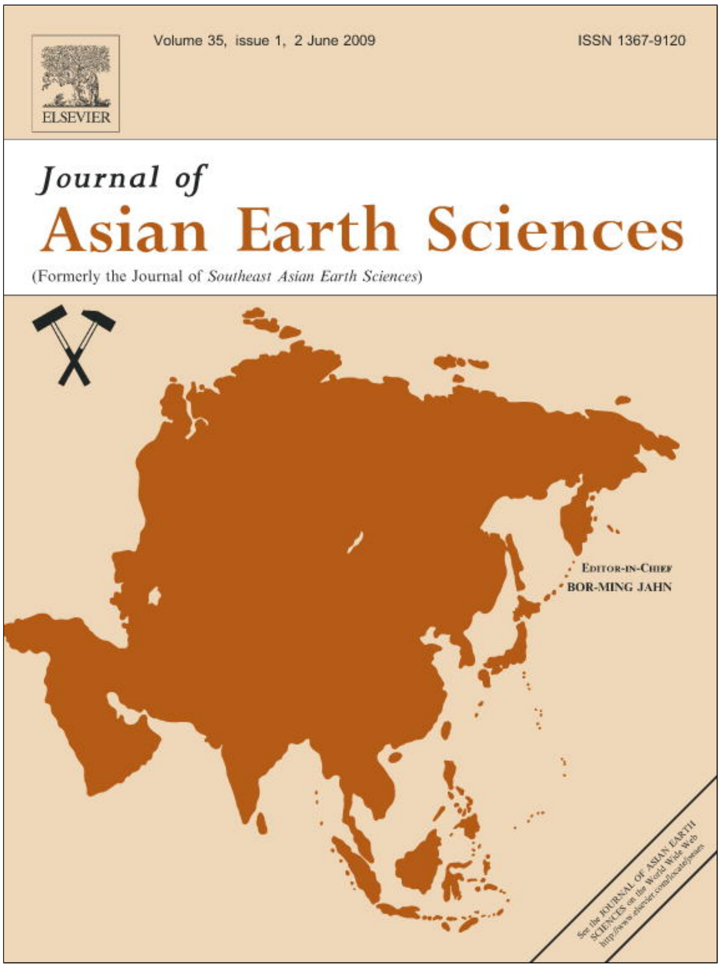
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Heavy mineral compositions of the Changjiang (Yangtze River) sediments and their provenance-tracing implication

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ABSTRACT

A total of 71 floodplain sediments were collected from the mainstream and major tributaries of the Changjiang for heavy mineral examinations. The upper Changjiang samples contain more heavy minerals in the very fine sand fraction than the middle-lower samples which are relatively enriched in polygenetic heavy minerals. The heavy mineral assemblages are characterized by Fe–Ti oxide minerals, calcic amphibole, epidote, garnet, biotite, and zircon, which exhibit large variations in percent between different tributaries and the mainstream. The widely distributed granitoids and Permian Emeishan Basalt in the drainage basins account for the high contents of zircon and hypersthene in the Xiangjiang and Daduhe samples, respectively. Most of the detrital magnetite grains are homogeneous in typomorphic feature and almost stoichiometric in chemical composition. The discrimination plot of $TiO_2 + V_2O_3$ versus $MgO/(MgO + Al_2O_3)$ suggests that most of the detrital magnetite grains are sourced from felsic plutonic/volcanic and metamorphic parent rocks, and those from different tributaries have distinct chemical compositions. Our study suggests that the combination of transparent heavy mineral assemblages and varietal study of individual heavy minerals sheds new light on the provenance discrimination of the Changjiang sediments and contributes to the mineralogical determination of ancient source rocks within a large drainage basin, despite the sediment recycling and complex source rock types.

1. Introduction

Although sedimentary processes such as weathering, physical abrasion and hydrodynamic sorting during transport, alluvial storage, and diagenesis may obscure or overprint the original provenance signal (Morton and Hallsworth, 1994, 1999; Svendsen and Hartley, 2002; Morton et al., 2005), heavy mineral assemblages has long been regarded as sensitive indicators of sediment source (Rubey, 1933; Pettijohn et al., 1987; Nechaev and Isphording, 1993; Heroy et al., 2003; Garzanti et al., 2005, 2006, 2007, 2008; Garzanti and Andó, 2007). Certain features of heavy mineral suites, especially the varietal characteristics including chemical compositions of individual mineral species, can directly indicate the source rock characteristics, because these varietal characteristics are mostly inherited from source rocks and are not likely to change with weathering and transportation. Over the last two decades, specific heavy minerals including zircon, monazite, garnet, tourmaline, apatite, rutile, and Ti–Fe oxide minerals have been widely used to decipher the provenances of marine and riverine sediments in terms of their unique varietal characteristics (Darby and Tsang, 1987; Grigsby, 1990, 1992; Razjgaeva and Naumova, 1992; Morton and Hallsworth, 1994; Datta and Subramanian, 1997; Dill, 1998; Sabeen et al., 2002; Svendsen and Hartley, 2002; Heroy et al., 2003; Lin et al., 2003; Zack et al., 2004; Mange and Otvos, 2005; Poulton and Raiswell, 2005). Among these heavy minerals, opaque Ti–Fe oxide minerals, especially magnetite, are more suitable for single-grain mineral chemical analysis than many other heavy minerals because they are relatively stable, easily separated from the bulk minerals and have unique typomorphic features and mineral chemistry diagnostic of provenance rocks (Darby and Tsang, 1987; Pettijohn et al., 1987; Basu and Molinaroli, 1989; Grigsby, 1990, 1992; Razjgaeva and Naumova, 1992; Yang et al., 2000; Hounslow and Morton, 2004).

The Changjiang as the longest river in Asia, delivers a large volume of sediment into the estuary, which exerts a significant influence on sediment budget, formation of sedimentary systems and environmental changes in East Asian marginal seas. Recognition of the source to sink transport pattern of the Changjiang sediments, therefore, allows us to better understand the above research topics. In recent years, sediment source discriminations of the Changjiang were performed primarily using elemental geochemical and clay mineralogical methods (Li et al., 1984; Yang, 1988; Qin et al., 1987; Yang et al., 2004; Yang et al., 2006; Lim et al., 2006), whereas heavy mineralogy of the Changjiang sediments has rarely been

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investigated, mainly due to the complicated river system and source rock types in the Changjiang drainage basins. Previous studies on heavy mineral assemblages of the Changjiang-derived sediments gave emphasis to the Changjiang estuarine and inner shelf area (Chen et al., 1980; Qin et al., 1987; Sun, 1990; Jin, 1992; Lu, 1992; Wang et al., 1997; Wang et al., 2007), and did not extend to the whole drainage system including the major tributaries of the Changjiang. Recent studies by Yang et al. (2000, 2006) show that single-grain mineral chemistry (magnetite and monazite) is useful in determining sediment provenance and deciphering the river evolution history of the Changjiang. Nevertheless, the heavy mineral investigations of the whole Changjiang and its major tributaries still remain incomplete.

In this contribution, we examine the transparent heavy mineral assemblages and chemistry of single-grain magnetic minerals in the Changjiang sediments. The principal research objectives are to characterize and differentiate the typical heavy mineral assemblages and chemical compositions of detrital magnetite grains between the Changjiang mainstream and its major tributaries, and further to relate them to sediment provenances and source rock types in the drainage basins.

2. River setting

The Changjiang is one of the largest rivers in the world in terms of its huge water and sediment discharges of about 900 × 10^9 and 480 × 10^6 ton/yr, respectively. The tributary system of the Changjiang is extensively developed in the drainage basin which fosters 49 tributaries with each catchment area above 10,000 km^2 (Fig. 1). Among them, the four largest tributaries, the Jialingjiang, Hanjiang, Minjiang, and Yalongjiang Rivers, all are located in the upper-middle valley of the Changjiang, with each occupying 100,000 km^2 in drainage area and yielding the sediment load >40 × 10^6 ton/yr based on fifty-year (1950–2000) hydrologic observations. The annual sediment loads average 501 × 10^6 ton at Yichang hydrologic station (about 1800 km away from the river mouth) and 433 × 10^6 ton at Datong hydrologic station (the tidal limit of the Changjiang, about 650 km away from the estuary), respectively. Nevertheless, the construction of the world's largest dam, the Three Gorges Dam, has greatly altered the sediment budget in the middle-lower reaches and the flux of suspended sediment into the Changjiang Estuary (Yang et al., 2007).

The Changjiang drainage basin spans the typical topography of China with three-grade relief terraces, which have the average elevations of 3500–5000 m, 500–2000 m and less than 500 m, respectively. The several large catchment basins including the Sichuan Basin, Jianghan Basin, Dongting Lake, Poyang Lake and Taihu Lake from west to east towards the river mouth, complicate the transport and deposition patterns of the Changjiang-derived sediments (Fig. 1). The upper Changjiang valley, especially the mountainous region in the Jinshajiang and Jialingjiang river basins, experiences the strongest soil erosion and has the highest sediment yield, up to 1000–5000 ton/km^2·a (Changjiang Water Resources Commission, 2005).

Geologically, the Changjiang drainage basin is primarily situated in the Yangtze Craton framed by the Mesozoic Yanshanian orogenic belt, and the westernmost upper part, the Jinshajiang valley, has been extensively influenced by the Tibetan uplift during the Cenozoic. The complicated source rock types in the drainage basin primarily comprise Archean metamorphic rocks, Paleozoic carbonate and sedimentary rocks, Mesozoic–Cenozoic igneous and clastic rocks, and Quaternary detrital sediments (Fig. 1; Changchun Institute of Geography, 1998; China Geological Survey, 2004). Different drainage basins in the Changjiang and its major tributaries consist of distinct tectonics and source rock types. The upper Jinshajiang valley comprises metapsammite and metapelite, carbonate rocks and acidic igneous rocks, and especially the intermediate-acidic rocks formed during the Himalayan Stage. The drainage basins of the Jinshajiang, Wujiang and Jialingjiang Rivers are characterized by Paleozoic carbonate rocks, Permian Emeishan

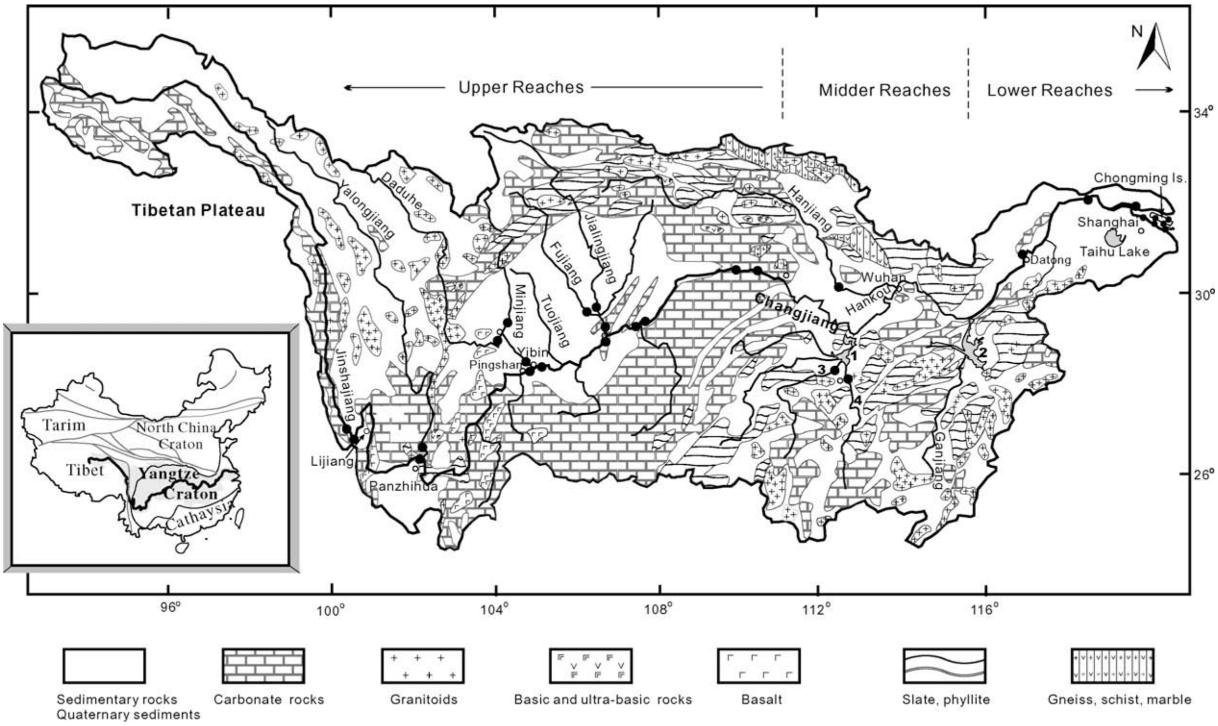

Fig. 1. A sketch map showing the Changjiang drainage basins, major tributaries, sampling locations and main provenance rock types. 1 Poyang Lake; 2 Dongting Lake; 3 Yuanjiang River; 4 Xiangjiang River. The geology of the Changjiang drainage basins is modified from Geological Map of China (1:2,500,000, CGS, 2004).

basalt, Jurassic red sandstone in the Sichuan Basin, Mesozoic–Cenozoic sedimentary and igneous rocks (Fig. 1). In particular, Paleozoic carbonate rocks and Emeishan basalt are two major source rock types in the upper Changjiang valley, and each occupies an area of about 300×10^3 km^2. The Emeishan basalt has been regarded as the only large igneous province in China and one of the largest basalt provinces in the world (Xiao et al., 2003). Quaternary loess deposits outcrop in the upper Jialingjiang and Hanjiang reaches where most of the sandy sediments are supplied into the Changjiang mainstream.

The middle and lower reaches of the Changjiang are characterized by Paleozoic sedimentary rocks, Mesozoic intermediate-acidic igneous rocks, and Quaternary detrital sediments (Fig. 1). The Mesozoic Yanshanian igneous rock belt widely outcrops along the Changjiang mainstream, whereas old medium-low grade metamorphic rocks occur sporadically in Hunan and Anhui Provinces. The Changjiang drainage basin is rich in various metal ore deposits, including the Panzhihua iron ore and a large bauxite deposit that characterize the upper valley, and polymetallic deposits (Cu, Fe, Mo, Au) accompanied by Mesozoic igneous rocks, that are widely distributed in the middle-lower reaches (China Geological Survey, 2004).

3. Materials and methods

A total of 71 sediment samples were collected from the main stream and major tributaries of the Changjiang during the dry season (April, 2003) using a pre-cleaned spoon. The samples ($\sim$ 500 g) were taken from the subsurface at 20 cm depth of the floodplains, and the sampling sites cover the whole river system from the upper Jinshajiang downstream to the river mouth area (Fig. 1). The sediment samples from the major tributaries were taken at the confluence with the main stream, at least 10 km far away from cities and pollution sources.

Grain size of the river sediments was measured by the laser particle size analyzer (Coulter LS-230) in the State Key Laboratory of Marine Geology at Tongji University, after removing organic matter and biogenic carbonate from the samples with 10% H_2O_2 and 1 N HCl, respectively. Subsamples for heavy mineral and mineral chemical determinations were selected from the 71 sediment samples. The detailed sample locations are listed in Table 1 and Fig. 1. Heavy mineral analysis was performed on the very fine sand fraction (63–125 μm) for 23 bulk samples. This fraction of sands was wet-sieved by a 62.5 μm nylon mesh and heavy minerals were separated using bromoform with specific gravity of 2.89 at 20 °C. For heavy mineral examinations, line counts of 300–500 grains were identified under a binocular microscope with incident light. In addition, detrital magnetite was separated from the very fine sand fraction for single-grain mineral chemical analysis in order to better identify the mineral sources. The detrital magnetite grains were selected from the heavy mineral fractions using a large bar magnet and then a needle during optical examination. The magnetite grains were placed on double-sided adhesive tape and then cast into an epoxy resin disk. The disk was sectioned, polished and coated with carbon prior to mineral chemical analysis using electron microprobe analyzer (JEOL-SXA 8800M) in the State Key Laboratory of Mineral Deposit Researches at Nanjing University. The electron beam is about 3 μm with working voltage and electronic current of 15 kv and 2.00×10^{-8} A, respectively.

4. Results and discussions

4.1. Heavy mineral assemblages of the Changjiang sediments

The grain size compositions of the bulk samples are given in Table 1 and Fig. 2. Sands dominate most of the samples from the major tributaries and the mainstream of the Changjiang, while silts dominate the estuarine portion of the river. The weight percentages of the heavy mineral fractions in the samples are also highly variable, ranging from 1.0% to 28.9%, and are generally higher in the major tributaries of the upper Changjiang valley such as the

Table 1
Inventory of the floodplain sediment samples from the Changjiang and its major tributaries.

Samples	Rivers	Locations	Median size (μm)	Clay (%)	Silt (%)	Sand (%)	HM (wt%)
CJ1-2	Jinshajiang	26°53′25″N, 99°57′46″E	171.3	0.5	7.7	91.7	28.9
CJ3-3	Jinshajiang	26°47′44″N, 100°25′44″E	86.7	1.7	36.3	62.0	4.4
CJ5-2	Jinshajiang	26°36′21″N, 101°48′03″E	225.5	0.2	4.8	95.0	9.7
CJ12-1	Jinshajiang	28°45’25”N, 104°36’40”E	74.5	6.6	39.6	53.8	10.1
CJ4-2	Yalongjiang	26°37′29″N, 101°48′38″E	105.8	2.1	28.2	69.8	9.8
CJ7-4	Daduhe	29°33′13″N, 103°45′36″E	180.4	2.1	22.7	75.1	8.9
CJ8-3	Minjiang	29°36′08″N, 103°45′38″E	310.2	0.2	4.4	95.3	9.9
CJ11	Minjiang	28°46’40”N, 104°37’23”E	113.5	5.2	32.6	62.2	5.8
CJ16-1	Fujiang	29°59′52″N, 106°13′37″E	135.6	1.5	21.7	76.8	1.5
CJ17-1	Jialingjiang	30°00’37”N, 106°16’37”E	40.2	6.0	57.7	36.3	6.5
CJ19-3	Jialingjiang	29°34′12″N, 106°33′16″E	181.3	0.8	10.7	88.5	6.1
CJ24	Hanjiang	30°50′54″N, 110°58′52″E	59.8	4.2	47.6	48.3	2.2
XJ1-1	Xiangjiang	28°10′36″N, 112°57′23″E	34.2	9.0	48.1	42.9	1.2
YJ1-1	Yuanjiang	29°01’26”N, 111°41’16”E	179.3	1.3	8.9	89.8	1.0
CJ9-5	Changjiang	28°46′19″N, 104°38′04″E	87.4	3.7	38.6	57.7	6.7
CJ18-1	Changjiang	29°32′48″N, 106°32′50″E	227.6	0.5	6.4	93.1	8.3
CJ20-4	Changjiang	29°41’58”N, 107°24’28”E	113.8	1.2	21.6	77.2	3.8
CJ20-5	Changjiang	29°41’45”N, 107°24’35”E	37.5	4.1	62.1	33.8	3.7
CJ21-2	Changjiang	30°48’38”N, 108°23’20”E	220.4	0.4	4.0	95.7	3.9
CJ22-3	Changjiang	30°50′54″N, 110°58′52″E	159.0	0.4	6.7	92.9	4.7
CJ27-2	Changjiang	30°55′48″N, 117°46′01″E	13.6	13.1	77.0	9.9	5.8
CJE1	Changjiang	31°38′25″N, 121°21′57″E	11.0	20.2	75.7	4.1	n.d.
CJE2	Changjiang	31°32′13″N, 121°36′57″E	19.0	11.4	79.7	8.9	n.d.
CJE3	Changjiang	31°41′46″N, 121°35′15″E	12.3	18.8	77.8	3.4	n.d.
CJE4	Changjiang	31°27′20″N, 121°25′44″E	14.9	16.6	75.3	8.2	n.d.
CJE5	Changjiang	31°10′37″N, 121°47′57″E	13.3	16.6	77.6	5.8	n.d.
CJE6	Changjiang	31°24′46″N, 121°40′33″E	17.7	12.5	76.7	10.8	n.d.
CJE7	Changjiang	32°13′14″N, 119°22′22″E	14.9	17.8	71.1	11.1	n.d.
CJE8	Changjiang	32°00′28″N, 120°43′45″E	8.7	25.6	71.6	2.8	n.d.

Note: HM denotes heavy mineral fraction in the bulk samples; n.d. = no determination.

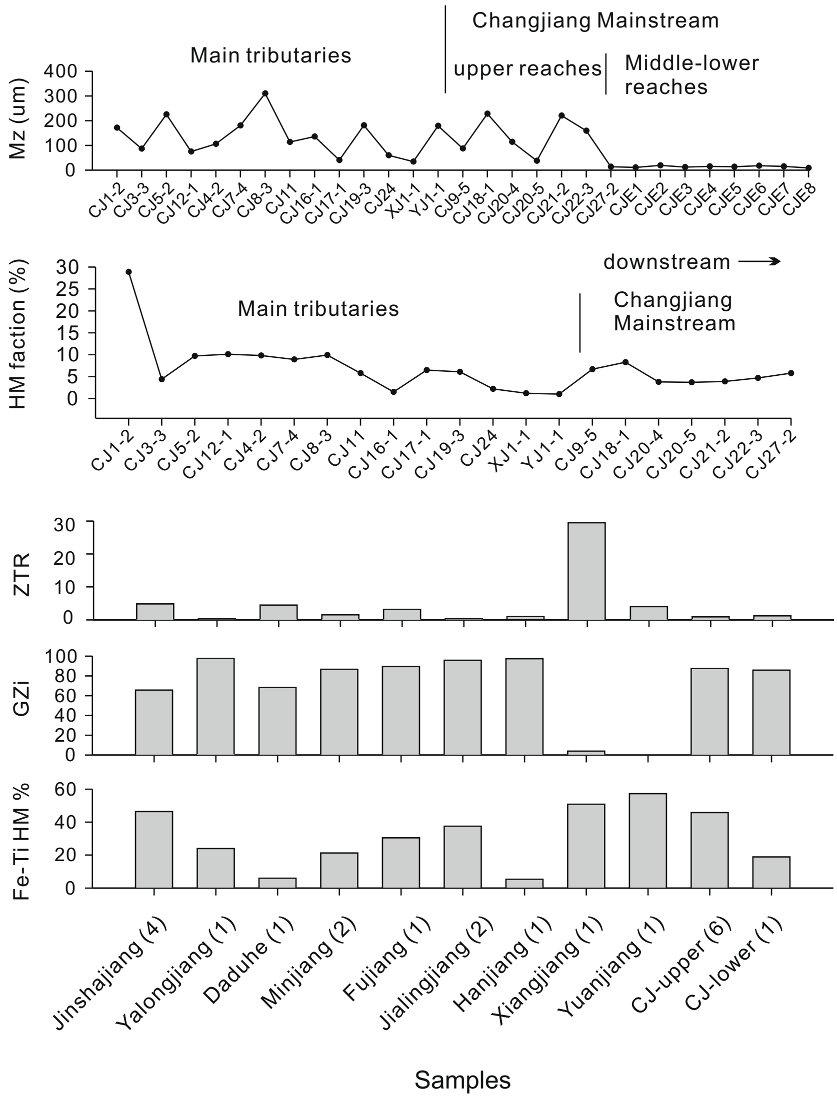

Fig. 2. Compositions of median grain size (Mz) and weight percentages of heavy mineral fractions in the sediments from the mainstream and tributaries of the Changjiang. ZTR = total counts of zircon, tourmaline and rutile; GZi = 100 × garnet count/(total garnet plus zircon); Fe–Ti HM = Fe–Ti heavy mineral group including magnetic minerals, ilmenite and limonite; CJ-upper denotes the upper Changjiang mainstream sediments; CJ-lower means the middle-lower Changjiang mainstream sediments.

Jinshajiang, Yalongjiang, Daduhe and Minjiang Rivers, and lower in the Hanjiang, Yuanjiang and Xiangjiang Rivers in the middle Changjiang valley (Fig. 2). Overall, main heavy mineral assemblages of the river sediments are calcic amphibole, epidote, magnetic minerals, limonite, and garnet, while other heavy minerals have much lower and more variable contents between different tributaries and the mainstream (Table 2). For example, the Jinshajiang sediments have the highest percentages of the heavy mineral fractions which are characterized by Fe–Ti oxide minerals, calcic amphibole, andalusite, chlorite, and apatite. Previous study also documented the dominance of calcic amphibole, chlorite, ilmenite and apatite in the heavy mineral fraction in the upper Changjiang sediments (Ren et al., 2006).

Some heavy minerals may have distinct sources of igneous and/or metamorphic origins (Deer et al., 1992; Spiegel et al., 2002; Zack et al., 2004; Garzanti and Andó, 2007). Zircon as a common accessory mineral of igneous rocks, has extraordinary higher contents in the Xiangjiang and Jinshajiang samples. Augite and hypersthene are essential constituents of mafic igneous rocks, and concentrated in the samples from the upper major tributaries and mainstream. To the contrary, some heavy minerals including andalusite, kyanite, and staurolite are ultimately sourced from metamorphic rocks. These heavy minerals have higher contents in the Minjiang samples but lower in the Xiangjiang, Hanjiang and Yuanjiang samples. Most of the examined heavy minerals such as apatite, garnet, epidote, biotite and calcic amphibole are found in a great variety of igneous and metamorphic rocks, which are relatively enriched in the Hanjiang, Daduhe and lower Changjiang mainstream samples but lower in the Xiangjiang and Yuanjiang samples (Table 2). The Fe–Ti oxide/hydroxide minerals include limonite, ilmenite and magnetic minerals with magnetite dominant. These heavy minerals are relatively concentrated in the Jinshajiang, Xiangjiang, Yuanjiang and upper Changjiang mainstream samples and depleted in the Daduhe, Hanjiang and lower Changjiang mainstream samples. Overall, the heavy mineral assemblages of the Changjiang mainstream sediments fall in the range of those major tributaries (Table 2; Fig. 2).

Previous studies suggested that provenance-sensitive index values such as ZTR (total counts of zircon, tourmaline and rutile) and GZi (100×garnet count/(total garnet plus zircon)) can discriminate heavy mineral origins (Hubert, 1962; Morton and Hallsworth, 1994, 1999; Morton et al., 2005). The ZTR values are extraordinary

Table 2
Percentages of individual minerals in the heavy mineral fractions of the sediments from the Changjiang and its major tributaries (%).

Minerals	CJ1-2	CJ3-3	CJ5-2	CJ12-1	CJ4-2	CJ7-4	CJ8-3	CJ11	CJ16-1	CJ17-1	CJ19-3	CJ24	XJ1-1	YJ1-1	CJ9-5	CJ18-1	CJ20-4	CJ20-5	CJ21-2	CJ22-3	CJ27-2
Rivers	JSJ	JSJ	JSJ	JSJ	YLJ	DDH	MJ	MJ	FJ	JLJ	JLJ	HJ	XJ	YJ	CJ	CJ	CJ	CJ	CJ	CJ	CJ
Magnetic minerals	20	5.0	15.0	25.0	15.7	2.5	2.1	7.0	8.3	12.2	33.3	0.0	16.7	10.0	15.0	12.5	33.3	33.3	35.0	10.0	12.5
Limonite	2.5	22.3	29.5	32.6	8.2	3.4	8.4	13.3	8.9	2.3	27.3	5.3	26.0	41.8	24.9	18.3	18.0	16.9	16.6	16.9	3.2
Ilmenite	32.0	1.5	0.0	0.0	0.0	0.0	1.9	9.8	13.3	0.0	0.0	0.0	8.1	5.5	10.6	0.0	0.0	0.0	2.1	11.5	3.2
Sphene	1.0	1.3	4.8	1.5	0.0	0.7	0.0	0.0	13.1	0.0	2.5	0.0	0.0	9.7	0.0	2.0	5.0	1.6	0.0	0.0	1.4
Rutile	0.9	0.0	1.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.4	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Zircon	13	0.9	2.1	0.3	0.0	1.4	0.0	1.4	1.2	0.4	0.0	0.4	29.4	1.0	2.3	0.2	0.0	0.0	0.0	2.1	0.5
Tourmaline	1.1	0.0	0.0	0.0	0.3	3.1	0.3	1.4	1.0	0.0	0.3	0.6	0.7	2.2	0.0	0.4	0.0	0.0	0.4	0.0	0.7
Epidote	3.1	4.5	5.8	3.3	4.5	10.3	12.1	7.7	7.9	20.8	4.1	17.3	3.4	4.5	5.9	13.3	2.1	4.3	4.5	1.1	14.9
Garnet	23.7	5.0	0.0	2.3	7.9	3.0	4.9	4.2	10.1	8.0	1.0	14.5	1.2	0.0	0.0	0.7	1.8	0.4	3.0	26.4	3.0
Calcic amphibole	2.6	35.5	12.7	14.7	49.8	65.2	66.5	28.7	32.5	36.2	16.3	55.9	9.8	20.6	13.5	45.2	7.4	23.5	22.6	15.5	55.2
Augite	0.0	8.7	0.0	11.1	8.2	0.7	3.4	6.3	0.0	2.3	13.5	0.0	4.7	3.0	10.8	3.2	6.5	16.9	15.7	7.1	2.3
Hypersthene	0.0	0.0	0.0	0.0	0.0	1.7	0.0	0.0	0.0	0.0	0.0	2.9	0.0	0.0	10.8	0.0	0.0	0.0	0.0	0.0	0.0
Apatite	0.0	0.0	2.7	0.0	0.0	0.0	0.0	0.0	1.7	3.1	0.0	2.0	0.0	1.0	0.0	0.0	0.0	1.6	1.4	0.6	0.5
Andalusite	0.0	4.3	12.7	2.8	2.0	0.7	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Biotite	0.0	0.4	4.1	3.8	1.7	5.2	0.4	4.2	0.0	0.0	0.1	0.0	0.0	0.0	2.6	1.5	1.8	0.4	0.0	0.8	0.2
Chlorite	0.0	2.1	8.9	1.5	0.0	0.0	0.5	4.9	1.0	0.2	0.4	0.0	0.0	0.0	3.9	2.7	3.1	1.3	0.5	0.8	1.6
Kyanite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.6	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Topaz	0.0	0.0	0.0	0.0	0.0	2.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Staurolite	0.0	0.0	0.7	0.0	1.5	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Weatheringminerals	0.0	8.7	1.4	1.3	1.2	1.0	0.0	3.9	1.2	13.5	0.0	0.0	2.1	0.0	0.0	1.2	20.0	0.0	0.0	8.2	0.0
Total	99.9	100.2	101.4	100.2	101.0	101.0	100.5	99.1	101.2	98.8	99.8	99.1	102.1	100.1	100.3	101.2	99.0	100.2	101.3	100.2	99.2

Note: JSJ = Jinshajiang; YLJ = Yalongjiang; DDH = Daduhe; MJ = Minjiang; FJ = Fujiang; JLJ = Jialingjiang; XJ = Xiangjiang; YJ = Yuanjiang; HJ = Hanjiang; CJ = Changjiang.

high in the Xiangjiang samples but mostly lower than 5 in the other river samples (Fig. 2). The highest ZTR value in the Xiangjiang clearly results from high zircon content (Table 2). In comparison, the GZi values are extraordinary low in the Xiangjiang and Yuanjiang samples, but higher in other rivers (Fig. 2).

Compared to the Changjiang mainstream sediments, the sediments from the subaqueous delta of the Changjiang have similar heavy mineral assemblages albeit with different abundances of specific minerals (Table 3, Wang et al., 2007). The offshore sediments are relatively enriched in epidote, tremolit, muscovite and weathering minerals, but depleted in zircon, garnet, chlorite and sphene. The Huanghe (Yellow River) sediments are characterized by higher contents of biotite, actinolite, muscovite and weathering minerals, and lower of epidote, hornblende, augite and Ti–Fe oxide minerals relative to the Changjiang sediments (Table 3, Lin et al., 2003). The heavy mineral compositions of the offshore sediments in the Changjiang estuarine area vary between those of the Changjiang and Huanghe sediments (Table 3). Previous studies suggested that the Huanghe River once emptied its huge sediments directly into the Yellow Sea during the late Holocene, and these sediments can be transported southeastward by the Yellow Sea Coastal Current and mixed with the Changjiang-derived sediments in the Changjiang estuarine area (Li et al., 1999, 2000; Yang et al., 2002).

4.2. Elemental concentrations of magnetite grains

The elemental concentrations of detrital magnetite grains are given in Fig. 3. The data show that almost all concentrations of Fe_2O_3 and FeO in the measured grains are somewhat lower than the stoichiometric composition of magnetite (68.96 and 31.04 wt% for Fe_2O_3 and FeO, respectively), except for FeO contents in the Fujiang and Hanjiang samples. The Jinshajiang samples have comparatively high concentrations of Al_2O_3, Cr_2O_3, and ZnO. The Yalongjiang samples are relatively enriched in most analyzed elements including Ti, Cr, V, Mn, Mg, and Al. The Daduhe and Minjiang samples are characterized by low concentrations of TiO_2, Al_2O_3, MnO and MgO. The Fujiang and Hanjiang samples have high concentrations of TiO_2 and V_2O_3 (Fig. 3). In particular, the Jialingjiang

Table 3
Comparison of heavy mineral compositions between the sediments from the Changjiang, Huanghe and estuarine area of the Changjiang (%).

Rivers	CJ-upper	CJ-lower	CJ-offshore	HH
Magnetic minerals	23.2	12.5	4.7	1.47
Limonite	18.6	3.2	2.9	3.13
Ilmenite	4.0	3.2	1.5	1.43
Sphene	1.4	1.4	0.4	0.91
Zircon	0.8	0.5	0.0	0.11
Tourmaline	0.1	0.7	0.2	0.0
Epidote	5.2	14.9	27.3	6.45
Garnet	5.4	3.0	0.5	2.80
Calcic amphibole	21.3	55.2	33.3	13.5
Augite	10.0	2.3	4.8	0.40
Apatite	0.6	0.5	0.4	0.58
Biotite	1.2	0.2	1.0	47.4
Chlorite	2.1	1.6	0.4	0.0
Hypersthene	1.8	0.0	0.0	0.0
Diopside	0.0	0.0	0.0	0.92
Tremolit	0.0	0.0	4.1	0.95
Actinolite	0.0	0.0	0.6	2.83
Muscovite	0.0	0.0	4.5	5.29
Weathering minerals	4.9	0.0	12.8	10.1
Total	100.6	99.2	99.4	98.3
Data source	This study	This study	Wang et al., 2007	Lin et al., 2003

Note: CJ-upper denotes the upper Changjiang mainstream; CJ-upper denotes the lower Changjiang mainstream; CJ-offshore denotes the subaqueous delta of the Changjiang; HH denotes Huanghe River.

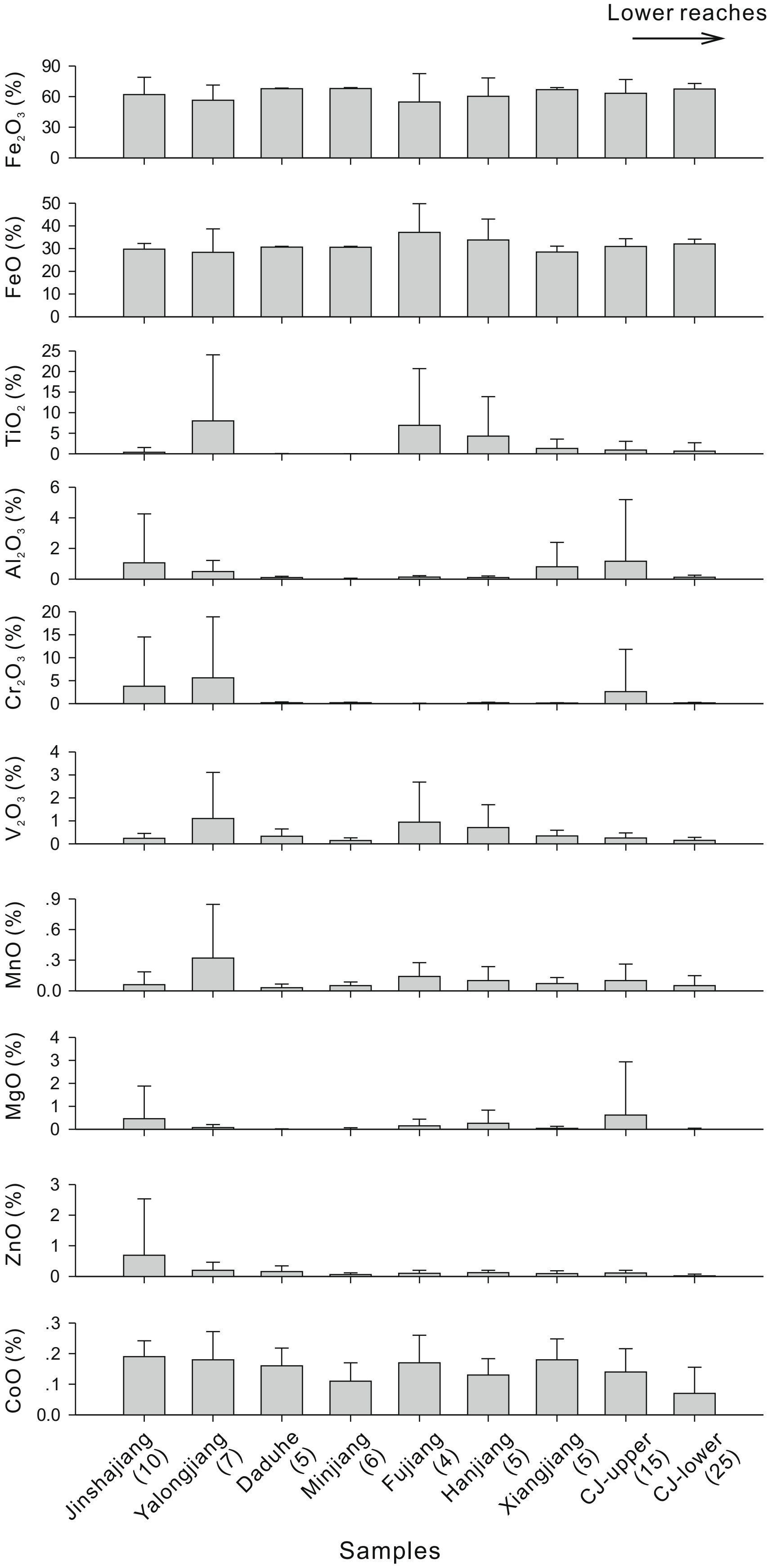

Fig. 3. The average and standard deviation (1δ error) of elemental concentrations of magnetite grains in the sediments from the mainstream and tributaries of the Changjiang. The numbers of measured magnetite grains are shown below each river. The All Fe was recalculated to weight-percent Fe_2O_3 and FeO following the procedure of Carmicheal (1967).

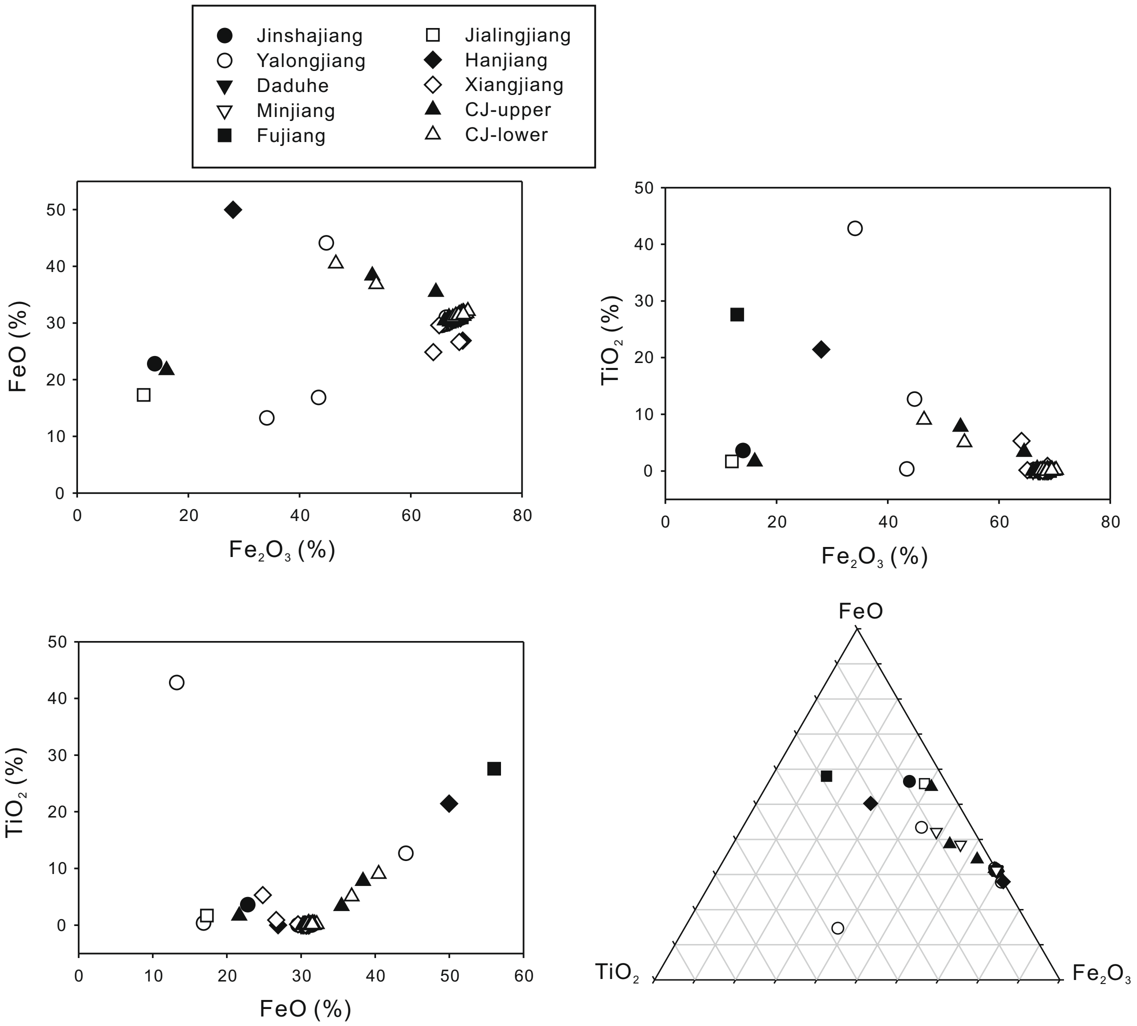

Fig. 4. Scatter plots and Fe_2O_3–FeO–TiO_2 ternary diagram of major elemental compositions in detrital magnetite grains.

sample has completely different magnetite chemistry from other river samples, diagnostic of chromium magnetite. The measured magnetite chemistry of the Jialingjiang samples may not represent the bulk river sediments since only one magnetite grain was picked up for chemical analysis. Overall, the magnetite grains from the upper Changjiang mainstream are more concentrated in Al_2O_3, Cr_2O_3 and MgO than those from the middle-lower mainstream (Fig. 3).

The plots of Fe_2O_3 versus TiO_2 and FeO versus TiO_2 indicate that Ti^{4+} can replace Fe^{3+} in some magnetite grains, which results in the negative relationship between Fe_2O_3 and TiO_2, and the positive relationship between FeO and TiO_2 (Fig. 4). A considerable amount of Ti can enter the magnetite structure and replace Fe^{3+} in various source rocks, particularly in the intermediate volcanic, mafic and metamorphosed mafic or ultramafic rocks (Basu and Molinaroli, 1989; Grigsby, 1990; Deer et al., 1992; Razjgaeva and Naumova, 1992; Ai et al., 2006). Furthermore, small amounts of Al, Cr and V can substitute for Fe^{3+} and generally similar small proportions of Ca, Mn, Mg, Ni, Co and Zn may replace Fe^{2+} in magnetite grains (Deer et al., 1992). The relatively low concentrations of these elements in detrital magnetite grains suggest that the substitutions of Fe by these elements are not significant for the Changjiang river samples, and the substitutions have variable degrees between these different river samples.

4.3. Provenance discrimination of transparent heavy minerals

The parent rock lithology is the most important factor controlling heavy mineral composition in fluvial sediments, although hydrodynamic sorting and mechanical breakdown during transport and weathering during alluvial storage on the floodplain can also fractionate heavy mineral assemblages. It has been suggested that the 63–1258 μm size fraction for heavy mineral examination can minimize the hydrodynamic effect (Morton and Hallsworth, 1994; Morton et al., 2005). However, the very fine sand fraction is not only rich in heavy minerals in general, but it is also relatively enriched in ultradense minerals such as zircon, magnetite, ilmenite and garnet because of settling-equivalence effect (Rubey, 1933; Garzanti et al., 2008). In this study we did not examine the heavy minerals in bulk samples or wider size-separated fractions which may provide a less biased representation of detrital heavy assemblages. Nevertheless, the sediments from the major tributaries and mainstream of the Changjiang are primarily composed of very fine sand (Table 1; Fig. 2), and thus, the 63–125 μm size fraction used in this study can overall reflect the heavy mineral assemblages of the Changjiang sediments. The Changjiang transports a large volume of suspended sediments (about 4.8×10^8 ton/yr at Datong Hydrologic Station) into the estuary, and most of the sediments eroded from the source terrains are rapidly transported into

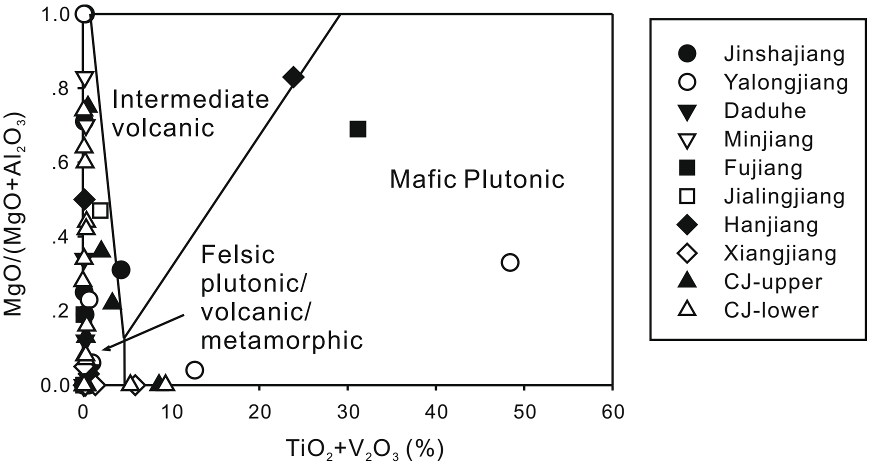

Fig. 5. Discrimination plot of $TiO_2 + V_2O_3$ versus $MgO/(MgO + Al_2O_3)$ for detrital magnetite grains. The plot is modified after Grigsby (1990).

and accumulated in the estuary and adjoining shelf area. As a consequence, mechanical abrasion during fluvial transport and weathering during alluvial storage on the floodplain cannot greatly fractionate heavy mineral assemblages. The wide occurrences of unstable heavy minerals such as calcic amphibole, epidote and augite in the Changjiang sediments further suggest the weak effects of hydraulic erosion and weathering during alluvial storage. Furthermore, the composition of sediment fed into the complex river system like the Changjiang was too heterogeneous to isolate the weathering effect, as suggested by Morton and Hallsworth (1999).

Accordingly, we infer that the heavy mineral assemblages of the Changjiang sediments are primarily controlled by source rock types. The extremely complicated and much variable source rock types in the large Changjiang drainage basins make it difficult, if not impossible, to sample each candidate parent rock for heavy mineral examinations. Furthermore, the existing documents on the heavy mineralogy in these variable source rocks are too few to allow us make a detailed comparison of heavy mineral compositions between the parent rocks and the river sediments. Nevertheless, the weight percentages of heavy mineral fraction and heavy mineral assemblages do show systematic variations between the tributaries and mainstream sediments (Table 2; Fig. 2). The sediments from the major tributaries of the upper Changjiang valley such as the Jinshajiang, Yalongjiang, Daduhe and Minjiang Rivers contain more heavy minerals than those from the Hanjiang, Yuanjiang and Xiangjiang Rivers in the middle Changjiang valley. The upper Changjiang mainstream sediments also have higher weight percentages of heavy mineral fractions than the middle-lower Changjiang mainstream samples. The upper Changjiang valley is predominantly situated in tectonically active area where the variable source rocks are easily uplifted and exposed to weathering, which may cause concentrated heavy minerals in the fluvial sediments. The Jinshajiang sample (CJ1-2) sourced from the upper Jinshajiang reaches has the highest weight percentage (28.9%) of heavy mineral fraction, much higher than the other samples, which corresponds well with the fact that the neotectonic movement in the upper Jinshajiang valley (east Tibetan Plateau) is the most active within the Changjiang drainage basin.

In comparison, the middle-lower Changjiang valley experienced relatively weak neotectonic movements and stronger chemical weathering. The siliciclastic sedimentary rocks and sediments occupy a large drainage area and the soil layer is more developed than the upper reaches. The heavy mineral fraction in fluvial sediments is therefore less concentrated than those from the upper major tributaries mainly due to the sediment recycling. The recycled sediments in the drainage basin may have a considerable influence on the heavy mineral compositions of the fluvial sediments. For example, some round zircon grains were clearly observed under the binocular microscope, which is diagnostic of the recycling origin. Recent study suggested that sediment recycling in the Changjiang drainage basin can significantly influence mineral chemistry of detrital monazite grains (Yang et al., 2006). Nevertheless, it is a challenging work to clarify the contribution of sediment recycling to heavy mineral compositions of the fluvial sediments considering that the source rock types in the Changjiang basin are much variable and few studies have been carried out on heavy minerals in sedimentary rocks.

The widely distributed granitoids in the Xiangjiang drainage basin predominantly account for the extraordinary high content (about 29.4%) of zircon (Fig. 1). The Permian basalt widely occurring in the Daduhe and upper Hanjiang drainage basins are responsible for higher contents of hypersthene in these river samples. Despite the effects of sediment recycling and hydrodynamic sorting on heavy minerals of the fluvial sediments our study reveal that the heavy mineral assemblages can overall represent a potential provenance tracer in a large river basin, as shown by recent studies on other rivers (Heroy et al., 2003; Garzanti et al., 2005, 2006, 2007).

4.4. Provenance discrimination of opaque Fe–Ti oxide minerals

Among the opaque Fe–Ti oxide minerals, magnetite occurs in many igneous and metamorphic rocks, and has special provenance-tracing implications in terms of their distinct mineral chemistry and typomorphic features (Chen et al., 1987; Darby and Tsang, 1987; Pettijohn et al., 1987; Basu and Molinaroli, 1989; Grigsby, 1990, 1992; Razjgaeva and Naumova, 1992; Yang et al., 2000; Hounslow and Morton, 2004). Various discrimination diagrams based on chemical compositions have been developed to identify the magnetite origins (Chen et al., 1987; Grigsby, 1990). In the discrimination plot of $TiO_2 + V_2O_3$ versus $MgO/(MgO + Al_2O_3)$, most of the magnetite grains are clustered into the felsic plutonic and volcanic, and/or metamorphic origins, whereas only few magnetite grains are grouped into intermediate volcanic or mafic plutonic fields (Fig. 5). This suggests that most of the detrital magnetite grains from the Changjiang sediments are sourced from felsic plutonic and volcanic, and/or metamorphic parent rocks.

Previous studies suggested that the presence of very fine intergrowths of magnetite with chromite, ilmenite, zircon, pleonaste, ulvöspinel, and sulphides of Ni, Cu, Zn is common in magnetite grains, which indicates typomorphic features of different genetic groups of various source rocks (Grigsby, 1990, 1992; Razjgaeva and Naumova, 1992; Yang et al., 2000). Most of the detrital magnetite grains measured in the present study are homogeneous and usually monomineralic and contain few inclusions, according to the electron microprobe observations. This finding is in well accordance with previous work on the magnetite grains collected from the Changjiang Estuary (Yang et al., 2000). Based on a large quantity of statistical analysis, Grigsby (1990) also found that detrital magnetite grains from felsic plutonic and volcanic parent rocks are dominated by homogeneous grains with low concentrations (<1%) of TiO_2, Al_2O_3, Cr_2O_3, V_2O_3 and MgO, while detrital magnetite grains from metamorphic parent rocks are characterized by exsolved pleonaste or ulvöspinel, but homogeneous grains are also common, with variable concentrations of TiO_2, Al_2O_3, Cr_2O_3, V_2O_3 and MgO. The concentrations of TiO_2, Al_2O_3, Cr_2O_3, V_2O_3 and MgO in most of the detrital magnetite grains from the river samples are less than 1% (Table 3; Fig. 3), which further suggests that the felsic plutonic and volcanic parent rocks are the main sources of these magnetite grains. Felsic plutonic rocks are widely distributed in the Jinshajiang, Yalongjiang, Daduhe, Xiangjiang, Yuanjiang, and Ganjiang valleys (Fig. 1). Magnetite is widely observed in these granitoids and in general has low concentrations of TiO_2, MnO and V_2O_3 (Wang et al., 1990; Chen and Zhang, 1991; Wang et al., 1992). The extraordinary high concentrations of TiO_2, Cr_2O_3 and V_2O_3 in the detrital magnetite grains from the Yalongjiang samples (Table 3; Fig. 5) are apparently related to the Panzhihua Fe–Ti–V oxide mine in the drainage basin. The Panzhihua Fe–Ti–V oxide mine is primarily hosted in the 260 Ma Emeishan Large Igneous Province which covers an area of 5×10^5 km^2 in southwest China. The Emeishan Large Igneous Province comprises the Emeishan Continental Flood Basalts and associated mafic–ultramafic intrusions in the western part of the Yangtze Block and the eastern margin of the Tibetan Plateau (Fig. 1; Zhou et al., 2005; Ai et al., 2006). The magnetite chemistry of the Panzhihua Fe–Ti–V oxide mine is characterized by high concentrations of TiO_2, Cr_2O_3 and V_2O_3 (Xiao, 2001; Zhou et al., 2005).

Most of the detrital magnetite grains from the Xiangjiang are homogeneous, with low concentrations (<1%) of TiO_2, Al_2O_3, Cr_2O_3, V_2O_3, MgO, ZnO and MnO (Table 3), probably reflecting the sources from the widely distributed granitoids in the drainage basin (Figs. 1 and 5). In contrast, few magnetite grains from the Xiangjiang with high concentrations of TiO_2, and Al_2O_3 may be sourced from the metamorphic rocks which occur in the basin (Figs. 1 and 5). Meanwhile, the magnetite grains with high concentrations of TiO_2 and V_2O_3 from the Fujiang and Hanjiang samples are primarily sourced from the widely distributed metamorphic parent rocks in their drainage basins.

5. Conclusions

Floodplain sediment samples were systematically collected from the Changjiang mainstream and the major tributaries for heavy mineral examination and single-grain mineral chemical analysis. The analytical results show that the weight percentages and assemblages of the heavy mineral fractions are much variable in the samples, and calcic amphibole, epidote, magnetic minerals, limonite, and garnet characterize the major heavy mineral assemblages. The upper Changjiang samples contain more heavy minerals in the very fine sand fraction (63–125 μm) and have higher contents of Fe–Ti oxide minerals whereas the middle-lower samples are relatively enriched in polygenetic heavy minerals. The high contents of zircon and hypersthene in the Xiangjiang and Daduhe samples respectively reflect the contributions of widely distributed granitoids and Permian Emeishan Basalt in their drainage basins.

The variable provenance rock types and active neotectonic movements in the upper drainage basins may cause rapid weathering of fresh source rocks and thus, concentrate the heavy minerals in the fluvial sediments. To the contrary, the middle-lower Changjiang valley has been experiencing weaker neotectonic movements and stronger chemical weathering. Different sources of the heavy minerals from the upper major tributaries and mainstream mix in the lower mainstream sediments, which causes the high percentage of polygenetic heavy minerals. Furthermore, sediment recycling may also have a considerable influence on the heavy mineral assemblages in the fluvial sediments.

Chemical analysis of detrital magnetite grains from these river sediments suggests that the concentrations of Fe_2O_3 and FeO in most of the measured grains are somewhat lower than the stoichiometric composition of magnetite due to the substitutions of Fe by other elements such as Al, Cr, V, Ti, Mn, Mg and Zn. Overall, the Jinshajiang magnetite grains have high concentrations of Al_2O_3, Cr_2O_3, and ZnO. The Yalongjiang magnetite grains are relatively enriched in Ti, Cr, V, Mn, Mg, and Al. The Daduhe and Minjiang magnetite grains are characterized by low contents of TiO_2, Al_2O_3, MnO and MgO relative to other river samples. The Fujiang and Hanjiang magnetite grains are relatively concentrated in TiO_2 and V_2O_3. Based upon the discrimination plot of $TiO_2 + V_2O_3$ versus MgO/(MgO + Al_2O_3), we infer that most of the detrital magnetite grains are sourced from felsic plutonic and volcanic, and/or metamorphic parent rocks. They are homogeneous and have low concentrations of Ti, Cr, V, Al, Mn, Mg, and Zn. The Panzhihua Fe–Ti–V oxide mine and the hosting mafic/ultramafic parent rocks in the Jinshajiang and Yalongjiang valleys determine the variable compositions of some magnetite grains from the upper Changjiang mainstream and the tributaries. The present study clearly demonstrates that combination of transparent heavy mineral assemblages and opaque magnetite chemistry can better discriminate different sediment provenances of the Changjiang River.

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