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Review

Spatial Distribution, Material Composition and Provenance of Loess in Xinjiang, China: Progress and Challenges

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Abstract: The loess in the arid area of Xinjiang is located at the eastern end of the Central Asia Loess Belt, and paleoclimate research about it is of great importance for understanding the mechanism of interaction of the Eurasian Westerly monsoon system and the aridity of Central Asia. This review focuses on recent progress concerning the spatial distribution, material composition and provenance of loess in Xinjiang and points out the shortcomings of and challenges to provenance and dust circulation. Field investigation and previous studies indicate that loess sediments have been mainly distributed on the river terraces and windward piedmont of the Tianshan Mountains and the Kunlun Mountains since the late Pliocene (mainly late Pleistocene). Grain size and age data show that Xinjiang loess deposits at some locations are rapid and discontinuous or sedimentary hiatus. The Siberian High system largely controlled dust mobilization and loess accumulation in northern Xinjiang but not southern Xinjiang. In southern Central Asia, the intensity of dust activity may be determined by the Caspian Sea–Hindu Kush Index (CasHKI) and local circulation. However, there is not enough evidence that the CasHKI index can affect the Tarim Basin area. Consequently, ascertaining the driving mechanism of mid-latitude Westerly winds and the dynamic process of loess deposition in Xinjiang is a specific suggestion for critical future research. Many indicators have shown that the loess dust sources in Xinjiang are composed of mainly proximal materials plus some remote materials. Alluvial plains and local proluvial fans contributed more to loess deposition, while Central Asian deserts comprise a small proportion of loess deposition in northern Xinjiang. In future provenance research, new technologies and new methods should be continuously tested to facilitate an objective understanding of the provenance of the loess in Xinjiang.

Keywords: Xinjiang loess; provenance; arid area; spatial distribution; Central Asia

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1. Introduction

Loess, a kind of silt-sized terrestrial sediment, is one of the most extensive deposits in terrestrial ecosystems and is valuable for elucidating paleoclimate changes [1]. In terms of geographical settings, loess is intermittently distributed in arid and semi-arid regions in the middle latitudes of the northern and southern hemispheres [1]. Loess deposits can be found at altitudes ranging from several meters near the coasts (such as in Argentina and New Zealand) to 5300 m north of the Kunlun Mountains of China [2]. The thickest and most continuous loess deposits in the world are located in China [3]. At present, there are three modes of understanding of loess provenance: continental glacier provenance–river transport (CR), mountain provenance–river transport (MR) and mountain provenance–river transport–desert transition (MRD) [1,4].

Central Asia (CA) extends to the Caspian Sea to the east of the Tianshan Mountains and is located at the eastern end of the dust belt [5]. The modern northern boundary of

Asia's summer monsoons can be divided into an approximate boundary of the westerly region and the monsoon region [6] (Figure 1). The Asian westerlies are located on the west side of mid-latitude Asia, and their extent is basically the same as that of arid regions of CA (marked with orange dotted lines in Figure 1). The region is characterized by an arid climate, sparse vegetation and a fragile ecological environment. It is a unique mountain basin structure with associated vertical divisions that include ice and snow, alpine meadows, forests, grasslands, oases, and deserts. The special topography of CA is a natural barrier and source of dust materials for the deposition of loess, and the area is affected by westerly circulation and basin circulation throughout the year, which is the main driving force of dust for the formation of piedmont loess. The loess in Siberia and CA are usually 10 to <200 m thick [4]. The Xinjiang loess is located in the arid region of CA and is an important part of CA loess. Compared with other loess distribution areas, the loess in this area is thinner and has scattered accumulation characteristics [7]. Loess is one of the most important archives of paleoenvironmental changes, including dust sources, temperature, precipitation, paleoclimatic variability and atmospheric circulation in CA [8–10]. The loess in arid areas of the Xinjiang and Chinese Loess Plateau (CLP) together constitute a rare terrestrial sedimentary record of the evolution of Asian continental climate and its dynamic correlation. However, due to the vague interpretation of indicators by regional differences in climate and topography, the Cenozoic climate and environmental changes in the arid region and their driving mechanism in Xinjiang are still under debate [11,12]. The inter-regional atmospheric circulation interaction between the mid-latitude westerly belt and the Asian monsoon circulation is controversial [6,11]. Furthermore, spatial–temporal distribution of CA loess deposits and their specific paleoclimatic implications have not yet been as clearly defined when compared to the substantial deposits at the western and eastern extremities of the eastern Eurasian loess belt, despite increasing research in recent years [7,13–16]. Therefore, the study of Xinjiang loess is helpful to understand basic scientific issues such as when and why the semi-arid environment in Asia was formed and its phase relationship with paleoclimate change in the East Asian monsoon region [17].

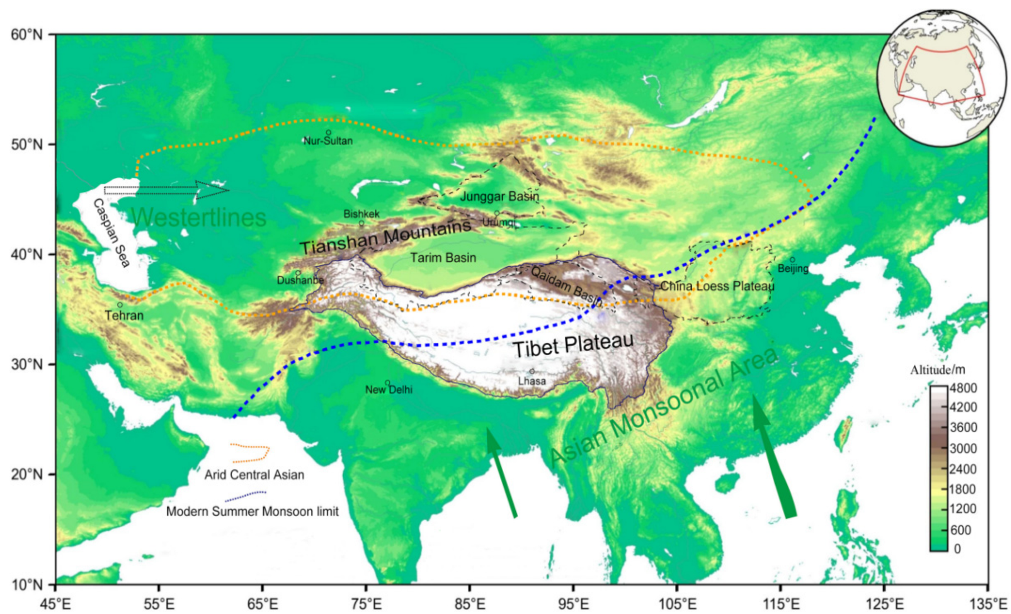

Figure 1. Topographic map of the Asian continent; the Asian continent CA be roughly divided into the Asian monsoon zone and the arid CA westerly zone including the northern Tibet Plateau (the orange dotted line) according to atmospheric circulation. The blue dotted line indicates the modern limits of the Asian summer winds (modified after [11]).

Determining the sources of loess and the mechanism of loess accumulation is crucial for loess dust source research [18]. CLP has been the focus of the investigation of loess provenance based on geochemistry, mineralogy, meteorological observation and modeling [19]. However, as of yet, the provenance of the Xinjiang loess is largely unknown and is mostly inferred. Loess research started relatively later in Xinjiang. Over the past several decades, great efforts have been put into extracting paleoclimate information from different geological archives (e.g., loess, lacustrine sediment, peat and stalagmite) in the Xinjiang area, and much progress has been made about how and why climate changed during the Cenozoic in this region. The main study area has included the Ili Basin [20–22], northern Kunlun Mountains [23] and North Tianshan Mountains [24–26]. Many studies have focused on loess deposits and have explored different issues. For example, to study provenance of loess, authors have used elemental geochemistry [9,27] and heavy mineral assemblage [2,28]. For paleoenvironment reconstruction, most researchers study pollen, magnetism, granularity, mineralogy and geochemistry [17,24,26,27]. A theoretical model for the genesis of the Xinjiang loess proposes that the fine-grained particles in the loess were produced by glaciers and rivers in the mountains, transported by rivers into desert basins, and then subsequently transported back onto the pediments. However, the provenance of Xinjiang loess is mainly inferred from the spatial characteristics of the grain size of loess or the present-day air circulation patterns [2,3,28]. Recent studies have suggested that loess deposits in the Ili Basin, eastern Central Asia, and the Afghan–Tajik Basin are dominated by proximal sources constituted by alluvial plains and local proluvial fans, whereas rare sediments rarely originate from the large deserts of CA [4,9,10,13,16]. The latest research shows that the Siberian High system largely controlled the mobilization of dust and the accumulation of loess in northern CA instead of southern CA [5]. Despite the large body of previous work, the provenance of loess deposits and the associated formation processes are poorly understood in Xinjiang [29]. Consequently, the provenance of Xinjiang loess is not well known and needs to be ascertained by further investigations. Xinjiang loess has an important value for understanding paleoclimate evolution and the westerly circulation. Based on the above considerations, this article systematically reviews recent research progress on the spatial distribution, material composition and provenance of loess in Xinjiang. The shortcomings of and challenges to current research on loess provenance in Xinjiang are analyzed. A favorable research basis and direction are provided for future research on dust sources, environmental changes and aridity in Xinjiang.

2. Materials and Methods

This review only focuses on the basic issues of the distribution and provenance of loess in Xinjiang and does not give a detailed introduction to the meaning of various indicators. Geochemical elements have been widely applied in the determination of the provenance of loess, and recently, much relevant research has explored qualitative and quantitative perspectives to understand the material sources of loess in CA [9,16,30]. Hence, this article restates the published article data for secondary citations. Basic material data for the Xinjiang loess include minerals [31–33], grain size [27,33–37], major elements [10,38,39], rare earth elements [13,27] (such as Rb/Sr, LREE/HREE, La_N/Sm_N, La_N/Yb_N, Gd_N/Yb_N, etc.), proximal material contribution ratio [10], etc. Samples were measured by an X-ray fluorescence spectrometer produced by Thermo Scientific company of USA to determine the content of major geochemical elements; a standard sample (GSS-8) was added to the experiment for calibration, and the measurement accuracy was $\geq$95%. Particle size was measured by a Mastersizer 2000 laser particle size analyzer of Malvern UK [27,33–37]. The dried whole rock samples of known weight and corundum powder with a purity of 99.99% were thoroughly ground and mixed in an agate mortar, and the main mineral content was measured [32] using an X'Pert Pro MPD poly-crystalline X-ray diffractometer (XRD) produced by PANalytical Company of the Netherlands; we used a copper target, Ni filter and super energy array detector with working tube pressure of 40 kV and tube flow of 40 mA [35]. All data cited in this article come from published articles and are reliable and scientific. Drawing software includes Origin (2021), PS (2022), CorelDRAW (2019), etc.

3. Loess Distribution in Xinjiang

Xinjiang (75–90° E, 35–45° N) is located in the center of Eurasia and covers an area of more than 1.6 square kilometers. Xinjiang is surrounded by the Tianshan Mountains and the Kunlun Mountains [40]. From north to south, it consists of the Altay Mountains, Junggar Basin, Tianshan Mountains (including North Tianshan Mountains, South Tianshan Mountains and Ili Basin), Tarim Basin and Kunlun Mountains (Figure 1). The Taklamakan Desert (330,000 km^2) and the Gurbantonggut Desert (48,800 km^2) are located in the center of the Tarim Basin and the Junggar Basin (Figure 2). CA is not only the main global dust source area, but it is also a loess accumulation area [29]. Regarding the climate system of Xinjiang, with the Tianshan Mountains as the boundary, most of the areas and the mountains of the northern Tianshan Mountains are mainly controlled by westerly circulation. However, the eastern Tianshan Mountains, eastern Junggar Basin and southern Tianshan Mountains are affected by different circulation systems with seasonal changes [29]. The distribution characteristics of the loess in Xinjiang are quite different from those of the loess in the CLP, namely the so-called 'piedmont loess', which is mainly controlled by terrain and wind circulation [3]. The loess in Xinjiang is attached to the bedrock of the windward slope of the Tianshan Mountains and the Kunlun Mountains. Loess strata develop mainly in the foothills of the desert edge of Tarim and the Junggar Basin and cover the northern and southern piedmont of the Tianshan Mountains, the western edge of the Junggar Basin and the northern Kunlun Mountains [1,17,29].

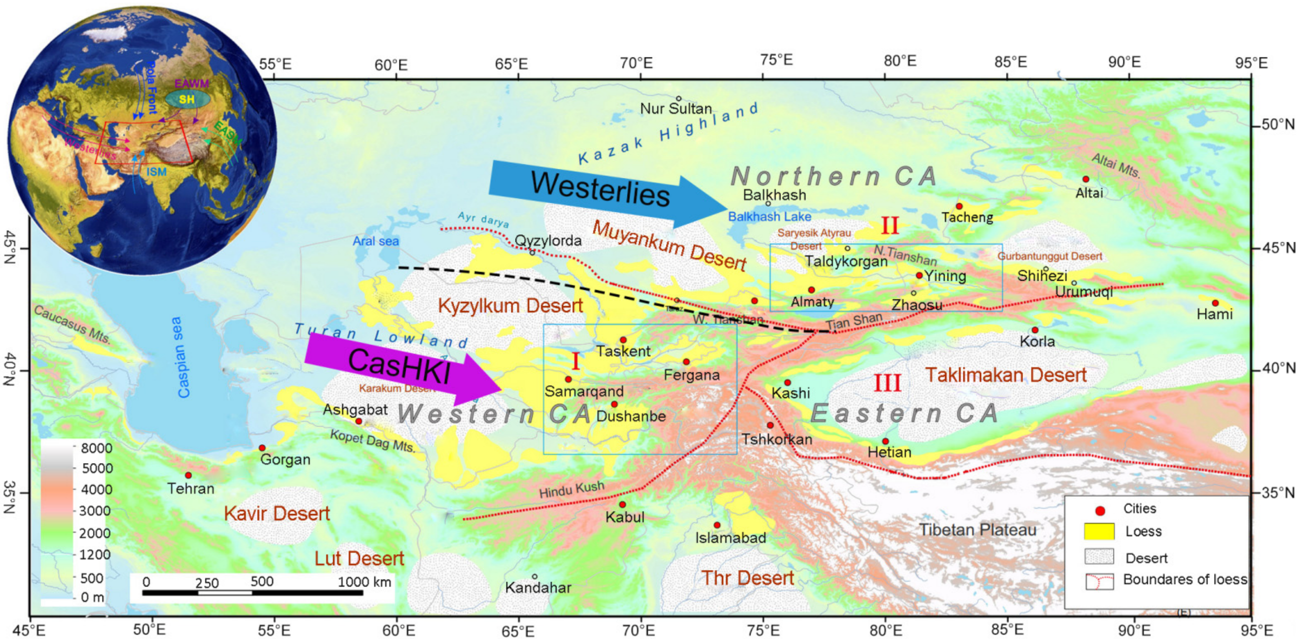

Figure 2. Spatial distribution of loess in CA (modified after [29]); Central Asia can be divided into two parts based on aeolian dust dynamics, with a boundary located in the North Tianshan Mountains and the south of Aral Sea, indicated by the black dotted line [5]. CasHKI refers to Caspian Sea–Hindu Kush Index; Westerlies refers to Siberian High Pressure.

From the perspective of a large region, Xinjiang loess is mainly distributed in the Tacheng area in the west of the Junggar Basin, the northern slope of the Tianshan Mountain, the Ili Valley region and the northern Kunlun Altun Mountain at the southern edge of the Tarim Basin [3,29] (Figure 2).

Recently, based on the composition of the loess, climate differences and topographic effects, the loess was divided into three subregions in the CA regions: Western (subregion I), Northern (sub-region II) and Eastern (subregion III) (Figure 2) [29]. According to this division scheme, the loess at the edge of the Tarim Basin belongs to subregion III, and the Ili Basin, Tacheng, Bole and the loess at the northern foot of the Tianshan Mountains are uniformly divided into subregion II. The division scheme is slightly different from the early Xinjiang loess division scheme proposed by Liu Dongsheng [36]. Combined with the above division, we found that the loess in Xinjiang is mainly deposited in river terraces, higher mountain terraces and open river valley regions [17].

The loess is widely developed in the Ili Basin. Loess research in the Yili Basin began earlier than in other areas in Xinjiang, and we have achieved rich research achievements in this region [21,22,28,35,41]. In the Ili Basin, loess covers the river terraces of the upper and middle reaches of the Ili River and its tributaries (Kunes, Tekes and Kashi Rivers) and extends across the edge of the deserts [26]. Paleosols are characterized mainly as light brown or taupe and are densely and weakly developed with white mycelium patches. Some loess–paleosol strata, especially at the bottom, contain gravel and sand, showing the characteristics of multiple genesis processes [10]. In the Ili Basin, loess is widely distributed on the river terraces from the southern slope of North Tianshan to the northern slope of the south Tianshan Mountains (Figure 2). The distinction between loess and paleosol in the western Ili Basin, with an arid climate and low altitude, is generally inconspicuous. On the second terrace of the Kashi River, the thickness of the loess is greater than 20 m at elevations of 1250–1700 m [15]. Previous survey data show that along the Ili Basin from west to east, the loess is a lens, and the grain size is gradually fine [3,28]. Horizontally, the distribution of the loess from the plain to the windward slope of the mountain front is the most concentrated and thickest, and few loess are distributed above the forest line [3]. The thickest loess sediment reported in the Ili Basin is approximately 202 m [3]. Field observations in recent years have shown that loess in the north forms a belt zone along the southern foothills of the Tarbagatai Mountains. The loess in the south is mainly distributed in the northern pediments of the Barluk Mountains at an elevation of 800–1200 m [18]. Loess sediments are also distributed between the Irtysh River and the southern slopes of the Altai Mountains [42]. The loess area of the Zhaosu basin is several meters to dozens of meters thick, covers the Tex River Terrace and the foothills of the Tianshan Mountains and ranges from 1300 m to 2100 m above sea level [43].

Along the southern edge of the Junggar Basin and the northern slope of the Tianshan Mountains, the loess is distributed in different geomorphic units (such as river terraces and piedmonts) from 700–2400 m above sea level. With increasing altitude, the loess shows the characteristics of lens distribution, and the loess thickens from the Junggar Basin to the south [3,29]. Although there is extensive loess deposition in the north of the Tianshan Mountains, the distribution is not continuous, and the thickness is not consistent [40]. To the west of Kuitun, the loess rapidly thins or even disappears, while the loess around Bole gradually thickens from west to east and is approximately 2 to 20 m thick on the Bortala River platform of the Bortala River [44]. The thickness of the loess sediment between Tacheng and Yumin in the western Junggar Basin is several meters to 30 m [27]. The loess sediments north of the Tianshan Mountains have a maximum elevation of about 2400 m, and most are between 1000 m and 1400 m [40]. Loess sediments spread from Kashi in the west to Ruoqiang in the east and constitute a loess belt to the northern slopes of the Kunlun Mountains between 1500 m and 4500 m [3,45]. Thin loess sediments occur sporadically between the Tarim River and the southern slopes of the Tianshan Mountains. Loess in this subregion is characterized by gray-to-light-grayish–yellow, homogeneous, coarse silt and fine sand. Pedogenesis is generally very weak; it is difficult to recognize paleosol layers in the field, but they can be distinguished with careful examination and by indicators [13]. In the broad and flat watershed of the Hotan–Kriya River, drilling core data show that the CA thickness reaches 670 m; above 3400 m, the loess suddenly thins, and the loess in the Kashgar and Pishan area is only 8–10 m thick [3]. New datasets on grain size and geochemical studies suggest that the Kunlun Mountains are the main source of the sand fraction, and both Kunlun and Tianshan Mountains are the main sources of the dust fraction [42,46].

4. Loess Material Composition of Xinjiang

Material composition and origin of loess provides basic information for the research of loess deposition and paleoenvironment reconstruction. In recent years, a lot of work has been carried out in Xinjiang loess, and this paper summarizes the aspects of mineral composition, grain size composition and geochemical composition.

4.1. Mineral Composition

As the main body of loess, minerals are undoubtedly important archives for paleoenvironment changes. However, the mineralogical study of the Quaternary sediments in Xinjiang is relatively weak compared to that of other proxies. Mineral composition analysis of loess in Xinjiang is mainly conducted using XRD (For details, see the Section 2). The results of analysis show that there are mainly detrital minerals, followed by carbonate and clay minerals, and a small amount of heavy minerals (generally less than 5%) [47]. The detrital minerals are quartz, feldspar and mica. The carbonate minerals are calcite and dolomite, and the clay minerals are mainly illite and chlorite. Some heavy minerals (such as pyroxene, amphibole, etc.) have also been found [47] (Figure 3a). The content of unstable minerals (such as plagioclase) in the Xinjiang loess is higher than in the Luochuan loess (Figure 3b). Magnetite in opaque minerals is one of the important factors affecting the change in magnetic susceptibility, implying that the magnetic susceptibility of the Xinjiang loess is lower than that of the CLP. Therefore, the loess in this area may be formed under weak pedogenesis. Feldspar minerals have high hardness and light color and are resistant physical weathering, but they are more chemically weathered than quartz and are unstable minerals. The content of feldspar in Xinjiang loess is significantly higher than that of CLP, which indicates that the chemical weathering of Xinjiang loess is weaker than that of CLP. Analysis of heavy minerals shows that the combination of heavy minerals in Xinjiang soil is similar to that of loess in the CLP [2,28,30]. The clay minerals in the loess of the CLP are mainly illite and contain a certain amount of chlorite and kaolinite, and the content of montmorillonite is less [36]. Clay minerals in Xinjiang loess are mainly chlorite, followed by illite [47]. Previous studies found that the amphibole/epidote ratio might serve as a proxy for wind intensity [13]. These mineral ratios provide new approaches to reconstruct paleoenvironmental changes. The main mineral content of the loess in various regions of Xinjiang is similar, but the differences in the mineral types are quite obvious, which may be due to the different sources of materials (Figure 3).

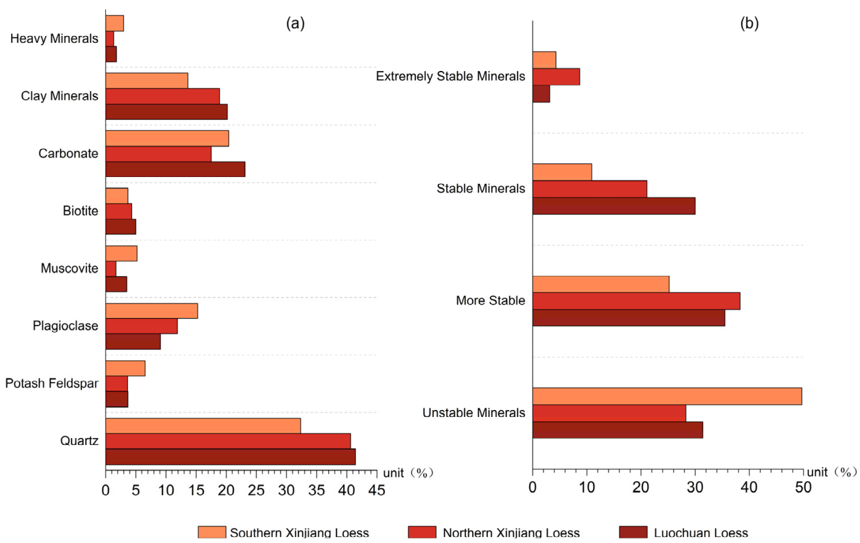

Figure 3. Comparison of the average content of different minerals between Xinjiang loess and Shaanxi Luochuan loess: (**a**) comparison of common minerals in Luochuan loess, northern Xinjiang loess and southern Xinjiang loess; (**b**) comparison of mineral weathering resistance between Luochuan Malan loess and Xinjiang loess [31–33].

4.2. Granular Composition

Grain size is the most common physical parameter used as a proxy for environmental change, especially for wind strength in aeolian sediments. Many achievements have been made in loess grain size research in Xinjiang. Various parameters deduced from grain size, such as median, mean, clay, sand, silt and ratios of different fractions, are employed to conceptually and practically reflect wind dynamics or distances from source-to-sink of the arid Xinjiang interior [9,10,27,34,48–51]. Particle size composition analysis shows that most of the Xinjiang loess is dominated by coarse silt particles, with an average particle size greater than 25 µm, while the CLP loess is dominated by fine silt (Figure 4b). This implies that the loess dust comes from inside the basin. The average grain size of the Xinjiang loess has good comparability within the region. The loess on the northern slope of the Kunlun Mountains is compared with the loess in the Yili Basin and the Junggar Basin. The former is composed of sand and silt with an average particle size greater than 30 µm, and the latter is mainly composed of silt and clay. (Figure 4a). This may be due to the composition of the granularity being affected by the regional paleoclimate, local geomorphology or near origin [27,37,51]. However, the main sources of aeolian sediments and the genetic relations among mountains, deserts and rivers in Xinjiang are still unclear.

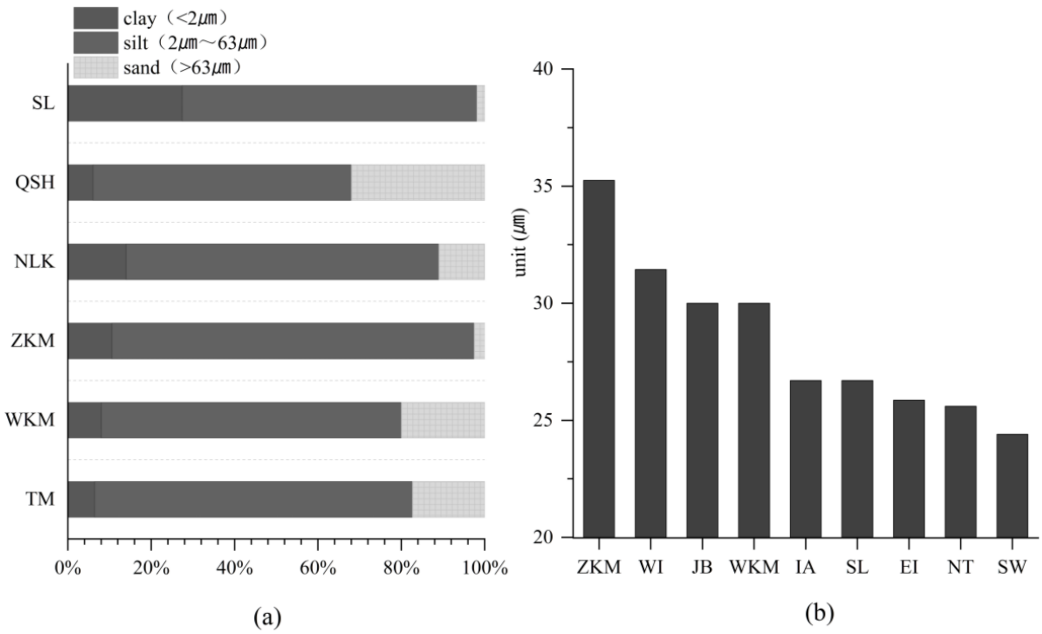

Figure 4. Comparison of loess grain size in different regions of Xinjiang: (**a**) comparison of grain size composition of loess sections in different regions (SL refers to Luochuan loess; QSH refers to Qingshuihe section in Ili Basin; NLK refers to Nileke section in Ili Basin; ZKM refers to the loess on the northern slope of the Central Kunlun Mountains; WKM refers to the loess on the northern slope of the West Kunlun Mountains; and TM refers to the North Tianshan Loess). (**b**) Comparison of average particle size of loess sections in different regions (SW refers to Shaanxi Wucheng Loess; NT refers to the loess of the North Tianshan Mountains; EI refers to the loess in the East of the Ili Basin; IA refers to the loess in the Ili area; WI refers to the west of the Ili Basin; and JB refers to the loess at the margin of the Junggar Basin) (data are from references [27,33–37]).

The Ili Basin is dominated by silt that contains a certain amount of fine sand, and the particle size is coarser than that of CLP. The sorting property is worse than that of the CLP; the content of sand is less, but the content of clay is slightly higher than that of the CLP. The loess of Ili Basin is mainly composed of silty sand and contains a certain amount of fine sand. The grain content of the sand is low, and the loess content is slightly higher than that of the CLP [28,52]. The components of the end-membrane of different grain sizes in the Ili Basin indicate different meanings. For example, the component of the end-member grain size of 21.22 μm represents a relatively stable background value in atmospheric dust, and changes in content are related to the intensity of the upper-altitude westerly circulation [49]. The suspension transport component of CA material can be considered a relatively sensitive paleoclimate indicator, and 47.5 μm is also a suspension transport component of close range [49]. The grain size of the loess and paleosol in the CLP can be used as a better indicator of the intensity of winter monsoons. However, the generally weak pedogenesis in the Ili Basin has little contribution to the production of fine-grained components, which are sensitive indicators of long-distance transport of dust particles. Therefore, it is considered to be a reliable indicator of the strength of the westerly [10,53,54]. The grain size composition of the loess on the northern slope of the Kunlun Mountains is relatively uniform, and the fine particle content is relatively small. The change in the grain size of the loess in this area is considered an indicator of the degree of drought [37,55–57].

The grain size composition of the loess in the north Tianshan Mountains is mainly silt, which is a typical aeolian sediment. The environmentally sensitive grain sizes are <31.7 μm and 31.7–282.5 μm, which may represent the accumulation of dust after storms and wind transport close to storms. For sediment composition in this area, the trend of finer grain size in the longitudinal direction is related to the classification of sediment particles caused by topography. In the southern margin of Tarim Basin, a higher coarse size fraction (>30 μm) in loess sediments was regarded as indicating stronger westerlies and increased aridity, while fine size fractions (<20 μm) are mostly transported by the upper-level westerly jet to more remote regions [9,27,50]. Therefore, when we discuss the implications of grain size proxies, we should pay attention to the effects of local landform, regional and global atmospheric circulation on grain size proxies.

4.3. Major Element Geochemical Composition

The composition of the major elements of loess in different regions of Xinjiang is similar, and difference in geochemical composition between the loess and paleosol layers are not apparent, whereas they are obviously different that that of CLP [9,21,38,58]. Study of geochemical data shows that the content of Si, Al and Ca in loess in the dry and arid regions of Xinjiang are higher. From SiO_2, Al_2O_3, CaO, Fe_2O_3, MgO, K_2O to Na_2O, the oxide content of major geochemical elements in loess decreases sequentially, which is similar to the average percentage of UCC (Upper Continental Crust, (UCC)) average content percentages. Compared to Shaanxi loess, the content of MgO, Na_2O and K_2O in Xinjiang loess is slightly higher, and the Fe_2O_3 content is lower. The Xinjiang loess was also found to contain a small amount of S, but the Shaanxi loess has little or no content [47]. The composition of other major elements is similar to the Shaanxi loess. Compared to the average value of UCC, the content of Al in Xinjiang loess is similar to UCC, while Ca, K and Mg elements in some sections are relatively enriched, and Si, Na, and Fe in some sections are slightly depleted (Figure 5a). Among them, the enrichment of Mg and Na in the Ili loess section is mainly due to the relatively dry climate of the basin, and the active chemical elements are not easily leached (Figure 5b). Generally speaking, higher K content in the stratum reflects a humid climate and more precipitation. By contrast, this indicates that precipitation is reduced and the climate is dry. The K element in the loess section of northern Xinjiang is more enriched than in the loess section of the west Kunlun Mountains in southern Xinjiang. This shows that the climate of northern Xinjiang is relatively humid compared to that of southern Xinjiang (Figure 5a,b). The content of SiO_2, Al_2O_3, Fe_2O_3 and Na_2O in the loess section of the West Kunlun Mountains is relatively lower, while the content of CaO and MgO is higher. This means that the loess in this area was formed in an arid climate (Figure 5d). In a word, the loess deposits in Xinjiang have distinctive local or regional geochemical characteristics.

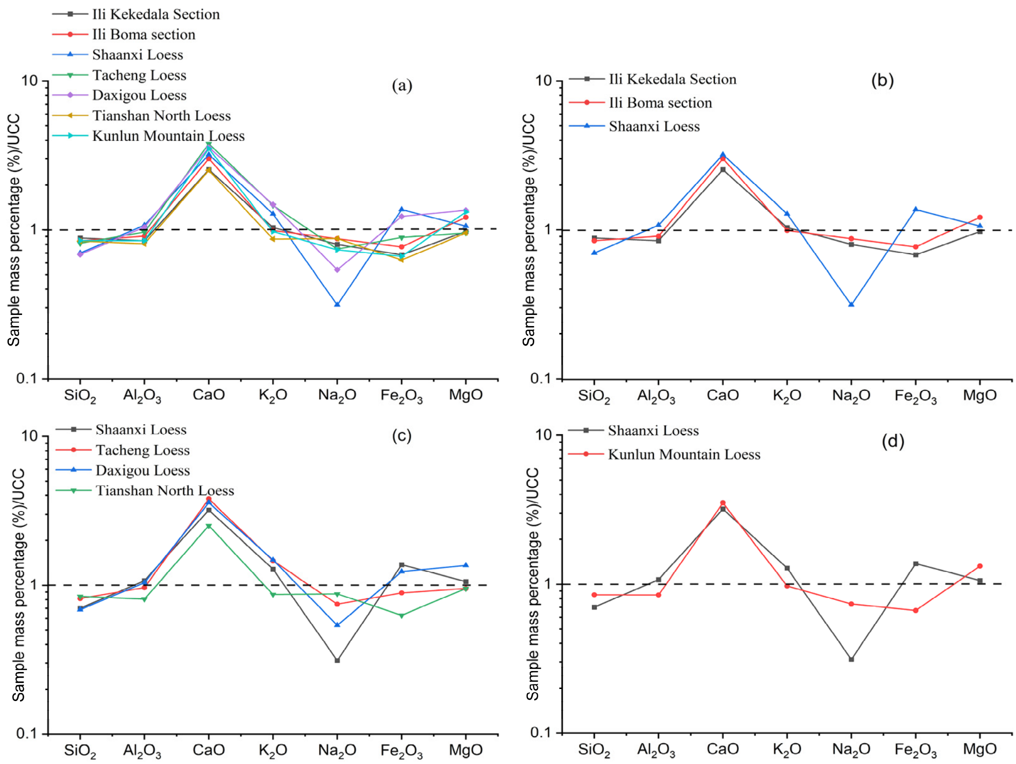

Figure 5. UCC standardization mode of major elements in Xinjiang loess and Shaanxi loess (data from references [10,38,59]). (**a**) Comprehensive comparison of UUC standardization model of major elements between Xinjiang loess and Shaanxi loess, (**b**) UCC standardization model of the average content of the main elements of the Kekedala section and the Boma section in the Ili River Valley is compared with the UCC standard model of the average content of Shaanxi loess, (**c**) UCC standardization model of the average content of the main elements of Tianshan Mountains loess, the Tacheng loess and the Daxigou loess is compared with the Shaanxi loess, (**d**) UCC standardization model of the average content of the main elements of the loess in the Kunlun Mountains is compared with the Shaanxi loess.

5. The Provenance of Loess Deposits in Xinjiang

Tracing the dust sources of Xinjiang loess helps to better understand atmospheric circulation patterns, transport paths and deposition processes of aeolian dust in CA. Abundant achievements have been made on provenance of loess in Xinjiang [5,13,18,49]. With the application of new technologies and indicators in provenance research, provenance of Xinjiang loess has also made new progress [4,5,9,16,49,60]. Some early researchers emphasized that main sources of dust in the Xinjiang loess are adjacent deserts [29,40,44]. However, this view is mainly inferred from geomorphology, atmospheric circulation, grain size and mineralogical properties. There was a lack of evidence from more reliable indicators. In recent years, methods of loess provenance research in Xinjiang have made great progress. In loess provenance tracking studies in the Ili Basin, North Tianshan Mountains and Tarim Basin, elemental geochemistry [9,13,27], heavy mineral assemblage [2,28,30], analysis of rare earth elements (REE) [16,41,61], and even various provenance tracking models have been used: for instance, Bayesian grain size end-member models [35,49], GLUE models [4], Monte Carlo models [10], etc. Among them, research on the provenance of loess in the Ili Basin and the North Tianshan Mountains is relatively abundant and uses various research methods, while research data on the provenance of loess in other regions are rare. Because loess in different regions of Xinjiang is affected by different atmospheric circulation and local circulation, loess sediments in the northern Tianshan Mountains have almost no similarities with those of the southern Tianshan Mountains [5]. Therefore, it is necessary to discuss loess provenance issues in different regions separately.

For provenance of loess in the Ili basin, it is inferred from topography, wind circulation and sediment particle size distribution that loess materials in the Ili area are likely to come from the CA desert in the west and from westerly transported dust to the Ili basin [3,40]. Recently, provenance tracking has been carried out by means of element geochemistry, heavy mineral assemblage, and REE analysis. Trace elements and REE have been shown to be powerful tools for studying the dust source of loess [62]. Rb is mainly concentrated in mica and potassium feldspar, while Sr is mainly found in calcium-bearing minerals such as plagioclase and carbonate minerals. Rb typically remains immobile during weathering and Sr is characterized by high mobility during genesis because these minerals differ in their resistance to weathering. Therefore, the Rb/Sr ratio can reflect the intensity of weathering and pedogenesis in the loess–paleosol sequence [62]. Trace element and REE studies in the Ili Basin found no correlation between Rb/Sr, ΣLREE/ΣHREE, La_N/Sm_N, La_N/Yb_N and Gd_N/Yb_N (Figure 6). Therefore, the influence of post-prepositional pedogenesis on loess geochemistry can be excluded. The sedimentary recovery of the Ili loess is not good, so loess provenance is likely to come from the interior of the basin [27]. The Zr/Hf ratio of the samples from potential source areas further proves that local sediments in the Ili Valley can be used as the proximal provenance of Ili loess. The relatively closed environment of Ili Basin greatly reduces massive input of distant dust (Figure 2).

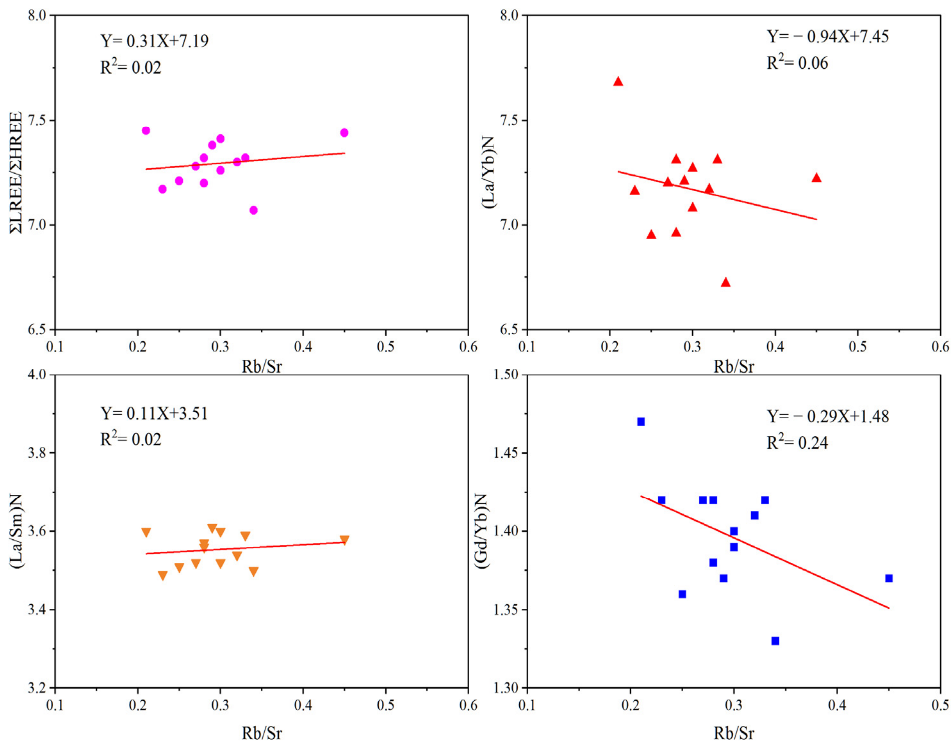

Figure 6. Correlation analysis of Rb/Sr, LREE/HREE, La_N/Sm_N, La_N/Yb_N and Gd_N/Yb_N of loess in the Ili Basin (subscript N indicates the normalized value of chondrites; data from [27]).

Ili loess is composed of proximal and distal sources. The study of the composition of potential provenance in the basin shows that there are various dust sources in the Ili loess. The provenance area is not only the arid deserts, but alluvial, bedrock and loose material on the inner surface of the basin are also potential sources of loess [2,10,35]. Recently, semi-quantitative analysis and elemental geochemical methods have been used to study local sediments and distant materials in the basin. The materials of the Ili loess near sources are found to be dominant in all areas of the valley, and the local topsoil contributes a great amount to the Ili loess (approximately 54–90%), while the CA deserts contribute little to the deposits of Ili loess [4,10,27].

The proximal end of Ili Valley has different material contributions, among which alluvial sediments have the largest contribution, followed by modern riverbed sediments, and finally, modern surface dust and loose sediment make less of a contribution [2,9,10]

The proportion of the modern riverbed sediment contribution in the east of Ili is significantly lower than that of the Zhaosu Basin. However, the proportion of dust and topsoil contributions is the highest in the west of Ili and lowest in Zhaosu (Figure 7a–c).

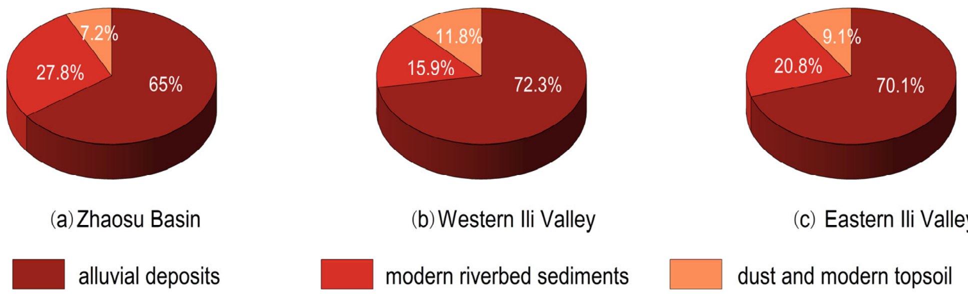

Figure 7. The contribution ratio of near-source materials in the Ili Valley to loess sediments in different regions (data from [10]).

Regarding the provenance of the loess in the Tacheng Basin, the Northern Tianshan Mountains and the Kunlun Mountains, for the early stage, based on particle size distribution, meteorological observations and geomorphology, it is speculated that the Sary–Ikshikotrau Desert is the main provenance of the Tacheng Basin [44]. The main sources of loess in the north Tianshan and Kunlun Mountains are the Gulbantonggut Desert and the Taklamakan Desert [41]. Recently, some scholars have carried out elemental geochemical analysis of topsoil and alluvial at the margins of the Tacheng Basin, North Tianshan Mountains and Tarim Basins. The results showed that long-distance transport components contribute less to the loess at the edge of the basin, but the loose sediments in the piedmont slopes and flood plains around the basin are the main dust sources for the loess north of the Tianshan Mountains. Trace element and REE analysis data from the loess in North Tianshan show that there is no good correlation between Rb/Sr, ΣLREE/ΣHREE, La_N/Sm_N, La_N/Yb_N and Gd_N/Yb_N [13]. It also implies that the weathering and pedogenesis of the loess in North Tianshan is weaker, and it is likely that the dust comes from the interior of the basin. This view is consistent with understanding the provenance of loess in the Ili basin [13]. Thus, loess in the Ili Basin and northern Tianshan Mountains formed a relatively arid environment.

Therefore, the provenance and formation of Xinjiang loess are largely dependent on local topography and dust dynamics. The different sources of loess sediments in the northern and southern Tianshan Mountains in CA can also be attributed to different atmospheric dust dynamics related to the climate circulation system in different seasons. The atmospheric dust dynamics in different regions of Xinjiang need to be further explained, because the differences in provenance are related to the dynamics of aeolian dust [9,63].

Recently, a new understanding of dust dynamics in CA has been presented, and CA can be divided into two parts in terms of wind dust dynamics. The boundary is located in the north at the Tianshan Mountains and in the south at the Aral Sea. According to the latest research, we can find that loess accumulation in southern CA is mainly determined by the Caspian Sea–Hindu Kush Index (CasHKI) [5]. However, understanding CasHKI is not enough, and much research is needed on the impact of the index. Little attention has been paid to the source and formation mechanism of loess dust at the piedmont of Kunlun Mountains. The current understanding of the provenance of loess at the edge of Tarim is consistent with that in the northern Tianshan Mountains and the Ili Basin. Remote materials contribute less to loess at the edge of the basin, and topsoil and piedmont materials in the basin are the main dust sources for loess formation. However, it has not yet been verified whether the distant source material comes from the CA desert or the Junggar Basin. The Tarim Basin is a relatively closed and arid region, and whether the dust dynamics of its marginal loess is controlled by CasHKI has not been fully discussed. Therefore, the focus of the next provenance research is to carry out quantitative or semi-quantitative research on the potential provenances of loess at the edge of Tarim Basin (such as alluvial deposits and loose sediment on the piedmont slopes) to determine the contribution ratio of potential provenances to piedmont loess.

Numerous indicators show that provenance of loess in Xinjiang has multiple sources, including loose surface sediment, alluvial deposits, surrounding mountains and adjacent deserts. Among them, alluvial deposits and loose sediment on piedmont slopes contributed more to piedmont loess deposition, while the adjacent deserts provided less material for loess.

6. Discussion

Loess in the arid area of Xinjiang is one of the important distribution areas of CA, and its loess records valuable paleoclimate information. Although existing research on loess provenance and paleoenvironmental indicators in Xinjiang has made great achievements, there are still many scientific issues and debates that have not been resolved. Therefore, a lot of research is still urgently needed.

Loess sediments in the arid area of Xinjiang are mainly distributed in the piedmont and river terraces of high mountains, such as the Tianshan Mountains and Kunlun Mountains and the river terraces of the Ili Valley. We found that the dust accumulation of Xinjiang loess is different from that of loess in the CLP. The Xinjiang loess deposits at some locations are rapid and discontinuous, which requires caution in the interpretation of the proxies and paleoenvironment. Previous chronostratigraphic data of Xinjiang loess and our field investigations indicated that most loess outcrops have developed since the last interglacial–glacial period. Xinjiang loess deposits could span the entire Quaternary and even extend into the Pliocene [29]. There is no consensus on the reliability and precision of the various dating methods for CA loess. For example, although many researchers have investigated the Zeketai (ZKT) loess, which was considered in the 1980s as important loess sediment in Xinjiang, similar to the Luochuan loess section in the CLP, its ages are still under debate [5]. The discontinuous distribution of Xinjiang loess may be related to the complex topography and atmospheric circulation in CA. The recently proposed loess division scheme for the arid region of CA divides the CA loess into three subregions [29]. According to this scheme, we can divide the Xinjiang loess into the southern loess and the northern loess, with the southern Tianshan Mountains as the boundary. However, this division scheme is not consistent with the recently proposed division of different dust dynamic zones in CA. However, this division provides us a new clue to understanding the regional differences of climate and environmental changes, and we should be cautious with paleoclimate reconstruction in such complex natural conditions.

Comparison of material composition shows that loess in this area has similarities and differences with the CLP with regard to mineral and major element compositions. For example, in terms of particle size composition, the loess in Xinjiang is relatively coarse compared to that of the CLP. This aspect supports that Xinjiang loess is dominated by proximal materials. In terms of mineral composition, the content of stable minerals, epidote minerals and opaque minerals in the northern loess is significantly higher than in the southern loess. On the one hand, this implies that loess in different regions of Xinjiang have different dust sources, and CLP and Xinjiang loess dust may come from different areas. Analysis of trace and main elements showed that piedmont loess in Xinjiang was formed in an arid environment.

In recent years, the understanding of loess provenance in Xinjiang has developed from single-source to multi-source. Previous paleoclimatic studies directly linked dust depositions in the CA region with westerlies [64–66]. However, mountain ranges in CA lead to variable climate and atmospheric circulation patterns from site-to-site [13,67]. Therefore, some debate is now being raised about whether it is possible to simply link the intensity of dust activity to the westerlies in CA. Through investigation of trace element geochemistry, loess deposits from pediments of CA mountains have been found to be dominated by proximal sources. Overall, they are of different origins in the north and south parts of the Tianshan Mountains. This provenance feature was associated with aeolian dust dynamics rather than CA topography [11,12]. Comparisons of grain size data of loess sedimentary sequences from CLP, Northern CA and Southern CA support the argument that the Siberian High system played a vital role in controlling dust mobilization in Northern CA, whereas it was not atmospheric dynamic processes responsible for loess deposition in Southern CA [5] (Figure 2). From this point of view, the Siberian High system controls the loess deposits in the northern Xinjiang region, including the Ili Basin, the Junggar Basin and the Tacheng Basin. Loess deposits at the edge of Tarim Basin may be controlled by local circulation and the CasHKI index. However, the reasons for the variation in CasHKI intensity represent future challenges [5].

Recent semi-quantitative research on provenance shows that the provenance of Xinjiang loess has multiple dust sources, including loose surface material, alluvial deposits, surrounding mountains, and adjacent deserts [9,12,13,16]. The adjacent deserts and CA deserts contributed less to the deposition of loess in the arid area of Xinjiang, but topsoil and alluvial deposits in the basin were the main sources of loess. The Xinjiang Junggar Basin, Tarim Basin and Ili Basin are all relatively closed environments, so this closed system does not allow the formation of large-scale loess pushing. From this point of view, the spatial distribution and dust sources of loess in arid areas of Xinjiang may be mainly controlled by local circulation and westerly circulation. All these methods suggest that the proportion of proximal materials of aeolian loess sediments in the Ili Basin or North Tianshan piedmont was higher than the previous conventional erosion–transportation–sediment model [42,46]. However, the contribution of Kunlun Mountains and Tianshan Mountains to the deposition of loess at the edge of Tarim Basin is not known for the time being.

Tracking of the provenance of loess in Xinjiang is of great significance for the reconstruction of past atmospheric circulation and the environmental evolution of the source area, and it is also the basis for understanding the basic process of loess formation and many paleoclimate indicators. Therefore, future research on provenance of loess in Xinjiang should be carried out from two aspects. First, it is necessary to further study the contribution rate of potential loess sources on the edge of Tarim Basin to loess deposition, such as quantitative or semi-quantitative research on alluvial deposits, sedimentary rocks and loose surface sediment in the basin. Whether the CasHKI index affects the climate circulation system in Tarim Basin needs further proof. Secondly, the connection between mid-latitude westerlies, CasHKI index and loess deposition and its spatial distribution has not been fully discussed and is one of the important subjects of future work. Finally, Sr–Nd isotopes, which are commonly used indicators for provenance tracking in CLP, and single minerals such as the U–Pb ages of detrital zircon are rarely used in the study of provenance of loess in Xinjiang. Therefore, it is necessary to constantly try new technologies and new methods in future provenance research to facilitate an objective understanding of the provenance of loess in Xinjiang.

7. Conclusions

Based on the previous literature, this article summarized the distribution, material composition and provenance of loess in Xinjiang and discussed the dust dynamics and provenance.

The latest field surveys and observations show that loess sediments in the arid area of Xinjiang are mainly distributed in the piedmont and river terraces of high mountains, such as the Tianshan Mountains and Kunlun Mountains and the river terraces of the Ili Valley. Elemental geochemical data show that the Xinjiang loess experiences poor sedimentary recycling with the main local sources. Alluvial sediments are the most important potential sources for northern Xinjiang loess. However, no quantitative research has been carried out on proximal materials of loess deposits in southern Xinjiang so far, which is an important direction for future work.

The Siberian High system controls dust circulation in the northern Xinjiang region, including the Ili Basin, Junggar Basin and Tacheng Basin. However, dust circulation of the southern CA may be controlled by local circulation and the CasHKI index. However, the Tarim Basin is a relatively closed environment. Whether the CasHKI index affects local circulation in this region through the Pamir Plateau needs to be fully discussed and studied. Consequently, ascertaining the dynamic processes linked to mid-latitude westerlies that drive changes in aeolian loess deposition in Xinjiang is our specific recommendation for future critical research.

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