

## Article

# Multiproxy Approach for Identification of Sequence Stratigraphic Elements: Implications on Continental Sequence Stratigraphy

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## ABSTRACT

The applications of sequence stratigraphy are mostly limited to areas in the vicinity of the shoreline. However, due to lack of distinct geological markers, its application to fine-grained continental and deep-marine sediments remains restricted. Hence a multi-proxy approach that integrates sedimentological, mineralogical, and chemostratigraphic proxies from both marine and continental successions is used with a focus on continental domains. The shifting trends of accommodation to sediment supply are comparable to the shifting trends of several proxies, which indicates the utility of such proxies in constraining the sequence stratigraphic architecture. Clay mineral assemblages indicate weathering and paleoclimatic conditions, while paleosols reflect subaerial exposure and landscape stability. Decreasing Ti/Al, Zr/Al and Si/Al ratios marks shift from continental to marine influence. In case of the lacustrine settings or glacial lakes, periodic paleoredox fluctuations and glacial-cycles can be constrained using Ti/Zr ratios. Upstream, high sediment supply leads to depleted Mo and V, while downstream, anoxic conditions promote organic matter preservation. T/SF trends distinguish upstream from downstream river segments. Similarly varying trends of the T/SF are utilized to interpret the upstream and downstream portions of a river system. However, several limitations are often associated with using these proxies, which have to be accounted for. The present review work documents the utility, applicability and limitations of such proxies using several case studies from marine and transitional settings and proposes their applicability in continental domain. By documenting changes in sediment supply, accommodation space, and water chemistry, this multi-proxy technique enables the reconstruction of transgressive–regressive cycles and systems tracts in fine-grained deposits, as observed in several case studies. The work demonstrates that the combination of all these proxies significantly enhances the reliability of sequence stratigraphic interpretations, despite intrinsic limitations.

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## Research Highlights

- Integrated Multiproxy approach to improve interpretations for high-resolution sequence stratigraphy.
- Clay mineral ratios as a proxy to delineate continental systems tracts.
- TSF trends distinguish HAST and LAST.
- Elemental ratios track continental versus marine processes.
- Redox proxies utilized for identification of spatial and temporal depositional shifts.

## 1. Introduction

Sequence stratigraphy is a useful tool to reconstruct palaeogeography and also to predict distribution of mineral resources. Such time-transgressive application of sequence stratigraphy makes it a useful tool in oil industries. However, there are certain limitations of using sequence stratigraphy in a stand-alone manner. Hence, other branches of stratigraphy are often used in conjunction with conventional sequence stratigraphy such as chemostratigraphy or isotope geochemistry [1–10] to achieve high-resolution correlations and identification of sequence stratigraphic elements. Chemostratigraphic analysis of fine-grained dominated sedimentary successions enables better precision of reconstructing the subtle changes in shoreline movement across a basin [11–13]. Multiple 4th or 5th order sequences may be identified within a major 3rd order basin scale sequence using chemostratigraphic datasets [12, 13]. The elemental concentration of certain elements varies with time and tracing the changes in the concentration of these elements within the stratigraphic record enables calibration of stratigraphic surfaces across a basin [14]. However, multiple factors such as the tectonism, climatic changes, redox potential, oceanographic chemistry, abiotic and biotic components in the system may have secondary influence on the concentration of such elements. Therefore, a careful analysis of the utility and limitations of these chemostratigraphic elements can divide and correlate apparently uniform fine-grained rock successions and help identify sequence stratigraphic elements. Dominantly, the concepts of sequence stratigraphy are mostly applicable for changes taking place due to shoreline movement [15–19]. Several case studies from the marine to transitional areas are available which relies on utilizing different geochemical proxies to identify the systems tracts. However, areas unaffected by shoreline movement such as the upstream continental part or deeper marine part are relatively less studied in a sequence stratigraphic framework [19]. Due to the poor preservation potential or inaccessibility in such areas, the development and implementation of multiple proxies to be used in association with the sequence stratigraphic concepts become necessary. The sequence stratigraphic architecture within a fluvial setting is often identified based on the changing channel to overbank ratios [18, 19]. Thus, the present review work identifies this gap based on lit-

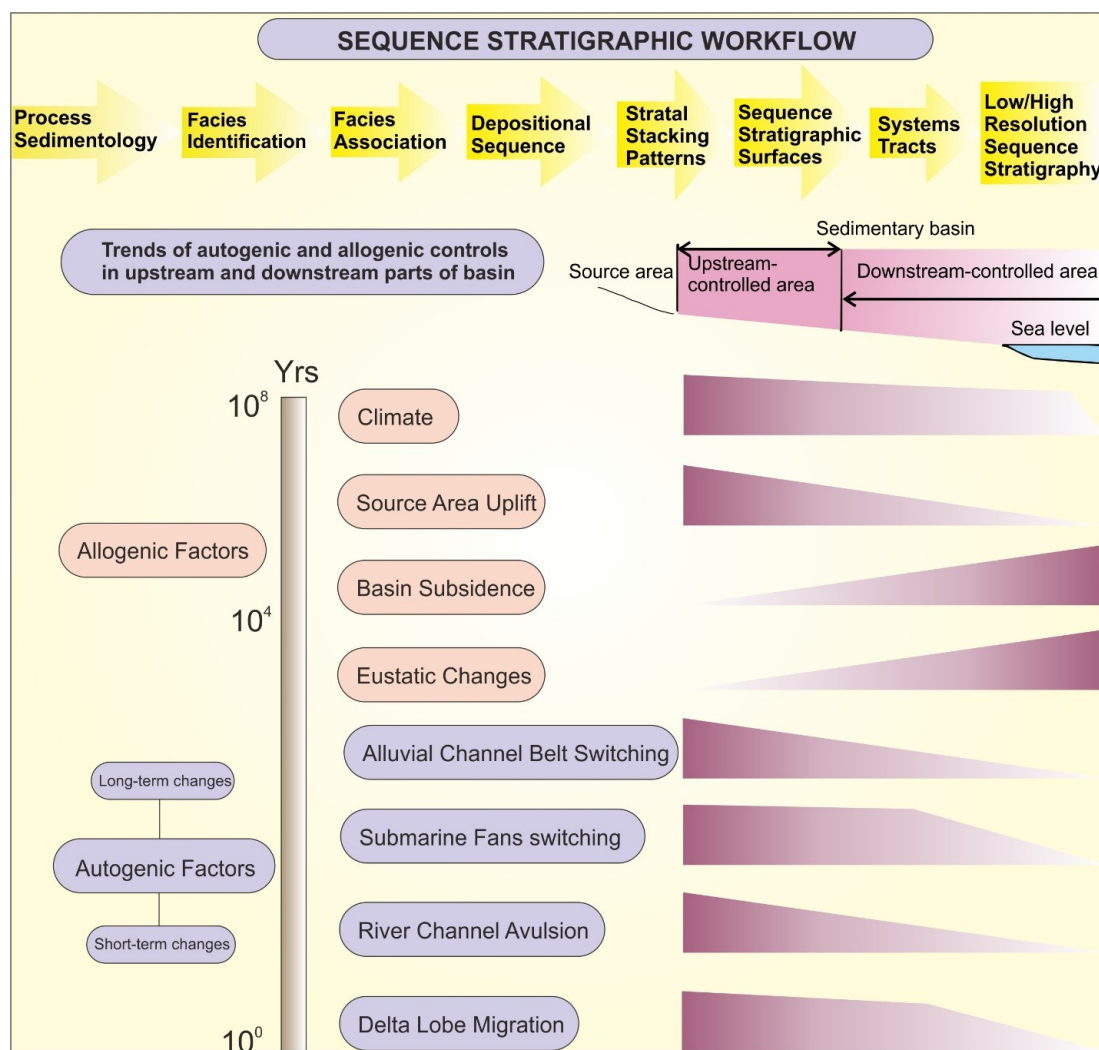
erature review and aims to shed light on the utility of integrating sequence stratigraphy with other mineralogical and geochemical proxies in the upstream-controlled continental systems. For high-resolution correlation and systems tracts identification in continental environments, where autogenic controls dominate over allogenic controls, understanding the elemental and mineralogical proxies might be useful in determining sequence boundaries, especially when it comes to their consistency in time and space across a basin. The changing trends of different proxies such as the ratio of clay minerals within the paleosols, detrital elemental ratios, redox-sensitive elemental ratios, or the thickness to sandstone fraction ratio (TSF) are applied experimentally in different scenarios by several authors to identify the sequence stratigraphic elements in parasequences ( $10^4$ – $10^5$  years sequences) [13, 20–26]. The integrated application of the proxies to a sequence stratigraphic framework helps improve the resolution of the study by identifying the lower order sequences. The present work reviews such scenarios to identify the controls on the different proxies that apply to in a continental setting.

### 1.1. Sequence Stratigraphy

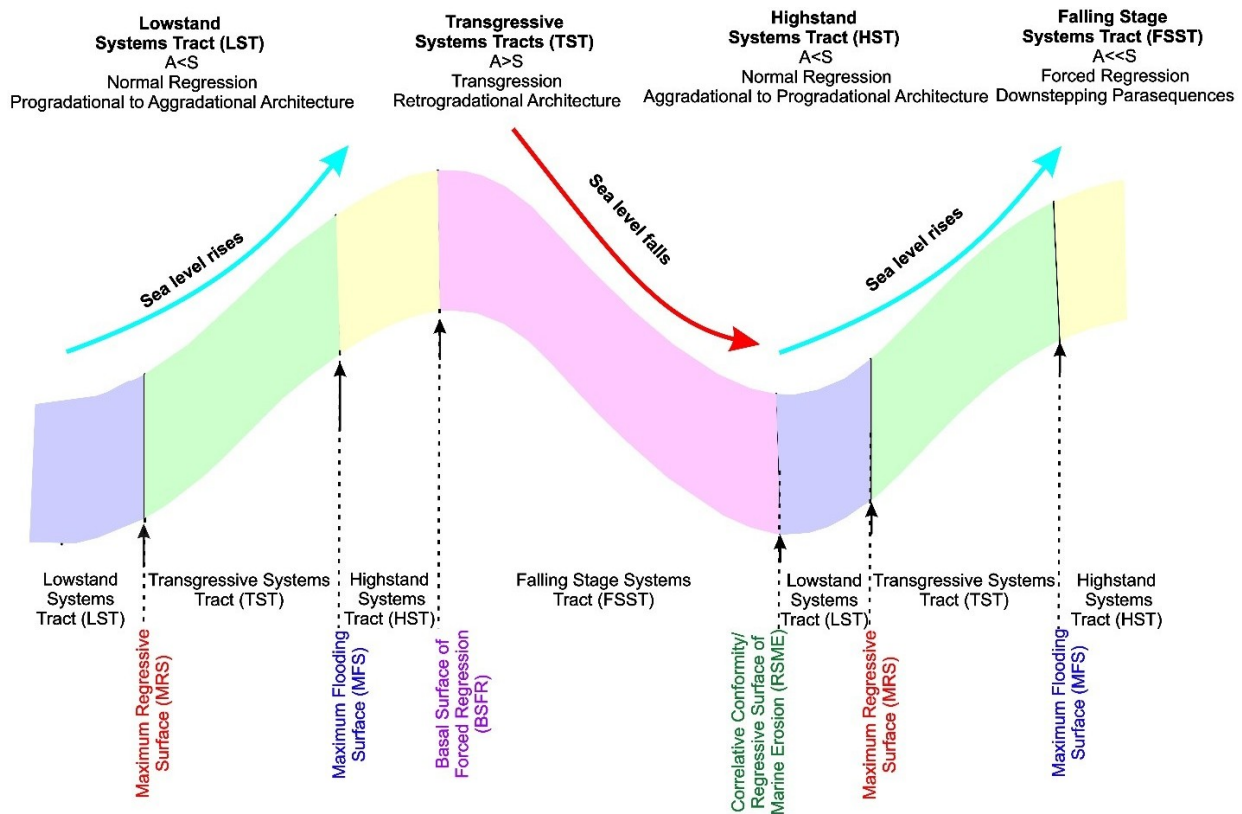
The repetitive arrangement of facies and their related stratal geometry as evident in successions of sedimentary rocks are examined using sequence stratigraphic analysis. These investigations involve identification of stratal stacking patterns, systems tracts and sequence boundaries that occur within a specific time span [17–19]. A systematic workflow is followed for the identification of the sequence stratigraphic elements at seismic, well log, core and outcrop scale of observation (Figure 1). Stratal stacking patterns aid in determining the sequence of sediment deposition while also aid in identification of the stratal geometry and architecture [27]. These patterns indicate sedimentation within a basin, which is determined by the balance of accommodation space and sediment supply, which in turn, is regulated by sea-level fluctuations, tectonics, and climate (Figures 1 and 2). Sequence stratigraphic surfaces separate various systems tracts, indicating systematic variations in stacking patterns. While commonly associated with coastal movements, similar patterns can also occur in continental or deep-marine environments, where they can be detected using facies architecture, paleosols, and basin-scale trends [14, 18, 19].

Several outcrop analogue studies and sub-surface geophysical studies employ the concepts of sequence stratigraphy to identify the sequence elements in a shoreline-influenced settings [18]. The changing nature of the stratal stacking patterns combined with the presence of different sequence boundaries such as Subaerial Unconformity (SU), Maximum Flooding Surface (MFS), Basal Surface of Forced Regression (BSFR), Regressive Surface of Marine Erosion (RSME), Maximum Regressive Surface (MRS), and Correlative Conformity (CC), help identify the different systems tracts such as Highstand Systems Tracts (HST), Falling Stage Systems Tracts (FSST), Lowstand Systems Tracts (LST) and Transgressive Systems Tracts (TST) (Figure 2). However, areas further away from the shoreline, where the shoreline movement does not influence the stratal stacking pattern instead autogenic processes play the dominant role in governing the stratal architecture. Systems tracts such as High Amalgamation Systems Tracts (HAST) and Low

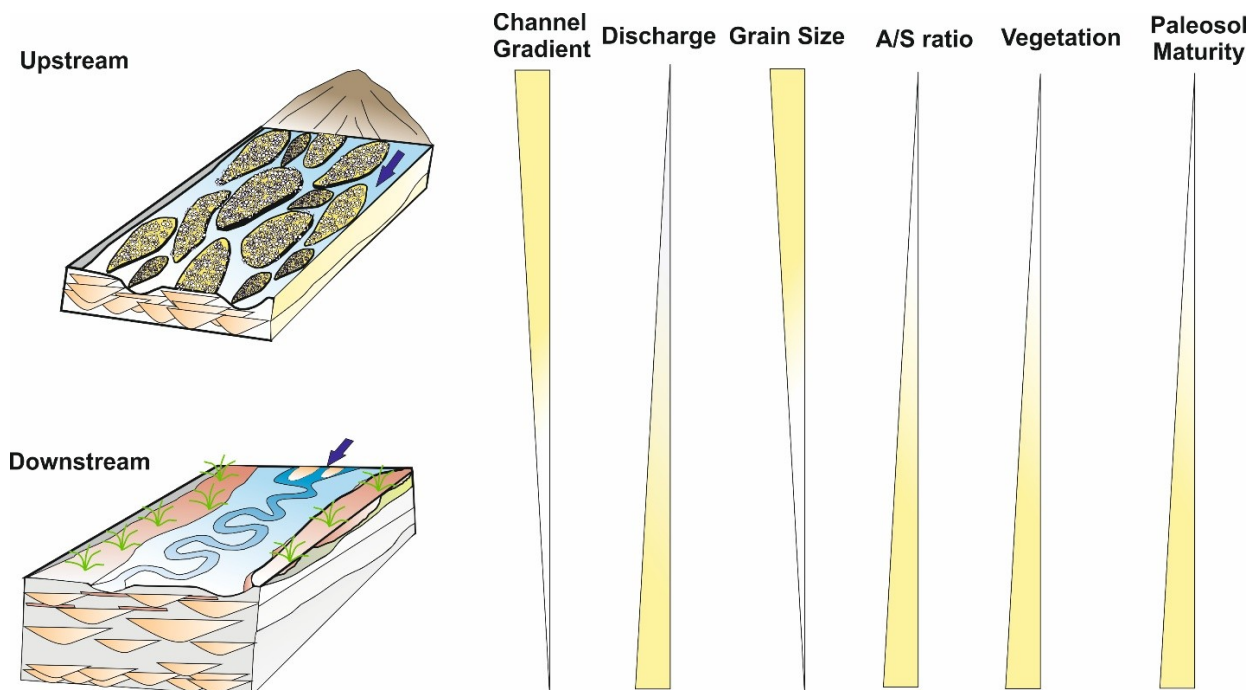
Amalgamation Systems Tracts (LAST) develop within the continental systems. In classical sequence stratigraphic models the lateral continuity of the sequence stratigraphic surfaces is traced in different scales to identify the controls by allogenic (long-term processes) and autogenic (long and short-term processes) (Figure 1). Different controlling factors such as river channel gradient, fluvial discharge, grain size, vegetation varies along the downstream direction, which in turn controls the river morphology (Figure 3). Similarly, several allogenic processes such as climate, and tectonic movement also plays a vital role in controlling the morphology of the river system. Therefore, disentangling the autogenic factors from allogenic factors becomes essential to develop the sequence stratigraphic architecture in continental settings unaffected by shoreline-movement. For such precise distinction multiproxy analysis is most suitable for its utility in identification of the superimposing regional vs local effects on sedimentation pattern.



**Figure 1.** Schematic diagram showing sequence stratigraphic workflow and controls of autogenic and allogenic factors in upstream and downstream controlled settings. The figure depicts the upstream and downstream influences of possible autogenic and allogenic factors in a sedimentary basin. Some autogenic factors are long-term ( $>10^3$  years) and some are short-term ( $10^0-10^3$  years). Frequent autogenic shadowing can take place over the allogenic forcings and vice versa.



**Figure 2.** Schematic diagram showing the base level change curve with corresponding systems tracts, and sequence boundaries. The curve depicts a complete cycle of change in transgression and regression (modified from [28]).



**Figure 3.** Schematic diagram showing the variations in the parameters influencing the upstream and downstream parts of a river system, specially within different fluvial morphological styles, showing the changing trends in fluvial discharge, channel gradient, sinuosity, grain size, paleosol maturity, vegetation and associated accommodation to sediment supply ratio. The figure gives an idea about how the A/S change can be utilized in association with other parameters to identify different fluvial morphological style within the rock record.

## 1.2. Chemostratigraphy

In the mid-20th century, the researchers recognized that sediments preserve different chemical signatures that reflect the conditions prevalent during the deposition of the sediments as well as the provenance [1]. In the 1960s–1980s, development of modern geochemical tools took place such as trace elemental and isotopic analysis. Variations in marine isotopic ratios were utilized for global stratigraphic correlation [14]. By the 1990s, the demand of chemostratigraphic tools in petroleum geology also increased. Along with it, it was used in basin analysis to differentiate and link sedimentary successions that seemed homogeneous [29]. Over 2000s and 2010s multiple elements and isotopic systems expanded such as use of C, Nd, Sr, and Zn, along with usage of chemostratigraphy in body fossils [30]. Following the work of [31], it was proposed that chemostratigraphic tools can be utilized for a separate stratigraphic classification technique [32, 33]. New studies suggested different terminology and techniques to categorize and correlate stratigraphic successions using geochemical attributes [31]. However, correlation in any fine-grained sedimentary successions is a challenging task as macroscale sedimentological variation is often more subtle in mudstone in comparison to coarse-grained sedimentary successions [34, 35]. Hence, an integrated lithostratigraphic and chemostratigraphic dataset is applied in many basins [31–35]. In this review, we present several such examples of integrated analysis, which are based on multiproxy approach using XRD, XRF or ICPMS datasets. This paper analyzes the utility of such datasets and also identifies the limitations pertaining to the role of post-depositional modifications within a basin. Understanding how post-depositional processes such as diagenesis or alteration of minerals impact the changing trends in the chemostratigraphic framework enables correct interpretation of the autogenic and allogenic processes. The post-depositional changes taking place within the minerals alter the bulk chemistry of the rocks and thus can impact the trends of the major oxides. Thus, choosing the less mobile, chemically inert trace elements may provide a more reliable dataset for establishing the changing the syn-depositional trends. The degree of weathering and post-depositional processes are influenced by climate and redox conditions, which change the geochemical signatures of sediments deposited downstream in the basin without necessarily altering their provenance. Understanding the limitations and usage of the different geochemical proxies will enhance the resolution of sequence stratigraphic architecture. To understand the utility and the limitations of such geochemical proxies several case studies are studied, that showcases identification of sequence stratigraphic elements within a chemostratigraphic framework.

### 1.2.1. Horn River Group, Northwest Territories, Canada

At Mountain River, a nearly complete exposure of Horn River Group was studied. This unit captures local ma-

rine conditions from the Middle to Late Devonian. This unit consist of three Formations, namely; Hare Indian, Canol and Imperial Formation [36]. Several members such as Bluefish, Francis Creek, Powell Creek Members form the sub-division of Hare Indian Formation, while the Vermillion Creek, Dodo Canyon Members form the sub-division of the Canol Formation [36]. The Bluefish Member at the base displays high Ti and low Al concentrations, and elevated EF(V) and EF(Mo) In the upper part of the Hare Indian Formation, these trends shift towards higher Al and lower Si, EF(V), and EF(Mo). Also, Al continues to increase towards the unsampled Bell Creek interval. Ca is higher in Lower Bluefish Member but shows variable trend throughout the succession. The Canol and Imperial Formations are characterized by similar but opposite trends of Al and Si. Ca is higher at the base of Canol Formation as compared to the Upper Canol and Imperial Formations. Also, EF (Mo) and EF (V) values are high and most of the values coincide but at certain intervals the values do not coincide [36]. Multiple chemostratigraphic signatures are combined to identify the boundaries such as MFS, MRS, and Unconformity between the different systems tracts such as TST, LST and HST in the case study discussed above [36]. Using such trends the sequence stratigraphic surfaces are marked in fine-grained sediments where standalone facies analysis restricts the application of sequence stratigraphy.

### 1.2.2. Woodford Shale Member, Arkoma Basin, USA

A pioneer study in application of chemostratigraphic proxies to sequence stratigraphic framework was done taking two sections within Woodford shale member of Upper Devonian in Arkoma Basin, USA [11, 12]. A third-order TST was identified in this case study using trace elemental concentration within the Woodford Shales. A decreasing trend of terrestrially supplied elements such as Ti, Zr, K, Al and redox sensitive elements such as Mo and V was observed. Such trends were interpreted to reflect decreasing basin restriction conditions. An increase in the biogenic silica proportion was interpreted using the increasing Si/Al ratio. Horizons with phosphatic nodules showed peaks in V concentration, which is interpreted to be due to presence of the nodules instead of reduced circulation [12]. Higher order sequences were identified by [12] using decreasing trends of Ti and Z within the sequence. Comparative analysis of the trends of Ti and Zr versus K and Al were studied by [11, 12] to identify superimposed fourth-order sequences on third-order trends within the Woodford Shale. Such analysis showed remarkable similarity, thus characterizing regressive intervals with increasing Ti, Zr, K, and Al. However, the trends decline strongly for elements associated with heavy minerals than with the clay minerals, establishing a clear relation with the textural modifications taking place within the shale sequence [12]. The increasing trends of Ti, Zr, K and Al, with decreasing Si/Al ratio and low Mo and V suggested a high stand condition [11, 12]. Using the geochemical signatures [12] were able to interpret the enhanced circulation between the then Paleotethys and the basin. Lower levels of redox sensitive

Mo and V within the HST of the Woodford Shale Member pointed to this enhanced circulation.

### 1.2.3. Haynesville Formation, Texas and Louisiana

Higher frequency T-R cycles superimposed on lower-frequency T-R cycles were identified by [34] in the Haynesville Formation. Several parameters such as the combination of the major oxides such as  $\text{Al}_2\text{O}_3$ ,  $\text{TiO}_2$ ,  $\text{Na}_2\text{O}$ , and  $\text{K}_2\text{O}$  were utilized to identify the occurrence of such high-frequency cycles. The net sum of the major oxides were used in association with other proxies to establish a chronostratigraphic framework in the Haynesville Formation. Declining trends of Zr/Nb and  $\text{SiO}_2/\text{Al}_2\text{O}_3$  were utilized to identify the lower-rank sequences. The cross-plots of Zr/Nb and  $\text{SiO}_2/\text{Al}_2\text{O}_3$  follows similar trends, which pointed to the occurrence of biogenic silica poor silt sized sediments in the Haynesville Formation [34]. Further, the interpretation is supported by the Si–Zr cross plot showing positive trend for the Haynesville Formation [34]. Similar trends in the same localities were identified by [37], emphasising on the observation that V enrichment decreases within a TST formed during transgression. Both [34, 37] showed the declining trends of the Zr/Nb ratio and Si/Al ratio paralleled the development of TST, which was identified by a fining-upward grain size trend. Several Regressive Systems Tracts (RST) were identified within the Haynesville Formation using the increasing trends of Zr/Nb and Si/Al and V concentration from bottom to top of the succession [34, 37]. The changing trends in the Zr/Nb and Si/Al are interpreted to be controlled by variations in the grain size. The sequence stratigraphic surfaces such as Maximum Flooding Surface (MFS) and Maximum Regressive Surface (MRS) were identified by the declining and increasing trends of Zr/Nb and V concentration respectively. These declining trends of Zr/Nb coincide with the low terrigenous input and marks the MFS within the Haynesville Formation [34, 37]. The increasing trend of Zr/Nb and increase in the terrigenous input identified by the peak summation of Al, K, Na, Ti was utilized to identify the MRS within the Haynesville Formation [34, 37]. However, the V concentration trends were used to identify the MFS across which enrichment of V decreased towards the top part of the succession. The Highstand systems tracts (HST) was identified based on the higher Al concentration from lower Transgressive Systems Tracts (TST) of the Haynesville Formation [38]. Similarly, Si/Al, Ti/Al Zr/Al showed elevated concentration compared to HST within the TST. The increased concentration of Ti and Zr pointed to the euxinic nature of the bottom water. However, in these case studies the limitations associated with the proxies are not discussed in detail.

Hence, through such case studies the significant issues such as proxy uncertainties, limitations of using the proxy due to overprinting by autogenic and allogenic factors and the applicability of the proxies at different scales can be scrutinized. The requirement for fairly continuous measurements from core or outcrop intervals in order to identify surfaces is considered as another drawback re-

lated to the utilization of chemostratigraphic datasets for sequence stratigraphic interpretation [39]. To investigate such factors understanding the mechanism in which the proxies behave in a sedimentary system becomes vital. Thus, based on the case studies the present work reviews the different mechanisms associated with the enrichment and depletion of different proxies. Also, using the case studies, which are mostly related with transitional and marine sedimentary systems, as analogues, the present review work provides a synthesis on the applicability of the proxies in developing an integrated sequence stratigraphic-chemostratigraphic framework in continental settings. Several other proxies are also analyzed alongside which are much abundant in a continental setting, to verify its applicability in upstream controlled continental settings.

## 2. Paleosols and Clay Minerals

Subaerial unconformities are prominent features within the continental settings. Such surfaces are seldom used for reconstruction of paleoenvironmental conditions, palaeogeographic and sequence stratigraphic analysis of the basin. Associated with such subaerially exposed surfaces, the paleosols are the relict soil developed over fine-grained sediments due to pedogenic processes [40–42]. Such paleosols have significant applications in the identification of the autogenic and allogenic process of sedimentation within the continental part of a basin. Thus, the paleosols have local as well as basin-wide implications that can be applied to sequence stratigraphy. Different criteria have evolved over time to describe paleosols, which is dominantly found within the continental settings [43–46]. The maturity of the paleosols is also studied and correlated to the changing climatic conditions as well as the morphology of the river system. Such correlations also bring out the relations between the net accommodation space generation and sediment supply within a basin. The degree of development of soil profile in the geological past indicated the degree of paleosol maturity. It is essentially the measure of pedogenic intensity, duration and stability of the land. Climate is the most important controlling factor of the paleosol development and modification. Other factors such as time, parent material, topography, vegetation, organisms all play a critical role in the development of paleosol [47, 48]. The occurrence of humid climate results in formation of deep, well-developed profiles. Intense chemical weathering takes place, with strong removal of bases such as Ca, Mg, Na and K. Development of lateritic soil horizon can also be observed under such climatic conditions [49, 50]. Similarly, the occurrence of arid climatic conditions also leads to the development of calcrete, silcrete, Ferricrete horizons depending on the availability of different cations in the system. Thus, different paleosols indicating strong illuviation and higher rates of evaporation than precipitation can be used to identify paleoclimatic conditions. Such evidence points to a warm tropical humid or monsoonal climatic conditions and a mature paleosol (Table 1) [42]. Similarly, the occurrence of the arid climatic conditions can be marked by the presence of limited leach-

ing within the soil profile, leading to the development of calcrete horizons (Table 1) [40, 42, 51]. Such evidence points to limited rainfall and dry climatic conditions in the area and the paleosols are moderately mature in nature. In the polar regions where, cold climatic conditions persist slow chemical weathering takes place within the soil profile with permafrost features visible (Table 1). Along with the climate, time as well plays a crucial role in the maturity of the paleosol. Longer the existence of a stable surface higher will be the maturity of the paleosol. Shorter exposure and rapid burial lead to the development of immature paleosol. Thus, a cold, dry or rapidly changing climatic conditions produced immature paleosol, while warm, wet and stable environmental conditions produce mature paleosols.

A standard classification of paleosols based on six pedogenic features: organic matter content, redox conditions, horizonation, illuviation of insoluble materials, *in situ* mineral alteration and accumulation is most widely recognized. Earlier paleosols were divided into nine different orders, four of which were borrowed from Soil Taxonomy and five were newly presented [43]. However, after several modifications [46] developed a system of classification of buried paleosols modified from the Modern Soil Taxonomy System selecting only those properties that can be measured, described and interpreted from geochemical data, field descriptions and thin sections. One of such intriguing data set is provided by the clay minerals within the paleosols.

The clay minerals found in paleosols are used for identification of the paleoclimatic conditions in the basin [52–54]. The clay mineral ratios in paleosols [55] and clay successions [24] are thus used to investigate the paleoclimatic conditions (Table 2), especially the hyperthermal events. The Paleocene-Eocene Thermal Maxima (PETM), a major hyperthermal event, identified by enhanced seasonal precipitation [56–58] with intervals of dryness or wetness [59]. Kaolinite forms due to intense chemical weathering of feldspar in humid tropical climate with high precipitation, whereas, muscovite, primarily persists as detrital mineral inherited from source rocks in cooler, drier conditions. (Table 2) [60]. Hence, the Kaolinite/Muscovite ratio is used to indicate the cyclic pattern of paleoprecipitation and paleotemperature (Table 2), correlating them with the short lived hyperthermal events in the Paleogene [55, 60]. However, precautions must be exercised while using the ratio as local factors may influence the occur-

rence of muscovite and kaolinite in the system. Similarly, the Kaolinite/Illite+Chlorite ratio signifies a changing paleoclimatic condition (Table 2) prevalent during Mid Miocene Climatic Optimum (MMCO) [24]. The analysis of clay mineral suggested high Kaolinite/ Illite+Chlorite ratio along with high Kaolinite content, lower Chlorite and Illite contents confirming a moist and warm climate (Table 2) during MMCO [24]. This change in climatic conditions can also be linked with the sedimentation rates, as it fluctuates during wetter and drier conditions. An increase in rainfall leads to increase in sediment supply to the basin, whereas, a decrease in rainfall leads to lower sediment supply to the basin. Reduced rainfall promotes preservation of minerals like Muscovite and Illite. Similar wet and dry climatic variations are also shown from the presence of clay minerals such as Kaolinite suggesting humid periods and dehydrated Halloysite suggesting drier periods during the formation of paleosols [54]. The Kaolinite to Smectite (K/Sm) ratio serves as a valuable proxy for tracking shifts between stable, humid conditions to more seasonal, arid climates (Table 2). Smectite typically points to warm climates with alternating wet and dry periods [60]. An increasing K/Sm ratio indicates intense weathering, whereas, a decreasing K/Sm ratio indicates moderate seasonal weathering. The Illite to Chlorite (I/C) ratio helps to constrain strength of monsoon and also identify glacial-interglacial periods in the rock record (Table 2) [20]. The susceptibility of Chlorite is comparatively higher than Illite [61]. So, an increase in I/C ratio depicts pronounced weathering of chlorite during the interglacial periods, whereas, decrease in I/C ratio points towards glacial periods (Table 2). Hence, cyclical changes in the sedimentation pattern can be linked with the glacial-interglacial periods through the clay mineral ratio analysis.

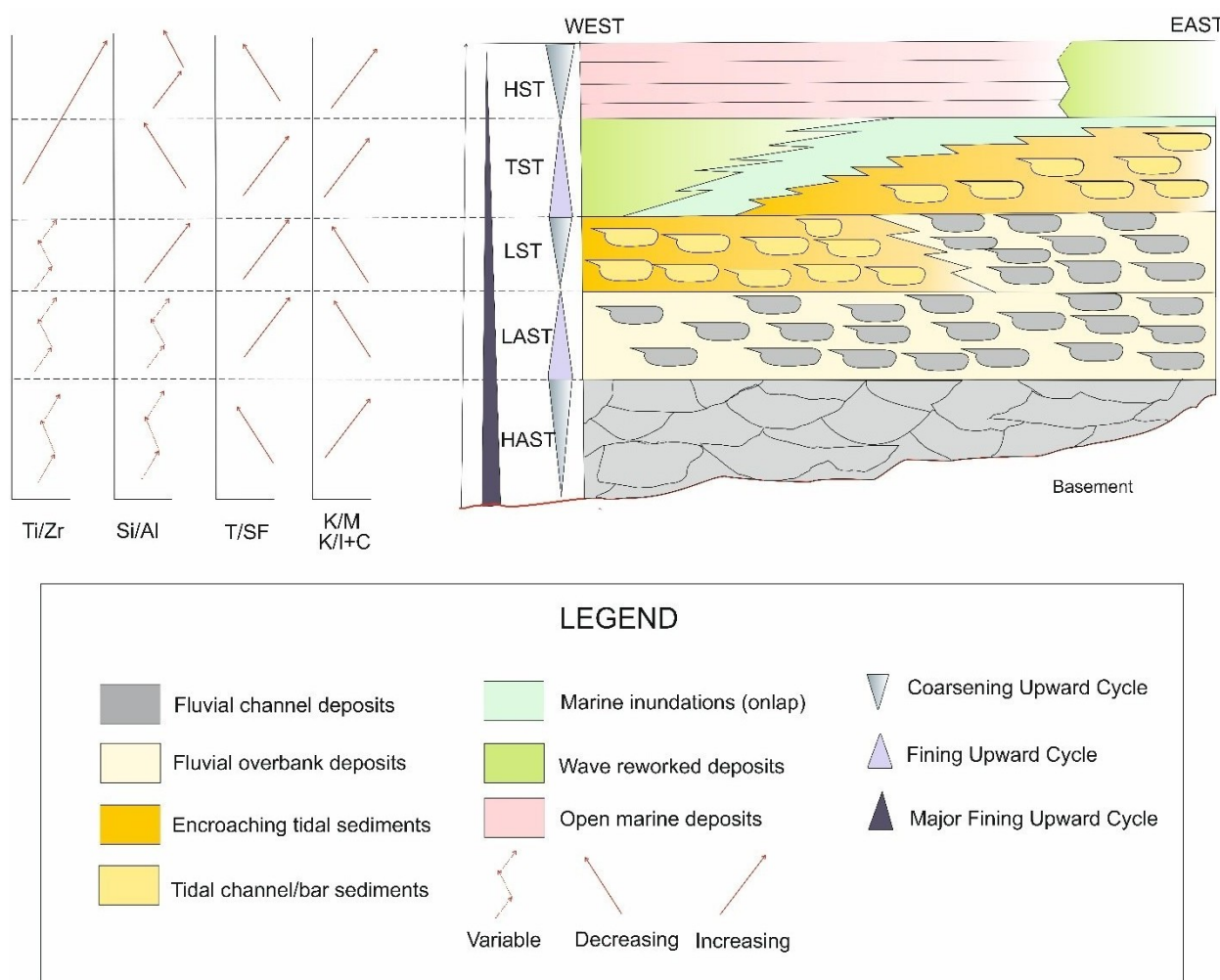
Thus, these changes in trends of the clay mineral ratios act as a proxy to identify changes in sediment supply, that is controlled by hinterland precipitation (Figure 4). However, such changes in the ratio of the clay minerals may also occur in the transitional to marine environment, with changing climatic conditions. Hence, it becomes essential to study the clay ratios within the paleosols, which occur as exclusive features in the continental settings (Figure 4). Thus, a critical analysis of applicability of the clay ratios as a proxy to identify the systems tracts on the continental side is assessed.

**Table 1.** Table showing the relationship between climate type, weathering intensity and paleosol maturity.

Climate Type	Weathering Intensity	Paleosol Maturity	Key Features
Humid tropical	Very high	Very mature	Deep profiles, Fe–Al oxides
Temperate	Moderate	Moderately mature	Clay-rich Bt horizons
Arid	Low	Weak–moderate	Carbonate nodules (calcrete)
Cold	Very low	Immature	Thin, gleyed soils

**Table 2.** Table showing clay mineral ratios and their interpretative proxies.

Clay Mineral Ratios	Proxies
Kaolinite/Illite or Illite/Kaolinite [62–64]	Chemical weathering when sediments contain acidic or felsic components
Smectite/Illite or Illite/Smectite [65, 66]	Chemical weathering when sediments contain basic or mafic lithologies
Kaolinite/Illite+Chlorite [67]	Type and degree of weathering in soils
Smectite/Illite+Chlorite [68]	
Illite-Smectite/Illite+Chlorite [69]	Paleoclimatic reconstruction
Smectite+Kaolinite/Illite+Chlorite [70]	
Kaolinite/Illite+Chlorite [24]	Intensity of weathering associated with monsoon periods
Illite/Chlorite [20]	
Smectite/Kaolinite [21]	



**Figure 4.** Schematic diagram showing trends of clay mineral ratios, elemental abundance ratios and T/SF ratio in different systems tracts. T/SF—Thickness/Sand Fraction; Si/Al—Silica/Aluminium; Ti/Zr—Titanium/Zircon; K/M—Kaolinite/Muscovite; K/I+C—Kaolinite/Illite+Chlorite (modified from [71]).

**2.1. Limitations in Usage of Clay Mineral Ratios as a Proxy to Identify Systems Tracts**

The most significant limitation of using clay mineral ratios such as Kaolinite/Muscovite, Kaolinite/Illite+Chlorite,

Illite/Chlorite, Kaolinite/Smectite is that they can be influenced by provenance of sediments rather than just by climate or by *in situ* weathering [60]. Though a low Kaolinite/Muscovite ratio may interpret a low weather-

ing phase, but, it may simply reflect a change in sediment source rather than just precipitation or temperature [55, 60]. High Illite/Chlorite ratio may simply reflect a metamorphic source terrain rather than high weathering during interglacial periods [60]. Due to this, the clay mineral ratios can be cross referenced with other indicators like Clay Mineral Alteration Index (CMAI) to ensure that the climate and weathering signal isn't being distorted by changes in the sediment source or local drainage (Figure 3) [72]. An increase in Kaolinite/Muscovite, Kaolinite/Smectite, Kaolinite/Illite+Chlorite or Illite/Chlorite (I/C) ratio may point to an increased sediment supply pointing to High Amalgamation Systems Tracts (HAST) (Figure 4) and a decreasing Kaolinite/Muscovite, Kaolinite/Illite+Chlorite or Illite/Chlorite (I/C) ratio may indicate the Low Amalgamation Systems Tracts (LAST) (Figure 4). Since LAST are dominated by fine-grained sediments, the probability of pedogenesis to occur are more within the LAST, whereas the HAST are dominated by thick channel deposits (Figures 2 and 4). Thus, along with the presence of paleosols the trends of clay mineral ratios within the paleosols can be used as proxies to identify systems tracts in continental settings (Figure 4).

### 3. Trace Elemental Ratios as a Proxy to Identify Sequence Boundaries and Systems Tracts

Several workers have shown the utility of trace elemental ratios in the identification of the sequence boundaries [13], which are in turn related to base level changes. In sequence stratigraphy, the bounding surfaces are identified on the basis of the changes in stratal stacking pattern [17–19]. The major bounding surfaces identified within a sequence includes Maximum Regressive Surface (MRS), Maximum Flooding Surface (MFS), Subaerial Unconformity (SU), Correlative Conformity (CC), Basal Surface of Forced Regression (BSFR) and Regressive Surface of Marine Erosion (RSME) (Figure 2). However, in case of sediments present either on the continental or deep-marine parts of a basin, often due to lack of preservation of primary sedimentary structures, body fossils, ichnofossils, or unavailability of sub-surface data or unsuitable resolution of seismic data, identification of different sequence stratigraphic elements becomes nearly impossible. To address this problem a few workers have carried out integrated chemostratigraphic and sequence stratigraphic workflow [11, 38, 73, 74].

Various mineral-based trace-elemental proxies are used to identify the autogenic and allogenic influences on the development of a stratigraphic sequence [13]. Aluminium (Al), Potassium (K) and Rubidium (Rb) mainly occur within clay minerals and feldspars [75–78], indicating siliciclastic input, while Titanium (Ti) is found in both silicates and titanium oxides minerals such as Rutile, Ilmenite etc. These affinities make Ti useful for tracing heavy-mineral provenance [75, 79, 80]. Molybdenum (Mo) occurs within magnetite, ilmenite like minerals or within basalt, granites and shales. Vanadium (V) is found in dif-

ferent minerals like Vanadinite, Carnotite, Patronite, Magnetite (vanadium-rich iron ores). Chromite (Cr) occurs in different oxidation states within some ferromagnesian minerals as well as clay minerals. Niobium (Nb) and Thorium (Th) are found in various silicates, Titanium Oxides, or can even be present in clay minerals, marking contributions from both igneous and sedimentary origins [81, 82]. Uranium (U) is found in detrital or authigenic accessory minerals. The Uranium cations get adsorbed onto mineral surfaces and precipitate as uranium oxide minerals, which are sensitive to redox conditions [77, 83, 84]. Zirconium (Zr) is found mostly in Zircon and other heavy minerals and interpreted as the input from high-durability sediment sources [75, 80, 85, 86]. Yttrium (Y) can be present in Zircon, Monazite, Apatite, and Garnet [82].

The trace elemental ratios and the trends of such ratios provide insights into sediment provenance, grain size variations, paleoredox conditions, and basin restrictions [16, 75, 87–89]. Detrital grain-size proxies like Ti/Al, Zr/Al, and Si/Al, as well as Zr/Nb, Zr/Rb, Y/Al, and Y/Rb in heavy minerals, can be used to delineate the fluctuating amount of coarse-sediment supply in a basin [34, 75, 82, 90, 91]. Another vital factor influencing sediment geochemistry is basin restrictions. For instance, excess silica can typically be evaluated by comparing Si/Al ratios to the top average shale values, where Si is contributed from biogenic or diagenetic silica [92, 93]. The abundance and the ratio of elements such as Vanadium (V), Uranium (U), Rhenium (Re), Chromium (Cr), Molybdenum (Mo), and Nickel (Ni) can be utilized to determine the paleo-redox conditions, since these elements become concentrated in anoxic to euxinic environments [77, 94–99]. Sedimentary systems impose numerous limits in open environments where many processes occur, despite the fact that distinct geochemical signatures are used to reconstruct stratigraphic sequences [77, 94]. Hydraulic sorting, source-rock heterogeneity, sediment recycling, and varying mineralogical compositions can all have an impact on detrital grain-size proxies (e.g., Ti/Al, Zr/Al, Si/Al, Zr/Nb, Y/Rb) [100, 101]. Elevated Si/Al ratios indicate excess biogenic or diagenetic silica, which can also indicate alterations in terrigenous input, authigenic clay formation, or post-depositional silica redistribution, making evaluations of basin restriction more difficult [102–104]. Organic matter flux, sedimentation rate, and diagenetic processes also affect redox-sensitive elements as V, U, Mo, Ni, and Re, which can separate their enrichments from bottom-water oxygenation [74, 94, 96].

#### 3.1. Detrital Trace Elements

##### 3.1.1. Si and Al

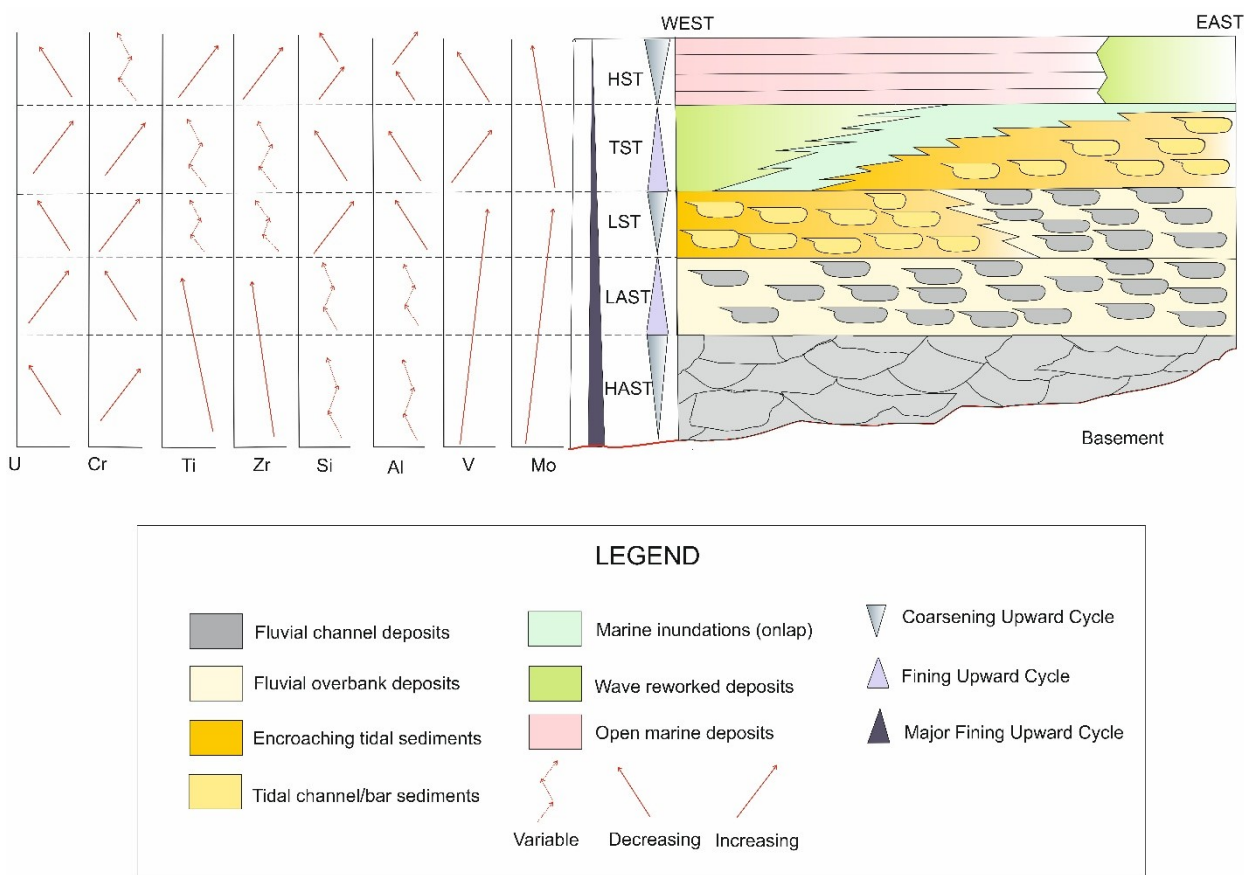
The Si/Al ratio shows a decreasing trend within the Transgressive Systems Tract (TST) and coincides with the Maximum Flooding Surface (MFS) (Figure 4; Table 3), owing to lower availability of continental clastic elements like Ti and Zr during episodes of marine incursion [12, 34, 37], while the Al and K remain elevated and increase in biogenic silica in the system [105]. The increasing Al con-

tent relative to Si or decreasing Si/Al ratio (Figure 5) indicates a relative increase in finer-grained, more distal, or condensed sedimentation (Figures 5). Hence, all the Ti/Al, Zr/Al, and Si/Al, ratios will show a decreasing abundance towards the top of TST (Table 3) [38, 73]. While a reverse trend is shown by these proxies during progradation or a Falling Stage Systems Tract (FSST) or Lowstand Systems Tract (LST) (Figure 4; Table 3) [13]. The Al content grad-

ually changes across a Highstand Systems Tract (HST) [11, 77, 105]. Within the early HST sequence the sand/silt-sized sediments dominate while the clay-rich mud/shale may be reduced, the proportion of quartz increases relative to the clay minerals (rich in Al) (Figure 4; Table 3). However, during the late HST due to thick deposition of shales the Al content may increase thus leading to decreasing Si/Al ratio (Figures 4 and 5; Table 3).

**Table 3.** Chemostratigraphic signatures of sequence stratigraphic bounding surfaces and systems tract [13].

Sequence Stratigraphic Surfaces and Systems Tracts	Observed Signatures
Maximum Flooding Surface (MFS)	Si/Al is abundant, Mo is high & V content is less and Ti and Zr is present in low concentration.
Maximum Regressive Surfaces (MRS)	Si/Al is less abundant, Mo & V content is usually minimum but can vary depending on paleo-hydrography and Zr is high
Transgressive Systems Tract (TST)	Si/Al is abundant, Mo & V content is elevated, Ti and Zr is present in low abundant.
Highstand Systems Tract (HST)	Si/Al is abundant, Mo & V content is not elevated, Ti and Zr is present in abundant but may vary.
Regressive Systems Tract (RST)	Si/Al is less abundant; Mo is less & V content may increase or decrease and Ti and Zr trend increases.



**Figure 5.** Schematic diagram showing trends of elemental abundances in different systems tracts. Ti—Titanium; Zr—Zircon; Si—Silica; Al—Aluminium; V—Vanadium; Mo—Molybdenum (modified from [71]).

### Limitations

**Aluminium (Al):** Although Al is frequently used as geochemical proxy, it has several drawbacks as it can come from a variety of sources, which can make it difficult to determine the provenance of sediments [94, 100]. The enrichment of fine-grained sediments is significantly impacted by mineralogy and grain size [77]. Post-depositional events and diagenetic change can bring limited mobility variation, which can affect the conservative behaviour of Al [74, 101]. Al-based interpretations can also be skewed by variations in sediment provenance and dilution by biogenic or carbonate material [77, 94]. By utilizing Al simultaneously with other conservative elements (such as Ti, Zr, and Sc), also applying grain-size normalization, interpreting Al trends within larger sedimentological, incorporating mineralogical or isotopic data, and geochemical context rather than in isolation, the limitations of Al as a geochemical proxy can be reduced [94, 100].

**Silicon (Si):** Since Si is influenced by both biogenic biogenic (opal from diatoms/radiolarians) and detrital (silicate minerals) sources, it is challenging to differentiate terrigenous input from biological productivity [103, 104]. Its concentration can also be impacted from dissolution and diagenetic modification of biogenic silica [102, 104]. When the dominant source is known, Si can be employed separately [103, 104]. With high biogenic productivity and low terrigenous input Si represents biogenic silica synthesis in environments [102, 104]. On the other hand, Si may be a sign of detrital influx or silicate weathering in clastic-dominated systems [94, 106]. The Si source must be carefully constrained by independent evidence, like microfossils or body fossils [103, 104].

However, detrital proxies such as Si/Al in continental settings are better understood in terms of regional sedimentary processes than in the context of marine sequence stratigraphy. Higher values indicate quartz-rich channel sands, while lower values correlate to clay-rich overbank or floodplain deposits. In fluvial systems, grain-size partitioning driven by hydrodynamic sorting is reflected by Si/Al ratios [107, 108]. Although signals may be confounded by biogenic silica synthesis and lake-level fluctuations, Si/Al variations in lacustrine habitats can track changes in detrital inflow vs internal lake processes within the framework of limnology [109]. As a result, while changes in Si/Al may still be indicative of changes in the availability of sediment or environmental factors, their interpretation in continental systems requires integration with independent sedimentological constraints like depositional architecture, grain-size data, and facies analysis [109]. Thus, Si/Al ratio solely cannot be used as a proxy to correlate with the net accommodation space generation and sediment supply within the basin.

#### 3.1.2. Ti and Zr

The Ti/Zr ratio shows an increasing trend or is quantitatively higher in TST with respect to its abundance within

HST, owing to redox-sensitivity of the elements (Figure 4; Table 3). Ti and Zr are derived from continental settings [110, 111]. Both Ti and Zr will increase in abundance within progradational settings due to increased continental influx of sediments. Unlike Zr, Ti is more likely to be incorporated into minerals from wind as dust fraction [111]. However, this only takes place in situations where the local sediment supply is dominated by the dust in the form of fine-grained sediments. In regressive systems tracts (RST), Ti and Zr vary with a trend similar to the trends of Al (Table 3) [11, 73, 86]. Hence, the Ti/Zr, Zr/Nb and Si/Al ratios can be used in combination to track the shoreline progradation pointing to the identification of the Transgressive systems tract (TST) and regressive systems tracts (RST) (Figure 4; Table 3). Since these proxies are also redox sensitive, the bottom water anoxic or euxinic nature can also be interpreted [38, 78, 110, 112]. On the continental side, within the lacustrine settings, periodic paleoredox fluctuations can be constrained using Ti/Zr ratios. Especially in glacial lakes, where periodic glacial and interglacial periods result in varve deposits created due to alternating oxic, sediment supply rich time intervals to anoxic sediment supply deprived intervals.

### Limitations

**Titanium (Ti):** Ti is resistant to chemical weathering and redox changes, so it is a detrital, mostly immobile element that is usually employed as a stand-in for terrigenous input [100]. However, enrichment of Ti-bearing heavy minerals, grain-size variability and hydrodynamic sorting can all have an impact on Ti concentrations, thereby preventing actual variations in detrital flux [77, 94]. When depositional energy and sediment origin are stable, Ti can be utilized separately; In spite of that, there is a necessity in grain size or other immobile elements normalization.

**Zirconium (Zr):** Since, Zr is a highly immobile element and is mostly found in zircon, it is frequently employed as a marker of sediment maturity and terrigenous input [100]. As zircon is preferentially concentrated in coarser fractions, sediment sorting and grain size influences its distribution, making Zr susceptible to variations in depositional energy and provenance [101]. Therefore, Zr is most dependable when used in systems with consistent grain size or in ratios (e.g., Zr/Al, Zr/Ti) for the reduction sorting effects.

Thus, by normalizing with grain-size-insensitive elements (e.g., Ti, Zr, Sc), and comparing with mineralogical data (heavy minerals, clay assemblages), with the consideration of sedimentological constraints (facies, depositional environment), it is possible to separate source-related signals from grain-size effects [100, 101, 106, 113]. Furthermore, isotopic tracers or detrital zircon dating can further confirm provenance shifts [114–117]. When all these approaches are combined, interpretation of elemental ratios in terms of sediment source versus depositional sorting strengthening their use as proxies in continental

sedimentary systems [101, 118, 119]. Although certain limitations exist in the interpretation of the Ti and Zr concentration, with careful assessment Ti/Zr ratio can be used as a proxy to identify the sediment supply rates within the continental part of a basin.

### 3.2. Redox Sensitive Elements

#### 3.2.1. Mo and V

The Mo and V are sensitive to oxidizing and reducing conditions and thus, may be used to interpret the paleo-redox conditions in a sedimentary basin. Enrichment of Mo indicates anoxic conditions while the depletion of Mo indicates organic Carbon degradation is not extensively limited to periodic episodes. In transgressive systems tracts (TST), Mo levels decline however, shows a higher value than in highstand systems tracts (HST) (Figure 5; Table 3) [13]. At maximum regressive surfaces (MRS), both Mo and V can be enriched, but V often shifts from increasing to decreasing concentrations (Figure 5). Such shift matches the changing trends in stratal stacking patterns within the systems tract [18]. However, depending on the hydrodynamic conditions, these proxies may also vary [37, 105]. For instance, low Mo/Al often marks MRS, while peaks in V during TST may occur without reduced circulation (Figure 5; Table 3). The Mo and V mobility increases under oxidizing conditions. Mo specifically requires sulfur to accumulate under euxinic (sulfidic) conditions, transforming from seawater molybdate to thiomolybdates ( $\text{MoS}_4^{2-}$ ) through reactions with sulfur-rich sediments and organic matter [77, 120]. These geochemical behaviors allow reconstruction of bottom-water redox states, basin restriction levels, water mass renewal, and even paleowater depth, alongside distinguishing continental versus marine influences [38, 84, 91, 121–126]. As a result, redox-sensitive elements are depleted in regions with significant sediment supply, which are primarily found in the upstream portion of continental settings. Biogenic silica (Si/Al) and redox-sensitive elements including Mo, V, Ni, and U are more prevalent in downstream within continental settings with minimal sediment supply. The downstream section's anoxic to euxinic waters promote the preservation of organic materials. The dynamic interaction between sediment supply, water chemistry, and basin circulation can thus be shown through the use of chemostratigraphic proxies to trace transgressive–regressive transitions.

#### Limitations

**Molybdenum (Mo):** Mo is frequently utilized as a redox proxy [127, 128]. However, there is a significant impact on Mo enrichment from basin restriction, seawater renewal rates, and the availability of dissolved sulphide [128, 129]. Even weakly sulfidic circumstances or environments with more intense sedimentation rates that dilute authigenic Mo can result in low Mo enrichment [74]. Diagenetic remobilization and adsorption onto organic matter or Fe–Mn oxides can complicate interpretations of redox

conditions, which can further overprint initial depositional signals [74, 96].

**Vanadium (V):** V is abundant in suboxic to anoxic environments, it is frequently utilized as a redox proxy [74]. However, post-depositional diagenetic processes, sedimentation rate and organic matter flux all affect V concentrations and can separate V enrichments from bottom-water oxygenation [74, 77]. Changes in sediment provenance or detrital input, can dilute V signals making it challenging to discern between lithogenic and redox-driven variations [94, 100]. Therefore, independent data is normally used (such as organic carbon content and mineralogy) to limit conclusions because, like Mo, V can be mobilized or redistributed during diagenesis [96, 128].

The Fe–Mn shuttle is crucial to the delivery of Mo and V enrichment, therefore their interpretation should not be limited to redox and sediment supply. Fe–Mn oxyhydroxides produced in oxic fluids enhance local enrichment regardless of bottom-water redox by scavenging Mo and V and releasing them upon reduction [77]. For Mo, enrichment depends on seawater resupply even though it is usually linked to euxinia. Depletion of the dissolved Mo reservoir in confined basins might result in low Mo concentrations despite anoxic or euxinic conditions [74]. As a result, Mo and V distributions may separate from straightforward redox interpretations and represent a combination of redox state, Fe–Mn shuttle dynamics, and basin restriction.

Thus, after careful consideration Mo and V can be utilized to understand the rate of sediment supply in the continental settings.

#### 3.2.2. Cr and U

Chromium (Cr) and Uranium (U) are also redox sensitive elements that are used to interpret paleo-redox conditions in sedimentary basins [75, 89, 90]. Enrichment of Cr and U indicates anoxic to euxinic environments [95]. However, under euxinic conditions, Cr get lost during remineralization of organic matter [71]. So, it may obscure original signals. This proxy can be used with caution as Cr bearing minerals may enter the system through detrital input, which in turn may complicate the interpretations of accumulation of authigenic Cr [77]. In oceans, Uranium can be found as detrital accessory minerals and gets dissolved in the form of U(VI) as well [83]. The reducing behavior of U(VI) to U(IV) depicts the enrichment of sediments under anoxic to euxinic conditions [125]. These enrichments in sediments deposits are derived from insoluble U(IV) which precipitate as uraninite ( $\text{UO}_2$ ). In LST, Cr shows higher enrichments whereas U shows lower enrichment (Figure 5). In TST, due to increase in organic matter preservation U generally show increasing trend and due to high detrital input Cr may also show increasing trend. On the contrary, in HST, U concentration can be decreased and Cr may show variable trend [77, 110] (Figure 5). In LAST due to low energy condition, more organic matter deposits in suboxic to

anoxic condition, as such redox sensitive elements like U increases. Also, due to low detrital input Cr concentration is low in LAST. Similarly, in HAST, U decreases due to less organic preservation and Cr increases due to increase in detrital input [75, 89, 90].

#### Limitations

**Chromium (Cr):** Since Cr is both detrital and redox-sensitive, it is complicated to use it as a stable proxy. There is a possibility of post-depositional remobilization due to redox transformations [77, 94, 130]. It is also heavily influenced by the provenance of the sediment and particle size. When sediment provenance is homogeneous, for detrital input or redox conditions Cr can be employed separately as a stand-in proxy [130]. To isolate Cr behaviour and lessen lithogenic bias, it is usually normalized to grain size or is compared with immobile elements [100].

**Uranium (U):** U is a high redox sensitive element, so it can be mobilized in oxidizing environments and enriched in anoxic ones. Primary depositional signals can be overprinted by post-depositional diffusion, adsorption onto organic matter, and authigenic enrichment [74]. Due to the high sensitivity of U to oxygen availability, U can be used alone as a redox proxy and as long as sedimentation rates are limited and post-depositional remobilization is minimal authigenic U enrichment is interpreted as evidence of reducing or anoxic conditions [128].

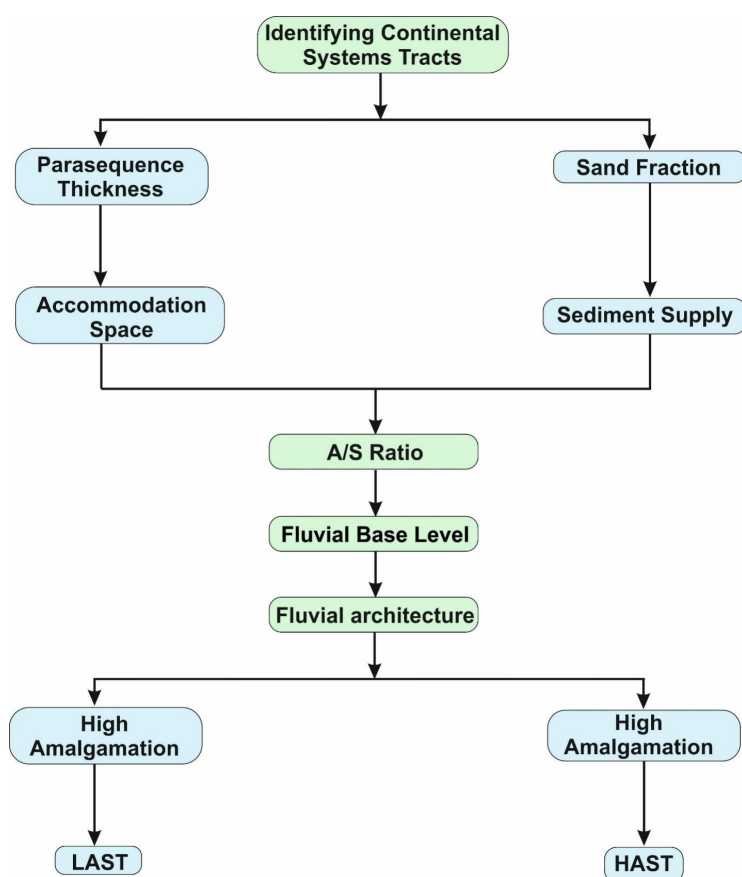
For identification of the systems tracts in continental settings the Cr and U proxies may be utilized under certain favorable conditions. However, due to the higher complexities and limitations associated with the proxies it is advised to use these proxies in association with other proxies and not in a standalone manner.

These restrictions result from the substantial modification of primary elemental signatures by post-depositional processes, such as pedogenesis and water table changes. Although Mo, V, and U are often trapped in reducing, water-saturated sediments, oxic circumstances can encourage groundwater to mobilize and redistribute them [131]. Similarly, primary and strong redox-sensitive elemental signatures also can be altered by post-depositional processes in continental environments, such as pedogenesis and variations in the water

table [107]. Through leaching, oxide precipitation, and the creation of redox gradients, pedogenic processes further modify Fe, Mo, V, and U, resulting in vertical chemical heterogeneity that may overprint initial depositional signals [109, 132].

#### 4. TSF Analysis

The thickness to sand fraction ratio (TSF) earlier used in clastic shallow-marine systems identifies parasequence thickness and the thickness of the sand within the parasequence, correlating the parasequence to accommodation space and sand fraction to sediment supply [23]. The vertical trends established using the ratio of thickness of a parasequence to the percentage of sandstone present within the parasequence, approximately matches the trends shown by changing accommodation to sediment supply ratio (Figure 3). Accommodation (A) can be defined by space available for sedimentation to take place over time. Thus, the unit of length per unit time is associated with Accommodation. The Sediment supply (S) represents total volume of sediments supplied within a fixed time interval. Thus, sediment supply can be expressed in terms of volume per unit time. Both the definitions of A and S include volume and time. The A/S ratio is used as number and changes in the ratio of A/S is expressed as changes taking place in the position of fluvial base level, which in turn results in changing fluvial architecture (Figure 6). Several case studies have shown that the rate of change of the A/S ratio or the increasing or decreasing trends of A/S ratio are utilized for correlation [23, 133]. Within a fluvial system the base-level fluctuations are governed by the changing ratio of accommodation space to sediment supply [134]. Thus, an increasing vertical trend of T/SF will indicate low amalgamation of channel sand reduced frequency of channel avulsions, due to higher accommodation space and reduced sediment supply along with increased space availability for floodplain aggradation (Figure 6). Conversely, a decreasing vertical trend of T/SF will indicate high amalgamation of channel sand higher frequency of channel avulsions due to reduced accommodation space and increased sediment supply, and decrease in space available for floodplain aggradation (Figure 6). Thus, the TSF analysis may be utilized for identification of changing systems tracts within the continental fluvial settings (Figure 6).



**Figure 6.** Flow chart showing the relationship between Accommodation Space and Sediment Supply. Parasequence thickness and sand fraction are serving as proxies for accommodation space and sediment supply. A/S: Accommodation/Sediment Supply; HAST: High Amalgamation Systems Tract; LAST: Low Amalgamation Systems Tract.

## 5. Discussions

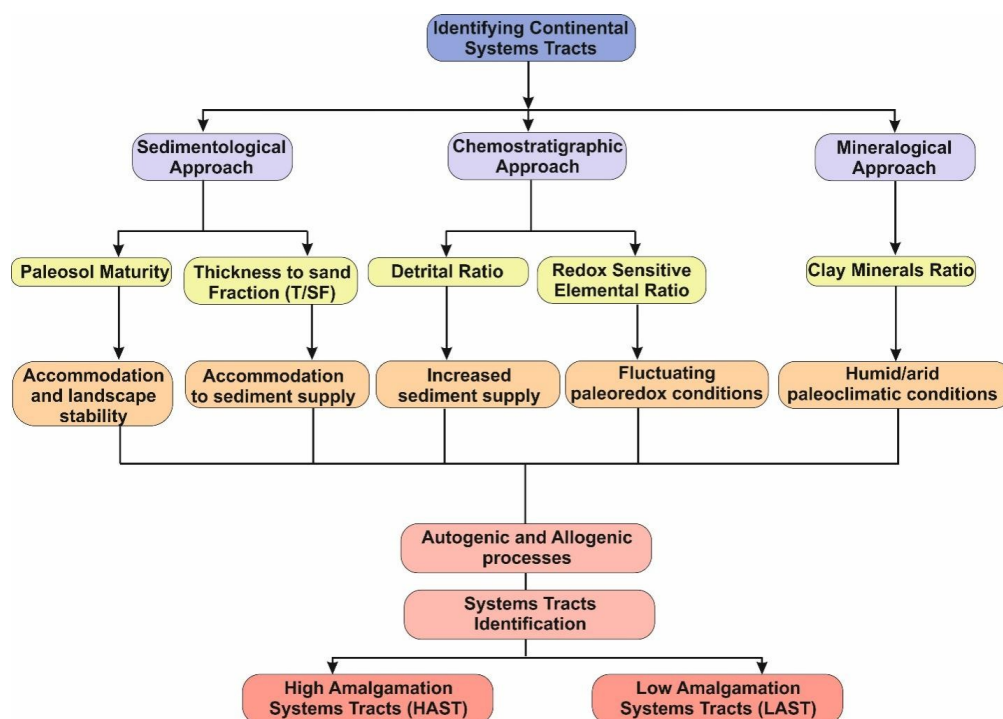
The present review work highlights the importance of using sequence stratigraphy in association with chemostratigraphy to achieve high-resolution correlations and identification of sequence stratigraphic elements. In basins dominated by fine-grained sedimentary successions sedimentological criteria, and paleontological criteria falls short in providing a robust interpretation of the evolutionary history of the basin. In such scenarios using geochemical proxies such as trace elemental ratios or major oxide ratios can help in reconstructing the paleodepositional history. Such integrated studies also help improve the resolution of the study. Along with the identification of the systems tracts within the fine-grained sedimentary successions in the marine realm, systems tracts identification in continental settings is also very challenging. Several case studies are identified which shows the utility and limitations of different proxies within a marine or a transitional realm, however, such proxies are limited within the continental settings. Thus, a wide variety of proxies are required to interpret the allogenic and autogenic controls and identify the overprinting effects of these controls on the sedimentation pattern. The present review thus highlights the importance, utility and limitations of such multiple proxies that occur more favourably on the continental side. The present review utilizes several case studies based on

the marine dominated settings, to identify the trends in elemental ratios, mineralogical ratios, paleosols maturity, thickness to sand fraction ratios. A thorough analysis of these trends helped in identification of the possible mechanisms associated with the development of such trends. Further, the mechanisms are utilized to understand the limitations of such trends on the continental settings. For example, in the LST deposits the level of continental proxies such as Mo/Total Organic Carbon (TOC) ratio is elevated which indicates basin restriction [13]. The TST records a decline in continental proxies as well as decline in basin restriction proxy [13]. Similarly, the HST records an increase in continental proxies but shows very low levels of basin restriction proxies [13].

Thus, upon careful synthesis of the trends and the mechanisms, it was observed that the proxies must not be utilized in a standalone fashion, instead a combination of multiple such proxies should be studied. During such study the limitations associated with each proxy must also be considered. Understanding the limitations associated with the proxies can help to correctly identify the allogenic and autogenic controlling factors. Thus, for the identification of the systems tracts on the continental side three-way approach is advised which involves a sedimentological approach, chemostratigraphic approach and mineralogical approach (Figure 7). The sedimentological approach

involves criteria such as paleosol maturity and identification of the varying trends in the ratio of the thickness of a parasequence to the amount of sand present within the parasequence (Figure 7). The chemostratigraphic approach is divided into two categories such as the detrital elemental ratios and the redox elemental ratios (Figure 7). The mineralogical approach involves identification of the changing trends in the ratio of the clay mineral present within such paleosols (Figure 7). Using this integrated approach can help in understanding how the net accommodation space generation and sediment supply varied over time within a particular basin. As these proxies are mostly the products of the accommodation to sediment supply ratio, hence understanding the mechanisms through which these proxies vary becomes essential. For example, a mature paleosol indicates stability in area, it indicates a warm, tropical climatic conditions, stability in the river systems can occur through vegetation. Vegetation growth which stabilizes the soil can occur when sufficient time is available for the overbank deposits to settle down. This indicates an increased accommodation space and reduced influx of sediments (increased A/S ratio) which commonly occurs within the Low Amalgamation Systems Tracts (LAST) of a river system (Figure 7; Table 4). Hence, the presence of mature paleosols can be used as an indicator to identify or distinguish the HAST and LAST deposits [134]. Similarly, shift in the climatic pattern will result in a shift in the type of associated clay minerals in the river sediments. Taking into consideration the several limitations that are associated with the clay minerals, the clay mineral ratios can also be used as proxies to identify

the changing rates of sediment supply in a river system (Figure 7; Table 4). Furthermore, the amount of coarse-sediment supply from a terrigenous source within a basin can also be traced using different trace element proxies. However, post-depositional silica redistribution, organic matter flux, sedimentation rate, and diagenetic processes significantly affect these proxies in both continental and marine realms. Careful consideration, corrections and a combination in utilizing the multiple proxies can help in delineating the systems tracts in the continental side (Figure 7; Table 4). Proxies such as Ti and Zr signifies a terrestrial input, thus the changing ratios of these proxies coupled with other sedimentological features can help identify the systems tracts on the continental side (Figure 7; Table 4). For example, as the continental influx of sediments increases the Ti and Zr concentration are also increased and at the same time increased sediment supply with reduced accommodation space will lead to the development of higher amalgamation within the channel. Thus, HAST can be identified under such scenarios. Thus, an increased Ti and Zr concentration with decreasing vertical trend of T/SF in combination can indicate the occurrence of HAST (Figure 7; Table 4). Similarly, the presence of Mo, Cr and Mn can be utilized to understand the fluctuating water table conditions that controls the paleoredox conditions. However, Cr signatures may be severely affected depending several factors in the provenance. Also, independent data (such as organic carbon content and mineralogy) must be used in association with the concentration of Mo and V, as they can be mobilized or redistributed during diagenesis.



**Figure 7.** Flow chart showing integrated multidisciplinary workflow for identification of continental systems tracts using sedimentological (paleosol maturity, thickness to sand fraction ratio), chemostratigraphic (detrital ratio, and redox sensitive elemental ratio) and mineralogical (clay mineral ratio) approaches.

**Table 4.** Table showing comparative analysis between the applicability and limitations of the proxies in continental and marine settings.

Proxy	Continental Realm Suitability	Key Strengths (Continental)	Key Limitations (Continental)	Marine Realm Suitability	Key Strengths (Marine)	Key Limitations (Marine)
<b>Mature paleosols</b>	High for systems-tract identification (HAST vs. LAST)	Linked to landscape stability, increased A/S, and reduced amalgamation; good indicator for LAST identification.	Develop only in low-energy, non-erosive settings; no expression in channel-dominated systems; laterally discontinuous in nature.	Generally low or absent	Not applicable as pedogenic indicators; soil-like horizons are rare and hard to distinguish.	Poor implications on classic marine systems tracts.
<b>Clay-mineral ratios</b> ( <i>Kaolinite/Smectite, Illite/clay ratios</i> )	Moderate–high for climate and drainage-style interpretations	Reflect pedogenic weathering intensity, hydrological regime, and vegetation-stabilized slopes; can be used to track shifts in A/S via changes in clay-mineral assemblage.	Highly sensitive to provenance, climate change, diagenesis, and secondary alteration, post-depositional modifications; Limited if basin receives multiple sourced sediments.	Moderate–high in marine shales.	Co-relatable to climate and drainage-style signals; Can be used in association with chemostratigraphic datasets in marine mudstones	Overprinted by basin-scale circulation, diagenesis, and burial history, thus require careful normalization.
<b>Detrital proxies</b> ( <i>Ti and Zr; Ti/Al; Zr/Al</i> )	High for HAST–LAST discrimination.	Ti and Zr track coarse detrital input; rising Ti/Zr along with decreasing T/SF and A/S is a diagnostic for HAST in alluvial/fluvial systems.	Provenance (heavy mineral supply), physical sorting, and diagenesis all have an impact; normalization is required (for example, Ti/Al and Zr/Al).	Moderate–high in marine mudstones.	Ti/Al is often robust for terrigenous supplies and can be used to discriminate between regressive (RST) and transgression (TST) intervals.	Authigenic and biogenic components can obscure detrital signals, whereas diagenesis and reworking confound short-term trends.
<b>Paleoredox proxies</b> ( <i>Mo and V</i> )	Moderate, but context-dependent.	Mo and V enrichments can track fluctuating water-table and redox conditions in wetlands, floodplain ponds, and incised-valley fills.	Mobilized during early diagenesis; total organic-carbon content and mineralogy must be combined.	High in organic-rich marine mudstones.	Mo and V are typical redox sensitive metals used to detect oxic-anoxic changes and MFS in marine sequences.	Sensitive to thermal maturity, authigenic stages, and subsequent diagenesis; must be linked to TOC and sedimentology.

Table 4. Continued.

Proxy	Continental Realm Suitability	Key Strengths (Continental)	Key Limitations (Continental)	Marine Realm Suitability	Key Strengths (Marine)	Key Limitations (Marine)
<b>Cr and Mn</b>	Moderate, but Cr is problematic.	Cr can monitor changes in provenance and redox conditions in river wetland systems, whereas Mn frequently reflects perched redox fronts.	Cr is significantly impacted by bedrock source and mineralogy, making it unreliable as a standalone proxy; Mn is easily mobilized.	Moderate in marine settings.	Cr can represent changes in provenance and basin constriction, whereas Mn is frequently associated with early diagenetic fronts such as the paleoredox borders.	Both metals are susceptible to pore water chemistry and diagenesis, with Cr seldom serving as a major sequence stratigraphic proxy.
<b>Ti/Zr + Zr/Al + Ti/Al + V + Mo + T/SF + Clay mineral ratio signals</b>	High when combined.	On the continental side, increasing Ti/Zr + high amalgamation (↓ T/SF, low A/S) implies HAST, whereas paleosols maturity + clay mineral changes + low amalgamation (↑ T/SF, high A/S) imply LAST.	High resolution sedimentological data and a stratigraphic framework are required, as well as corrections to mixing models and provenance effects.	High in marine mudstone successions.	Chemostratigraphic profiles (Ti/Al, Si/Al, Mo/Al, and V/Al) are good in tracking relative sea level cycles and regressive vs. transgression circumstances.	Due to diagenetic and organic matter controls, chemostratigraphy must be integrated with mineralogy, and sedimentology.

Index:  High  Moderate-High  Moderate  Low

The present review work uses logical analysis to establish relationship among different proxies that can be possibly utilized to identify the systems tracts within a continental setup. After thorough review no such work of chemostratigraphy has been found to be applied on the continental settings. Definitely the reason being availability of well-preserved, unaltered sections, generation of large and continuous data sets. Several approximations, corrections and limitations must be considered before application of these proxies even in an integrated manner. The list of proxies utilized in the present review work is not exhaustive and future works in the domain of chemostratigraphy can further contribute to the refinement of this review work.

## 6. Conclusions

Based on the review, the identification of the continental (non-marine) systems tracts might be possible based on a multi-proxy approach. Thus, in areas further away from the influence of shoreline movement, or with other constraints on data, an integrated sedimentological, mineralogical and chemostratigraphic approach may help to identify the sequence stratigraphic elements.

A comprehensive analysis of existing research reveals the following key findings:

1. The paleosol maturity index used to infer humid/arid conditions and pedogenetic intensities, serves as a proxy to define the relationship between net accommodation space and sediment supply within a basin.
2. An increase in clay mineral ratios such as Kaolinite/Muscovite, Kaolinite/Smectite, Kaolinite/Illite+Chlorite, Illite/Chlorite suggest a higher sediment supply indicative of HAST and declining values points to reduced sediment supply characteristic of LAST of the continental sedimentary systems.
3. A declining Si/Al ratio indicates finer-grained, more distant or condensed sedimentation, which is usually connected to maximum flooding conditions and marine transgression (TST). But various parameters such as grain size, provenance and biogenic input can hinder in interpreting sediment supply or accommodation space on its own.

4. Increasing values of the Ti/Zr ratio indicate larger continental input and contributes in differentiating TST from RST, making it a useful proxy for determining sediment supply and coastline progradation.
5. Mo enrichment indicates anoxic–euxinic conditions, and their fluctuations aid in tracking transgressive–regressive shifts, sediment supply, and water circulation. Mo and V are dependable proxies for reconstructing paleo-redox conditions and basin dynamics.
6. Redox conditions and systems tracts can be identified using Cr and U, where Cr reflects both detrital input and redox variations over several depositional phases and U enrichment indicates anoxic conditions.
7. In areas where core sedimentary structures are poorly preserved, vertical trends in T/SF offer a helpful way to differentiate between Low Amalgamation Systems Tracts (LAST) and High Amalgamation Systems Tracts (HAST).

The list of proxies discussed here by no means must be considered comprehensive. As analytical methods and sequence stratigraphic concepts continue to evolve, the range of sedimentological, mineralogical, and geochemical proxies that might be utilized for identification of sequence stratigraphic elements is anticipated to grow considerably. Future research and technological advancements will therefore surely make it easier to find more proxies, which will enhance the precision and resolution of basin-scale stratigraphic and architectural analysis and the quantitative connection between sedimentary records and the underlying autogenic and allogenic processes.

### Author Contributions

A.S.: Conceptualization, visualization, investigation, formal analysis, supervision, writing-original draft, construction of figures, review and editing. A.G.: Writing original draft, investigation, methodology, construction of tables and figures. R.C.: Writing original draft, investigation, methodology, construction of tables and figures. D.B.: Validation, review and editing. P.K.: Validation and review. All authors have read and agreed to the published version of the manuscript.

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### Data Availability Statement

All data used in this study are presented in the paper.

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### Conflict of Interest

The authors declare no conflict of interest, and they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Use of AI and AI-Assisted Technologies

The authors have only used Chat GPT and Grammarly for language improvement.

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