

Research Paper

Effects of chemical weathering and grain size sorting on Sr—Nd isotopic source rock signatures of river sediments in the lower Mekong River Basin: Implications for provenance studies

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ARTICLE INFO

Editor: Dr. Christian France-Lanord

Keywords:

Sr—Nd isotopes

Source rock

Chemical weathering

Grain size sorting

Mekong River

ABSTRACT

Sr—Nd isotopic compositions are reliable proxies for tracing the provenance of riverine and marine sediments. However, these isotopic compositions can be influenced by processes such as chemical weathering in the source region and grain size sorting during transport, which can obscure the original provenance signals. In this study, Sr—Nd isotopic compositions of clay, silt, and sand fractions from river sediments in the Lower Mekong River Basin are analyzed to investigate the influence of chemical weathering and grain size sorting and their implications for provenance studies. Mainstream sediments exhibit higher $^{87}\text{Sr}/^{86}\text{Sr}$ (0.724) and lower ϵ_{Nd} (−9.72) values compared to tributary sediments (0.717 and −5.61, respectively). The clay fractions in both mainstream and tributary sediments show more radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ (0.726) and higher ϵ_{Nd} (−7.29) values than the silt (0.721 and −8.88, respectively) and sand (0.718 and −9.27, respectively) fractions. Rb/Sr and $^{87}\text{Sr}/^{86}\text{Sr}$ in both mainstream and tributary sediments present moderate or strong correlations with $\text{K}_2\text{O}/(\text{CaO} + \text{Na}_2\text{O})$ and $\text{SiO}_2/\text{Al}_2\text{O}_3$, indicating that chemical weathering and grain size sorting moderately influence Sr isotopes. In contrast, Sm/Nd and ϵ_{Nd} display no or weak correlations with $\text{K}_2\text{O}/(\text{CaO} + \text{Na}_2\text{O})$ and $\text{SiO}_2/\text{Al}_2\text{O}_3$, suggesting that Nd isotopes are less affected by these factors. Despite these influences, significant differences in Sr—Nd isotopic compositions between mainstream and tributary sediments are evident, with moderate to strong negative correlations between $^{87}\text{Sr}/^{86}\text{Sr}$ and ϵ_{Nd} across clay, silt, and sand fractions. These differences effectively distinguish the mainstream from the tributary sediments, reflecting the control of source rock lithology and the preservation of source rock signatures in this region. To minimize the effects of chemical weathering and grain size sorting, this study recommends using Sr—Nd isotopic data from uniform grain size fractions for provenance investigations of riverine and marine sediments, with the silt fraction being the most suitable.

1. Introduction

Source-to-sink transport processes of fluvial sediments play an important role in redistributing weathering products (e.g., minerals, elements, and isotopic compositions) on Earth's surface (Goldstein and Jacobsen, 1988; Liu et al., 2012; Garzanti et al., 2019; Dinis et al., 2020). These sediments are weathering products of parent rocks in continental crust, which contain valuable information for reconstructing continental weathering, sediment transport, oceanic circulations, tectonic events, and climatic evolution (Chen and Li, 2013; Wan et al., 2015; Liu et al.,

2016). In these studies, identifying sediment provenance plays a crucial role because it provides the foundation for investigating continental weathering, tectonic events, and climatic evolution in the source region, as well as tracking transport pathways and understanding how oceanic circulation influences sediment composition. Numerous methods have been widely employed to trace sediment sources, including clay mineralogy, element geochemistry, isotopic compositions, heavy minerals, magnetic minerals, and detrital zircon U—Pb dating (Clift et al., 2006; Liu et al., 2010; Wan et al., 2015; Liu et al., 2016; Jagodziński et al., 2020; Sang et al., 2024). Among them, Sr—Nd isotopic

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<https://doi.org/10.1016/j.chemgeo.2025.123199>

Received 12 May 2025; Received in revised form 28 November 2025; Accepted 9 December 2025

Available online 10 December 2025

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compositions are considered one of the most robust indicators for sediment provenance studies (Goldstein and Jacobsen, 1988; Colin et al., 2006; Wan et al., 2015; Awasthi et al., 2018). These isotopes retain valuable information about their parent rocks and are less affected by surface processes because: (1) $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ depend on Sm/Nd, Rb/Sr, mineral age, and rock type; (2) particularly $^{143}\text{Nd}/^{144}\text{Nd}$ ratio remains largely stable during surficial processes (e.g., diagenesis, chemical weathering, and transport) (McLennan et al., 1990; McLennan and Hemming, 1992). Generally, felsic rocks exhibit high Rb/Sr and low Sm/Nd, leading to radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ and low ϵ_{Nd} values, whereas mafic rocks have low Rb/Sr and high Sm/Nd, resulting in non-radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ and high ϵ_{Nd} values (Taylor and McLennan, 1995; Banner, 2004). DePaolo and Johnson (1979) demonstrated that weathering of ancient crustal rocks typically produces sediments with low ϵ_{Nd} (< -6) and high $^{87}\text{Sr}/^{86}\text{Sr}$ values, whereas weathering of juvenile crust yields sediments with high ϵ_{Nd} ($> +5$) and low $^{87}\text{Sr}/^{86}\text{Sr}$ values. Due to these characteristics, Sr–Nd isotopes have been successfully applied in tracing the sources of river sediments (Awasthi et al., 2018; Duan et al., 2023), sedimentary rocks (McLennan and Hemming, 1992; Xie et al., 2012), marine sediments (Wei et al., 2012; Liu et al., 2016), and loess dust (Chen et al., 2007; Chen and Li, 2013; Zhu et al., 2021).

Despite the effectiveness of Sr–Nd isotopes in determining sediment provenance above, they could be influenced by chemical weathering in the source region and by grain size sorting during transport, particularly Sr isotopes, which may change their source rock signatures (Dasch, 1969; Goldstein et al., 1984; Goldstein and Jacobsen, 1988; Colin et al., 2006; Garçon et al., 2014; Wan et al., 2015). For example, Sr isotopes of loess dust from the Lantian in the Chinese Loess Plateau and Xiashu along the Yangtze River (Feng et al., 2009; Zhu et al., 2021) as well as river sediments in the Amazon and Red Rivers (Bouchez et al., 2011; Duan et al., 2023) are strongly influenced by grain size sorting, with $^{87}\text{Sr}/^{86}\text{Sr}$ ratios increasing significantly in finer fractions due to enhanced chemical weathering. In contrast, Nd isotopes are generally more stable compared to Sr isotopes. Goldstein et al. (1984) found minimal variation in ϵ_{Nd} (-9.3 to -9.6) across grain size ($< 2\text{ }\mu\text{m}$, $2\text{--}45\text{ }\mu\text{m}$, $> 45\text{ }\mu\text{m}$) in Amazon River sediments. Similarly, Bayon et al. (2015) reported consistent ϵ_{Nd} values in clay and silt fractions from rivers, sedimentary systems, and volcanic provinces, with small variability of < 1 . Additionally, Xiashu Loess grain size fractions along the Yangtze River ($< 2\text{ }\mu\text{m}$, $2\text{--}75\text{ }\mu\text{m}$, $> 75\text{ }\mu\text{m}$) also exhibit similar ϵ_{Nd} values (-11.79 , -12.16 , and -11.78 , respectively), suggesting negligible chemical weathering or grain size sorting effects (Zhu et al., 2021). However, some studies have reported that Nd isotopes are also affected by grain size. For instance, different provenance components of the 2006 Beijing eolian dust are represented by different grain size fractions ($< 10\text{ }\mu\text{m}$ and $> 10\text{ }\mu\text{m}$), resulting in dissimilar Nd isotopic compositions (Feng et al., 2009). The $< 10\text{ }\mu\text{m}$ finer fractions, which could have remained airborne for a long time and been transported great distances by atmospheric currents, likely resulted from well-mixed contributions of large dust-storm source areas, whereas the coarser ($> 10\text{ }\mu\text{m}$) fractions were not as thoroughly mixed. Similarly, hydrological sorting can cause distinct sediment sources at different water depths in the Yangtze River, yielding variations in Nd isotopic compositions of suspended sediments (Luo et al., 2012). Thus, controlling factors such as chemical weathering and grain size sorting must be carefully evaluated before applying Sr–Nd isotopes for provenance studies of riverine and marine sediments, as well as loess dust.

The Mekong River is one of the world's largest rivers and originates on the eastern Tibetan margin and traverses the Indochina Peninsula before discharging into the sea (Fig. 1A). As the largest river bordering the South China Sea, it delivers immense annual fluxes of water (473 km^3) and sediment (160 Mt) (Milliman and Syvitski, 1992). Its basin spans six countries (China, Myanmar, Laos, Thailand, Cambodia, and Vietnam) and can be relatively subdivided into upper, middle, and lower reaches, each characterized by distinct lithologic, tectonic, and climatic

conditions (Liu et al., 2004, 2007). These features make the Mekong River an ideal natural laboratory for studying source-to-sink sediment transport. Previous studies have employed detrital zircon U–Pb dating (Clift et al., 2006), clay mineralogy (Liu et al., 2007), and integrated clay mineralogy and element geochemistry (Sang et al., 2024), but none of them have utilized Sr–Nd isotopes for sediment provenance studies in this basin. In the Lower Mekong River Basin, Sang et al. (2024) indicated, based on clay mineralogy and geochemistry, that mainstream sediments are mainly derived from the middle reach, dominated by intrusive igneous rocks (mostly felsic), whereas tributary sediments are largely sourced from local extrusive igneous rocks (mostly mafic). These findings demonstrate that mainstream and tributary sediments reflect different source rock lithology, chemical weathering intensities, and grain size sorting during transport. Consequently, mainstream and tributary sediments in the Lower Mekong River Basin represent an excellent system to investigate Sr–Nd isotopic signatures and their controlling factors (e.g., chemical weathering and transport effects).

In this study, Sr–Nd isotopic compositions are integrated with major/trace element geochemistry from Sang et al. (2024) on clay, silt, and sand fractions from the Lower Mekong River Basin to (1) characterize the Sr–Nd isotopic signatures of river sediments, (2) evaluate the influence of chemical weathering and grain size sorting, and (3) assess their implications for provenance studies.

2. Regional setting

The Mekong River Drainage Basin is primarily located in the Qiangtang and Indochina blocks, with a minor portion extending into the Sibumasu block (Deng et al., 2014; Fig. 1B1). Based on lithologic, tectonic, and climatic conditions, this basin can be relatively subdivided into upper, middle, and lower reaches (Liu et al., 2004, 2007; Figs. 1A and B). The upper and middle reaches are predominantly situated in the Qiangtang block, which has experienced active tectonics since the Late Cenozoic (Zhang et al., 2004). In contrast, the lower reach lies within the Indochina block, which has remained tectonically stable since the Early Jurassic (Singsoopho et al., 2014). The upper reach has an elevation of $\sim 2500\text{ m}$ to over 4500 m (Liu et al., 2004; Lauri et al., 2012) and features dominant Paleozoic sedimentary rocks and minor Precambrian metamorphic rocks (Commission for the Geological Map of the World, 1975). The middle reach is characterized by steep mountainous terrain with high relief between valleys and ridges, where Paleozoic–Mesozoic sedimentary rocks dominate, alongside lesser amounts of Precambrian rocks, Tertiary sedimentary rocks, and intrusive (mostly felsic)/extrusive (mainly mafic) igneous rocks. The lower reach stretches from Vientiane (Laos) to the Mekong Delta (Vietnam) and consists of a broad alluvial plain. Mesozoic sedimentary rocks are most common, with minor occurrences of Precambrian, Tertiary sedimentary, and intrusive/extrusive igneous rocks. Climatically, the upper reach experiences a cold and dry climate throughout the year, whereas the middle and lower reaches share a tropical monsoon climate, with distinct rainfall and temperature variations between wet and dry seasons (Sang et al., 2024).

3. Materials and methods

A total of 40 river sediment samples (20 muddy and 20 sandy) were collected from the mainstream and tributaries in the Lower Mekong River Basin (Cambodia and Vietnam) in April–May 2021 (Fig. 1; Tables 1 and 2). Sampling targeted distinct sub-environments: 12 tributary samples (6 muddy and 6 sandy) represent the lower reach setting, while 28 mainstream samples (14 muddy and 14 sandy) reflect the average sediment composition of the Mekong River. Based on transport mechanisms and hydrodynamic properties, the muddy sediments were separated into two size fractions: clay ($< 2\text{ }\mu\text{m}$) and silt ($0\text{--}63\text{ }\mu\text{m}$), while the sandy sediments were used to collect sand fractions ($63\text{--}1000\text{ }\mu\text{m}$). Firstly, a small amount of muddy and sandy sediments were dried at $\sim 50\text{ }^\circ\text{C}$, then immersed in 500 ml bottles containing 40–50 ml of

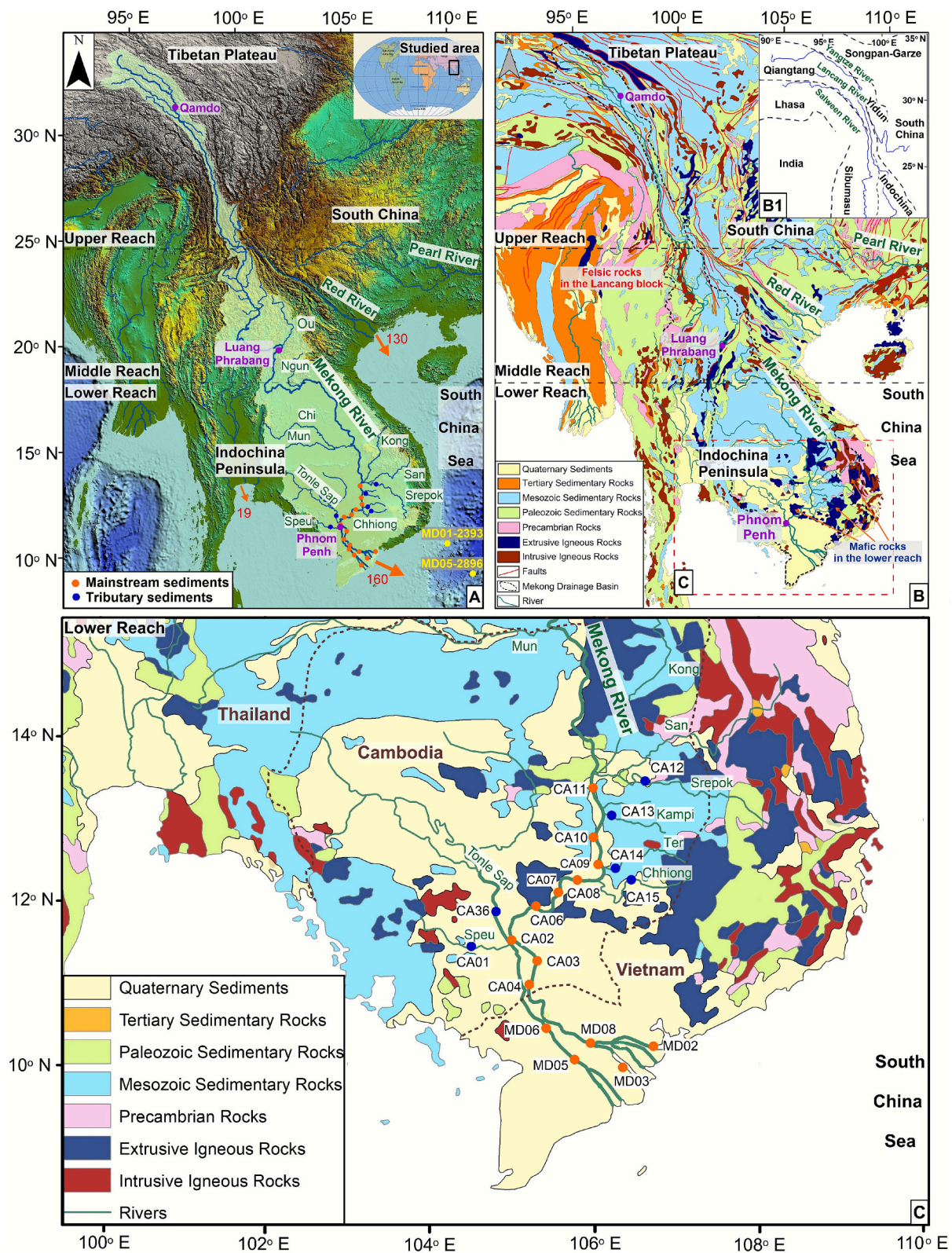


Fig. 1. (A) Topographic map of Southeast Asia highlighting the Mekong River Basin. The map shows the locations of mainstream and tributary river samples (green and purple circles, respectively) in the lower reach and referred cores (yellow circles) MD01–2393 (Liu et al., 2005) and MD05–2896 (Sang et al., 2022) offshore from the Mekong River. (B) Geological map of the Mekong River Basin (modified from Commission for the Geological Map of the World, 1975) with (B1) tectonic framework of blocks, sutures, and faults near the Upper Mekong River (modified after Deng et al., 2014) and referred mafic rocks in the lower reach (Hoang et al., 2018; Yu et al., 2022) and felsic rocks in the middle reach (Huang et al., 2021). (C) Geological map of the Lower Mekong River Basin with detailed sampling locations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1

Geographic locations and Sr–Nd isotopic compositions of clay and silt fraction sediments in the Lower Mekong River Basin.

No	Sample	Location	Latitude (N)	Longitude (E)	$^{87}\text{Sr}/^{86}\text{Sr} \pm 2\sigma$ (Clay)	$^{143}\text{Nd}/^{144}\text{Nd} \pm 2\sigma$ (Clay)	$\epsilon_{\text{Nd}} \pm 2\sigma$ (Clay)	$^{87}\text{Sr}/^{86}\text{Sr} \pm 2\sigma$ (Silt)	$^{143}\text{Nd}/^{144}\text{Nd} \pm 2\sigma$ (Silt)	$\epsilon_{\text{Nd}} \pm 2\sigma$ (Silt)	Δ $^{87}\text{Sr}/^{86}\text{Sr}$ (clay-silt)	$\Delta \epsilon_{\text{Nd}}$ (clay-silt)
Mainstream in Cambodia												
1	CA02–1	Prek Eng	11°32.24'	104°59.33'	0.733137 ± 13	0.512152 ± 8	−9.49 ± 10	0.726688 ± 13	0.512074 ± 7	−11.01 ± 14	0.006	1.52
2	CA03–1	Kompong Chomlong	11°15.46'	105°16.63'	0.729613 ± 11	0.512173 ± 9	−9.07 ± 7	0.725855 ± 13	0.512091 ± 9	−10.67 ± 17	0.004	1.59
3	CA04–1	Chong Koh	10°58.83'	105°10.79'	0.724328 ± 14	0.512232 ± 10	−7.91 ± 11	0.720543 ± 12	0.512097 ± 9	−10.55 ± 17	0.004	2.64
4	CA06–1	Peam Jikong	11°56.55'	105°16.08'	0.734742 ± 13	0.512132 ± 8	−9.87 ± 10	0.730239 ± 9	0.512044 ± 6	−11.58 ± 12	0.005	1.71
5	CA07–1	Ti 6	12°6.17'	105°32.11'	0.725077 ± 14	0.512206 ± 7	−8.43 ± 8	0.722137 ± 12	0.512160 ± 8	−9.33 ± 15	0.003	0.90
6	CA08–1	Ti 4	12°14.93'	105°46.03'	0.724153 ± 11	0.512212 ± 7	−8.30 ± 8	0.722745 ± 11	0.512148 ± 8	−9.55 ± 15	0.001	1.25
7	CA09–1	Ta Lus	12°25.70'	105°01.90'	0.731474 ± 13	0.512182 ± 10	−8.89 ± 9	0.720799 ± 10	0.512169 ± 10	−9.14 ± 20	0.011	0.26
8	CA10–1	Sambour	12°46.66'	105°57.88'	0.729315 ± 10	0.512181 ± 6	−8.92 ± 8	0.728398 ± 13	0.512101 ± 9	−10.48 ± 17	0.001	1.56
9	CA11–1	Srae Krosang	13°21.75'	105°57.46'	0.727943 ± 16	0.512237 ± 9	−7.83 ± 12	0.723810 ± 13	0.512049 ± 9	−11.48 ± 17	0.004	3.65
Mainstream in Vietnam												
10	MD02–1	Thua Duc	10°00.08'	105°45.11'	0.723307 ± 12	0.512206 ± 11	−8.43 ± 18	0.721498 ± 13	0.512161 ± 8	−9.31 ± 16	0.002	0.88
11	MD03–1	Long Duc	10°26.81'	105°23.27'	0.723343 ± 14	0.512213 ± 8	−8.29 ± 13	0.721961 ± 13	0.512154 ± 8	−9.45 ± 15	0.001	1.15
12	MD05–1	Binh Thuy	10°36.05'	105°25.22'	0.724124 ± 11	0.512177 ± 9	−9.00 ± 10	0.721018 ± 11	0.512106 ± 8	−10.37 ± 16	0.003	1.37
13	MD06–1	Anh Chau	10°13.83'	106°20.49'	0.722822 ± 9	0.512185 ± 7	−8.84 ± 8	0.720790 ± 11	0.512138 ± 8	−9.76 ± 16	0.002	0.92
14	MD08–1	An Truong	10°12.47'	106°41.94'	0.725195 ± 18	0.512175 ± 6	−9.03 ± 8	0.723662 ± 11	0.512134 ± 11	−9.84 ± 21	0.002	0.81
Tributaries in Cambodia												
15	CA01–1	Speu	11°27.40'	104°29.73'	0.728960 ± 18	0.512345 ± 8	−5.72 ± 11	0.716748 ± 11	0.512297 ± 8	−6.65 ± 16	0.012	0.93
16	CA12–1	Srepock	13°26.60'	106°36.19'	0.717436 ± 17	0.512477 ± 8	−3.13 ± 8	0.715408 ± 16	0.512328 ± 6	−6.04 ± 19	0.002	2.91
17	CA13–1	Kampi	13°02.40'	106°10.88'	0.725048 ± 13	0.512442 ± 9	−3.82 ± 10	0.712658 ± 13	0.512345 ± 7	−5.72 ± 13	0.012	1.90
18	CA14–1	Ter	12°23.60'	106°14.44'	0.719166 ± 17	0.512510 ± 10	−2.49 ± 11	0.712564 ± 10	0.512399 ± 8	−4.66 ± 15	0.007	2.17
19	CA15–1	Chhiong	12°14.77'	106°25.47'	0.718366 ± 12	0.512643 ± 8	0.10 ± 9	0.710844 ± 14	0.512487 ± 8	−2.95 ± 15	0.008	3.05
20	CA36–1	Tonle Sap	11°51.58'	104°47.65'	0.722120 ± 13	0.512202 ± 6	−8.51 ± 8	0.720897 ± 15	0.512173 ± 7	−9.07 ± 13	0.001	0.56

deionized water for several hours. Afterward, the samples were wet-sieved to collect the silt and sand fractions, respectively. Organic matter and carbonates were removed from both fractions using 30 % H_2O_2 and 0.5 % HCl , respectively. The sand fraction and a portion of the silt fraction were dried for Sr–Nd isotopic analysis. Another portion of the silt fraction suspension was used to isolate the clay fraction. Based on Stokes' Law, the clay fraction was separated by allowing particles to settle for 95 min at a liquid depth of 2 cm. The collected clay fraction was then dried at $\sim 50^\circ\text{C}$ to prepare for Sr–Nd isotopic analysis.

Sr and Nd isotopic compositions of carbonate-free river sediments were analyzed using a Thermo Scientific Neptune Plus MC-ICP-MS at the State Key Laboratory of Marine Geology, Tongji University. Geo-standards GSR-6 and GSD-9 were used to monitor the precision and accuracy. A small subsample of each sediment sample was dried at low temperature ($\sim 50^\circ\text{C}$) and crushed into fine powder. These powder samples were heated at 600°C for 2 h to eliminate organic carbon. Approximately 50 mg of each sample was digested with a mixture of concentrated HF and HNO_3 in high-pressure Teflon bombs at 190°C for at least 48 h. Sr and Nd were separated following standard ion exchange techniques. Sr and Nd isotopic compositions were normalized to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ and $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$, respectively. Standards NBS987 ($^{87}\text{Sr}/^{86}\text{Sr} = 0.710248 \pm 0.000023$, Thirlwall, 1991) and JNdi-1 ($^{143}\text{Nd}/^{144}\text{Nd} = 0.512115 \pm 0.000007$, Tanaka et al., 2000) were used

to ensure quality control of $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$, respectively. The mean measured $^{87}\text{Sr}/^{86}\text{Sr}$ value of NBS987 was 0.710242 ± 0.000014 (2σ , $N = 13$), and the mean measured $^{143}\text{Nd}/^{144}\text{Nd}$ of JNdi-1 was 0.512116 ± 0.000009 (2σ , $N = 16$), both of which fall within the recommended values. Nd isotopic data are expressed as $\epsilon_{\text{Nd}} = [(^{143}\text{Nd}/^{144}\text{Nd})_{\text{measured}} / (^{143}\text{Nd}/^{144}\text{Nd})_{\text{CHUR}} - 1] \times 10^4$, with the CHUR (Chondritic Uniform Reservoir) value set at 0.512638 (Jacobsen and Wasserburg, 1980).

Additionally, major and trace element concentrations of the clay, silt, and sand fractions from these samples were collected from Sang et al. (2024), where they were previously published. Major elements were determined using inductively coupled plasma optical emission spectrometry (ICP-OES), and trace elements were analyzed by inductively coupled plasma-mass spectrometry (ICP-MS) (Supplementary Material). For comparison, Sr–Nd isotopic compositions of two sediment cores MD01–2393 (Liu et al., 2005) and MD05–2896 (Sang et al., 2022) are also included in this study (Fig. 1A). Core MD01–2393 ($10^\circ 30.15'\text{N}$, $110^\circ 03.68'\text{E}$; 1230 m water depth; 42.55 m long; ~ 147 kyr) and core MD05–2896 ($8^\circ 49.5'\text{N}$, $111^\circ 26.47'\text{E}$; 1657 m water depth; 11.03 m long; ~ 45 kyr) were collected from the southern South China Sea during the cruise of MARCO POLO in 2005 (Laj et al., 2005) and the IMAGES cruise VII-WEPAMA in 2001 (Bassinot and Baltzer, 2002), respectively. Both cores consist predominantly of dark olive-gray homogeneous silty clay,

Table 2

Geographic locations and Sr–Nd isotopic compositions of sand fraction sediments in the Lower Mekong River Basin.

No	Sample	Location	Latitude (N)	Longitude (E)	$^{87}\text{Sr}/^{86}\text{Sr} \pm 2\sigma$	$^{143}\text{Nd}/^{144}\text{Nd} \pm 2\sigma$	$\varepsilon_{\text{Nd}} \pm 2\sigma$	$\Delta \varepsilon_{\text{Nd}} \text{ (clay-sand)}$	$\Delta \varepsilon_{\text{Nd}} \text{ (silt-sand)}$	$\Delta \varepsilon_{\text{Nd}}$
Mainstream in Cambodia										
1	CA02–2	Prek Eng	11°32.24'	104°59.33'	0.720658 ± 12	0.512148 ± 8	−9.56 ± 12	0.012	0.07	−1.45
2	CA03–2	Kompong Chomlong	11°15.46'	105°16.63'	0.718822 ± 10	0.512099 ± 7	−10.52 ± 9	0.011	1.45	−0.14
3	CA04–2	Chong Koh	10°58.83'	105°10.79'	0.719342 ± 12	0.512122 ± 7	−10.07 ± 9	0.005	2.16	−0.48
4	CA06–2	Peam Jikong	11°56.55'	105°16.08'	0.718612 ± 10	0.512113 ± 10	−10.23 ± 11	0.016	0.36	−1.35
5	CA07–2	Ti 6	12°06.17'	105°32.11'	0.719197 ± 11	0.512113 ± 9	−10.24 ± 12	0.006	1.81	0.90
6	CA08–2	Ti 4	12°14.93'	105°46.03'	0.718329 ± 9	0.512085 ± 8	−10.78 ± 10	0.006	2.48	1.23
7	CA09–2	Ta Lus	12°25.70'	105°01.90'	0.721788 ± 12	0.512117 ± 10	−10.15 ± 11	0.010	1.27	−0.001
8	CA10–2	Sambour	12°46.66'	105°57.88'	0.721824 ± 18	0.512130 ± 7	−9.91 ± 9	0.007	0.99	−0.57
9	CA11–2	Srae Krosang	13°21.75'	105°57.46'	0.722187 ± 13	0.512091 ± 9	−10.66 ± 10	0.006	2.83	−0.82
Mainstream in Vietnam										
10	MD02–2	Thua Duc	10°00.08'	105°45.11'	0.716215 ± 12	0.512044 ± 5	−11.59 ± 7	0.007	3.16	2.28
11	MD03–2	Long Duc	10°26.81'	105°23.27'	0.722253 ± 11	0.512139 ± 10	−9.73 ± 15	0.001	1.44	0.28
12	MD05–2	Binh Thuy	10°36.05'	105°25.22'	0.719113 ± 20	0.512050 ± 9	−11.46 ± 10	0.005	2.46	1.09
13	MD06–2	Anh Chau	10°13.83'	106°20.49'	0.718189 ± 14	0.512149 ± 10	−9.53 ± 10	0.005	0.69	−0.22
14	MD08–2	An Truong	10°12.47'	106°41.94'	0.721181 ± 13	0.512189 ± 7	−8.77 ± 9	0.004	−0.26	−1.07
Tributaries in Cambodia										
15	CA01–2	Speu	11°27.40'	104°29.73'	0.723737 ± 11	0.512380 ± 10	−5.03 ± 12	0.005	−0.69	−1.62
16	CA12–2	Srepok	13°26.60'	106°36.19'	0.713379 ± 14	0.512179 ± 11	−8.95 ± 14	0.004	5.81	2.91
17	CA13–2	Kampi	13°02.40'	106°10.88'	0.708916 ± 11	0.512416 ± 8	−4.32 ± 10	0.016	0.50	−1.40
18	CA14–2	Ter	12°23.60'	106°14.44'	0.710231 ± 11	0.512299 ± 9	−6.60 ± 13	0.009	4.11	1.94
19	CA15–2	Chhiong	12°14.77'	106°25.47'	0.708059 ± 12	0.512205 ± 7	−8.46 ± 6	0.010	8.55	5.50
20	CA36–2	Tonle Sap	11°51.58'	104°47.65'	0.716791 ± 12	0.512181 ± 10	−8.91 ± 12	0.005	0.40	−0.16

without slumping structures or mass transport deposits. Sr–Nd isotopic compositions of both cores MD01–2393 (average 0.722 and −11.53, respectively) and MD05–2896 (average 0.725 and −10.39, respectively) show consistent temporal variations throughout their records, implying no significant changes in sediment provenance. Furthermore, Sr–Nd isotopic compositions of mafic rocks (average 0.704 and 4.24, respectively) in the lower reach (Hoang et al., 2018; Yu et al., 2022) and felsic rocks (average 0.738 and −10.41, respectively) in the middle reach (Huang et al., 2021) are also used in this study for comparison.

4. Results

Sr–Nd isotopic compositions of sediments in the Lower Mekong River Basin exhibit systematic variations between mainstream and tributary samples (Fig. 2; Tables 1 and 2). Mainstream sediments display consistently higher $^{87}\text{Sr}/^{86}\text{Sr}$ values across all clay, silt, and sand fractions (average 0.727, 0.724, and 0.720, respectively) compared to those in the Srepok, Kampi, Ter, and Chhiong tributaries (average 0.720, 0.715, and 0.710, respectively). However, these values are similar to those from the Tonle Sap (0.722, 0.721, and 0.717, respectively) and Speu tributaries (0.729, 0.717, and 0.724, respectively). On the contrary, ε_{Nd} values of clay, silt, and sand fractions (average −8.74,

−10.18, and −10.23, respectively) in the mainstream are less radiogenic than those in the Srepok, Kampi, Ter, and Speu tributaries (average −3.01, −6.10, and −6.67, respectively) but similar to those of the Tonle Sap sediments (−8.51, −9.07, and −8.91, respectively). Notably, clay fractions in both the mainstream and tributaries exhibit systematically more radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ and ε_{Nd} than either silt or sand fractions. Mainstream sediments display relatively consistent isotopic signatures, while tributary sediments exhibit greater variability. Clear differences between mainstream and tributary sediments, which may relate to distinct source rocks. Additionally, the isotopic differences between the clay fraction and coarser fractions (silt and sand) are larger than those between the silt and sand fractions.

5. Discussions

In the Lower Mekong River Basin, clay fractions of both mainstream and tributary sediments exhibit higher $^{87}\text{Sr}/^{86}\text{Sr}$ and more radiogenic ε_{Nd} compared to silt and sand fractions, with greater variability observed in the tributary sediments (Fig. 2; Tables 1 and 2). In the mainstream, clay fractions generally show higher $^{87}\text{Sr}/^{86}\text{Sr}$ and ε_{Nd} values compared to silt ($\Delta_{\text{clay-silt}}$: 0.003 and 1.445, respectively) and sand ($\Delta_{\text{clay-sand}}$: 0.007 and 1.494, respectively) fractions. However, the differences

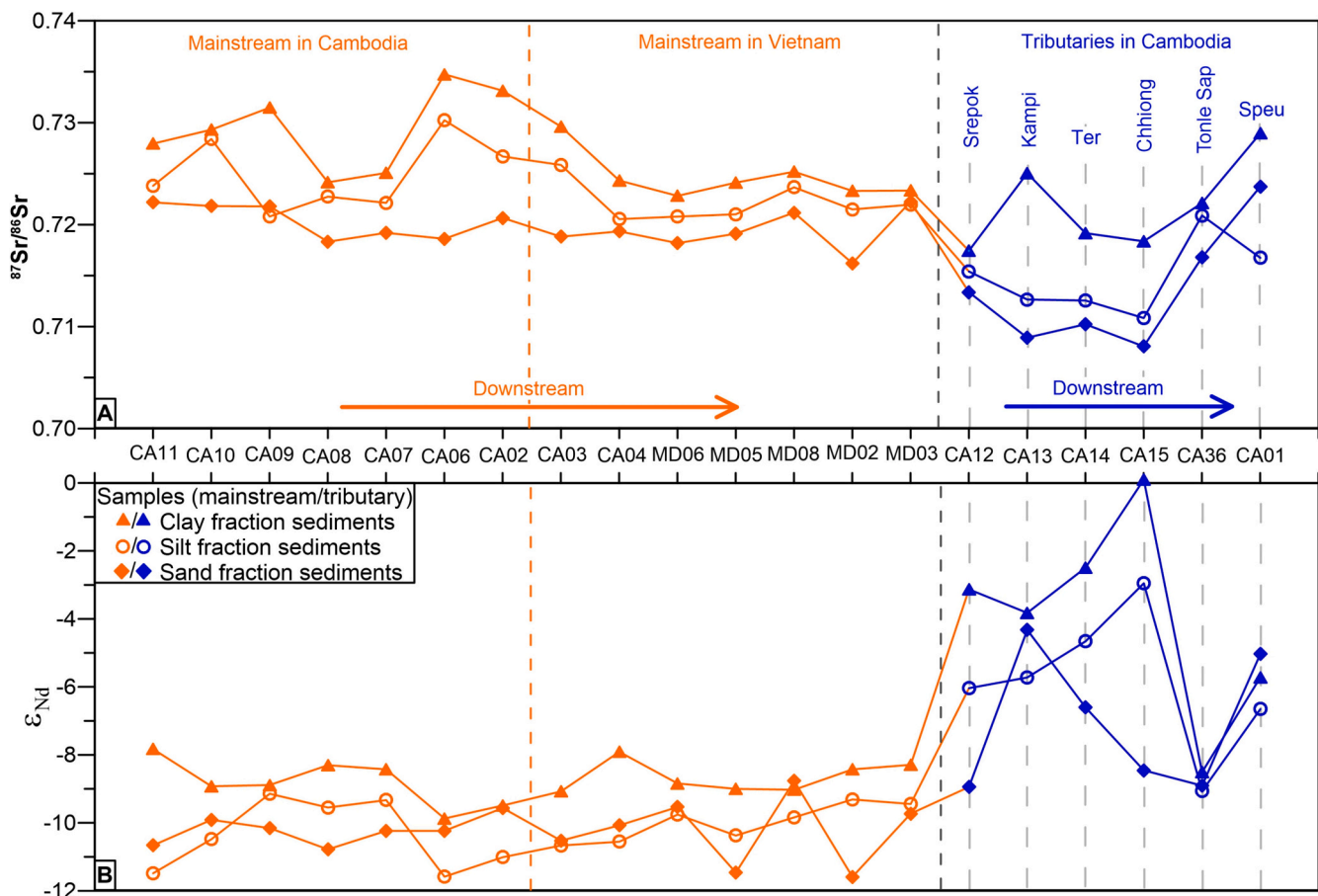


Fig. 2. Spatial variations of Sr (A) and Nd (B) isotopic compositions of clay, silt, and sand fraction sediments in the Lower Mekong River Basin.

between silt and sand fractions are a little larger for $^{87}\text{Sr}/^{86}\text{Sr}$ ($\Delta_{\text{silt-sand}}$: 0.004) but smaller for ϵ_{Nd} ($\Delta_{\text{silt-sand}}$: 0.049) values. In the tributaries, clay fractions significantly exhibit higher $^{87}\text{Sr}/^{86}\text{Sr}$ and ϵ_{Nd} values than both silt ($\Delta_{\text{clay-silt}}$: 0.007 and 1.919, respectively) and sand ($\Delta_{\text{clay-sand}}$: 0.008 and 3.114, respectively) fractions, while differences between silt and sand fractions remain less pronounced ($\Delta_{\text{silt-sand}}$: 0.001 and 1.195, respectively). These variations in $^{87}\text{Sr}/^{86}\text{Sr}$ and ϵ_{Nd} values among clay, silt, and sand fractions likely reflect the preferential depletion or enrichment of minerals and elements in different grain size fractions, leading to Sr–Nd isotopic fractionation. This suggests that the Sr–Nd isotopic compositions of river sediments in this basin could be affected by chemical weathering and grain size sorting, as discussed in detail below.

5.1. Effect of chemical weathering

Chemical weathering is a key Earth's surface process that alters the mineralogical, geochemical, and isotopic compositions of weathering products relative to their parent rocks (Parker, 1970; Nesbitt and Young, 1982). During the generation, transport, and deposition, clay, silt, and sand fraction sediments can be controlled by different physical and chemical processes, leading to compositional differences (Garzanti et al., 2019; Dinis et al., 2020; Sang et al., 2024). Coarse fractions (e.g., sand) are primarily generated by physical weathering and dominated by primary minerals (e.g., quartz, plagioclase, and feldspar), whereas fine fractions (e.g., clay) are largely derived from chemical weathering products and enriched in secondary minerals (e.g., smectite, kaolinite). These mineralogical differences result in distinct major/trace element and isotopic signatures among grain size fractions.

To evaluate the influence of chemical weathering on these isotopic

compositions of river sediments in the Mekong River Basin, Sr–Nd isotopic compositions of this study are employed to compare with $\text{K}_2\text{O}/(\text{Na}_2\text{O} + \text{CaO})$ from Sang et al. (2024), which is a well-established proxy for chemical weathering intensity (Dasch, 1969; Nesbitt et al., 1980; Fig. 3). Because K-feldspar is more stable than plagioclase during chemical weathering, implying that K is less preferentially depleted than Na and Ca. Thus, an increase in $\text{K}_2\text{O}/(\text{Na}_2\text{O} + \text{CaO})$ indicates enhanced chemical weathering, with preferential hydrolysis of plagioclase relative to K-feldspar and mica. Furthermore, $\text{K}_2\text{O}/(\text{Na}_2\text{O} + \text{CaO})$ is less affected by source rock lithology, hydraulic sorting or grain size, and sedimentary recycling compared to the chemical index of alteration (CIA; Nesbitt and Young, 1982) and the weathering index of Parker (WIP; Parker, 1970), especially in silt and sand fractions (Lupker et al., 2013; Garzanti and Resentini, 2016; Dinis et al., 2020). Therefore, $\text{K}_2\text{O}/(\text{Na}_2\text{O} + \text{CaO})$ ratio is considered a reliable proxy for chemical weathering processes in this study (e.g., Liu et al., 2007; Duan et al., 2023). Strong positive correlations of $\text{K}_2\text{O}/(\text{Na}_2\text{O} + \text{CaO})$ with Rb/Sr (0.937 and 0.566, respectively) and $^{87}\text{Sr}/^{86}\text{Sr}$ (0.520 and 0.444, respectively) in both mainstream and tributary sediments demonstrate a strong relationship between Sr isotopes and chemical weathering in this region (Figs. 3A and B). In contrast, ϵ_{Nd} in tributary and mainstream sediments show weak to moderate correlations with $\text{K}_2\text{O}/(\text{Na}_2\text{O} + \text{CaO})$ (0.065 and 0.398, respectively), while Sm/Nd exhibits negligible relationships with $\text{K}_2\text{O}/(\text{Na}_2\text{O} + \text{CaO})$ (0.0071 and 0.003, respectively) (Figs. 3C and D), reflecting no significant effects of chemical weathering. These findings suggest that Sm/Nd and ϵ_{Nd} values are largely unaffected by chemical weathering processes in the source region, unlike Rb/Sr and $^{87}\text{Sr}/^{86}\text{Sr}$, which show stronger weathering-dependent trends.

^{87}Sr forms from the radioactive decay of ^{87}Rb , and its abundance depends on rock age, type, and Rb/Sr (Dasch, 1969). Older rocks and K-

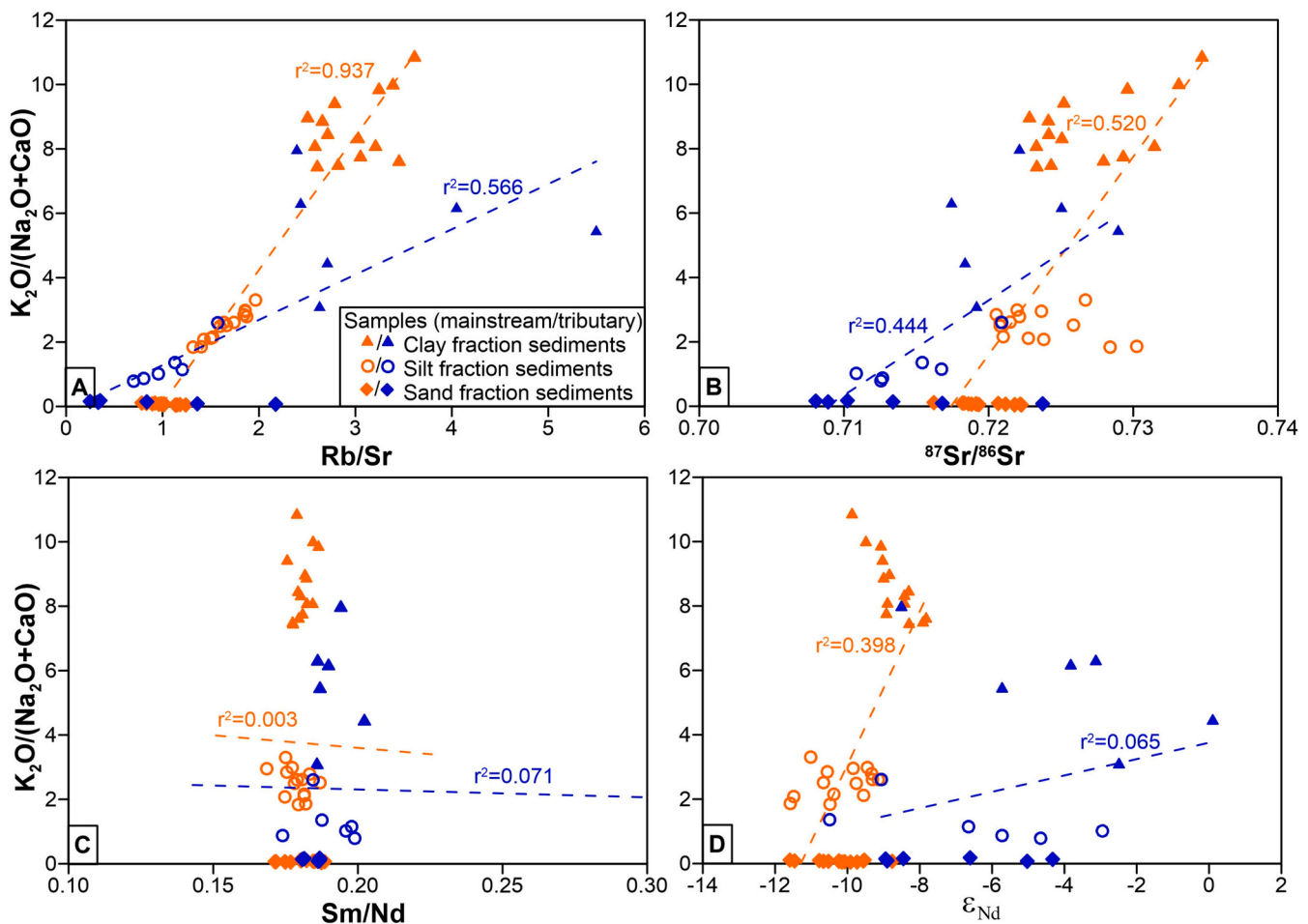


Fig. 3. Correlation plots of $K_2O/(CaO + Na_2O)$ with Rb/Sr (A), $^{87}Sr/^{86}Sr$ (B), Sm/Nd (C), and ϵ_{Nd} (D) of clay, silt, and sand-fraction sediments in the Lower Mekong River Basin. Major and trace elements are from Sang et al. (2024).

rich minerals with higher Rb/Sr yield higher $^{87}Sr/^{86}Sr$, while Sr is mainly hosted in Ca-rich minerals. Because Sr is more mobile than Rb during chemical weathering, weathering products generally have higher Rb/Sr and thus more radiogenic $^{87}Sr/^{86}Sr$ (Chen and Li, 2013). In both mainstream and tributary sediments, Rb concentration increases sharply from sand (average 60.03 and 45.47 mg/kg, respectively) to silt (average 115.96 and 76.81 mg/kg, respectively) and further to clay fractions (average 215.25 and 156.47 mg/kg, respectively) (Fig. 4A). This pattern reflects greater Rb enrichments in finer fractions due to its higher susceptibility to chemical weathering. Nevertheless, Sr concentration in mainstream sediments slightly increases from sand (average 59.77 mg/kg) to silt (average 70.01 mg/kg) and further to clay fractions (average 73.19 mg/kg) (Fig. 4B). Tributary sediments show a slight increase in Sr from sand (average 57.19 mg/kg) to silt (average 73.21 mg/kg), but exhibit the lowest values in clay fractions (average 50.24 mg/kg). This divergence likely reflects differences in chemical weathering intensity between the source regions. Mainstream sediments are derived from the middle reach of this basin and experience weaker chemical weathering compared to tributary sediments from the lower reach (Sang et al., 2024), explaining their distinct Sr distribution. Despite these differences, Rb/Sr in both mainstream and tributary sediments consistently increase from sand (average 1.01 and 0.88, respectively) to silt (average 1.66 and 1.06, respectively) and clay fractions (average 2.98 and 3.28, respectively) (Fig. 4E), leading to their strong correlations with $K_2O/(Na_2O + CaO)$. These findings demonstrate that chemical weathering in the source regions plays a pivotal role in modifying Rb, Sr, and Rb/Sr , resulting in Sr isotope fractionation of river sediments in the Lower Mekong River Basin.

^{143}Nd forms from the radioactive decay of ^{147}Sm , meaning $^{143}Nd/^{144}Nd$ increases in older rocks with high Sm/Nd (Amelin and Rotenberg, 2004; Andreasen and Sharma, 2006). Because Sm and Nd are chemically similar and resistant to weathering, they remain coherent in the same resistant minerals (e.g., monazite and allanite), preserving relatively constant Sm/Nd throughout chemical weathering processes. In this region, Sm concentration in both mainstream and tributary sediments follow a consistently increasing trend from sand (average 3.42 and 2.92 mg/kg, respectively) to silt (average 6.06 and 5.06 mg/kg, respectively) and further to clay fractions (average 8.58 and 8.61 mg/kg, respectively) (Fig. 4C). Similarly, Nd concentration in mainstream and tributary sediments rises sharply from sand (average 18.89 and 15.86 mg/kg, respectively) to silt (average 33.86 and 26.69 mg/kg, respectively) and clay fractions (average 47.46 and 45.28 mg/kg, respectively) (Fig. 4D). Both Sm (0.756 and 0.606, respectively) and Nd (0.762 and 0.574, respectively) in mainstream and tributary sediments display nearly identical trends during chemical weathering, as evidenced by their similar strong correlations with Al_2O_3 . Consequently, all grain size fractions of mainstream and tributary sediments maintain nearly consistent Sm/Nd ratios (average 0.184, 0.182, and 0.182, respectively) (Fig. 4F), with slightly higher values in the tributaries, likely reflecting differences in source rock compositions. The stability of Sm/Nd is further supported by its lack of correlation with $K_2O/(Na_2O + CaO)$ (Fig. 3C). These findings indicate that chemical weathering in the source region has a negligible influence on Sm/Nd and ϵ_{Nd} across clay, silt, and sand fractions in the Lower Mekong River Basin.

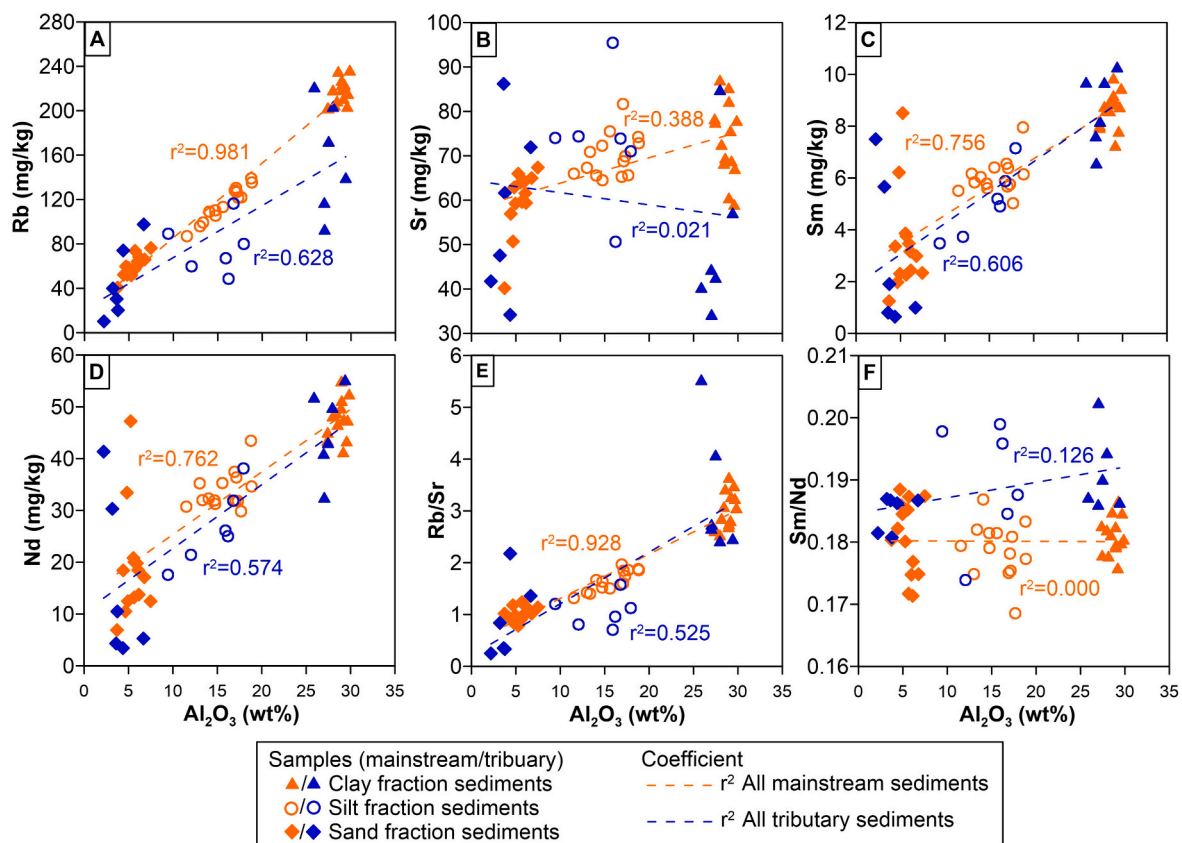


Fig. 4. Correlation plots of Al_2O_3 with Rb (A), Sr (B), Sm (C), Nd (D), Rb/Sr (E), and Sm/Nd (F) of clay, silt, and sand fraction sediments in the Lower Mekong River Basin. Major and trace elements are from Sang et al. (2024).

5.2. Effect of grain size sorting

During sediment erosion, transport, and deposition, grain size sorting redistributes minerals by density, shape, and size, leading to geochemical and Sr–Nd isotopic variability (Dasch, 1969; Garzanti et al., 2013; Garçon et al., 2014). In the Lower Mekong River Basin, the observed variation in $^{87}\text{Sr}/^{86}\text{Sr}$ and ϵ_{Nd} between clay, silt, and sand fractions may therefore reflect not only chemical weathering but also grain size sorting effects (Fig. 2). To assess this effect, Rb/Sr, Sm/Nd, $^{87}\text{Sr}/^{86}\text{Sr}$, and ϵ_{Nd} of mainstream and tributary sediments are compared with a grain size proxy ($\text{SiO}_2/\text{Al}_2\text{O}_3$) (Fig. 5). Moderate to strong correlations of $\text{SiO}_2/\text{Al}_2\text{O}_3$ with Rb/Sr (0.301 and 0.649, respectively) and $^{87}\text{Sr}/^{86}\text{Sr}$ (0.297 and 0.415, respectively) in tributary and mainstream sediments indicate a moderate grain size sorting influence on Sr isotopes. Notably, mainstream sediments show stronger correlations of Rb/Sr and $^{87}\text{Sr}/^{86}\text{Sr}$ with $\text{SiO}_2/\text{Al}_2\text{O}_3$ than those in tributary sediments (Figs. 5A and B), suggesting that grain size sorting has a greater impact on Sr isotopes in mainstream sediments. This may result from longer transport distances in the mainstream, where sediments are derived highly from the middle reach, whereas tributary sediments originate from more proximal local source rocks (Sang et al., 2024; Fig. 1). In contrast, Sm/Nd (0.015 and 0.155, respectively) and ϵ_{Nd} (0.191 and 0.197, respectively) in mainstream and tributary sediments show negligible or weak correlations with $\text{SiO}_2/\text{Al}_2\text{O}_3$, indicating minimal grain size sorting or transport-distance effects on Nd isotopes. Thus, while grain size sorting moderately controls Sr isotope fractionation in the Lower Mekong River Basin, it does not significantly influence Nd isotope variability.

Generally, Sr is highly enriched in Ca-plagioclase and apatite, whereas Rb is mainly concentrated in K-feldspar, mica, and clay minerals, leading to Rb/Sr variability across different grain sizes (Bottino and Fullagar, 1968; Dasch, 1969). In this study region, Sr trends differ

between mainstream and tributary sediments (Fig. 4B). Mainstream sediments show a gradual increase in Sr from sand to silt and clay fractions, whereas tributary sediments display higher Sr in silt fractions than in sand fractions but the lowest Sr in clay fractions. This suggests that finer fractions (particularly clays) do not always retain higher Sr concentration than coarser fractions, likely due to the breakdown of Sr-bearing minerals (e.g., Ca-plagioclase and apatite) during sediment erosion and transport. Additionally, tributary sediments in the lower reach may contain more Ca-plagioclase than mainstream sediments, owing to their mafic source rocks (Fig. 1C). On the other hand, both mainstream and tributary sediments exhibit a strong increase in Rb concentration from sand to silt and clay fractions (Fig. 4A). This trend implies that finer fractions are enriched in Rb-bearing minerals (e.g., K-feldspar, mica, and clay minerals), leading to higher Rb in fine fractions, especially clay fractions. Despite the differing trends in Sr and Rb across grain size, Rb/Sr of both mainstream and tributary sediments follow a consistent increase from sand to silt and clay fractions (Fig. 4E). These findings suggest that grain size sorting exerts a strong control over mineral composition, thereby influencing their Sr and Rb concentrations, Rb/Sr, and ultimately $^{87}\text{Sr}/^{86}\text{Sr}$ signatures in river sediments of this region.

In contrast, Sm and Nd are typically hosted in the same resistant minerals, such as monazite, allanite, bastnasite, and zircon (Garçon et al., 2014), which leads to relatively stable Sm/Nd across different grain sizes (Feng et al., 2009; Garzanti et al., 2013). In this study region, both mainstream and tributary sediments exhibit a significant increase in Sm and Nd concentrations from sand to silt and clay fractions (Figs. 4C and D). Strong correlations between Sm, Nd, and Al_2O_3 in both mainstream and tributary sediments indicate that these elements behave cohesively across grain sizes. This likely explains why Sm/Nd remains stable in clay, silt, and sand fractions of both mainstream and tributary sediments, with slightly higher values in the tributaries than in the

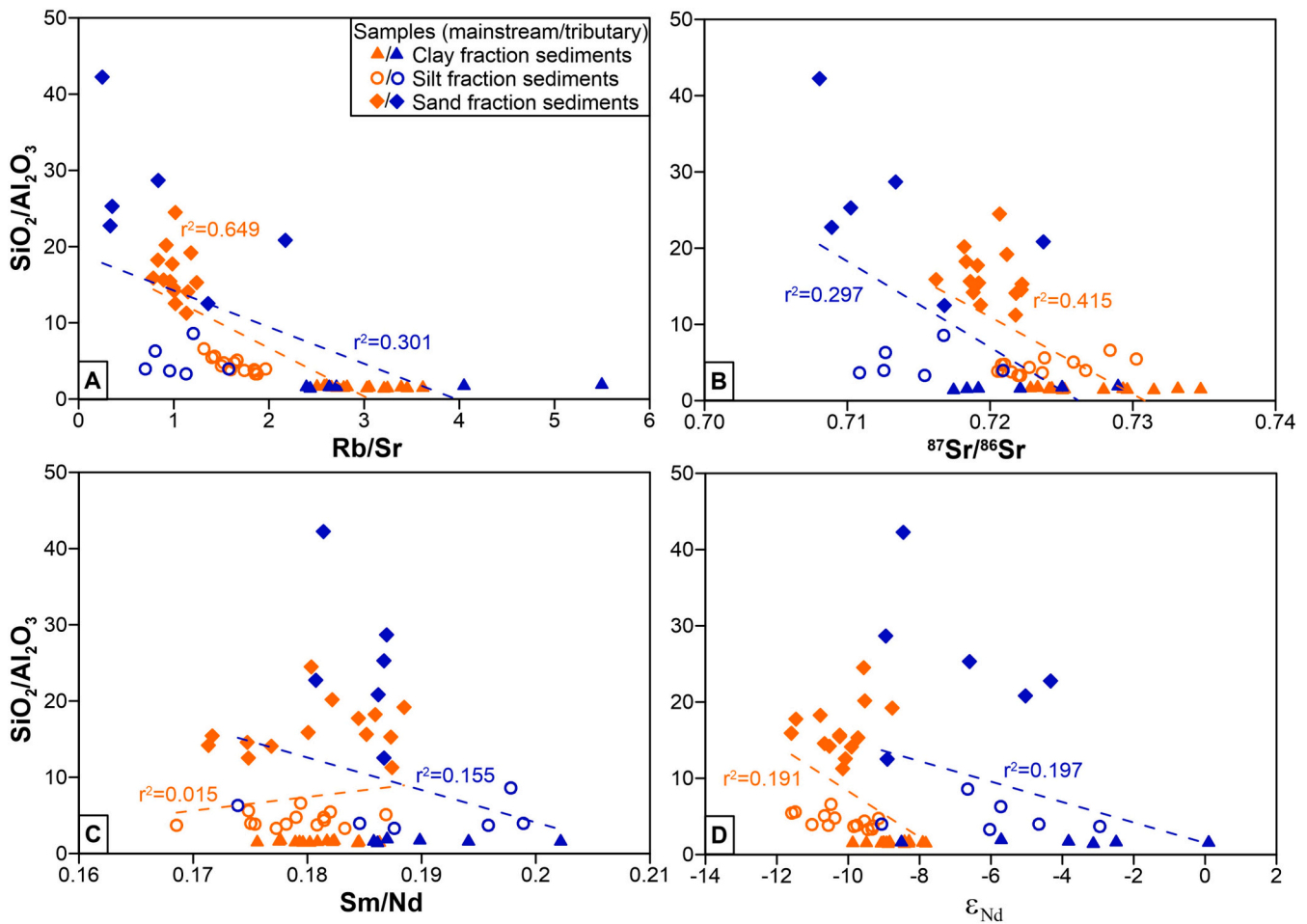


Fig. 5. Correlation plots of $\text{SiO}_2/\text{Al}_2\text{O}_3$ with Rb/Sr (A), $^{87}\text{Sr}/^{86}\text{Sr}$ (B), Sm/Nd (C), and ϵ_{Nd} (D) of clay, silt, and sand-fraction sediments in the Lower Mekong River Basin. Major and trace elements are from Sang et al. (2024).

mainstream (Fig. 4F). Moreover, the stability of Sm/Nd and ϵ_{Nd} , together with their weak correlations with $\text{SiO}_2/\text{Al}_2\text{O}_3$ (Figs. 5C and D) suggests that both Sm/Nd and ϵ_{Nd} are minimally affected by grain size sorting.

5.3. Source rock signatures

In river basins, parent rock compositions strongly control the mineralogy, geochemistry, and isotopic compositions of river sediments, particularly Sr–Nd isotopes (Liu et al., 2012; Garzanti et al., 2013; Bayon et al., 2015; Awasthi et al., 2018). Mafic rocks are directly derived from depleted or enriched mantle sources and are rich in pyroxene, amphibole, plagioclase, biotite, and olivine (Hoang et al., 2018; Yu et al., 2022). They contain high Ca, Sr, and Sm but low K, Rb, and Nd, resulting in low Rb/Sr and $^{87}\text{Sr}/^{86}\text{Sr}$ and high Sm/Nd and ϵ_{Nd} (Banner, 2004; Taylor and McLennan, 1995; Figs. 6 and 7). By contrast, felsic rocks frequently form through crustal partial melting and are dominated by quartz, K-feldspar, and muscovite (Huang et al., 2021). They show opposite geochemical trends, being enriched in K, Rb, and Nd but depleted in Ca, Sr, and Sm, thus yielding high Rb/Sr and $^{87}\text{Sr}/^{86}\text{Sr}$ with low Sm/Nd and ϵ_{Nd} . Moreover, older rocks typically exhibit more radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ and ϵ_{Nd} than younger rocks (McLennan et al., 1990; Milliman and Syvitski, 1992). Consequently, Sr–Nd isotopic compositions of river sediments primarily reflect the type, mineralogy, and age of source rocks.

In the Lower Mekong River Basin, mainstream sediments are characterized by high Rb/Sr (1.880) and $^{87}\text{Sr}/^{86}\text{Sr}$ (0.724), coupled with low Sm/Nd (0.180) and ϵ_{Nd} (−9.72) (Figs. 2 and 4; Tables 1 and 2). These

signatures plot close to felsic rocks of the Lancang block in the middle reach (Huang et al., 2021; Figs. 1 and 6), reflecting highly felsic rocks in the source region. Sediments in the Srepok, Kampi, Ter, Chhiong, and Speu display similar Rb/Sr, Sm/Nd, and Sr–Nd isotopic compositions, with low Rb/Sr (1.737) and $^{87}\text{Sr}/^{86}\text{Sr}$ (0.716) but high Sm/Nd (0.188) and ϵ_{Nd} (−4.96), relating significantly to mafic rocks in the lower reach (Hoang et al., 2018; Yu et al., 2022). However, Tonle Sap sediments exhibit similar Rb/Sr (1.775), $^{87}\text{Sr}/^{86}\text{Sr}$ (0.720), Sm/Nd (0.188), and ϵ_{Nd} (−8.827) compared to those in mainstream sediments because this tributary mostly receives sediments from the mainstream (Sok et al., 2021; Sang et al., 2024). These distinct Rb/Sr, Sm/Nd, and Sr–Nd isotopic compositions enable clear discrimination between mainstream and tributary sediments in this study region, reflecting dissimilar parent rocks in the source region (felsic versus mafic rocks) and source rock control (Figs. 1, 6, and 7). The results also confirm that tributaries in the lower reach contribute relatively minor sediment inputs to the mainstream (Fig. 7). Additionally, moderate to strong negative correlations between $^{87}\text{Sr}/^{86}\text{Sr}$ and ϵ_{Nd} across all grain size fractions underscore the first-order control of source rock composition on Sr–Nd isotopic signatures, particularly in the silt fractions (Grousset and Biscaye, 2005; Chen and Li, 2013; Fig. 6). While chemical weathering and grain size sorting can notably influence Rb/Sr and $^{87}\text{Sr}/^{86}\text{Sr}$, Sr–Nd isotopic compositions of river sediments are fundamentally governed by parent rock characteristics in source regions, thus preserving significantly valuable information from their source rock signatures.

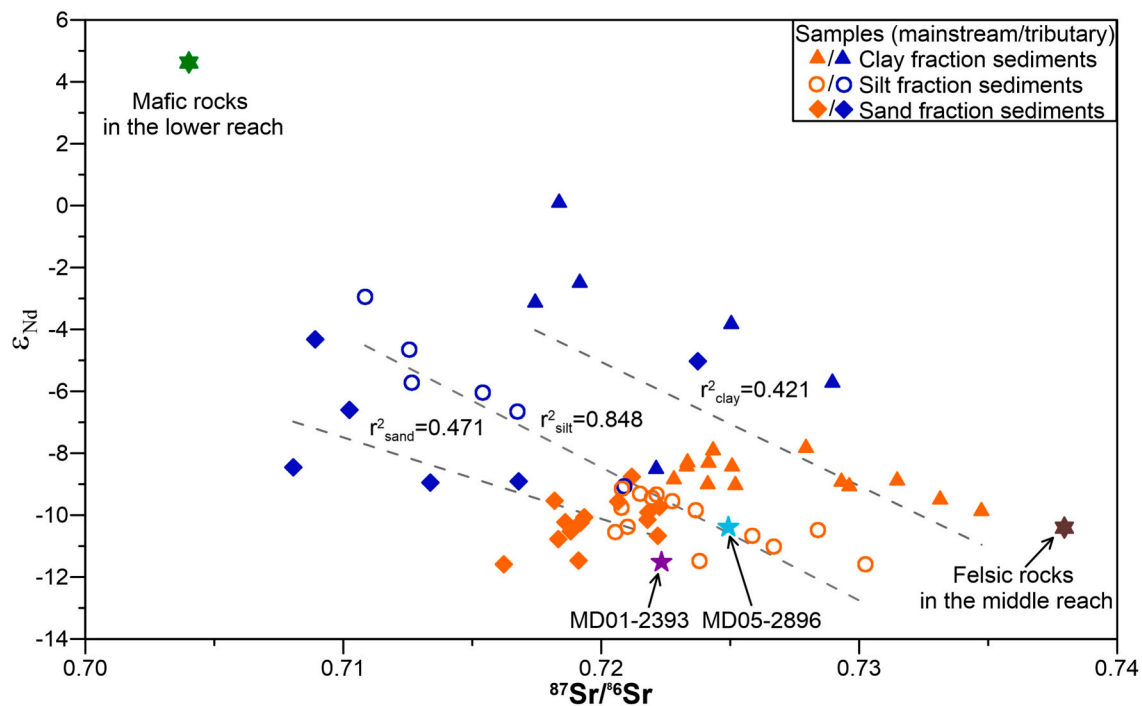


Fig. 6. Correlation plot of $^{87}\text{Sr}/^{86}\text{Sr}$ and ϵ_{Nd} of clay, silt, and sand fraction sediments in the Lower Mekong River Basin. Average referred data of Cores MD01–2393 (Liu et al., 2005) and MD05–2896 (Sang et al., 2022) offshore from the Mekong River, felsic rocks of the Lancang block in the middle reach (Huang et al., 2021), and mafic rocks in the lower reach (Hoang et al., 2018; Yu et al., 2022) are plotted for comparison.

5.4. Implications for provenance studies

Sr–Nd isotopic compositions of riverine and marine sediments, sedimentary rocks, and loess dust are extensively employed as tracers in sediment provenance studies (McLennan and Hemming, 1992; Colin et al., 2006; Xie et al., 2012; Wan et al., 2015; Awasthi et al., 2018; Zhu et al., 2021). These applications highlight the importance of identifying which isotopic systems and sediment fractions provide the most reliable provenance signals. Our study demonstrates that Nd isotopes serve as particularly robust provenance indicators due to their minimal sensitivity to chemical weathering and grain size sorting effects. Despite significant variations in mineral and element compositions, chemical weathering histories, and grain size distribution among clay, silt, and sand fractions in the Lower Mekong River Basin, Sm/Nd and ϵ_{Nd} consistently retain the geochemical and isotopic signatures of their parent rocks (Figs. 2–4). This consistency indicates that Sm/Nd and ϵ_{Nd} essentially remain unfractionated during both chemical weathering and sediment transport processes, faithfully preserving source rock characteristics. In contrast, Sr and Rb concentrations, as well as Rb/Sr are more susceptible to alteration by chemical weathering and grain size sorting effects, leading to significant variations in $^{87}\text{Sr}/^{86}\text{Sr}$ among different sediment fractions. This sensitivity complicates the application of Sr isotopes for provenance studies unless these modifying factors are carefully accounted for.

When properly interpreted, with consideration of chemical weathering and grain size sorting effects, $^{87}\text{Sr}/^{86}\text{Sr}$ and ϵ_{Nd} together can provide a robust proxy for sediment provenance studies. As clay fractions are strongly influenced by chemical weathering, while sand fractions are more affected by grain size sorting, both processes can obscure source rock signatures. To minimize these effects, provenance investigations should compare isotopic compositions within uniform grain size fractions. In this study, comparison with marine sediment cores (MD01–2393 and MD05–2896) receiving Mekong River inputs reveals that bulk sediment isotopic compositions (mostly $<63\ \mu\text{m}$) of these cores are more consistent with silt fractions rather than with clay or sand fractions (Liu et al., 2005; Sang et al., 2022; Fig. 6). This observation

underscores the importance of consistent size-fraction analysis in provenance studies. Additionally, all size fractions (clay, silt, and sand) from the Lower Mekong River Basin exhibit moderate to strong negative correlations between $^{87}\text{Sr}/^{86}\text{Sr}$ and ϵ_{Nd} (0.421, 0.848, and 0.471, respectively), confirming parent rock lithology as the primary control and demonstrating the utility of these isotopic signatures as useful provenance indicators (Grousset and Biscaye, 2005; Chen and Li, 2013). Notably, silt fractions show the strongest correlation, suggesting they may represent the most reliable proxy for provenance discrimination. While clay and sand fractions are more susceptible to weathering and sorting effects, their Sr–Nd isotopic signatures still effectively distinguish between mainstream and tributary sources. However, silt fractions emerge as the most suitable for provenance investigations, given their optimal balance between the influence of chemical weathering and grain size sorting. The findings of this study can help to more efficiently elucidate sediment provenance not only for fluvial sediments in this basin, but also for other river basins and marine sediments, all of which are affected by chemical weathering in the source region and hydraulic sorting during transport.

In summary, Sr isotopes are influenced by chemical weathering and grain size sorting, whereas Nd isotopes remain largely unaffected by these processes. These fundamental differences make Nd isotopes more reliable tracers for sediment provenance studies compared to Sr isotopes. Despite these effects, all clay, silt, and sand fractions in the mainstream exhibit more radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ and less radiogenic ϵ_{Nd} compared to tributary sediments, reflecting differences in parent rock compositions (felsic versus mafic rocks) and retaining valuable information about source rock lithology. For optimal provenance investigations, this study recommends analyzing Sr–Nd isotopes within uniform-sized fractions, with the silt fraction representing a particularly robust choice due to its intermediate sensitivity to chemical weathering and grain size sorting. These recommendations can apply not only to fluvial sediments in the Mekong River Basin but also to other river basins and marine sediments, as these sediments are also influenced by source-region weathering and hydraulic sorting during transport. Additionally, the Mekong River, Southeast Asia's largest river

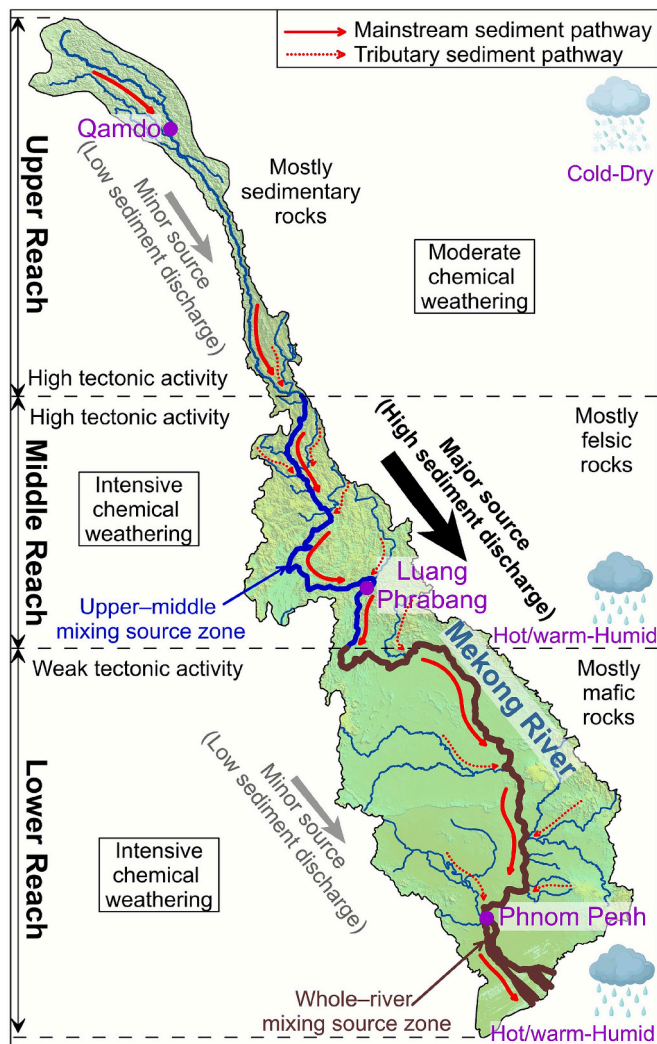


Fig. 7. Schematic illustration of sediment provenance, weathering, and transport pathways in the Mekong River Basin.

system and the primary sediment source for the South China Sea, offers an exceptional natural laboratory for such studies. Originating on the Tibetan Plateau and traversing six countries with diverse lithological terranes before reaching the sea, its complex watershed provides critical insights into how natural processes affect isotopic fractionation. By examining Sr–Nd isotope behaviour across different size fractions and under various environmental controls (chemical weathering and grain size sorting), this study enhances our understanding of (1) isotopic fractionation mechanisms in natural systems, and (2) the optimal application of these tracers in global provenance studies.

6. Conclusions

Sr–Nd isotopic compositions of clay, silt, and sand fractions from the Lower Mekong River Basin were analyzed to evaluate the effects of chemical weathering and grain size sorting and their implications for provenance interpretation. The key findings from the investigation are as below:

In general, clay, silt, and sand fractions in the mainstream exhibit more radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ (0.727, 0.724, and 0.720, respectively) and less radiogenic ϵ_{Nd} (−8.74, −10.18, and −10.23, respectively) values compared to the tributaries ($^{87}\text{Sr}/^{86}\text{Sr}$: 0.722 and 0.715, and 0.714; ϵ_{Nd} : −3.93, −5.85, and −7.04). Among the grain size fractions, the clay fraction in both mainstream and tributary sediments show the most

radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ and ϵ_{Nd} .

Moderate to strong correlations between Rb/Sr and $^{87}\text{Sr}/^{86}\text{Sr}$ with $\text{K}_2\text{O}/(\text{CaO} + \text{Na}_2\text{O})$ and $\text{SiO}_2/\text{Al}_2\text{O}_3$ indicate that Sr isotopes are influenced by chemical weathering and grain size sorting. In contrast, Sm/Nd and ϵ_{Nd} values show no to weak correlations with $\text{K}_2\text{O}/(\text{CaO} + \text{Na}_2\text{O})$ and $\text{SiO}_2/\text{Al}_2\text{O}_3$, suggesting minimal impact from these processes. However, all clay, silt, and sand fractions in the mainstream notably exhibit more radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ and lower ϵ_{Nd} values than those in the tributaries, reflecting differences in source rocks (felsic versus mafic rocks) and the preservation of distinct source rock signatures.

Despite the influences of chemical weathering and grain size sorting, moderate to strong negative correlations between $^{87}\text{Sr}/^{86}\text{Sr}$ and ϵ_{Nd} values across all grain size fractions suggest that Sr–Nd isotopic compositions remain robust indicators for provenance analysis. To minimize the effects of chemical weathering and grain size sorting, our study recommends using Sr–Nd isotopic compositions from uniform grain size fractions, with the silt fraction being the optimal choice. These findings and recommendations can apply to provenance studies of riverine and marine sediments, which are similarly affected by chemical weathering and hydraulic sorting.

CRediT authorship contribution statement

Pham Nhu Sang: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Zhifei Liu:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Yulong Zhao:** Writing – review & editing, Investigation, Conceptualization. **Pham Trung Hieu:** Writing – review & editing, Investigation. **Sopheak Thav:** Writing – review & editing, Investigation.

Declaration of competing interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Acknowledgments

The authors thank Pham Minh and Do Ngoc Thanh at the Faculty of Geology, University of Science Ho Chi Minh City for fieldwork assistance and discussion. We especially thank Juan Xu, Jiahuan Du, and Mingyang Yu for laboratory assistance at the State Key Laboratory of Marine Geology, Tongji University. This work was supported by the National Natural Science Foundation of China (42188102, 42130407) and the Second Tibetan Plateau Scientific Expedition and Research (STEP) Program (2019QZKK0204).

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.chemgeo.2025.123199>.

Data availability

Data will be made available on request.

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