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Implications of major oxides and trace elements geochemistry in recent river sediment provenance: An overview

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ABSTRACT

The geochemical analysis represents a potential approach for understanding sediment provenance, important aspect for source characterisation, weathering pattern and understanding the transport mechanism. This study highlights the significance of major oxides such as CaO, SiO_2, Al_2O_3, Na_2O etc. and trace elements such as Al, Fe, Ti, Th etc. as key indicators in providing insights into recent river sediment provenance. These geochemical markers help to unravel sediment source characteristics, weathering, and erosion processes despite the complexities introduced by factors such as grain size sorting, mixing, and hydrodynamic effects. Methods such as the A-CN-K diagram, elemental ratios, and inter-element relationships are particularly powerful for analysing recent sediments, as they help define source geochemistry and recent weathering and erosion patterns. Major oxides and trace element geochemistry are therefore used as a powerful tool for investigating sediment provenance in recent river sediments. This study aims to provide an overview of major and trace element proxies, including the chemical index of weathering and elemental ratios commonly used in provenance evaluation, while assessing their strengths and limitations in determining sediment origin. Their major strength lies in their ability to define source geochemistry and recent weathering and erosion patterns. However, the challenge lies in their inability to distinguish sources with similar lithology. To address this, it is suggested to use the A-CN-K diagram in combination with inter-element ratio relationships for a more comprehensive and accurate analysis.

Keywords: Sediment provenance; Geochemistry; Major oxide; Trace elements

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INTRODUCTION

Sediment provenance is explained as a way of inverting the deposited sedimentary record to elucidate the roles of climate and tectonic activity in the erosion and transport of sediments using geochemical parameters such as major oxide and trace elements geochemistry, mineral age and heavy mineral (Cullers et al., 1988; Roser and Korsch, 1988; Nesbitt et al., 1996; Yang et al., 2003; Singh, 2009; Sharman et al., 2019). In sedimentology, the term river sediment provenance encompasses all aspects related to sediments, from their formation to final deposition. This include the physical and chemical properties of sediments as well as the climatic characteristics of the source area, as well as transport and deposition mechanism (Pettijohn et al., 1974; Weltje and von Eynatten, 2004; Clift, 2016; Mazumder, 2017). Many studies focusing on the concept of river erosion and crustal deformation in the mountain building process (Koons, 1989; Molnar and England, 1990; Armitage et al., 2011) has highlighted river sediments as an important aspect in sediment provenance at global and regional scales (Molnar and England, 1990; Gabet et al., 2004; West, 2008; Burbank et al., 2012; Deng et al., 2019). This influence arises because recent fluvial or river sediments transports information from its origin to diverse depositional environments. In doing so, they provide valuable insights into the issues related to tectonic, climate, land use and erosion as well as landform evolution over time (Nyberg et al., 2018; Garzanti, 2019). This information is important for improving decision-making processes in soil erosion control and basin management strategies.

Major oxides are essential components present in rocks and minerals. Their significant variation across different rock types and geological processes makes them valuable for understanding sediment provenance and weathering. Common major oxides in rocks and minerals include oxide of silica, alumina, iron, calcium, magnesium, potassium, sodium, titanium, nickel, carbon and sulphur. Although trace elements are characterised as the elements present in minute quantities nearly equal to 0.1 wt% of Earth's crust composition (Kennedy, 1998), they reflect provenance compositions because they experience minimal alteration during weathering and transport processes (Taylor and McLennan, 1985). Examples of trace elements encompass Rare Earth Elements (REEs) and High-field-strength Elements (HFSE), which include Zr, Nb, Hf, Y, and Th (Jenner and Wyman, 1996). Therefore, major oxide and trace elements provide a valuable record of source type as well as the weathering conditions (Singh, 2009; Manuela Vinha G. Silva et al., 2016; Hossain, 2019). They also provide insights into the source geochemistry and the weathering conditions at the origin, both of which are by geotectonic and climatic factors (Pang et al., 2018).

Researchers use different standard end-member models, such as the elemental ratios La/Co, Th/Sc, Ba/Co, La/Sc, and Ba/Sc, ternary diagrams, binary diagrams to the estimate the relative proportions of erosion sources using mixing modelling (Cullers et al., 1988; Singh, 2010; Bhuiyan et al., 2011; Pulley et al., 2017; Nosrati et al., 2018; Gholami et al., 2019). These well-established approaches provide insights into the contributions of major and trace elements to sediment provenance, aiding in decoding the complex processes influencing sediment transport and deposition.

This article aims to explore the various methods used in recent fluvial provenance studies, focusing on major oxides and trace elements. It focuses on comprehensive review of major and trace element indicators, which encompass the chemical index of weathering and elemental ratios, commonly employed in evaluating provenance. Furthermore, this study seeks to evaluate the advantages and drawbacks associated with these proxies when determining the origin of sediment. However, it does not assess the success or failure of individual methods.

FACTORS AFFECTING THE PROVENANCE ANALYSIS

Source composition

Numerous investigations employed on the river sediments unravels the fact that the physical and chemical properties of the sediments are controlled by the source property (Singh, 2009; Pramod, 2010; Lawrence et al., 2011). A source is defined as the area where sediment is produced. and they are distinguished by their chemistry, geochronology, or tectonic evolution (Clift, 2016).. Rocks, soil, and minerals undergo chemical and physical weathering at their origin, through the interaction of agents such as water, air, biological organisms, and climatic leading to the erosion and subsequent transport of the disintegrated materials from their source (Miller et al., 2015). In the process of transport, materials from different sources combine and form a bulk composition. Therefore, changes in source result in changes in the composition and mineralogy of bulk sediments (Collins et al., 1997; Emilia et al., 2001; Galy, 2001). This greater sediment heterogeneity is one reason why larger basins have greater uncertainty (Jian et al., 2020).

Studies suggest that the geological unit source and tributary catchment area are much less heterogeneous than soil type or land use (Miller et al., 2015; Patault et al., 2019). Geological unit used as spatial source is sometime less useful if the watershed has homogenous geology (Patault et al., 2019) whereas the geological unit is identified as one of the major factors controlling the source differentiation if the watershed has heterogeneous (He et al., 2014; Collins et al., 2017). The careful use of geochemical indicators can accurately quantify the element abundance in sediment, which makes geochemical as an important tool in the study of sediment sources (Zhou et al., 2015b). Emphasize is given to provenance identification even if one has to understand and mitigate the sediment related contamination on aquatic (Miller, 2015).

Weathering

Weathering processes can be broadly categorized into physical and chemical weathering. Physical weathering refers to the mechanical breakdown of rock and mineral materials without altering their chemical composition. Physical weathering occurs through various mechanisms such as plucking, abrasion, hydrological and biological activities (Kodama, 1994; Kumar et al., 2016). On the other hand, chemical weathering involves the alteration of rock and mineral materials through chemical reactions such as dissolution, hydrolysis, and oxidation (Mondal et al., 2012). Climate, wind, biological organisms and water are the primary agents responsible for weathering at the source, as they break down and mineral materials into smaller particles..(Guagliardi et al., 2013). Once weathered, these materials are then transported to new location. For instance, water facilities weathering and transport sediments downstream, wind and biological organism also move sediment from source to new location. Additionally, soil formation is a product of weathering from the underlying bedrock. For instance, clay minerals are formed from the weathered feldspar, which are accumulated as fine-grained mud. Similarly, quartz in granite or pegmatite weathered to sands (Nesbitt et al., 1996). Overall, the dynamic interplay between physical and chemical weathering continuously shapes river sediments, influencing their properties and characteristics over time and appropriate use of geochemical proxies can unravel the sediment provenance information. The major oxide and trace element ternary and binary diagrams based on these proxies has been utilized to comprehend weathering and provenance. Many methods have been suggested to assess the degree of alteration and the Chemical Index of Alteration (CIA) is the most extensively utilized one (Price and Velbel, 2003; Liu et al., 2009; Mondal et al., 2012; Huyan and Yao, 2022).

Grain size distribution

The variability in the concentration of elements can be influenced by grain size distributions and it helps to explain the source and hydrodynamic activities of the river. For instance, REEs are predominantly found in fine sediments due to their chemical stability and resistance to weathering. In contrast, silicates, oxides of silica, typically combined with aluminium, magnesium, iron, calcium, sodium, and potassium, which are also resistant to weathering, are more likely to remain in sand-sized sediments. In order to incorporate grain size analysis into provenance studies, some researchers classify sediments based on specific grain size ranges, such as the ~63-mm size fraction, known as the narrow window strategy (Singh et al., 2001; Whitmore et al., 2004; Fu et al., 2008; Von Eynatten et al., 2011). Some researchers argue that employing a narrow window strategy may result in a loss of bulk chemistry information and advocate for a wide window strategy, which includes the entire grain size distribution (Garzanti et al., 2009). There have been many approaches to analyse provenance based on the grain size and concluded that grain size alone is not enough to define the source, but when used with other parameters like mineralogy, geochemistry improves the information on provenance (Laceby et al., 2017).

GEOCHEMICAL INDICES

Hypothetically, sediments are fundamental to understanding the geotectonic environment and climatic changes (Burbank et al., 2012; Clift, 2016). Therefore, appropriate analysis and interpretation of sedimentary records is crucial as, how and where the sediments in each basin were derived. This is because changes in sediment source also result in changes in composition and mineralogy (Collins et al., 2002; Clift, 2016). Based on this understanding, researches on sedimentary provenance started in the 19th century with the microscopic investigation of accessory minerals in recent sands. In pioneering work on sediment geochemistry, Mackenzie and Veizer (1971) studied trace elements, major elements, isotopes and petrography of clastic sediments and proposed different binary and ternary (quartz-feldspar-lithic fragments, A-CN-K) diagrams to identify the sediment provenance. Subsequently, these standard end-member models have been widely used in sediment provenance. Following their milestone, a revised A-CN-K ternary diagram (Nesbitt et al., 1996) and Upper Continental Crust (UCC) diagram (Taylor and McLennan, 1995), elemental ratios using were later developed which used bulk geochemistry for the quantitative and qualitative analysis.

Major oxide and trace elements

Major oxides are fundamental components of rocks and minerals, while trace elements are present in minute quantities. Commonly used major oxides include SiO_2, Al_2O_3, FeO, MgO, CaO, Na_2O, and K_2O, while commonly used trace elements include Ba, Sr, Zr, Cr, V, Rb, Zn, Ni, Cu, Co, Y, Nb, Li, Sc, Ga, Pb, Th, Hf, U, La, Ce, Nd, Pr, Gd, Dy, Er, Yb, Eu, Ho, Tb, Tm, and Lu The application of major and trace element geochemistry in provenance studies has been documented for all major rivers worldwide (Bhuiyan et al., 2011). Respective laboratory data are analysed based on standard models and statistical analysis (clustering, regression and principal components). Established standards compositions such as Upper Continental Crust (UCC), Post Archean Australian Shale (PAAS), N. American Shale Composite (NASC), granite etc., are also utilized as standard (Gromet et al., 1984; Taylor and McLennan, 1985). For instance, Cr, Sc, Ni, Co, V are commonly found in felsic rocks, whereas, Zr, Nb, Y, Th and U are characteristics elements of mafic rock (Condie, 1993). These elements acts as tracers to identify felsic or mafic sources. Similarly, major oxide SiO_2, TiO_2, and Al_2O_2 represent aluminosilicate phase and are typically reliable to provide information about the mineralogical composition of sand and silt fractions. However, it is important to note that grain size distribution is more accurately assessed through physical techniques such as sieving and particle size analysis. It should also be noted that using combines multiple proxies strengthen our understanding and analysis in the sediment provenance.

Chemical Index of alteration

The chemical weathering plays key role in understanding tectonic upliftment-climate-erosion interrelationship (Shao and Yang, 2012). The major oxides are used to calculate the weathering index. There are many weathering indexes researchers proposed (Price and Velbel, 2003; Shao et al., 2012). Among them, most commonly used index are CIA (Nesbitt and Young, 1982; McLennan et al., 1993; Price and Velbel, 2003) and Weathering Index of Parker (WIP) (Price and Velbel, 2003). Nesbitt and Young (1982) developed a ternary A-CN-K (Al_2O_3– (CaO^*+ Na_2O) – K_2O) diagram to quantify the chemical weathering of the sediments as well as to identify the potential source if the source information is available. Its application can be used in both felsic and mafic sources.

$$CIA= [Al_2O_3/ (Al_2O_3 +CaO^*+Na_2O+K_2O)] \times 100 \quad (1)$$

$$WIP= [2\ Na_2O/0.35+MgO/0.9+2\ K_2O/0.25+CaO^*/0.7] \times 100, \quad (2)$$

where, >0.5 represent highly weathered and <0.5 poorly weathered. Here, CaO* refers to the CaO content in the silicate fraction

The A-CN-K diagram or the ternary diagram serves as an essential geochemical tool for evaluating the degree of chemical weathering in sediments and rocks. We have selected examples from several major rivers (Table 1), sourced from existing literature, and plotted them on A-CN-K diagram. The CIA represent the molecular proportion; thus all oxide percentages were converted to molar form. The accurate data on carbonate content are often unavailable, thus to estimate the silicate CaO content, we applied an accepted approach: if the mole fraction of CaO is less than or equal to that of Na_2O, we used the CaO value directly. However, if CaO exceeds Na_2O, we assumed the moles of silicate CaO to equal Na_2O (following (McLennan, 1993; Jian et al., 2013). For comparison, we also calculated the CIA values for the UCC, NASC and PAAS (Gromet et al., 1984; McLennan, 1988; Piper and Bau, 2013). These standards offer a comprehensive context for understanding the chemical weathering processes reflected in the sediments.

The A-CN-K ternary diagrams, which depict major rivers worldwide, reveal that the majority of sediments fall within the intermediate to weak weathering zone (Fig. 1). Researchers have determined that in fluvial system sediments undergo both physical and chemical weathering processes during erosion and transport. For example, in mountainous regions like the Andes or the Himalayas, sediments are initially subjected to intense physical weathering from high current river flows, but they aren't altered chemically. As these sediments travel downstream into warmer, more humid environments, such as the Amazon, Mekong or Congo Basin, chemical weathering becomes more dominant. Some, such as those from the Congo, Rio and Niger rivers show more stable constituents such as Al^{3+}, Ti^{2+} and removal of cation like Na^+, K^+ indicating significant chemical weathering influenced by the prevailing hot and humid climate (Mondal et al., 2012). Rivers, including the Amazon, Mississippi, Yangtze etc, exhibit intermediate weathering characteristics with an abundance of muscovite and biotite. The sediments of the Indus, Brahmaputra, and Ganga rivers show lower CIA values, which suggest that physical weathering predominates over chemical weathering. This is likely due to the tectonically active nature of the Himalayan region (Maharana et al., 2018). The average CIA values for Upper Continental Crust (UCC) and unaltered granite rocks are approximately 46.5 and 50.8, respectively and the sediments tend to weather above the Upper Continental Crust (UCC), with variability ranging from low to high (Table 1, Fig. 1). The Himalayan rivers, such as the Indus, Brahmaputra, and Ganga, depict a very close resemblance to UCC unlike, most of the rivers whose compositions closely resemble those of the North American Shale Composite (NASC) and Post Archean Australian Shale (PAAS). The chemical weathering advances the formation of clay minerals occurs as feldspars and other minerals undergo alteration, causing the bulk composition to shift upwards along the expected weathering trend.

Table 1: Major concentration and CIA of major rivers (Galy, 2001; Singh, 2009; Wu et al., 2012; Bayon et al., 2015)

River	Weight percentage						CIA
	Al_2O_3	CaO	K_2O	Na_2O	P_2O_5	LOI	
Congo	22.13	0.19	1.42	0.03	1.04	12.40	91.97
Niger	22.56	0.56	1.61	0.13	1.09	10.98	88.35
Rio Caroni	22.44	0.38	2.42	0.17	1.27	9.43	86.21
Murray	19.35	0.23	2.26	0.28	0.88	9.79	85.34
Chao Phraya	12.46	0.34	1.96	0.56	0.90	3.83	77.29
Amazon	17.78	0.46	3.03	0.84	0.13	5.11	76.38
Red River	14.61	0.34	2.84	0.68	0.94	9.23	75.23
Mekong	10.00	0.31	1.50	0.70	0.93	3.11	74.97
MacKenzie	14.23	0.44	2.71	0.63	0.89	5.41	74.90
Loire	17.37	0.86	2.96	0.76	1.06	5.15	74.27
Mississippi	13.03	0.54	2.56	0.90	0.82	4.74	71.34
Orinoco	7.68	0.40	1.32	0.65	1.02	1.85	70.42
Vistula	13.15	0.48	3.34	0.67	0.77	5.04	70.17
Danube	10.97	0.97	1.89	0.53	0.58	32.85	70.09
PAAS	**18.9**	**1.3**	**3.7**	**1.2**	**0.16**	**n**	**69.38**
Yangtze	15.69	0.84	3.11	1.41	0.95	3.97	68.51
Northern Dvina	14.43	1.06	2.79	1.29	0.77	3.10	67.12
Volga	10.95	0.93	2.16	1.43	0.86	4.22	63.18
Don	8.06	0.58	1.81	1.28	0.58	2.06	61.16
Fraser	14.56	2.41	1.95	2.33	0.90	7.72	58.51
Yellow River	11.27	1.29	2.19	2.18	0.69	2.38	57.58
NASC	**16.9**	**3.63**	**3.97**	**1.14**	**0.13**	**n**	**56.95**
Seine	6.20	0.61	1.71	1.06	0.69	8.33	56.86
Rhine	9.83	1.96	2.15	1.13	0.66	3.43	55.92
Nile	12.27	3.21	2.26	0.88	1.10	7.68	55.77
Brahmaputra River	13.01	2.44	2.69	1.89	0.20	4.18	55.45
Ganga River	11.93	2.11	1.33	2.63	0.15	4.91	55.40
Amu Darya	12.17	2.33	1.82	2.43	0.89	2.38	54.39
Ume	13.97	2.23	2.96	2.74	0.78	2.72	54.28
SINO granite	13.33	1.09	4.87	3.54	0.13	0.94	50.48
Indus	9.66	3.04	2.18	0.99	0.12	5.41	50.39
UCC	**15.2**	**4.2**	**3.4**	**3.9**	**n**	**n**	**46.15**

Remarks: Al_2O_3 *(moles) =* Al_2O_3 *(wt%) / 101.96128 (g/mol); CaO (moles) = CaO (wt%) / 56.0774 (g/mol);* Na_2O *(moles) =* Na_2O *(wt%) / 61.97894 (g/mol);* K_2O *(moles) =* K_2O *(wt%) / 94.19600 (g/mol);* P_2O_5 *(moles) =* P_2O_5 *(wt%) / 141.9445 (g/mol)*

Elemental ratio and Inter-element relationship

A study of river sediment and bed rock suggests that provenance analysis can be improved using trace elements and their elemental ratios such as La/Co, Th/Sc, Ba/Co , La/Sc and Ba/Sc (Cullers et al., 1988). The most of the trace elements ratio are used to identify the source is mafic or felsic. The Co/ Th versus La/Sc diagram are used to distinguish felsic and mafic provenance (Wu et al., 2012). The presence of chromium (Cr) and nickel (Ni) in sediment samples can indicate the contribution of ultramafic rocks. Other ratios, such as Th/Cr vs La/Cr, Th/Sc vs La/Sc, La/Th vs Hf, Cr/V vs Y/Ni, and Co/ Th vs La/Sc, aid in distinguishing between different sources including felsic, intermediate, and mafic rocks.

Binary plots of major elemental ratio (SiO_2, FeO, TiO_2, MgO, Na_2O, K_2O, Al_2O_3) compared with source rock information to find out the dominance. Pettijohn (1963) developed log (SiO_2/ Al_2O_3) Vs log (Na_2O/ K_2O) to classify the maturity of the sediments. The SiO_2/ Al_2O_3 and Al_2O_3 /Na_2O ratio is mostly used for the rough grain size proxy and the binary diagram of major elements analysis is done to understand the sediment maturity and weathering (Singh, 2010). The Al_2O_3/TiO_2 ratio is commonly used characterised feature to infer the composition of the igneous type of source rock. Further, the relationship between the TiO_2 to Zr, Cr and SiO_2 can also trace the parent rocks' compositions. The inter-elemental relationship or the bi-plot of two elemental ratio and immobile elements is expected to have tie line passing through the sources and different types of sediments (Singh, 2009). It is assumed that as the source is same therefore their tie-line should pass through source.

DISCUSSION

The qualitative and quantitative assessment of element concentrations and ratios provide valuable insights into the source composition. The major oxide can give idea of both weathering pattern and source rock type. This geochemical information offers clues about the weathering conditions and processes that transformed source rocks into dissolved substances and new minerals. Moreover, the geochemical composition helps in determining the origin or provenance of sedimentary materials and understanding climate processes. Such as, concentration of SiO_2, TiO_3, and Al_2O_3 in sediment indicate the lithology of the source rock and serves as a reference element for comparisons against recognized baselines (Singh et al., 2005).

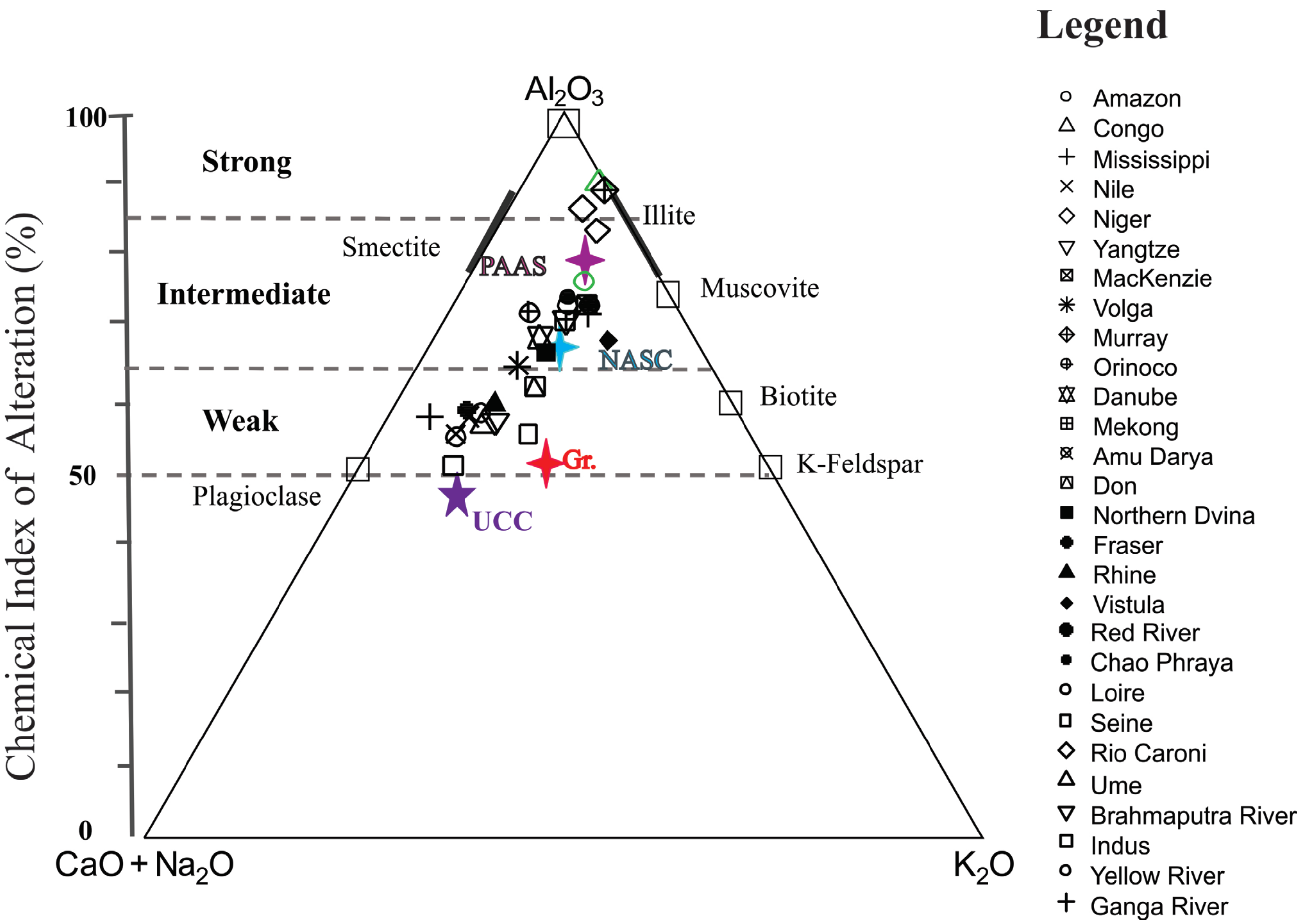

Fig. 1. A-CN-K diagram (Nesbitt and Young, 1982) UCC value (Taylor and McLennan, 1985; McLennan, 1988; McLennan, 2001), PAAS (McLennan et al., 1980; Singh and Rajamani, 2001), NASC (Gromet et al., 1984; Piper and Bau, 2013), Granite (Nagudi et al., 2003), Major river composition (Singh, 2009; Wu et al, 2012; Bayon et al., 2015).

The A-CN-K diagram effectively captures the intensity of chemical weathering, as it highlights the depletion of mobile elements (such as Ca, Na, and K) while preserving relatively immobile elements like Al. The CN–K line trend indicates chemical sorting. A greater scatter of samples on the A–CN–K diagram suggests a higher degree of feldspar sorting (Nesbitt and Young, 1982). By plotting sediment samples from various river systems or geological environments, this diagram helps distinguish between sediment sources that have experienced different degrees of weathering. Its strength lies in its ability to evaluate the extent of chemical weathering that sediments have undergone during transport from their source to depositional areas, making it a valuable tool for interpreting the geochemical history of river sediments. A-CN-K diagram combined with other geochemical data, such as elemental ratios (e.g., Th/Sc, La/Co), can understand the geochemical signature of the source, even after long-distance transport. However, the diagram does have limitations, particularly in capturing the complexities of sedimentary processes in environments affected by secondary alterations. To overcome these limitations, combining them with elemental ratio analysis, inter-element relationships, or isotopic studies can provide a more thorough understanding of sedimentary processes.

Use of trace elements and elemental ratio improve the source discrimination (Cullers et al., 1988). They also gives insights into the granitoids and acidic to intermediate-acidic volcanic source rocks (Singh et al., 2005). The Different types of igneous rocks exhibit different Al_2O_3/TiO_2 ratios, providing information of the nature of the rock contributing to the sediment (Hayashi et al., 1997). The ratios of incompatible to compatible element ratios, such as Th/Co and Th/Sc, enables identification of source terrains and magma differentiation signatures. These ratios, when combined with biplot analyses, offer a comprehensive understanding of sediment provenance. Strong correlations between elements indicate a common origin, while linear trends suggest sorting effects (Singh et al., 2005; Mondal et al., 2012). The grain size distribution (GSD), when coupled with geochemistry, can sometimes provide additional insights into weathering and transport mechanisms. However, for a comprehensive approach in recent sediments, it is advisable to consider a broad range of GSD (Singh, 2009; Bhuiyan et al., 2011). Recent research has highlighted the limitations of interpretations based solely on similar geotectonic properties, underscoring the importance of grain size distribution and multiple geochemical proxies to enhance the quality of analysis (Liu et al., 2016).

Studies based on major and trace elements in sediments provenance are challenged in recent decades and U–Pb geochronology and Sr-Nd-isotopes have been the dominant tools in the investigations of sediment provenance. The reason may be their ability to provide insights into erosion and transport processes (Clift et al., 2006; He et al., 2014). However, their cost constraints limit the number of samples that can be analysed, thus restricting the depth of inspection into provenance and potentially introducing bias into the results. In addition, their ability to represent as distinct populations may be unlikely (Mapes et al., 2004; Guo et al., 2020). On the other hand, the relatively low cost of bulk geochemical composition analysis allows researchers to analyse large datasets. This is a significant advantage, as it enables more comprehensive analysis and additionally offers information on the weathering conditions of the sediments potentially leading to more robust conclusions. In recent years, with advances in statistical analysis using different mixing models, the recognition of potential tracers and quantification of sources contribution has improved to optimum.

CONCLUSIONS

The major oxides and trace elements present in sediments provide valuable insights into their provenance, despite undergoing processes of transportation and deposition accompanied by chemical and physical weathering. Utilizing larger datasets on source geochemistry information enhances the analysis and interpretation of river sediments provenance. Geochemical indices such as A-CN-K diagram and elemental ratio are a fundamental tool for evaluating sediment provenance and weathering intensity in recent river sediments. It's important to recognize that physical and chemical weathering can alter the environment and complicate the process of identifying provenance. Additionally, there may be secondary modifications during river routing, further complicating the identification process. Though geochemical indices offer valuable insights into the geochemical processes governing sediment formation and transport, its limitations requires the use of complementary methodologies for a more accurate and holistic analysis. As instruments and methods advance, it's essential to refine and update geochemical methodologies to reconstruct the sediment route path to the source. In recent times, the use of statistical methods has offered more precise results.

Integrating multiple methods enhances understanding and analysis. For example, analysing elemental concentrations and ratios, studying tracer signatures, utilizing statistical and mathematical modelling tools and combining geochemical indices with geochronological or isotopes datasets enhances the interpretation of sediment sources. By integrating these methods and collaborating with specialists from different disciplines, we can accurately trace the origins and transportation of sedimentary materials and gain a better understanding of their provenance. Therefore, employing more than one geochemical approaches is recommended before drawing conclusions on probable sediment sources. It's important to consider various factors influencing sediment composition and utilize a range of methodologies to accurately determine their origins. . In the future, further development and refinement of these techniques will be essential to deepen our knowledge of sediment provenance.

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