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ORIGINAL ARTICLE

Sediment recycling and indication of weathering proxies

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Abstract As a result of recycling, the mineralogical and chemical compositions of riverine sediments may reflect the combined effects of the present-day weathering regime as well as previous weathering and diagenetic alteration history. River sediments can be interpreted as a mixture of non-weathered bedrock—of igneous, metamorphic, or sedimentary origin—and solids formed by the modern weathering system. The correlation between the weathering proxies chemical index of alteration and weathering index of Parker offers an approach to distinguish fine suspended particles, coarse bedload sediments, and recycled sediments under the influence of quartz dilution. Recycling of cation-depleted source rocks formed during past geological weathering episodes may have great impacts on the weathering indices of sediments from the Changjiang (Yangzte) and Zhuoshui Rivers. Special caution is required when using chemical weathering indices to investigate the intensity of chemical weathering registered in fluvial sediments. To minimize the effect of hydrodynamic sorting or sediment recycling, we suggest that the fine sediments (e.g. suspended particles and <2 μm fractions of bedload sediments) in rivers better reflect the average of weathered crust in catchments and the terrigenous end-member in marginal seas.

Keywords River sediments · Weathering indices · Sediment recycling · Source-to-sink

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1 Introduction

Sedimentary and metamorphic rocks, formed of minerals inherited from one or several paleoweathering cycles, are common rock types in river catchments, especially in orogenic areas (Cox et al. 1995; Gaillardet et al. 1999). The mineralogical and chemical composition of newly produced detritus thus reflects the present weathering regime as well as the effects of previous weathering and diagenetic histories. On the basis of the Sm/Nd isotopic systematics of sediments, Veizer and Jansen (1985) suggested that 90% of sedimentary rocks are formed by the recycling of post-Archean sedimentary rocks. Gaillardet et al. (1999) used the dissolved and particulate loads of rivers to calculate the proportion of recycled sediments in the world's largest river basins, and suggested that large rivers do not predominantly transport modern weathering products but that their sediments largely constitute ancient sediments formed during past weathering cycles. Whether the weathering intensity of terrigenous sediments can indicate changes in climate largely depends on the better understanding of recycling effects on sediment composition. Separating climatic influence on newly formed sediments from weathering histories of previous sedimentary cycles is perhaps the most challenging problem in sedimentary geochemistry (Gaillardet et al. 1999; Garzanti et al. 2013).

The chemical index of alteration (CIA) first proposed by Nesbitt and Young (1982) is defined as Al_2O_3/

$(Al_2O_3 + CaO^* + Na_2O + K_2O) \times 100$, and reflects the extent of feldspar weathering to clays. The weathering index of Parker (WIP) was pioneered by Parker (1970) to quantitatively evaluate the weathering degree of silicate rocks, and is defined as $(2Na_2O/0.35 + MgO/0.9 + 2K_2O/0.25 + CaO^*/0.7) \times 100$. Both CIA and WIP are calculated using molecular proportions of mobile alkali and alkaline earth metals, and only the amount of CaO incorporated in silicate phases (expressed as CaO*) is considered. Polycyclic reworking processes tend to accumulate stable minerals like quartz (SiO_2) in sediment, diluting other components and elements. WIP simply reflects depletion in Ca, Na, K, and Mg due to different factors, including the dilution of quartz. Thus, with increasing sediment recycling, the WIP value will decrease linearly, but CIA is largely immune to this process. CIA–WIP plots can be used to differentiate the compositional modifications of sediments due to weathering from those due to recycling (Garzanti et al. 2013).

Two types of river systems co-exist along the eastern China coast: large river systems, represented by the Changjiang (Yangtze River), and small mountainous river systems, represented by those in Taiwan and in Zhejiang and Fujian provinces (Yang et al. 2015). These two types of river systems have different sediment routing processes and physical and chemical weathering mechanisms, providing natural sedimentological laboratories for the investigation of potential influences (provenance, climate, and sediment recycling and sorting) on weathering intensity. In this study, correlation between CIA and WIP was adopted to evaluate the effect of sediment recycling and sorting.

2 Samples and methods

Seasonal suspended samples of the lower Changjiang were collected weekly from April 2008 to April 2009. A total of 22 bedload sediments and 26 suspended particulate matter (SPM) samples were taken from Zhe-Min rivers (Jiaojiang, Oujiang, and Mulanxi) between 2011 and 2012. In May 2013, ten bedload sediment samples were collected from the Zhuoshui River in Taiwan.

Geochemical analyses of sediments were carried out at the State Key Laboratory of Marine Geology, Tongji University. The proportions of major elements (oxides) were determined by ICP-AES following a $HF–HNO_3$ digestion. CIA and WIP were obtained after correction for non-silicate-bound CaO. We leached the sediments with 1-N HCl to remove the non-silicate-bound CaO, following the method described in Selvaraj and Chen (2006).

3 Results and discussion

A great convenience of modern river system studies is a priori knowledge of rock types of the source area, which is prerequisite for the investigation of silicate weathering intensity. As one of the world's largest rivers, the Changjiang integrates weathering and erosion processes over vast portions of the continental crust. Changjiang sediments witness cannibalistic processes, and a majority of the sediments may be derived from pre-existing sediment (Gaillardet et al. 1999). In contrast, the catchments of the Jiaojiang, Oujiang, and Mulanxi Rivers investigated in this study mainly consist of granite and granodiorite, and thus, the effect of recycling is negligible. The Zhuoshui basin in Taiwan is characterized by friable sedimentary–metasedimentary rocks; the residence time of eroded sediments in the catchment is very short and soil profile development is restricted by severe erosion in this mountainous catchment (Dadson et al. 2003; Selvaraj and Chen 2006). As a consequence, chemical indices of Taiwan river sands are determined primarily by the original concentrations of relatively mobile chemical elements in the source rocks, and chiefly reflect provenance information of recycled materials rather than alteration processes (Garzanti and Resentini 2015).

In this study, significant inverse correlation occurred between CIA and WIP in the SPM sediments from the Jiaojiang, Oujiang, and Mulanxi Rivers, suggesting that these river particles are largely first-cycle weathering products (Fig. 1a). In comparison, all the bedload sediments deviated from the CIA–WIP correlation line of those first-cycle SPM samples, displaying relatively lower CIA values, which suggests the existence of recycled rock fragments. The SPM sediments of the Changjiang plot somewhat below this "first-cycle weathering product line" and the correlation of CIA and WIP was not good, indicating that the suspended particles of the lower Changjiang are recycled materials, and confirming the previous argument that suspended sediments in the Changjiang are largely derived from recycled continental rocks (Gaillardet et al. 1999). Note that a spurious positive correlation was found between CIA and WIP in the bedload sediments of the Zhuoshui River, reflecting the controlling of quartz dilution.

Sediment sieving before chemical analysis is thought to be an effective pretreatment for reducing the grain-size and hydrodynamic sorting bias. Size-fractional sediments of rivers in East China (Bi et al. 2015; He et al. 2015; Zhou et al. 2015) were plotted in the CIA versus WIP diagram (Fig. 1b). The <63 μm fraction of the Changjiang sediments plotted much below the "first-cycle weathering product line," suggesting this size fraction is not fine

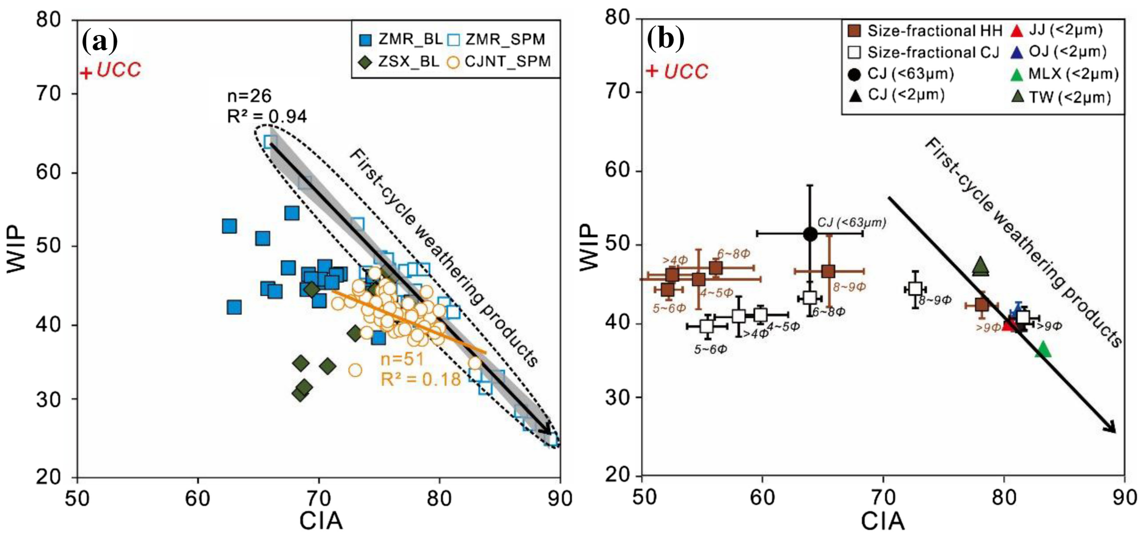

Fig. 1 **a** Correlation between CIA and WIP in river sediments, distinguishing the fine SPM sediments, coarse bedload sediments, and Zhuoshui sediments under the influence of recycling and quartz dilution. The coefficients of the regression line are calculated based on the SPM sediments of Jiaojiang, Oujiang, and Mulanxi. *Gray* envelopes represent a 95% confidence band of the linear regression. *Error bars* represent 2δ around the means. *ZMR* Zhe-Min rivers. **b** Correlation of CIA and WIP for the samples of different grain-size grades, showing only the <2 μm (or >9Φ) fraction of river sediments can represent present day weathering products

enough to represent present-day weathering products. Zhou et al. (2015) studied the mineralogy and geochemistry of different grain-size fractions of bedload sediments of the Changjiang and Huanghe Rivers. The <2 μm fractions yielded the highest CIA values that plot on the line of first-cycle weathering products, while the other size fractions exhibited lower CIA values that deviate considerably from the CIA–WIP correlation line. The results suggest that the silty and sandy sediments of the Changjiang and Huanghe are subject to hydrodynamic sorting effects and are of mixed sources with variable weathering intensities. Recent work by Bi et al. (2015) focused on the weathering mechanisms of river clays (<2 μm) in SE China. In the CIA versus WIP diagram, the clays of Changjiang, Jiaojiang, Oujiang, Mulanxi, and Taiwan rivers are also located on the line of present day weathering products. Therefore, we infer that the clay fraction (<2 μm) of river sediments can represent present day weathering products, without clear effects from hydrodynamic sorting and quartz dilution.

4 Conclusion

Chemical weathering indices based on sediment chemistry not only reflect the integrated weathering history of a specific provenance (i.e. catchment) but also depend on hydrodynamic sorting and sediment recycling effects during sedimentary processes. Hydraulic sorting, quartz dilution, and catchment recycling may have a great influence on the absolute values and scientific implications of weathering indices, which can be evaluated by detailed analysis of correlations among geochemical parameters. To better investigate the mean intensity of silicate weathering in river basins, it is necessary to select the fine suspended samples or extract the clay fraction (<2 μm) of bedload sediments.

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