Ltd. All rights reserved.

Keywords: ⁸⁷Sr/⁸⁶Sr; Yangtze River; Main channel; Basin weathering; Flux

1. Introduction

Continental erosion is a major geological process which is responsible for landscape evolution and weathering matters transport from continents to the oceans. Drainage basin weathering studies of major river systems are of importance to elucidate erosion processes on a global scale and to estimate the global fluxes of continent derived material to the oceans (Martin and Meybeck, 1979; Goldstein et al., 1984; Taylor and McLennan, 1985; Négrel et al., 1993; Gaillardet et al., 1995, 1997). Studies of Sr isotopes combined with major elements on river materials are useful to understand basin erosion processes (Wadleigh et al.,

1985; Goldstein and Jacobsen, 1987; Åberg et al., 1989; Edmond, 1992; Asmerom and Jacobsen, 1993; Négrel et al., 1993; Gaillardet et al., 1995; Allègre et al., 1996; Dupré et al., 1996) and to quantify the mixing of waters from different origins: e.g., silicates and carbonates (Goldstein and Jacobsen, 1987; Palmer and Edmond, 1992; Négrel et al., 1993; Pande et al., 1994; Ben Othman et al., 1997).

The Yangtze River is one of the largest rivers in the world. So that, studies on hydrology and geochemistry of the river have already been carried out extensively (Hu et al., 1982; Zhang et al., 1990; Chen et al., 2002; Yang et al., 2002; Ding et al., 2004). However, there were few data on the Sr isotopic compositions of dissolved and suspended loads that had been systemically reported for the Yangtze River drainage basin, besides two scatter ⁸⁷Sr/⁸⁶Sr ratios of dissolved loads reported by Palmer and Edmond

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(1989) (0.7109) and Gaillardet et al. (1999) (0.7104) when they calculated the global budget of Sr isotopes. The purpose of this paper is to present here a systematic investigation of Sr isotopic compositions of dissolved and suspended particulate matters in the Yangtze River mainstream water and describe the geochemical and environmental implications of these observations.

2. Sampling and analytical methods

The map of the Yangtze River and sampling locations are presented in Fig. 1. Our samples were collected in the main channel of the Yangtze River from river mouth (CJ02, near Shanghai City) to upstream (CJ27, near Chongqing City), over a distance of about 2500 km in October 13–19, 1997. The sampling stations were scheduled every 100 km. According to hydrologic and geographic criteria, the Yangtze River can be divided into upper, middle and lower reaches. The upper reaches are belongs to a gorge type with steep slope whereas the middle and lower reaches run through plains. Samples CJ27 to CJ19 were collected from the Yangtze Gorge area of upper reaches, where the rock outcrops are mainly carbonates of Cambrian, Ordovician and Triassic ages. Samples CJ18 to CJ02 were collected from the middle and lower reaches. There are various rocks exposed in this section, including igneous, metamorphic, clastic rocks, carbonates and shales.

Sampling was made using a 10 l nitric acid-cleaned polyethylene bucket firstly. The samples used for the determination of Sr isotopes were filtered through 0.22 μm fibers (Millipore) immediately after collection and were acidified to pH about 1.5 using high-degree pure HCl acid and stored in 100 ml high-density polyethylene bottles. Additional water samples were also obtained at each station

and filtered in situ to measure major anions and cations, the latter were acidified with HNO_3 . Base cations and Sr^{2+} were analyzed by graphite furnace atomic absorption spectrometry and anions by ion chromatography within one week. The suspended solids retained on the membrane were also collected and then decomposed in the laboratory using mixture acid for determination of Sr isotopes in the suspended particulate matters.

Strontium separation from major elements for isotopic analysis was carried out by conventional ion-exchange techniques using a Dowex 50 W-8X 200–400 mesh resin column. Strontium isotopic ratios were measured on a VG 354 mass spectrometer with five Faraday collectors in the Institute of Geology, Chinese Academy of Sciences, Beijing. The details of their precision and accuracy are summarized in Table 1. The measured value of the NBS987 standard was $^{87}\text{Sr}/^{86}\text{Sr} = 0.710268 \pm 11$ (2σ , $n = 25$), with an analytical uncertainty of 0.00535% compared to the given value of 0.71023 ± 5 (2σ).

3. Results

The measured $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the dissolved and suspended loads as well as the concentrations of dissolved Sr^{2+} and major anions and cations in the Yangtze River mainstream water are listed in Table 1. The major element composition is dominated by the anion HCO_3^- and the cation Ca^{2+} . HCO_3^- with the concentrations ranging from 154 to 217 mg kg^{-1} accounts for about 80% (in mg kg^{-1} units) of the total anions. Whereas Ca^{2+} , with the concentrations ranging from 48 to 60 mg kg^{-1} , accounts for about 75% of the total cations. The concentrations of SO_4^{2-} (23–37 mg kg^{-1}) and Cl^- (6–9 mg kg^{-1}) are generally lower

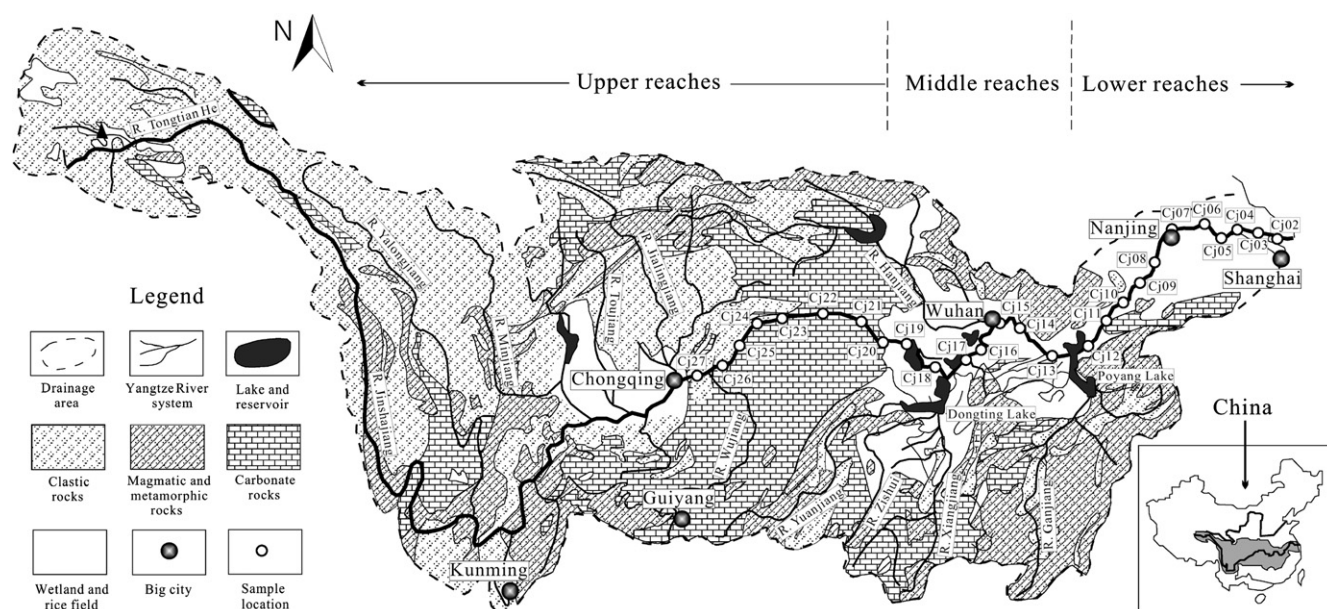


Fig. 1. Geological map of the Yangtze River drainage basin (modified from the map in CWRC, 1999 and Ding et al., 2004) and location of the sampling stations.

Table 1

The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in the dissolved ($^{87}\text{Sr}/^{86}\text{Sr}_{\text{diss}}$) and suspended ($^{87}\text{Sr}/^{86}\text{Sr}_{\text{susp}}$) loads and the concentrations of dissolved Sr^{2+} ($\mu\text{g kg}^{-1}$), Si (mg kg^{-1}) and major anions and cations (mg kg^{-1}) of the Yangtze River mainstream water

Sample no.	$^{87}\text{Sr}/^{86}\text{Sr}_{\text{diss}} \pm 2\sigma$	$^{87}\text{Sr}/^{86}\text{Sr}_{\text{susp}} \pm 2\sigma$	Sr^{2+}	Si	HCO_3^-	SO_4^{2-}	Cl^-	NO_3^-	Ca^{2+}	Mg^{2+}	Na^+
CJ02	0.710837 ± 10		220	7.09	159.11	23.96	9.38	3.77	53.54	11.08	8.05
CJ03	0.710787 ± 11		220	7.06	160.08	27.16	8.04	4.16	50.73	11.04	7.49
CJ04	0.710726 ± 11		237	7.10	159.67	27.79	8.25	3.82	52.30	10.72	7.56
CJ05	0.710751 ± 10		228	7.11	157.32	24.52	7.39	3.52	51.34	10.67	6.97
CJ06	0.710741 ± 12		220	7.16	156.77	26.00	8.11	3.45	51.20	10.35	6.90
CJ07	0.710727 ± 14		211	7.09	157.32	24.44	6.84	3.49	51.34	10.02	6.47
CJ08	0.710669 ± 14	0.725257 ± 6	203	7.11	154.97	23.91	6.84	3.25	49.96	10.20	6.46
CJ09	0.710753 ± 9		203	7.12	157.87	26.64	6.83	3.71	49.05	10.67	6.71
CJ10	0.710688 ± 11		211	7.13	156.22	24.89	6.99	3.23	51.34	10.38	6.38
CJ11	0.710689 ± 8		203	7.03	160.08	23.41	6.85	3.04	48.58	10.05	6.13
CJ12	0.710682 ± 10		220	7.08	165.60	24.05	7.11	3.21	51.20	9.94	6.07
CJ13	0.710553 ± 13	0.723596 ± 3	237	6.94	171.12	26.28	7.96	4.27	50.92	9.74	5.98
CJ14	0.710596 ± 10		237	6.93	171.53	25.00	7.76	4.00	49.40	9.80	5.87
CJ15	0.710546 ± 14	0.720222 ± 4	228	6.94	175.67	25.35	7.32	3.64	51.34	10.14	5.96
CJ16	0.71057 ± 10		211	6.90	166.15	23.41	6.65	3.14	48.01	9.95	5.66
CJ17	0.710464 ± 10		228	6.86	172.64	26.91	7.00	3.75	51.34	11.67	6.78
CJ18	0.710304 ± 15		262	6.82	190.99	31.22	6.77	3.71	58.10	12.85	7.49
CJ19	0.709986 ± 14		270	6.70	195.82	31.81	6.21	4.18	56.72	12.85	7.33
CJ20	0.710051 ± 9		270	6.69	196.93	32.13	7.09	4.27	56.72	12.97	7.33
CJ21	0.710331 ± 11	0.72331 ± 12	279	6.68	201.62	31.62	7.30	3.52	56.95	13.28	7.09
CJ22	0.710482 ± 9		330	6.62	217.07	37.18	6.78	3.92	60.20	13.97	7.69
CJ23	0.710197 ± 8		304	6.73	207.00	31.81	6.79	4.12	57.41	13.68	7.23
CJ24	0.710259 ± 9	0.72163 ± 6	270	6.79	195.13	31.70	6.87	4.11	58.10	13.63	6.94
CJ25	0.710276 ± 8		279	6.80	195.13	32.69	7.18	3.69	54.36	13.28	7.23
CJ26	0.710293 ± 8		279	6.77	192.79	33.31	7.29	3.61	54.10	13.25	7.26
CJ27	0.709844 ± 10	0.717858 ± 7	262	6.81	187.54	30.00	8.25	3.66	52.03	13.07	8.14
NBS987 ^a	0.710264 ± 11										
	0.710285 ± 9										
	0.710266 ± 10										
	0.710263 ± 12										
	0.710261 ± 8										

^a Five replicates of standard NBS987 determination are present here.

than that of HCO_3^- , possess about 13% and 3% of the total anions, respectively (Table 1).

The concentrations of dissolved Sr in the Yangtze River mainstream water ranging from 202 to 330 $\mu\text{g kg}^{-1}$ with the average value of 240 $\mu\text{g kg}^{-1}$ (Table 1), are about three times higher than the average value of 78 $\mu\text{g kg}^{-1}$ in global rivers (Palmer and Edmond, 1989). The dissolved $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in the Yangtze River water are about 0.7098–0.7108 and slightly lower than the average $^{87}\text{Sr}/^{86}\text{Sr}$ value of big rivers of the world (0.7119) (Palmer and Edmond, 1989). In the upper reaches of the watershed (CJ27–CJ19), waters exhibit low $^{87}\text{Sr}/^{86}\text{Sr}$ values around 0.710 (Table 1). In the middle and lower reaches of the watershed (CJ18–CJ02), waters present slight higher $^{87}\text{Sr}/^{86}\text{Sr}$ values around 0.7103–0.7108 (Table 1). The suspended loads in the Yangtze River mainstream water have higher values of $^{87}\text{Sr}/^{86}\text{Sr}$ (0.7178–0.7252) comparing that of dissolved loads (Table 1).

The other significant characteristic is that major cations (Ca^{2+} and Mg^{2+}) and anions (HCO_3^- and SO_4^{2-}) and dissolved Si varying systematically with the various lithologies encountered, probably reflecting the influence of the parent rocks (Fig. 2). And also, dissolved Sr and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of

dissolved and suspended phases systematically varied from the upper to lower reaches in the Yangtze River drainage basin (Fig. 3).

4. Discussion

4.1. Water chemistry of the Yangtze River mainstream water

4.1.1. Rock weathering in the Yangtze drainage basin

The major soluble elements in river waters can originate from rock weathering, atmosphere deposition and anthropogenic input. According to the predominance proportions of HCO_3^- and Ca^{2+} in river waters, carbonate weathering tends to dominate the solute loads in the main channel of the Yangtze River. This is coincident with the result that carbonates occur as the dominated bedrock within the Yangtze River drainage basin (Fig. 1). Moreover, according to the mass-balance calculation between the major cations (Ca^{2+} and Mg^{2+}) and the major anions (HO_3^- and SO_4^{2-}) of the Yangtze River mainstream water in equivalent units, it is extrapolated that besides the predominance of carbonate weathering, the dissolution of evaporate rocks can be significant and is the second major source of main

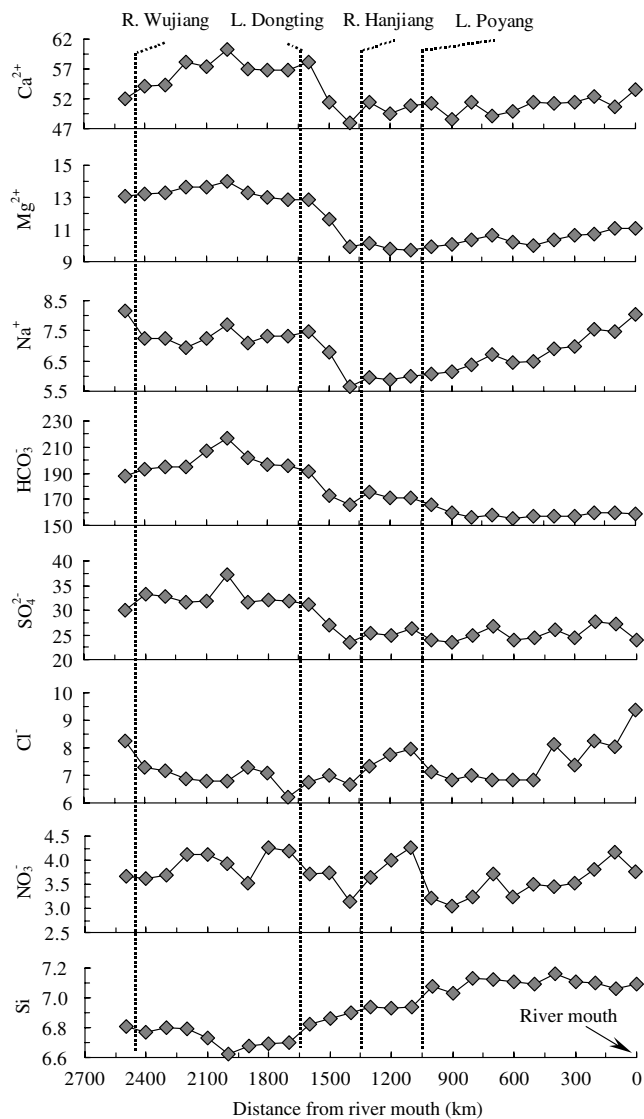


Fig. 2. The concentrations of major cations and anions (mg kg^{-1}) and dissolved Si (mg kg^{-1}) in the Yangtze River mainstream water and their variations from the upper to lower reaches. The locations of major branches (River Wujiang, Lake Dongting, River Hanjiang and Lake Poyang) that enter the studied section of the river are also marked.

ions in the Yangtze River drainage basin. This is because mosaic distributions of evaporate rocks in the upper reaches of the Yangtze River (Fig. 1).

In lower reaches of the Yangtze River, more wide spread of silicate rocks, including igneous, metamorphic, clastic rocks, carbonates and shales, were observed, especially in the River Xiangjiang and River Ganjiang drainage basins (Fig. 1). Evident from the Fig. 2 is that there is a systematic increase of dissolved Si concentrations in the Yangtze River mainstream water from upper to lower reaches, although all are Ca^{2+} – HCO_3^- dominated, suggesting more and more important contribution of the weathering of silicate rocks. Correspondingly, the concentrations of Ca^{2+} , Mg^{2+} , SO_4^{2-} and HCO_3^- decrease from upper to lower reaches.

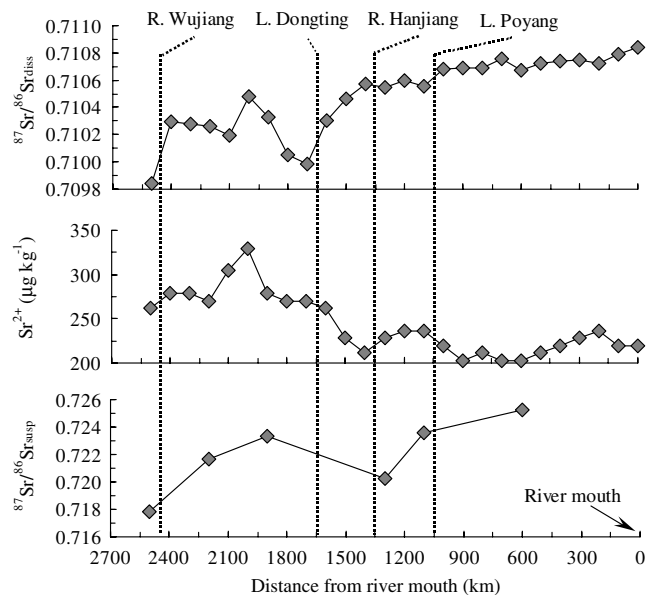


Fig. 3. The concentrations of dissolved Sr^{2+} and $^{87}\text{Sr}/^{86}\text{Sr}$ values in the dissolved ($^{87}\text{Sr}/^{86}\text{Sr}_{\text{diss}}$) and suspended ($^{87}\text{Sr}/^{86}\text{Sr}_{\text{susp}}$) loads from the Yangtze River mainstream water (Abbreviations are the same as those in Fig. 2).

4.1.2. Sea salts deposition and anthropogenic inputs

In the Yangtze River mainstream water, the slight downstream increase of chloride concentration from the lower reaches (CJ07) to the river mouth (CJ02) may reflect very weak marine originated sea salts deposition (Fig. 2). This is very different from those observed for many rivers of the world that significant decline of chloride concentration with increasing distance from the sea (Stallard and Edmond, 1981). Whereas slightly elevated chloride concentrations that found in the farther inland stations (CJ27, CJ26, et al.) in the upper reaches may reflect the influence of the weathering of clastic and evaporate rocks that widely spread in the upper reaches of the Yangtze River drainage basin (Figs. 1 and 2).

The NO_3^- levels in the Yangtze River mainstream water is about 10 times higher than those from large and less disturbed world rivers (Meybeck, 1982). This may be ascribed to both extensive influences from agricultural and domestic activities over the Yangtze River drainage basin (Zhang, 1996).

The concentrations of dissolved SO_4^{2-} in the Yangtze River mainstream water range from 23 to 37 mg kg^{-1} (Table 1), also showing significantly higher than that of world large rivers (Roy et al., 1999). There are several possible sources, such as dissolution of evaporites, oxidation of sulfides and atmospheric input of sulfate ion in river waters. Considering the main value of 9.6 mg kg^{-1} of the SO_4^{2-} concentration in the rainwater in the studied drainage basin (Han and Liu, 2006), cyclic SO_4^{2-} from rainfall is expected as a major source of SO_4^{2-} in the Yangtze mainstream river water. As high as 20 mg kg^{-1} of sulfate with a pH often lower than 4.1 have been reported in the rainwater at Chongqing and Guiyang cities, due to predomi-

nant usage of sulfur-rich coals (Zhao et al., 1994; Larssen et al., 1999). Moreover, the sulfur isotopes in water of the River Wujiang, one of the biggest branches in the upper reaches of the Yangtze River (Fig. 1), indicated that oxidation of sulfides and dissolution of gypsum may also were potential sources of SO_4^{2-} in the Yangtze River water, due to both sulfide and gypsum deposits were commonly observed in the carbonate stratum in the studied area (Jiang et al., 2006).

4.2. Sr isotopes in the Yangtze River mainstream water

4.2.1. $^{87}\text{Sr}/^{86}\text{Sr}$ variations and its implications

In major world rivers, variations in Sr concentrations and its isotopic composition are defined largely by mixing of Sr derived from carbonates and/or evaporates, having high concentrations of Sr and low $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratio, and Sr derived from silicate rocks, having low concentrations and high $^{87}\text{Sr}/^{86}\text{Sr}$ ratio (Palmer and Edmond, 1989, 1992). In the Yangtze River drainage basin, the concentration of dissolved Sr ($876 \mu\text{g kg}^{-1}$) and $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratio (0.709) of carbonate water end-member can be referred from Han and Liu (2004). The concentration of dissolved Sr in the silicate water end-member ($34 \mu\text{g l}^{-1}$) can be referred from Zhang et al. (1996). The value of 0.725 of $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic composition of the suspended load that collected from silicate distribution area (CJ08) in the present study is chosen as the $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic composition of the silicate water end-member. In fact, the value of 0.725 were always as the average value of $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic composition of silicate rocks in the previous studies (Goldstein and Jacobsen, 1988; Négre et al., 1993). Thus, an $^{87}\text{Sr}/^{86}\text{Sr}$ versus $1/\text{Sr}$ mixing diagram of the dissolved loads in the Yangtze River mainstream water together with the carbonate and silicate end-members can be drawn (Fig. 4). Obviously, results from our strontium isotopic

analyses showing that the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in the Yangtze River mainstream water are more close to the carbonate end-member, indicate that the $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic values of 0.7098–0.7108 in the Yangtze River mainstream water are mainly dominated by carbonate weathering and evaporate dissolution (Fig. 4). As mentioned above, carbonate and evaporate rocks are widely spread throughout the Yangtze River drainage basin and are particularly abundant in the section of the upper reaches. Therefore, based on available data (Han and Liu, 2004), the Sr dissolved from these rocks should have high concentrations and relatively lower $^{87}\text{Sr}/^{86}\text{Sr}$ values.

In the middle and lower reaches, the downriver increase of dissolved $^{87}\text{Sr}/^{86}\text{Sr}$ values was just coincide to the marked increase of dissolved Si, indicating the influence of silicate weathering on riverine geochemistry when close to the silicate-bearing terranes (Figs. 2 and 3). Therefore, silicate rocks distributed widely in the lower reaches of the Yangtze River as another end-member could also provide a little part of Sr into Yangtze River mainstream water and elevate the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio from 0.7106 to 0.7108 (Fig. 3). In the Yangtze middle reaches, there are five large tributaries: River Yuanjiang, Zishui, Xiangjiang, Hanjiang and Ganjiang (Fig. 1). There are various rocks exposed along these tributaries, including igneous, metamorphic, clastic rocks, carbonates and shales. Considering the variety of source rocks, the concentrations of dissolved Sr of river water input to the middle reaches will be lower than that of the upper reaches of carbonate drainage area. For example, the concentration of dissolved Sr in the Lake Dongting is about $85.5 \mu\text{g l}^{-1}$ and in the Lake Poyang only about $34 \mu\text{g l}^{-1}$ (Zhang et al., 1996). Correspondingly, the sediments in the River Xiangjiang and River Ganjiang have higher $^{87}\text{Sr}/^{86}\text{Sr}$ values of about 0.731–0.736 due to those silicate rocks have very high $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratios (Meng et al., 2000), especially metamorphic rocks having $^{87}\text{Sr}/^{86}\text{Sr}$ values as high as 0.75 (Hu et al., 1999). Therefore, water that enters the mainstream of middle reaches will have relatively lower concentrations of dissolved Sr and higher $^{87}\text{Sr}/^{86}\text{Sr}$ values than the section from CJ27 to CJ19 sampling stations.

4.2.2. The relative contributions of different end-members for dissolved Sr

Quantifying the amount of Sr obtained from carbonate or silicate-derived fractions is of primary interest, because the size of the calculated silicate-derived Sr flux implies corresponding solid-Earth CO_2 degassing of sufficient magnitude to alter global climate. Previous attempts to calculate the relative contributions from carbonate and silicate weathering have used single end-member values in two-component mixing equation based on Ca/Sr , Mg/Sr and Na/Sr ratios of the bedrocks (Galy and France-Lanord, 1999; Krishnaswami et al., 1999) or Sr isotope ratios (Edmond and Huh, 1997). The Sr isotopic ratios in river waters can be described by the following equation:

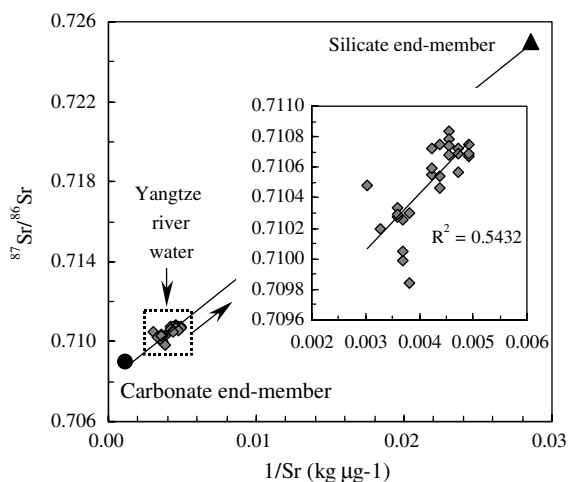


Fig. 4. An $^{87}\text{Sr}/^{86}\text{Sr}$ versus $1/\text{Sr}$ mixing diagram for the dissolved loads in the Yangtze River mainstream water. The carbonate and silicate water end-members were also inserted. The data of Sr concentrations and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of carbonate and silicate end-members are referred from Zhang et al. (1996) and Han and Liu (2004), respectively.

$$\left[\frac{^{87}\text{Sr}}{^{86}\text{Sr}} \right]_{\text{riv}} = \left[\frac{^{87}\text{Sr}}{^{86}\text{Sr}} \right]_{\text{rw}} \times \text{Sr}_{\text{rw}} + \left[\frac{^{87}\text{Sr}}{^{86}\text{Sr}} \right]_{\text{carb}} \times \text{Sr}_{\text{carb}} + \left[\frac{^{87}\text{Sr}}{^{86}\text{Sr}} \right]_{\text{ev}} \times \text{Sr}_{\text{ev}} + \left[\frac{^{87}\text{Sr}}{^{86}\text{Sr}} \right]_{\text{sil}} \times \text{Sr}_{\text{sil}} \quad (1)$$

Here, $^{87}\text{Sr}/^{86}\text{Sr}_{\text{riv}}$, $^{87}\text{Sr}/^{86}\text{Sr}_{\text{rw}}$, $^{87}\text{Sr}/^{86}\text{Sr}_{\text{carb}}$, $^{87}\text{Sr}/^{86}\text{Sr}_{\text{ev}}$ and $^{87}\text{Sr}/^{86}\text{Sr}_{\text{sil}}$ represent the $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic compositions of river water, rainwater, carbonate, evaporate and silicate rocks, respectively. Sr_{rw} , Sr_{carb} , Sr_{ev} and Sr_{sil} represent the percent of relative contributions of dissolved Sr from rainwater, carbonate, evaporate and silicate rocks.

It has been previously reported that the main value of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in the carbonate river waters and rainwater both were about 0.709 (Han and Liu, 2004, 2006). Since there was no $^{87}\text{Sr}/^{86}\text{Sr}$ data of evaporate rocks previously published in the Yangtze River drainage basin, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio found in the modern seawater at about 0.709 may be the most appropriate. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio at 0.725 determined for the suspended loads of the Yangtze River water in the present study was thought to be the most representative of the Sr isotopic composition of the silicate reservoir. So that, the formula 1 can be simplified as

$$\left[\frac{^{87}\text{Sr}}{^{86}\text{Sr}} \right]_{\text{riv}} = (\text{Sr}_{\text{rw}} + \text{Sr}_{\text{carb}} + \text{Sr}_{\text{ev}}) \times 0.709 + \text{Sr}_{\text{sil}} \times 0.725 \quad (2)$$

Thus, based on Formula (2) and by using a simple two end-member mixing equation, we can get that the average percent of carbonate weathering together with evaporite dissolution and rainwater accounts for about 91% (range 89–94%) of total dissolved Sr in the Yangtze River mainstream water, whereas silicate weathering accounts for the other 9% (range 6–11%).

4.3. $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic compositions of suspended loads

$^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratios of suspended particulate matters in the Yangtze River mainstream water ranging from 0.7178 to 0.7252, are about 0.015 higher than that of corresponding dissolved loads (Table 1 and Fig. 3). Differences between $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic compositions of suspended and dissolved loads have been previously attributed to differences in weathering susceptibility between carbonate and silicate minerals (Goldstein and Jacobsen, 1988), since Sr is dominantly carried in solution. This feature reflects preferential dissolution of carbonate rocks which have low $^{87}\text{Sr}/^{86}\text{Sr}$ and easily present in the dissolved loads and more important contribution of silicate particles which have more radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ and less soluble and easily exist in the suspended matters. Moreover, the downriver increase of suspended $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in the Yangtze River mainstream water may reflect the increase of relative contributions of silicate particles in the suspended matters from upper to lower reaches (Fig. 3), and is coincident the silicate rock distribution (Fig. 1). This implies that $^{87}\text{Sr}/^{86}\text{Sr}$ in the suspended loads same as $^{87}\text{Sr}/^{86}\text{Sr}$ in the

dissolved loads, are also mainly controlled by the bedrocks. So that, a positive correlation exists between $^{87}\text{Sr}/^{86}\text{Sr}$ in the suspended load and $^{87}\text{Sr}/^{86}\text{Sr}$ in the dissolved loads in the Yangtze River mainstream water, which were also observed in both Congo and Amazon basins (Négre et al., 1993).

4.4. Flux of dissolved Sr and impact on the oceanic $^{87}\text{Sr}/^{86}\text{Sr}$

For quantitative estimates the dissolved Sr annual flux of the Yangtze River, the concentrations of dissolved Sr in the different seasons should be provided. Chen et al. (2002) have reported that the concentrations of major ions of the river water do not vary greatly over a yearly period, despite of the fact that the season fluctuant of the discharge of the Yangtze River. In the present study, the river waters available for dissolved Sr flux calculation were sampled in August and October which represent the high flow season and the middle flow season, respectively, from the Datong station (CJ08). Station Datong was chosen because it is the most downstream main channel station without tidal influence. The dissolved Sr concentrations are $197 \mu\text{g kg}^{-1}$ in August and $202 \mu\text{g kg}^{-1}$ in October, respectively, suggesting very little variation and enough for the flux calculation. So that, the dissolved Sr concentration and water discharge data at Datong station were used to calculate dissolved Sr annual flux of the Yangtze River. By taking the discharge-weighted average concentration of dissolved Sr of $200 \mu\text{g kg}^{-1}$ ($2.28 \mu\text{M}$) and the annual river discharge of $9.282 \times 10^{14} \text{ kg yr}^{-1}$, we obtain the dissolved Sr annual flux from the Yangtze River to the East China Sea is about $1.86 \times 10^{11} \text{ g yr}^{-1}$ ($2.12 \times 10^9 \text{ mol yr}^{-1}$) with the $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.7108. This contribution is about 6.37% of the total global dissolved Sr flux ($33.3 \times 10^9 \text{ mol yr}^{-1}$, Palmer and Edmond, 1989) to the oceans via rivers.

Recently, extensive studies on $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic geochemistry of the Himalayan–Tibetan rivers have been carried out due to the unusually elevated $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of silicate and carbonate rocks in the Himalaya and its significance of Sr fluxes for changes in seawater $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (Palmer and Edmond, 1989; Edmond, 1992; Krishnaswami et al., 1992; Galy et al., 1999; Bickle et al., 2003; Singh et al., 2006). This significance has been estimated by calculating an “ $^{87}\text{Sr}_{\text{excess}}$ flux”, a measure of the relative flux of ^{87}Sr in excess of the seawater Sr isotope composition (0.709) from the formula (Bickle et al., 2003):

$$^{87}\text{Sr}_{\text{excess}} \text{flux} = \left(\frac{^{87}\text{Sr}}{^{86}\text{Sr}} - 0.709 \right) \times \text{Total Sr}_{\text{flux}} \quad (3)$$

The calculated “ $^{87}\text{Sr}_{\text{excess}}$ flux” of the Yangtze River is about $2.12 \times 10^7 \text{ mol yr}^{-1}$. This indicated that even though the Yangtze River is supplying less radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ to the oceans compared to that of the Himalayan–Tibetan rivers, the “ $^{87}\text{Sr}_{\text{excess}}$ flux” from the Yangtze River are 4–10 times higher than that of the Brahmaputra (range: 2–

$5 \times 10^6 \text{ mol yr}^{-1}$) or the Ganges (range: $2\text{--}5 \times 10^6 \text{ mol yr}^{-1}$) (Krishnaswami et al., 1992; Galy et al., 1999; Singh et al., 2006), implying the important impact of Yangtze River on seawater Sr isotope evolution.

5. Conclusions

The average concentration of dissolved Sr in the main channel of the Yangtze River is about $240 \mu\text{g kg}^{-1}$ and the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios range from 0.7098 to 0.7108. Carbonate and evaporate weathering plays a controlling role in the dissolved Sr and the major ion chemistry in the Yangtze River drainage basin. The contribution from silicate weathering is minor, although the influence of silicate weathering plays more and more significant role from middle to lower reaches. On average, carbonate weathering together with evaporite dissolution accounts for about 91% of total dissolved Sr in the Yangtze River mainstream water, whereas the weathering of silicates accounts for the other 9%. The Yangtze River transports about $1.86 \times 10^{11} \text{ g yr}^{-1}$ ($2.12 \times 10^9 \text{ mol yr}^{-1}$) of dissolved Sr annually to the East China Sea, with an average $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.7108.

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