Evolutionary Process and Provenance Tracing of Mineral Maturity in Sediments of the Yarlung Zangbo River

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Abstract

Focusing on surface sediments of the Yarlung Zangbo River on the Qinghai-Tibet Plateau, this study analyzes their provenance and evolutionary processes. Through systematic collection of river sediment samples, combined with high-precision chemical analytical techniques, chondrite-normalized methods, indices including δEu, La/Yb, and Rb/Sr, and multivariate diagrams were used to investigate geochemical characteristics, evolutionary processes, and provenance. The results show that: (1) the total rare earth element contents of surface sediments in the Yarlung Zangbo River Basin are generally high, and the rare earth element distributions are characterized by significant enrichment of light rare earth elements, typical negative Eu anomalies, and no obvious Ce anomalies. (2) Weathering in the basin exhibits clear spatial differences, with physical weathering dominating in the upper reaches and chemical weathering dominating in the lower reaches. (3) From the upper to the lower reaches, mineral sorting in the sediments gradually intensifies, and mineral maturity shows a significant increasing trend. (4) The results of the geochemical mixing model indicate that the sediments in the study area are mainly contributed by metapelitic rocks of the Himalayan orogenic belt (89.7%), Himalayan leucogranites (8.3%), and Gangdese batholith granites (2.3%). These findings provide important geochemical support for research on regional tectonic evolution processes and material migration patterns.

Full Text

Evolutionary Process and Provenance Tracing of Mineral Maturity in Sediments of the Yarlung Zangbo River

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Abstract: Focusing on surface sediments of the Yarlung Zangbo River on the Qinghai–Tibet Plateau, this study analyzes their provenance and evolutionary process. River-sediment samples were systematically collected and, in combination with high-precision chemical analysis techniques, the chondrite-normalization method was adopted. Using indicators such as δEu, La/Yb, and Rb/Sr, together with multivariate diagrams, the geochemical characteristics, evolutionary process, and provenance were analyzed. The results show that: (1) The total rare-earth-element content of surface sediments in the Yarlung Zangbo River basin is generally relatively high; the rare-earth elements exhibit significant enrichment of light rare earth elements, with a typical negative Eu anomaly and no obvious Ce anomaly. (2) Weathering in the basin shows marked spatial differences: the upstream area is dominated by physical weathering, whereas the downstream area is dominated by chemical weathering. (3) From upstream to downstream, mineral sorting in the sediments gradually strengthens, and mineral maturity shows a significant increasing trend. (4) The results of the geochemical mixing model indicate that the provenance of sediments in the study area is jointly contributed mainly by Xigaze Group pelitic rocks (89.7%), Himalayan leucogranite (8.3%), and Gangdese basement granite (2.3%). The research results can provide important geochemical supporting evidence for studies of regional tectonic evolution processes and patterns of material migration.

Keywords: Yarlung Zangbo River; river surface sediments; trace elements; rare earth elements

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Geochemical studies of rare earth elements and trace elements in river sediments can not only effectively characterize the elemental abundance background at different regional scales, but also, through the spatial distribution patterns of elements, infer the lithologic composition of drainage basins and the mineralization characteristics of potential bedrock, thereby providing important geochemical evidence for in-depth elucidation of basin weathering–erosion processes, sediment transport pathways, and migration mechanisms.

Mineral maturity is a core indicator characterizing the evolutionary process of sediments. Specifically, it refers to the degree to which clastic sediments, throughout the entire chain of transport and deposition, undergo physical sorting abrasion and chemical weathering alteration and progressively evolve toward a stable state. In practical evaluation, this indicator usually takes sedimentary structure–mineralogical characteristics as its core basis, covering key parameters such as the selectivity of mineral grains and the abundance ratios of stable weathering-resistant minerals to unstable minerals.

Although research methods for mineral maturity are relatively well developed, their evaluation accuracy and application effectiveness are constrained by factors such as parent-rock lithology and sedimentary dynamic conditions. Rare earth elements, because of their distinctive geochemical properties, have become important indicators for provenance and evolutionary tracing. Their distribution patterns can reveal parent rocks, weathering, and aqueous-rock interaction[1]; characteristic trace-element ratios can distinguish the superimposed effects of provenance and maturity. Combining the two provides an effective means for analyzing the coupled relationship among provenance, weathering, and mineral maturity. River sediments are the main carrier of material transport; their rare earth elements and maturity indicators jointly record the evolution of the geological environment of a basin and are an important carrier for reconstructing regional geological processes.

[1] 1

Researchers worldwide have conducted systematic studies on sediments of large rivers such as the Congo River, Amazon River, Rhine River, Mississippi River, and Indus River[2], demonstrating that tectonic setting controls provenance and rare-earth-element distribution, that the dominant factors of mineral maturity have regional differences, and that a research approach centered on the combined use of multiple indicators is essential. Studies related to rivers in China have both verified the above common patterns and, by incorporating regional climatic and tectonic characteristics, used cases such as the Yangtze River, Yellow River, rivers around the Yellow Sea, Pearl River, Red River, Lancang River, and rivers flowing into the sea along the southeast coast[3] to improve understanding of weathering, sorting, provenance, and sea-land material migration in rivers of different climatic zones.

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In recent years, high-precision analytical techniques represented by inductively coupled plasma mass spectrometry (ICP-MS) have continuously promoted the deepening of elemental geochemical methods. Elemental ratios such as La/Sc and Th/Sc, as well as multivariate diagrams such as La-Th-Sc, have become common means for effectively distinguishing the tectonic background of provenance areas

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, and have continually advanced research on the provenance of fluvial sediments.

However, geochemical research on sediments of the Yarlung Zangbo River still has obvious deficiencies. The existing limitations mainly include: incomplete coverage of basin-scale data and a lack of systematic studies on mineral maturity and spatial differentiation; provenance tracing mostly adopts single indicators, without achieving integrated constraints using rare earth elements and trace elements; and discussion remains weak regarding the coupling mechanism between the special regional geological background and the fractionation of rare earth elements.

This study systematically analyzes the rare earth and trace element compositions of sediments from the Yarlung Zangbo River. By using multi-index joint provenance tracing with rare earth and trace elements, it systematically reveals

[2] 2-6
[3] 7-12

the spatial evolution patterns of mineral maturity in Yarlung Zangbo River sediments and quantitatively evaluates the proportions of sediment source contributions. This research can supplement rare earth and trace element geochemical data for the basin, provide key evidence for revealing mechanisms of regional geological evolution, and is also of great significance for understanding material transport processes in the arid-humid transition zone of the Qinghai–Tibet Plateau.

1 Data and Methods

1.1 Overview of the Study Area

The Yarlung Zangbo River originates from the Jiemayangzong Glacier on the northern slope of the Himalayas. Its basin area is 239,228 km^2, and its total length is 2,229 km

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. It is a typical river in the semi-arid to humid transition zone (Fig. 1). In the upper reaches of the basin, annual precipitation is less than 300 mm

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, whereas at the Nuxia station in the lower reaches, multi-year average precipitation exceeds 5,000 mm. In addition, the intra-annual distribution of precipitation is also extremely uneven, with summer precipitation accounting for 65%–80% of the annual total

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. The Yarlung Zangbo River is located in the core region of the Himalayan–Tibetan Plateau orogenic belt (Fig. 2). Its left bank is the Lhasa terrane, dominated by igneous rocks represented by magmatic rocks and widely exposed Gangdese rocks. The right bank is the Himalayan orogenic belt, mainly composed of thick Paleozoic to Mesozoic sedimentary rocks and metamorphic rocks. Under intense orogenesis, these argillaceous rocks underwent partial melting, forming large quantities of Himalayan-type leucogranite

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1.2 Data Sources

From July to August 2020–2021, systematic sampling of the Yarlung Zangbo River was carried out in the Qinghai–Tibet Plateau region (Fig. 1). Sampling points were selected according to "appropriate

Fig. 1 Schematic diagram of the study area

Fig. 2 Geologic map of the main rock types in the Yarlung Zangbo Basin

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Figure 1: Fig. 1 Schematic diagram of the study area

Fig. 2 Geologic map of the main rock types in the Yarlung Zangbo Basin

Figure 2: Fig. 2 Geologic map of the main rock types in the Yarlung Zangbo Basin

According to the principle of "distance interval + representative location selection," spatial coverage was set to include 13 longitude belts and 2 latitude belts (82°–95°E, 29°–30°N). Along the basin from west to east, sampling sites were arranged at an average interval of 50 km, with a total of 33 sampling sites covering the entire mainstream of the Yarlung Zangbo River and its major tributaries; ultimately, 27 valid samples were retained.

This study adopted a bulk-sample analysis method. This method can effectively characterize the overall geochemical background of the basin[^19–20]; when provenance signals dominate, the influence of grain-size factors on the distribution of rare earth elements will be significantly weakened[^21–23]. The study area is in the high-water period from July to August, and strong hydraulic erosion and transport promote sufficient mixing of provenance materials, making the sediments dominated by fine-grained components (<63 μm), with relatively uniform grain-size distribution[^19] and relatively consistent elemental compositions among different regions[^24]. The analytical procedure for rare earth elements and trace elements was as follows: the whole-rock samples were dried at low temperature and ground in an agate mortar to 200 mesh. The contents of rare earth elements and other trace elements in the sediments were determined by ICP-MS at the Beijing Geological Research Institute of Nuclear Industry. The relative standard deviation of the analytical results was less than 2%. For quality control, one laboratory standard sample (andesite AGV-2) was added simultaneously for every 10 samples analyzed.

This study comprehensively considers the longitude distribution pattern, geomorphological features, basement geological attributes, and provenance differentiation pattern of the Yarlung Zangbo River basin, and, with reference to existing related research results for this basin[^25–26], divides it into three reaches: upstream, midstream, and downstream. The sampling-site distribution and core characteristics corresponding to each reach are as follows: the upstream reach comprises Y01–Y14, distributed from Ngari in Tibet to west of Xigazê (<88.5°E); the midstream reach comprises Y15–Y26, located from Xigazê to west of Mainling (88.5°–94.5°E); the downstream reach comprises Y27–Y33, covering the Mainling area to the great bend of the Yarlung Zangbo River (>94.5°E). This study used chondrite as the reference standard for the surface sediments of the Yarlung Zangbo River. The calculation methods for δCe and δEu in the text are as follows:

$$\delta\text{Ce} = \text{Ce}_N/(\text{La}_N \times \text{Pr}_N)^{1/2} \qquad (1)$$

$$\delta\text{Eu} = \text{Eu}_N/(\text{Sm}_N \times \text{Gd}_N)^{1/2} \qquad (2)$$

In the formulas: δCe is the cerium anomaly; δEu is the europium anomaly; Ce, La, Pr, Eu, Sm, and Gd are the contents of cerium, lanthanum, praseodymium, europium, samarium, and gadolinium, respectively; N denotes the value after chondrite normalization[^27].

2 Results and analysis

2.1 Trace-element and rare-earth-element contents in surface sediments of the Yarlung Zangbo River

The statistical data for trace elements and rare earth elements in surface sediment samples from the study area are shown in Table 1. The contents of most trace elements are relatively stable, while some elements show pronounced fluctuations. Taking Cr as an example, its average value is only 174.46 $\mu g \cdot g^{-1}$, whereas the maximum value reaches 2366.00 $\mu g \cdot g^{-1}$ (13.6 times the average), and the standard deviation (430.78 $\mu g \cdot g^{-1}$) far exceeds 1/2 of the average value. This geochemical characteristic indicates that local Cr-enriched areas may exist in the study area. Its genetic interpretation is inferred to be closely related to two major factors: local special lithologic input (such as contribution from the Yarlung Zangbo River ophiolite belt) and selective enrichment of heavy minerals[^28-29]. The overall fluctuation of rare earth elements is gentle: for the 14 rare earth elements, the "maximum/average" values are mostly between 1.2 and 1.6, and the coefficients of variation (the ratio of standard deviation to average value) are generally less than 0.3. This indicates that the contents of rare earth elements are little affected by local interference, are mainly controlled by the overall rock-weathering process of the basin, and can serve as reliable indicators reflecting the regional "natural background."

The total rare earth element content (ΣREE), light rare earth element (LREE: La–Eu) content, and heavy rare earth element (HREE: Gd–Lu) content in surface sediment samples from each sampling site are shown in Figure 3. The results show that there are significant differences in the overall abundance of rare earth elements in sediments from different sampling sites, and ΣREE exhibits a staged gradient variation. According to the data distribution characteristics, the sediments in the study area can be roughly divided into three groups: a low-total group (Y03, Y04, Y22) with $\Sigma\text{REE} < 110$ $\mu g \cdot g^{-1}$; a medium-total group (Y01, Y02, Y05, Y07, Y08, Y21) with ΣREE ranging from 102 to 155 $\mu g \cdot g^{-1}$; and a high-total group (Y09-Y11, Y13-Y20, Y24–Y33) with ΣREE ranging from 180 to 233 $\mu g \cdot g^{-1}$. The above grouping characteristics may be closely related to the spatial location of each sampling site, parent-rock type, and material transport process.

Overall, the sediment samples in the study area generally show significant enrichment of LREE. The LREE content is much higher than the HREE content, and LREE/HREE is about 10. Among them, sample Y33 shows an obvious peculiarity: its HREE content reaches 24.526 $\mu g \cdot g^{-1}$, the highest value among all samples, and its LREE/HREE is the lowest (6.66), indicating that the sediment at this sampling site has a differentiation characteristic of relatively enriched HREE.

2.2 Differentiation characteristics of rare earth elements in surface sediments of the Yarlung Zangbo River

Figure 4 shows the distribution pattern of rare earth elements after chondrite normalization[^27]. The LREE-normalized values of all samples gradually decrease with increasing atomic number, whereas the HREE are relatively flat, overall forming a "high on the left and low on the right" distribution curve, indicating significant enrichment and fractionation of LREE relative to HREE. Compared with sediment data from the Yangtze River and Yellow River basins[^8], the upper continental crust[^1], and North American shale[^30], the surface sediments of the Yarlung Zangbo River show distinct characteristics: not only is the total ΣREE higher, but the negative Eu anomaly is also more pronounced, and the degree of LREE enrichment is stronger. The formation of this geochemical difference is inferred to be directly related to the uniqueness of the provenance in the Himalayan orogenic belt and the particularity of basin weathering.

From the rare-earth-element differentiation characteristic parameters listed in Table 2, it can be seen that the δEu values of all sampling sites are less than 1 (0.50–0.67), with no extreme discrete values, indicating typical negative Eu anomalies; the δCe values are all close to 1 (0.91–

Table 1 Contents of trace elements and REEs in surface sediments of the Yarlung Zangbo River /$\mu g \cdot g^{-1}$

Sampling site	Li	Be	Sc	V	Cr	Co	Ni	Cu	Zn	Ga	Rb	Sr	Y	Mo	Cd
Y01	47.40	4.76	4.80	29.00	58.10	6.54	24.00	10.20	45.40	13.30	149.00	189.00	18.80	0.27	0.11
Y02	45.30	5.58	4.03	31.00	48.50	5.47	20.40	9.79	43.70	14.30	172.00	163.00	19.00	0.63	0.11
Y03	33.40	4.81	3.21	23.60	44.50	4.16	20.50	5.25	33.80	12.00	179.00	194.00	12.20	0.22	0.03
Y04	30.90	3.95	4.50	44.90	106.00	8.03	47.80	15.70	42.00	10.30	111.00	95.00	13.70	0.21	0.07
Y05	62.70	4.75	7.27	50.60	62.40	8.91	28.90	18.90	68.00	16.40	182.00	150.00	18.10	0.40	0.12
Y07	50.10	2.42	7.53	58.10	50.80	8.71	27.70	17.30	71.90	13.10	116.00	233.00	20.20	0.46	0.12
Y08	36.70	3.02	7.88	55.60	54.40	10.10	31.60	29.60	62.10	13.20	117.00	135.00	19.40	0.38	0.09
Y09	41.30	2.50	9.29	76.30	81.30	11.10	28.60	25.00	72.70	15.20	123.00	136.00	24.90	0.38	0.08
Y10	51.50	3.21	9.56	69.60	84.90	12.40	40.10	27.10	77.70	15.00	114.00	203.00	22.10	0.47	0.10
Y11	36.70	2.82	8.56	70.50	134.00	12.40	56.30	26.50	73.30	13.00	103.00	156.00	24.50	0.46	0.07
Y13	40.10	2.60	9.46	84.70	112.00	13.60	60.10	31.80	77.10	14.70	104.00	174.00	22.10	0.51	0.10
Y14	46.40	2.60	11.10	77.80	107.00	16.40	62.80	39.80	86.50	16.70	109.00	185.00	25.40	0.64	0.12

Sampling site	Li	Be	Sc	V	Cr	Co	Ni	Cu	Zn	Ga	Rb	Sr	Y	Mo	Cd
Y15	38.60	2.42	10.40	75.40	124.00	15.10	66.40	33.00	79.20	15.10	102.00	163.00	23.40	0.47	0.08
Y16	33.90	3.17	9.63	83.30	72.10	10.30	30.00	25.00	71.20	14.90	110.00	224.00	26.90	0.50	0.07
Y17	35.50	2.71	10.00	94.60	120.00	13.00	43.30	28.40	76.20	15.20	107.00	221.00	24.30	0.63	0.09
Y18	38.40	2.52	10.10	81.50	100.00	12.80	49.30	29.80	76.70	15.40	105.00	228.00	24.50	0.64	0.08
Y20	38.70	2.51	10.10	81.90	141.00	13.60	43.10	38.80	83.70	15.90	110.00	199.00	24.70	0.67	0.10
Y21	26.00	1.90	8.24	76.90	48.80	9.41	24.40	22.90	60.20	14.50	106.00	278.00	19.80	0.81	0.10
Y22	26.20	1.65	8.40	65.70	2366.00	27.10	322.00	19.20	62.60	11.30	77.50	178.00	14.00	0.37	0.07
Y24	35.80	2.35	9.89	88.00	133.00	12.60	43.40	30.60	78.50	15.50	99.30	216.00	28.40	0.57	0.08
Y25	32.60	1.95	9.02	98.40	137.00	12.00	36.50	25.30	82.80	15.10	92.60	242.00	23.00	0.64	0.10
Y26	43.40	2.17	10.60	84.40	84.30	14.70	46.40	36.40	96.20	16.60	107.00	203.00	29.30	0.60	0.13
Y27	34.90	1.98	9.76	84.10	100.00	12.80	41.20	30.80	80.60	15.10	96.20	221.00	27.00	0.57	0.10
Y28	48.00	2.47	12.20	95.70	77.90	18.20	50.80	65.90	104.00	18.20	116.00	194.00	28.10	0.78	0.17
Y29	35.90	2.19	9.42	81.60	79.20	12.40	34.90	31.50	79.50	15.10	105.00	191.00	25.20	0.47	0.13
Y31	15.10	1.66	7.42	78.20	79.30	8.37	22.30	12.40	77.10	14.60	72.50	217.00	33.30	0.45	0.11
Y33	16.00	2.19	14.20	90.60	104.00	15.50	32.10	24.80	60.20	16.60	93.20	150.00	39.80	0.50	0.09
Average	37.83	2.85	8.76	71.56	174.46	12.06	49.44	26.36	71.22	14.68	114.01	190.30	23.41	0.51	0.10
Maximum	62.70	5.58	14.20	98.40	2366.00	27.10	322.00	65.90	104.00	18.20	182.00	278.00	39.80	0.81	0.17
Minimum	15.10	1.65	3.21	23.60	44.50	4.16	20.40	5.25	33.80	10.30	72.50	95.00	12.20	0.21	0.03
Standard deviation	10.06	1.02	2.41	20.13	430.74	4.39	54.97	11.65	15.82	1.70	26.37	38.43	5.80	0.15	0.03

Sampling site	In	Sb	Cs	Ba	W	Re	Tl	Pb	Bi	Th	U	Nb	Ta	Zr	Hf
Y01	0.03	5.16	73.60	358.00	3.04	0.00	0.78	36.60	0.74	14.20	4.17	9.34	1.18	47.20	1.64
Y02	0.04	1.55	39.70	408.00	7.13	<0.002	1.02	43.50	0.97	15.30	3.85	10.80	1.38	40.40	1.49
Y03	0.02	1.36	34.40	425.00	3.09	0.00	1.07	31.70	0.39	10.10	2.60	7.78	0.85	35.20	1.30
Y04	0.02	0.78	21.10	333.00	1.61	<0.002	0.60	28.10	0.40	6.62	1.47	8.22	0.72	65.00	1.89
Y05	0.04	1.73	48.20	402.00	4.28	<0.002	0.89	34.10	1.17	13.20	2.43	12.80	1.34	62.70	1.79
Y07	0.05	1.94	27.90	324.00	3.11	0.00	0.59	27.30	0.60	13.30	2.57	12.90	1.19	89.40	2.61
Y08	0.04	1.29	34.20	328.00	3.86	<0.002	0.61	25.20	0.42	11.20	1.81	11.10	1.04	81.40	2.51
Y09	0.05	1.14	26.80	338.00	3.47	<0.002	0.67	23.60	0.43	16.40	2.67	14.80	1.32	119.00	3.63
Y10	0.05	2.38	43.10	326.00	4.86	0.00	0.55	22.10	0.58	13.40	2.10	14.30	1.33	81.60	2.40
Y11	0.04	1.52	25.70	309.00	7.29	<0.002	0.58	20.70	0.50	13.70	2.23	15.20	1.55	90.00	2.54
Y13	0.05	1.58	28.80	313.00	3.12	0.00	0.58	22.00	0.64	15.80	2.19	13.50	1.14	77.10	2.29
Y14	0.05	1.60	33.60	339.00	3.48	<0.002	0.54	23.90	0.75	18.20	2.95	14.70	1.30	89.70	2.77
Y15	0.05	1.38	19.60	359.00	3.24	<0.002	0.48	21.60	0.30	16.60	2.11	14.10	1.17	86.10	2.51
Y16	0.05	1.53	23.10	380.00	3.01	0.00	0.62	24.10	0.72	16.60	2.45	12.70	1.10	78.30	2.43

Table 1 (continued)

Sampling point	In	Sb	Cs	Ba	W	Re	Tl	Pb	Bi	Th	U	Nb	Ta	Zr	Hf
Y17	0.04	3.47	24.50	383.00	3.09	<0.002	0.59	21.70	0.28	16.00	2.71	14.00	1.14	85.80	2.54
Y18	0.04	1.40	26.80	361.00	2.78	<0.002	0.57	22.60	0.31	17.00	2.91	12.20	1.05	93.00	2.73
Y20	0.05	1.47	29.90	391.00	2.99	<0.002	0.58	24.70	0.37	22.50	4.32	14.00	1.29	91.00	2.85
Y21	0.04	1.02	16.70	432.00	2.51	0.00	0.68	22.70	0.31	10.40	2.14	9.50	0.86	66.90	2.14
Y22	0.03	1.16	17.30	308.00	1.49	0.00	0.46	16.80	0.17	7.48	1.65	7.18	0.65	44.90	1.51
Y24	0.05	1.21	24.30	352.00	5.51	0.00	0.60	21.70	0.32	20.40	3.02	14.40	1.28	95.80	3.29
Y25	0.05	0.90	15.30	365.00	3.37	<0.002	0.54	22.20	0.23	24.70	3.46	14.60	1.30	52.70	1.75
Y26	0.05	1.21	28.60	378.00	3.84	<0.002	0.63	25.00	0.41	21.50	3.20	14.00	1.23	97.40	2.81
Y27	0.05	1.16	22.90	356.00	2.67	<0.002	0.57	22.70	0.28	17.90	2.59	13.30	1.12	77.90	2.59
Y28	0.07	1.20	29.10	405.00	3.32	0.00	0.72	29.20	0.44	17.70	3.31	14.40	1.18	70.10	2.21
Y29	0.05	0.94	24.50	368.00	2.50	<0.002	0.63	24.50	0.31	16.50	2.72	13.40	1.24	67.40	2.30
Y31	0.05	1.23	3.27	278.00	4.84	<0.002	0.39	25.10	0.17	29.20	5.35	16.30	1.48	58.00	2.01
Y33	0.06	0.13	4.12	334.00	1.72	<0.002	0.44	13.50	0.13	17.30	3.36	12.50	1.29	38.60	1.36
Mean	0.04	1.53	27.67	357.53	3.53	0.00	0.63	25.07	0.46	16.04	2.83	12.67	1.17	73.43	2.29
Maximum	0.07	5.16	73.60	432.00	7.29	0.00	1.07	43.50	1.17	29.20	5.35	16.30	1.55	119.00	3.63
Minimum	0.02	0.13	3.27	278.00	1.49	0.00	0.39	13.50	0.13	6.62	1.47	7.18	0.65	35.20	1.30
Standard deviation	0.01	0.91	13.29	37.40	1.38	0.00	0.15	5.88	0.24	4.86	0.85	2.36	0.21	20.50	0.56

Sampling point	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Y01	32.20	57.40	7.11	26.20	4.99	0.76	4.24	0.70	3.49	0.66	1.68	0.28	1.69	0.24
Y02	33.90	61.20	7.29	25.80	4.87	0.84	4.12	0.70	3.46	0.66	1.68	0.30	1.82	0.25
Y03	24.10	42.90	5.18	18.10	3.25	0.59	2.69	0.44	2.28	0.42	1.14	0.19	1.27	0.17
Y04	19.80	37.70	4.67	16.90	3.16	0.66	2.76	0.50	2.31	0.49	1.26	0.22	1.35	0.19
Y05	30.70	55.40	6.57	23.80	4.51	0.76	3.88	0.65	3.20	0.64	1.68	0.29	1.89	0.24
Y07	34.80	65.70	7.74	27.30	4.96	0.87	4.36	0.70	3.48	0.68	1.76	0.32	1.95	0.29
Y08	31.50	58.50	6.93	25.40	4.72	0.87	3.85	0.67	3.44	0.67	1.83	0.31	1.97	0.27
Y09	45.40	89.60	10.90	39.40	6.73	1.18	5.51	0.92	4.60	0.89	2.39	0.41	2.48	0.35
Y10	39.80	75.00	9.25	33.70	6.18	1.05	5.13	0.84	4.13	0.80	2.07	0.34	2.12	0.30
Y11	47.50	93.70	11.40	41.90	7.32	1.25	5.98	0.96	4.57	0.87	2.43	0.39	2.46	0.34
Y13	46.20	89.60	11.10	39.70	6.81	1.19	5.76	0.90	4.04	0.76	2.17	0.34	2.21	0.31
Y14	42.30	84.80	10.20	37.20	6.88	1.17	5.61	0.93	4.41	0.88	2.41	0.37	2.54	0.34
Y15	44.00	87.50	10.40	37.70	6.59	1.19	5.60	0.86	4.22	0.84	2.20	0.38	2.29	0.34
Y16	42.80	83.10	10.30	38.50	6.91	1.16	5.61	0.97	4.61	0.95	2.41	0.41	2.61	0.37
Y17	43.40	85.60	10.20	36.80	6.57	1.11	5.14	0.82	4.21	0.82	2.25	0.39	2.33	0.35

Sampling point	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Y18	47.30	86.00	10.50	37.40	6.45	1.17	5.38	0.85	4.28	0.85	2.27	0.37	2.36	0.32
Y20	47.50	93.90	11.50	41.10	7.47	1.22	6.11	0.98	4.78	0.89	2.27	0.40	2.56	0.38
Y21	34.30	59.80	7.19	25.10	4.45	0.81	3.82	0.63	3.29	0.67	1.83	0.34	2.04	0.32
Y22	23.90	43.80	5.42	19.70	3.63	0.67	2.92	0.50	2.46	0.51	1.32	0.23	1.43	0.21
Y24	49.40	97.90	12.10	44.40	7.89	1.40	6.51	1.08	5.26	1.02	2.65	0.46	2.85	0.40
Y25	43.80	80.60	10.20	36.90	6.24	1.22	5.47	0.81	4.30	0.83	2.24	0.37	2.32	0.34
Y26	48.10	95.90	11.50	42.50	7.49	1.27	6.61	1.08	5.16	1.02	2.68	0.46	2.80	0.40
Y27	45.40	89.70	11.10	40.20	7.44	1.32	6.00	0.98	4.76	0.94	2.48	0.44	2.73	0.37
Y28	43.20	84.00	10.30	37.30	6.95	1.34	5.80	0.97	4.95	0.97	2.70	0.44	2.55	0.35
Y29	43.70	86.20	10.40	37.90	7.34	1.26	5.86	0.96	4.77	0.89	2.41	0.41	2.51	0.35
Y31	50.70	91.50	11.20	38.20	6.79	1.23	6.37	1.04	5.45	1.17	3.05	0.54	3.42	0.45
Y33	39.60	72.70	9.03	34.00	6.93	1.16	6.18	1.16	6.53	1.41	3.66	0.64	4.34	0.60
Mean	39.83	75.91	9.25	33.45	6.06	1.06	5.08	0.84	4.16	0.82	2.18	0.37	2.33	0.33
Maximum	50.70	97.90	12.10	44.40	7.89	1.40	6.61	1.16	6.53	1.41	3.66	0.64	4.34	0.60
Minimum	19.80	37.70	4.67	16.90	3.16	0.59	2.69	0.44	2.28	0.42	1.14	0.19	1.27	0.17
Standard deviation	8.27	17.45	2.15	7.89	1.37	0.23	1.14	0.19	0.97	0.21	0.54	0.09	0.62	0.09

Note: $\sum$REE is the total content of rare earth elements; LREE denotes light rare earth elements; HREE denotes heavy rare earth elements. The same below.

Fig. 3 Contents of $\sum$REE, LREE and HREE in samples

(a) Comparison after rare earth element normalization

(b) Rare earth element normalization

Note: Yellow River and Yangtze River data are from Yang et al.[8]; UCC denotes upper continental crust, data from Taylor et al.[1]; NASC denotes North American shale, data from Haskin et al.[30]. The same below.

Fig. 4 Chondrite normalization of REEs in surface sediments of the Yarlung Zangbo River

Table 2 Fractionation characteristic parameters of REEs in samples

Sampling site	δEu	δCe	$(La/Yb)_N$	$(Gd/Yb)_N$	LREE/HREE
Y01	0.50	0.91	10.59	1.88	9.91
Y02	0.57	0.93	10.35	1.70	10.31
Y03	0.60	0.92	10.55	1.59	10.95
Y04	0.67	0.94	8.15	1.54	9.13

Sampling site	δEu	δCe	$(La/Yb)_N$	$(Gd/Yb)_N$	LREE/HREE
Y05	0.55	0.94	9.03	1.54	9.76
Y07	0.56	0.96	9.92	1.68	10.44
Y08	0.62	0.95	8.89	1.47	9.83
Y09	0.58	0.97	10.18	1.67	11.01
Y10	0.56	0.94	10.43	1.82	10.50
Y11	0.57	0.97	10.73	1.83	11.29
Y13	0.57	0.95	11.62	1.96	11.80
Y14	0.56	0.98	9.26	1.66	10.44
Y15	0.59	0.98	10.68	1.84	11.20
Y16	0.56	0.95	9.11	1.61	10.19
Y17	0.57	0.98	10.35	1.66	11.26
Y18	0.60	0.93	11.14	1.71	11.32
Y20	0.54	0.96	10.31	1.79	11.04
Y21	0.59	0.91	9.35	1.41	10.18
Y22	0.62	0.92	9.29	1.53	10.14
Y24	0.59	0.96	9.63	1.72	10.53
Y25	0.63	0.92	10.49	1.77	10.73
Y26	0.54	0.98	9.55	1.77	10.23
Y27	0.59	0.96	9.24	1.65	10.44
Y28	0.63	0.96	9.42	1.71	9.77
Y29	0.58	0.97	9.68	1.75	10.29
Y31	0.56	0.92	8.24	1.40	9.29
Y33	0.53	0.92	5.07	1.07	6.66

Note: δCe and δEu are cerium anomaly and europium anomaly, respectively; La, Yb and Gd are lanthanum, ytterbium and gadolinium, respectively; N denotes values normalized to chondrite; LREE denotes light rare earth elements; HREE denotes heavy rare earth elements. The same below.

0.98), indicating no obvious Ce anomaly. The key parameters reflecting light-heavy rare earth fractionation, $(La/Yb)_N$ and LREE/HREE, together show that the sediments in the study area are characterized overall by significant enrichment of LREE and a high degree of fractionation. Only sampling site Y33 exhibits an obvious anomaly, which is inferred to be influenced by specific geological or environmental factors.

3 Discussion

3.1 Evolution process

The Sr versus Rb/Sr relationship diagram can, to a certain extent, reflect information on weathering and diagenesis in the source area[31]. Sr content is significantly negatively correlated with the Rb/Sr value, and the Rb/Sr value varies over a relatively large range (0.33-1.21) (Fig. 5), indicating···

Fig. 5 Sr-Rb/Sr diagram of samples

Figure 3: Fig. 5 Sr-Rb/Sr diagram of samples

Fig. 5 Sr-Rb/Sr diagram of samples

There are significant differences in the chemical weathering intensity among different regions of the Yarlung Zangbo River basin. Among them, sampling sites with low Rb/Sr values and high Sr contents (such as Y21, Y22, Y25, and Y31) are concentrated in the middle and lower reaches, which may indicate relatively strong chemical weathering in this region. Because a large amount of Sr is carried into the fluvial sediments, the Rb/Sr value is diluted; whereas sampling sites with high Rb/Sr values and low Sr contents (such as Y04, Y05, Y08, and Y09) are all located upstream, corresponding to relatively weak chemical weathering. This inverse variation indicates that, during the transition of the Yarlung Zangbo River from a cold and dry to a humid environment, the weathering intensity in the downstream reaches is much greater than that upstream, and the proportion of mudstone in the downstream reaches may show an increasing trend.

Significant and stable negative Eu anomalies indicate that the sediment provenance is mainly derived from felsic basement rocks such as granites, without interference from reductive diagenesis, and that the provenance signal is well preserved[^32]. This feature also indicates that the physical denudation of granitic rocks is stronger than chemical weathering. In combination with the above data characteristics, it can be further inferred that the upstream Yarlung Zangbo River is dominated by physical weathering. As the river enters the middle-upper reaches with gentler topography, the flow velocity decreases and chemical weathering gradually intensifies. In the downstream reaches, weathering is dominated by chemical weathering.

Ce anomalies are closely related to the redox state of the depositional environment. In this study, δCe shows no obvious anomaly and remains stable, indicating that the redox state of the sedimentary environment was relatively stable. At the same time, within the present sampling-depth range, diagenesis did not produce a significant overprinting effect on the original provenance signals of rare earth elements, and source-area weathering and fluvial transport processes were the main factors controlling the geochemical characteristics of the sediments.

The Th/Sc-Zr/Sc diagram can be used to compare provenance components, infer compositional changes during the deposition of clastic sedimentary rocks, and reflect the influence of sediment sorting and recycling[^14,^33]. The provenance discrimination criteria of this diagram are as follows: when Th/Sc < 1, the source is a young undifferentiated arc; when Th/Sc 1, the source is ancient upper continental crust; and when Th/Sc ≥ 1, the source is recycled sedimentary rock[^14]. As shown in Fig. 6, comparison of the sediment samples with

Fig. 6 Th/Sc-Zr/Sc diagram of samples

Figure 4: Fig. 6 Th/Sc-Zr/Sc diagram of samples

the "trend line dominated by igneous differentiation—active continental margin" and the "trend line dominated by sorting—passive continental margin" drawn by McLennan et al.[^13] in 1993 shows that all samples are basically distributed in the upper-left region above the "cross-shaped" reference lines formed by the continental crust and the passive margin, suggesting that the provenance may be recycled sedimentary rock.

In addition, larger Zr/Sc values represent a higher degree of zircon enrichment[^34]. In this study, the Zr/Sc values of the fluvial sediment samples are all lower than that of the upper continental crust; among them, zircon and other heavy minerals are relatively more enriched in the upstream samples (Fig. 6). This feature indicates that the upstream flow is turbulent and has strong transport capacity; mineral sorting is relatively weak, and coarse particles and heavy minerals occur in a mixed depositional state, without being sufficiently sorted by density. In the middle reaches, the proportion of heavy minerals decreases and the content of light minerals increases, indicating that the flow velocity in the middle reaches decreases, density sorting strengthens during transport, heavy minerals are preferentially deposited, and light minerals continue to be transported downstream. In the lower reaches, sorting is further strengthened, light minerals occupy an absolute advantage, and heavy minerals are largely removed by sorting. However, the Zr/Sc values of sampling sites such as Y25 and Y31 increase abruptly, suggesting that local provenance input or topographic changes may have caused abrupt changes in flow velocity, leading to re-enrichment of heavy minerals and weakening of sorting. In summary, the mineral maturity of the surface sediments of the Yarlung Zangbo River shows a significant increasing trend from upstream to downstream.

3.2 Provenance

After clarifying the weathering and sorting evolutionary processes in the basin, this study further uses geochemical indicators sensitive to provenance to constrain the specific sources of the sediments. The Th/U value can effectively distinguish the provenance characteristics of clastic sedimentary rocks: for clastic sedimentary rocks derived from the upper continental crust, the Th/U value is usually characterized by 4; if the Th/U value is lower than 4, it can be inferred that there may be a contribution from mantle-derived material to the provenance[^35]. Except for Y01, Y02, and

Note: The data for the active margin and passive margin are from McLennan[^13].

Fig. 6 Th/Sc-Zr/Sc diagram of samples

Except for sampling point Y03, the Th/U values of the other sampling points are all greater than 4; whereas the average Th/U value of Y01, Y02, and Y03 is only 3.76 (Fig. 7a), close to the Th/U range of intermediate rocks (such as diorite), or indicating a mixed source of basic rocks and a small amount of granite. From the transitional reach between the middle and upper reaches to the middle reaches, the Th/U-value plots of the sampling points gradually fall completely within the typical granite field. The downstream material source is affected by the sedimentary environment and local tectonic disturbances; the Th/U values show fluctuating changes and ultimately tend toward low values in the estuary area.

The contents of Th and Sc are not affected by sedimentation[^1] and are important indicators for discriminating provenance and sedimentary environment. As can be seen from Fig. 7b, according to the Th–Sc relationship diagram proposed by McLennan et al.[^13] in 1993, the ratio line of Th/Sc = 1 divides the samples into two categories: continental felsic provenance characteristics and other provenance characteristics. Except for Y22, all the other samples show continental felsic provenance characteristics. In addition, Y33 exhibits the coupling characteristics of high Sc and low Th, a phenomenon indicating that fine-grained clay deposition dominates in this area.

Th and La are relatively enriched in felsic igneous rocks, whereas Sc is higher in mafic igneous rocks. This difference in elemental contents is the core basis for distinguishing two types of provenance[^36]. As can be seen from the La–Th–Sc ternary diagram, the plotted characteristics of all samples indicate that the provenance is dominated by felsic rocks (Fig. 8). Most sediment samples plot within the area enclosed by five reference points: China granite[^37], upper continental crust, world granite (Ca-rich), world granite (Ca-poor)[^38], and Wudangshan granite[^39]. The sample plots overlap extensively with the areas for Himalayan leucogranite[^40], Wudangshan granite pegmatite dikes[^39], and Himalayan orogenic-belt metapelites[^41], indicating that their compositions are highly similar.

To test the main components of the source rocks and understand their content proportions, a mixing calculation matrix was established with reference to the method of constructing δEu, $(\mathrm{La/Yb})_N$, and $(\mathrm{Gd/Yb})_N$[^42], as follows:

$$\begin{bmatrix} \delta\mathrm{Eu} \\ \mathrm{La/Yb} \\ \mathrm{Gd/Yb} \end{bmatrix} = \begin{bmatrix} 0.49 & 0.59 & 0.37 \\ 11.25 & 9.64 & 4.16 \\ 2.51 & 1.59 & 0.97 \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \\ \gamma \end{bmatrix} = \begin{bmatrix} 0.58 \\ 9.68 \\ 1.66 \end{bmatrix} \quad \text{`shale'} \qquad (3)$$

In the equation: a is Himalayan leucogranite; b is Himalayan orogenic-belt metapelite; c is Wudangshan granite. La/Yb and Gd/Yb were both normalized to chondrite[^27]. The calculation results show that Himalayan orogenic-belt metapelites are the principal source rock of the Yarlung Zangbo River surface sediments, accounting for 89.7%; Himalayan leucogranite accounts for 8.3%; and Wudangshan granite accounts for 2.3%.

Fig. 7

Figure 5: Fig. 7

Fig. 8

Figure 6: Fig. 8

To verify whether the obtained source-rock proportions accurately reflect the actual geochemical composition of the sediments, mass-balance calculation is also required. The geochemical compositions of the various source rocks are weighted according to their contribution proportions and averaged to obtain the theoretically mixed sediment composition. The formula is as follows:

$$\mathrm{WR}^{\mathrm{mix}} = \alpha C_1 + \beta C_2 + \gamma C_3 \qquad (4)$$

In the equation: $\mathrm{WR}^{\mathrm{mix}}$ is the calculated whole-rock composition; α, β, and γ are respectively the mixing–

Fig. 7 Th/U–Th and Th–Sc diagrams of samples

Legend
Surface sediments of the Yarlung Zangbo River
- UCC

China granite
World granite (Ca-rich)
World granite (Ca-poor)
Himalayan leucogranite
Wudangshan granite pegmatite dike
Himalayan orogenic-belt metapelite
Wudangshan granite

Note: China granite data are from Zhang Yigang et al.[^37]; world granite data are from Turekian et al.[^38]; Himalayan leucogranite data are from Guo et al.[^40]; Wudangshan granite pegmatite dike and Wudangshan granite data are from Wang Haifeng et al.[^39]; Himalayan orogenic-belt metapelite data are from Zeng Lingsen et al.[^41].

Fig. 8 La–Th–Sc diagram of samples and related provenances

The proportions of Himalayan leucogranite, Himalayan metamorphic muddy rock, and Gangdese basement granite calculated from the mixing calculation; C_1, C_2, and C_3 are respectively the average values of the geochemical compositions of a given element in the three source rocks.

The comparison between the rare earth element model values calculated accordingly and the measured average values of rare earth elements in the Yarlung Zangbo River is shown in Table 3 and Fig. 9. The percentage changes of the three indices δEu, $(La/Yb)_N$, and $(Gd/Yb)_N$ are all 0. This indicates that Himalayan leucogranite, Himalayan metamorphic muddy rock, and Gangdese basement granite can, through reasonable mixing proportions, accurately reproduce the three geochemical characteristics of the average composition of the Yarlung Zangbo River sediments. Individual elements show only low-amplitude variations of 0.95%-2.66%, indicating that the model performs well in provenance-mixing simulation. However, some elements among the HREE have relatively large deviations—such as Er at 36.36%, Lu at 29.14%, and Yb at 22.31%—which clearly indicates the presence of a non-negligible mineral sorting effect.

Table 3 Measured and modeled rare earth element data of three provenances and samples

Tab. 3 Measured and modeled rare earth element data of three provenances and samples

Element	Himalayan leucogranite / $\mu g \cdot g^{-1}$ [40]	Himalayan metamorphic muddy rock / $\mu g \cdot g^{-1}$ [41]	Gangdese basement granite / $\mu g \cdot g^{-1}$ [39]	Average value of surface sediments in the Yarlung Zangbo River / $\mu g \cdot g^{-1}$	Model-predicted value / $\mu g \cdot g^{-1}$	Percentage change / %
La	11.99	38.16	12.40	39.83	35.52	10.82
Ce	22.48	76.33	25.92	75.91	70.96	6.53
Pr	2.54	8.54	2.84	9.25	7.94	14.12
Nd	9.75	31.63	9.94	33.45	29.42	12.05
Sm	2.47	6.27	2.87	6.06	5.90	2.66
Eu	0.36	1.16	0.31	1.06	1.07	0.95
Gd	2.12	5.90	2.46	5.08	5.53	8.71
Tb	0.34	0.94	0.50	0.84	0.89	6.01
Dy	1.83	5.22	3.09	4.16	4.90	17.78
Ho	0.32	1.04	0.63	0.82	0.98	19.17
Er	0.79	3.19	2.11	2.18	2.98	36.36
Tm	0.11	0.46	0.30	0.37	0.43	16.10
Yb	0.70	3.05	2.12	2.33	2.85	22.31
Lu	0.10	0.45	0.33	0.33	0.42	29.14
δEu	0.49	0.59	0.37	0.58	0.58	0.00
$(La/Yb)_N$	11.25	9.64	4.16	9.68	9.68	0.00
$(Gd/Yb)_N$	2.51	1.59	0.97	1.66	1.66	0.00

Fig. 9 Comparison of actual average values and model-predicted values of REEs in samples

Because HREE are mainly enriched in high-density accessory minerals—such as zircon and xenotime—combined with the interpretation of zircon and other heavy-mineral sorting effects in the Th/Sc-Zr/Sc diagram discussed above, it can be inferred that the distribution deviations of HREE are mainly derived from density sorting during river transport. Accessory minerals containing HREE undergo selective differentiation due to density differences, ultimately causing their concentrations to deviate from the prediction range of the purely lithologic mixing model.

4 Conclusions

(1) The surface sediments of the Yarlung Zangbo River have relatively high $\sum$REE. Overall, they show significant enrichment of LREE and relative depletion of HREE, while also presenting signals of typical negative Eu anomalies and no obvious Ce anomalies.

(2) Weathering in the Yarlung Zangbo River basin shows clear spatial differentiation. Overall, the upstream reaches are dominated by physical stripping, and the system gradually transitions downstream toward dominance by chemical weathering.

(3) Sorting in the upper reaches of the Yarlung Zangbo River is weak, whereas sorting in the middle and lower reaches is ⋯

the effect of sorting is strengthened; it is weakened only locally by material-source input or changes in topography. Correspondingly, the mineral maturity of the sediments shows an obvious trend of progressively increasing downstream along the river.

(4) The provenance of the surface sediments of the Yarlung Zangbo River is dominated by metapelitic rocks of the Himalayan orogenic belt (accounting for 89.7%), with joint contributions from Himalayan leucogranite (8.3%) and Gangdese basement granite (2.3%). The geochemical model confirms that mineral sorting has a significant influence on sediment composition.

References

[1] Taylor S R, McLennan S M. The continental crust: Its composition and evolution[M]. Oxford: Blackwell, 1985: 1-312.

[2] Dupré B, Gaillardet J, Rousseau D, et al. Major and trace elements of river-borne material: The Congo Basin[J]. Geochimica et Cosmochimica Acta, 1996, 60(8): 1301-1321.

[3] Sholkovitz E R. Rare earth elements in the sediments of the North Atlantic Ocean, Amazon Delta, and East China Sea: Reinterpretation of terrigenous input patterns to the oceans[J]. American Journal of Science, 1988, 288(3): 236-281.

[4] Tricca A, Stille P, Steinmann M, et al. Rare earth elements and Sr and Nd isotopic compositions of dissolved and suspended loads from small river systems in the Vosges Mountains (France), the River Rhine and groundwater[J]. Chemical Geology, 1999, 160(1-2): 139-158.

[5] Savoy L E, Stevenson R K, Mountjoy E W. Provenance of Upper Devonian-Lower Carboniferous Miogeoclinal Strata, southeastern Canadian Cordillera: Link between tectonics and sedimentation[J]. Journal of Sedimentary Research, 2000, 70(1A): 181-193.

[6] Wani H, Mondal M E A. Evaluation of provenance, tectonic setting, and paleoredox conditions of the Mesoproterozoic-Neoproterozoic Basins of the Bastar Craton, Central Indian Shield: Using petrography of sandstones and geochemistry of shales[J]. Lithosphere, 2011, 3(2): 143-154.

[7] Yang Shouye, Li Congxian. Research progress in REE tracer for sediment source[J]. Advances in Earth Sciences, 1999, 14(2): 164-167. [Yang Shouye, Li Congxian. Research progress in REE tracer for sediment source[J]. Advances in Earth Sciences, 1999, 14(2): 164-167.]

[8] Yang Shouye, Li Congxian. REE geochemistry and tracing application in the Yangtze River and the Yellow River sediments[J]. Geochimica, 1999, 28(4): 374-380. [Yang Shouye, Li Congxian. REE geochemistry and tracing application in the Yangtze River and the Yellow River sediments[J]. Geochimica, 1999, 28(4): 374-380.]

[9] Yang Shouye, Li Congxian. Characteristic element compositions of the Yangtze and the Yellow River sediments and their geological background[J]. Marine Geology & Quaternary Geology, 1999, 19(2): 21-28. [Yang Shouye, Li Congxian. Characteristic element compositions of the Yangtze and the Yellow River sediments and their geological background[J]. Marine Geology & Quaternary Geology, 1999, 19(2): 21-28.]

[10] Yang Shouye, Li Congxian, Lee C B, et al. REE geochemistry of rivers around the Yellow Sea and sediment provenance tracing[J]. Chinese Science Bulletin, 2003, 48(11): 1233-1236. [Yang Shouye, Li Congxian, Lee C B, et al. REE geochemistry of rivers around the Yellow Sea and sediment provenance tracing[J]. Chinese Science Bulletin, 2003, 48(11): 1233-1236.]

[11] Tong Shengqi. Study on elemental geochemistry of surface sediments in the Pearl River, Red River and Mekong River Basins[D]. Shanghai: Tongji University, 2007. [Tong Shengqi. Study on elemental geochemistry of surface sediments in the Pearl River, Red River and Mekong River Basins[D]. Shanghai: Tongji University, 2007.]

[12] Guo Yulong, Yang Shouye, Su Ni, et al. Rare earth element geochemistry of the sediments from small rivers draining southeast China[J]. Marine Geology & Quaternary Geology, 2018, 38(1): 139-149. [Guo Yulong, Yang Shouye, Su Ni, et al. Rare earth element geochemistry of the sediments from small rivers draining

southeast China[J]. Marine Geology & Quaternary Geology, 2018, 38(1): 139-149.]

[13] McLennan S M, Hemming S, McDaniel D K, et al. Geochemical approaches to sedimentation, provenance, and tectonics[J]. Geological Society of America Special Papers, 1993, 284: 21-40.

[14] McLennan S M. Weathering and global denudation[J]. The Journal of Geology, 1993, 101(2): 295-303.

[15] Liu Tianchou. Hydrological characteristics of Yalungzangbo River[J]. Acta Geographica Sinica, 1999, 54(Suppl. 1): 157-164. [Liu Tianchou. Hydrological characteristics of Yalungzangbo River[J]. Acta Geographica Sinica, 1999, 54(Suppl. 1): 157-164.]

[16] Lin Zhenyao, Wu Xiangding. Climatic regionalization of the Qinghai-Xizang Plateau[J]. Acta Geographica Sinica, 1981, 36(1): 22-32. [Lin Zhenyao, Wu Xiangding. Climatic regionalization of the Qinghai-Xizang Plateau[J]. Acta Geographica Sinica, 1981, 36(1): 22-32.]

[17] Ma Xuxuan, Xu Zhiqin, Liu Fei, et al. Continental arc tempos and crustal thickening: A case study in the Gangdese arc, southern Tibet[J]. Acta Geologica Sinica, 2020, 95(1): 107-123. [Ma Xuxuan, Xu Zhiqin, Liu Fei, et al. Continental arc tempos and crustal thickening: A case study in the Gangdese arc, southern Tibet[J]. Acta Geologica Sinica, 2020, 95(1): 107-123.]

[18] Li C L, Kang S C, Zhang Q G, et al. Rare earth elements in the surface sediments of the Yarlung Tsangbo (Upper Brahmaputra River) sediments, southern Tibetan Plateau[J]. Quaternary International, 2009, 208(1-2): 151-157.

[19] Gong Chuandong, Dai Huimin, Yang Zuosheng. Comparison of REE variations with grain sizes in sediments between the Yangtze River and the Yellow River[J]. Geology and Resources, 2013, 22(2): 148-154. [Gong Chuandong, Dai Huimin, Yang Zuosheng. Comparison of REE variations with grain sizes in sediments between the Yangtze River and the Yellow River[J]. Geology and Resources, 2013, 22(2): 148-154.]

[20] Fang Haichao, Huang Peng, Sun Jiawen, et al. Provenance and controlling factors of major elements in graded components of sediments from the Yalu River[J]. Marine Geology & Quaternary Geology, 2019, 39(3): 72-83. [Fang Haichao, Huang Peng, Sun Jiawen, et al. Provenance and controlling factors of major elements in graded components of sediments from the Yalu River[J]. Marine Geology & Quaternary Geology, 2019, 39(3): 72-83.]

[21] Xiao Chunhui, Wang Yonghong, Lin Jian, et al. Characteristics of rare earth elements in deep-water sediments in

Mariana "Trench-Basin" system and their provenance constraints[J]. Marine Geology & Quaternary Geology, 2021, 41(1): 103-114.]

[22] Mi Beibei, Zhang Yong, Mei Xi, et al. The rare earth element content in

surface sediments of coastal areas in eastern China' s sea areas and analysis of material sources[J]. Geology in China, 2020, 47(5): 1530-1541. [Mi Beibei, Zhang Yong, Mei Xi, et al. The rare earth element content in surface sediments of coastal areas in eastern China' s sea areas and analysis of material sources[J]. Geology in China, 2020, 47(5): 1530-1541.]

[23] Huang Long, Geng Wei, Lu Kai, et al. Rare earth element composition and provenance implications of sediments in the central South Yellow Sea since MIS6[J]. Marine Geology & Quaternary Geology, 2023, 43(2): 92-105. [Huang Long, Geng Wei, Lu Kai, et al. Rare earth element composition and provenance implication of sediments in the central south Yellow Sea since MIS6[J]. Marine Geology & Quaternary Geology, 2023, 43(2): 92-105.]

[24] Chen Pengfei, Li Chaoliu, Kang Shichang, et al. Study of geochemical elements in surface sediments of the Yarlung Zangbo River[J]. Geochimica, 2012, 41(4): 387-392. [Chen Pengfei, Li Chaoliu, Kang Shichang, et al. The geochemical characteristics of sediments of the Yarlung Zangbo River[J]. Geochimica, 2012, 41(4): 387-392.]

[25] Liang W D, Hu X M, Garzanti E, et al. Contrasting provenance budgets for suspended load and bedload of the Yarlung Tsangpo, Tibet: Lhasa block or Himalaya?[J]. Geology, 2025, 53(4): 333-337.

[26] Li S, Ding L, Xu Q, et al. The evolution of Yarlung Tsangpo River: Constraints from the age and provenance of the Gangdese conglomerates, southern Tibet[J]. Gondwana Research, 2017, 41: 249-266.

[27] Anders E, Grevesse N. Abundances of the elements: Meteoritic and solar[J]. Geochimica et Cosmochimica Acta, 1989, 53(1): 197-214.

[28] Yan Mingshu, Li Yu, Bao Liran, et al. Geochemical characteristics of 1:50,000 stream sediments in Xainza, Tibet, and their prospecting significance[J]. Geophysical and Geochemical Exploration, 2016, 40(1): 10-16. [Yan Mingshu, Li Yu, Bao Liran, et al. Geochemical characteristics of 1:50000 stream sediments in Xainza, Tibet, and their prospecting significance[J]. Geophysical and Geochemical Exploration, 2016, 40(1): 10-16.]

[29] Liu Fei, Yang Jingsui, Chen Songyong, et al. Geochemistry and Sr-Nd-Pb isotopic characteristics of mafic rocks in the western segment of the Yarlung Zangbo suture zone: Evidence for intra-oceanic subduction within the Neo-Tethys[J]. Geology in China, 2013, 40(3): 742-755. [Liu Fei, Yang Jingsui, Chen Songyong, et al. Geochemistry and Sr-Nd-Pb isotopic composition of mafic rocks in the western part of Yarlung Zangbo suture zone: Evidence for intra-oceanic subduction within the Neo-Tethys[J]. Geology in China, 2013, 40(3): 742-755.]

[30] Haskin M A, Haskin L A. REE in European shales: A redetermination[J]. Science, 1966, 154(3748): 507-509.

[31] Nesbitt H W, Young G M. Early Proterozoic climates and plate motions inferred from major element chemistry of lutites[J]. Nature, 1982, 299(5885):

715–717.

[32] Lin Y J, Zheng M P, Ye C Y, et al. Rare earth element and strontium isotope geochemistry in Dujiali Lake, central Qinghai-Tibet Plateau, China: Implications for the origin of hydromagnesite deposits[J]. Geochemistry, 2019, 79(2): 337–346.

[33] McLennan S M, Taylor S R, McCulloch M T, et al. Geochemical and Nd-Sr isotopic composition of deep-sea turbidites: Crustal evolution and plate tectonic associations[J]. Geochimica et Cosmochimica Acta, 1990, 54(7): 2015–2050.

[34] Chang Haiqin. Geochemical characteristics and provenance study of sediments in the middle and lower reaches of the Pearl River[D]. Xi' an: Chang' an University, 2019. [Chang Haiqin. Geochemical characteristics and provenance of sediments in middle and lower reaches of the Pearl River[D]. Xi' an: Chang' an University, 2019.]

[35] Roddaz M, Viers J, Brusset S, et al. Controls on weathering and provenance in the Amazonian foreland basin: Insights from major and trace element geochemistry of Neogene Amazonian sediments[J]. Chemical Geology, 2006, 226(1–2): 31–65.

[36] McLennan S M, Nance W B, Taylor S R. Rare earth element-thorium correlation in sedimentary rocks and the composition of the continental crust[J]. Geochimica et Cosmochimica Acta, 1980, 44(11): 1833–1839.

[37] Shi Changyi, Yan Mingcai, Liu Chongmin, et al. Abundances and characteristics of chemical elements in granitoids of China[J]. Geochimica, 2005, 34(5): 470–482. [Shi Changyi, Yan Mingcai, Liu Chongmin, et al. Abundances of chemical elements in granitoids of China and their characteristics[J]. Geochimica, 2005, 34(5): 470–482.]

[38] Turekian K K, Wedepohl K H. Distribution of the elements in some major units of the earth' s crust[J]. Geological Society of America Bulletin, 1961, 72(2): 175–192.

[39] Wang Haitao, Zeng Lingsen, Gao Li' e, et al. Timing and geochemical characteristics of granitoids in the Ridu area of the Gangdese batholith, southern Tibet[J]. Acta Petrologica Sinica, 2019, 35(2): 439–454. [Wang Haitao, Zeng Lingsen, Gao Li' e, et al. Timing and geochemical characteristics of the Ridu granitic pluton within the Gangdese batholith, southern Tibet[J]. Acta Petrologica Sinica, 2019, 35(2): 439–454.]

[40] Guo Z F, Wilson M. The Himalayan leucogranites: Constraints on the nature of their crustal source region and geodynamic setting[J]. Gondwana Research, 2012, 22(2): 360–376.

[41] Zeng Lingsen, Liang Fenghua, Xu Zhiqin, et al. Metapelites in the Himalayan orogenic belt and their geochemical characteristics[J]. Acta Petrologica Sinica, 2008, 24(7): 1517–1527. [Zeng Lingsen, Liang Fenghua, Xu Zhiqin,

et al. Metapelites in the Himalayan orogenic belt and their protoliths[J]. Acta Petrologica Sinica, 2008, 24(7): 1517-1527.]

[42] Kasanzu C, Maboko M A H, Manya S. Geochemistry of fine-grained clastic sedimentary rocks of the Neoproterozoic Ikorongo Group, NE Tanzania: Implications for provenance and source rock weathering[J]. Precambrian Research, 2008, 164(3-4): 201-213.

Evolutionary process of mineral maturity and provenance tracing of sediments in the Yarlung Zangbo River

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Abstract: Focusing on the surface sediments of the Yarlung Zangbo River in the Qinghai-Xizang Plateau, this study analyzes their provenance and evolutionary processes. River sediment samples were systematically collected and analyzed using high-precision geochemical analytical techniques. Chondrite normalization, along with elemental ratios such as δEu, La/Yb, and Rb/Sr, and multivariate diagrams, were employed to characterize geochemical features, reconstruct evolutionary processes, and determine sediment provenance. The results show that: (1) The total content of rare earth elements ($\sum$REE) in this basin is generally high. The distribution of REEs is characterized by significant enrichment of light rare earth elements, a typical negative Eu anomaly, and no obvious Ce anomaly. (2) There are clear spatial variations in weathering processes across the basin: Physical weathering dominates in the upper reaches, whereas chemical weathering becomes dominant in the lower reaches. (3) From the upper to the lower reaches, the mineral sorting of sediments gradually increases, and mineral maturity shows a significant increasing trend. (4) The geochemical mixing model shows that the provenance of sediments in the study area is mainly derived from metamorphic argillaceous rocks of the Himalayan orogenic belt (89.7%), with additional contributions from Himalayan leucogranites (8.3%) and Gangdese batholith granites (2.3%). These results provide important geochemical evidence for understanding regional tectonic evolution processes and sediment transport mechanisms.

Keywords: Yarlung Zangbo River; river surface sediments; trace elements; rare earth elements

Note: Figure translations are in progress. See original paper for figures.