Accepted Manuscript

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PII: S0012-8252(17)30201-5
DOI: doi:10.1016/j.earscirev.2017.11.005
Reference: EARTH 2518

To appear in: *Earth-Science Reviews*

Received date: 17 April 2017
Revised date: 6 November 2017
Accepted date: 7 November 2017

Please cite this article as: J. Vandenberghe, Y. Sun, X. Wang, H.A. Abels, X. Liu , Grain-size characterization of reworked fine-grained aeolian deposits. The address for the corresponding author was captured as affiliation for all authors. Please check if appropriate. Earth(2017), doi:10.1016/j.earscirev.2017.11.005

Grain-size characterization of reworked fine-grained aeolian deposits

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Abstract

After a previous review of the grain-size characteristics of in situ (primary) fine-grained aeolian deposits, reworked (secondary) aeolian deposits, as modified in lacustrine environments and by alluvial and pedogenic processes, are discussed in this paper. As a reference , the grain-size characteristics of primary loess deposits are shortly described. Commonly, pedogenesis and weathering of primary loess may lead to clay neoformation and thus to an enrichment in grain diameters of 4-8 µm, a size which is comparable to the fine background loess. Remarkably, the modal grain-size values of primary loess are preserved after re-deposition in lakes and floodplains. But, secondary lacustrine settings show a very characteristic admixture with a clayey population of 1-2,5 µm diameter due to the process of settling in standing water. Similarly, alluvial settings show often an addition with coarse-grained sediment supplied by previously eroded sediment. However, floodplain settings show also often the presence of pools and other depressions which behave similarly to lacustrine environments. As a result, alluvial secondary loess sediments are characterized by the poorest grain-size sorting when compared with the other secondary loess and primary loess. Despite the characteristic texture of each of these deposits, grain-size characteristics of the described individual sediment categories are not always fully diagnostic and thus grain-size analysis should be complemented by other information, as sedimentary structures and fauna or flora, to reliably reconstruct the sedimentary processes and environments.

Keywords: grain size, aeolian, loess, reworked loess

Introduction

Dust transport is determined by atmospheric circulation and thus dust records can be appropriate indicators of palaeoclimatic conditions. Grain size is a prominent property of aeolian sediments that is a dominantly controlling variable of sedimentation processes, despite the fact that the grain-size distribution is a complex function of wind dynamics and other environmental conditions such as source material, vegetation, topography and microclimate, apart from the potential influence of post-sedimentary processes. Especially the grain-size distribution of fine-grained aeolian sediments appears to be an appropriate property for process reconstruction (e.g. Tsoar and Pye, 1987; Derbyshire et al., 1998; Nilson and Lehmkuhl, 2001; Vandenberghe et al., 2006; Weltje and Prins, 2007; Prins et al., 2009; Vriend et al., 2011; Stevens et al., 2011; Markovic et al., 2012; Vandenberghe, 2013; Licht et al., 2014; Nottebaum et al., 2015; Krauss et al., 2016; Obreht et al., 2016; Sprafke and Obreht, 2016; Ujvari et al., 2016). Different grain-size populations in primary (in situ) dust deposits have been related to different sedimentation and transport processes (e.g. Pye and Zhou, 1989; Pye, 1995; Stuut et al. 2009). Aeolian process reconstructions, however, do not only pertain to direct dust fall, but also to the reworking of the primary dust by (secondary) surface processes (e.g. Lehmkuhl, 1997; Vandenberghe et al., 2012; Ijmker et al., 2012; Meszner et al., 2014). In case of reworking, the linkage of a specific grain-size distribution to a corresponding transport and deposition process has still to be determined more precisely.

The use of grain-size distributions for palaeoenvironmental reconstructions is certainly not new, as sedimentologists as Folk (1966) and Doeglas (1968) used it already half a century ago. However, renewed interest in primary and secondary aeolian reconstructions is now favored by instrumental progress in grain-size measurements and methodological novelties. At first, since the early work of McCave et al. (1986) and Syvitski et al. (1991) laser diffraction replaced the traditional dry and wet sieving and settling devices. Laser diffraction enables to determine the grain-size distribution of a sample with considerably more detail and considerably increases the measurement speed, especially for fine-grained sediments, thus multiplying manifold the number of analyses (e.g. Konert and Vandenberghe, 1997; Beuselinck et al., 1998; Buurman et al., 2001; Goossens, 2008). Secondly, different grain-size populations within the bulk data may be separated and quantified for their modal size and relative proportion, for instance by end-member modelling (e.g. Weltje, 1997; Weltje and Prins, 2007) and Weibull distribution modelling (e.g. Sun et al., 2002). Such statistical treatment of large datasets enables substantial progress in the sedimentological and geomorphological interpretation of the depositional conditions (e.g. Dietze et al., 2012; Ijmker et al., 2012; Varga et al., 2017; references cited above).

Post-depositional modification of original primary loess may be physical or chemical. Physical processes often occur by the agency of water, including transport by rivers and runoff and re-deposition as alluvia in floodplains or fans and deltas, potentially followed by sorting (e.g. Visher, 1969), but also dispersion and settling in lakes (e.g. Houbolt and Jonker, 1968; Torres et al., 2005; Xiao et al., 2012, 2015). Or, physical modification may occur merely by gravitational forces, mainly represented by different kinds of mass movement. Chemical modification is often supposed to be caused by in-situ weathering in soils, sometimes accompanied by short vertical transport and re-deposition of colloids and clay minerals (e.g. Bronger and Heinkele, 1989; Kemp, 2001). Although traditionally many authors accept that secondary clay minerals are strong indicators for chemical weathering processes (e.g. Mason et al., 2003; Stevens et al., 2011; Sprafke and Obreht, 2016;

Schulte and Lehmkuhl, 2017), it may be mentioned that the amount of pedogenic clay in loess palaeosols is still debated.

It may be assumed that all those processes had a definite impact on the grain-size distribution of the reworked (secondary) sediments when compared with their primary equivalents. For the palaeoenvironmental reconstructions, the challenge is to investigate to what degree the grain-size characteristics of the original windblown material was changed by secondary processes. Will the original grain-size signature be preserved or drastically changed by weathering, dilution, dispersion or sorting that accompany those secondary processes? In other words, can the primary windblown process still be recognized or is the imprint of the secondary process the dominant one?

In a previous review, Vandenberghe (2013) focused on the grain-size characteristics of primary loess, it means the purely windblown fine-grained material, while the reworked (secondary) loess was only shortly described. In that study, the characteristic grain-size distributions of specific primary aeolian populations were defined and their respective processes and conditions of transport and deposition interpreted. Here, most attention is paid to the post-depositional processes that took place on the primary dust. In particular, the impact on the grain-size distributions by each of those secondary processes is discussed. Once such process- grainsize relationships are known and understood, they may significantly contribute to the identification of the different processes of reworking. Such a comparison needs at first a short summary of the different processes of primary loess transport and the related grain-size characteristics. In this way, we aim to demonstrate how the grain-size distributions of the different kinds of secondary loess may be distinguished from those of the primary loess. The ultimate objective of the present overview, in combination with the previous one by Vandenberghe (2013), is to provide grain-size properties as an appropriate tool for the reconstruction of most (fine-grained) primary and secondary aeolian sedimentary environments. However, it will be shown that grain-size characterization will always have to be supplemented with additional arguments to arrive at a confident reconstruction of sedimentary environment and processes (Lehmkuhl et al., 2016).

Methods and approach

The individual (sub-)environments were selected from sites where the depositional processes could be established with sufficient certainty. For that purpose other information, as sedimentary structures, physico-chemical properties, geomorphological position and experiments, was used. Also published archives were used in addition to a few new ones. In accordance with availability and properties of the source material, specific sediment transport processes were characterized by their typical energy conditions and values which are reflected in the respective grain-size distributions of that sediment. For a description of the numerous individual sites we refer to the original publications .

The samples were prepared according to the methods described originally by Konert and Vandenberghe (1997) or slightly modified. A few grams of sediment were pre-treated with H_2O_2 and HCl to remove organic matter and carbonates respectively. It means that the pure siliciclastic fraction was measured. All samples were analysed with a laser particle sizer (a Fritsch Analysette 22 or HELOS from SYMPATEC in Amsterdam, a Malvern equipment in Nanjing and Xian). A grain-size distribution shows up with 56 size classes in the range between 0.15 and 2000 µm. Goossens (2008) and Roberson and Weltje (2014)demonstrated by very detailed comparative analyses that there is no significant difference of results between different laser equipment. Analyses presented here were carried out at the institutes of the authors, and derived mostly from China and Europe and occasionally from South America and compared with results from other locations.

(Sub)populations are primarily characterized by their modal grain-size and the relative proportion of specific grain size intervals (e.g. clay or sand fraction). Often, the U-ratio is successfully applied to indicate the proportion of medium and coarse-grained silt (44-16 µm) versus fine-sized silt (5.5-16 µm) (Vandenberghe et al., 1985). It is especially applied when the pedogenic clay should be eliminated for depositional interpretation purposes. Recently, Schulte and Lehmkuhl (2017) showed how laser diffraction calculations of grain-size distribution obtained by two optical models enable to determine the enrichment of fine-grained material by post-depositional chemical weathering.

Most sediments are mixtures of several subpopulations. As a consequence, parameters of bulk sediments are less informative in those cases. In general, two methods may be applied to identify the composing subpopulations of a bulk sample. The first one is based on the visual inspection of grain-size distribution curves. This analysis, however, is qualitative and only successful when the individual subpopulations are sufficiently different from each other. The second method uses statistical decomposition analysis which has the principal advantage to be quantitative. It has turned out to be well suited to the unmixing of fine grain-size distributions, as exemplified by, for instance, Prins and Weltje (1999), Vriend and Prins (2005), Prins et al., (2007), Dietze et al., 2012; Ijmker et al., 2012 and Liu et al. (2016). A first end-member modeling technique is based on a numerical-statistical inversion technique (Weltje, 1997). A second method of end-member decomposition uses parametric curve-fitting procedures (Sun D. et al., 2002, 2004). Despite theoretical differences, it has been shown recently that both methods in practice lead to similar results (Liu et al., 2016; Ujvari et al., 2016; Varga et al., 2017). In this paper, we apply both approaches and compare them with analyses from other studies. Occasionally, cluster analysis has been applied.

Summary of primary aeolian deposition from suspension clouds

In the present paper, the primary silt-sized, aeolian dust supply is only described as a reference for the reworking (secondary) processes; for more details we refer to Vandenberghe (2013). Besides fine-sandy deposits transported by saltation (type 1.a), two main populations of primary windblown loess transported in suspension were recognized according to their grain-size distributions: one is dominated by medium-to-coarse silt (type 1.b), and the other is mainly composed of fine silt to clayey silt (type 1.c). Each population reflects specific aeolian transport conditions. A few examples are represented in Fig. 1.

The grain size of loess type 1.b varies between 25 and 65 µm, which is transported in short-term, near-surface to low-suspension clouds (Tsoar and Pye, 1987) probably during cyclonal dust storm outbreaks in spring time, especially in cold conditions. It may be the product of episodic suspension fall-out of moderate-to-coarse dust supplied by surface-level, often monsoonal wind (e.g. northwestern winter monsoon in China) (Zhang et al. 1994, 1999; Prins et al., 2007). More specifically, type 1b may be subdivided in three subgroups with modal diameters of 51-60 µm (type

1.b.1), 35-40 µm (type 1.b.2) and 25-31 µm (type 1b.3) (Vandenberghe, 2013). Subgroup 1.b.2 is the most common one and globally dominating in most primary loess sediments (e.g. Rousseau et al., 2002; Antoine et al., 2009; Bokhorst et al., 2011, Novothny et al., 2011 and Vandenberghe et al., 2014 in central and east Europe; Prins et al., 2007, Vriend et al., 2011 and Nottebaum et al., 2015 in China, and Muhs and Bettis, 2003 in N. America). The rapid variability or interchange between the different subgroups of type 1.b sediments support the idea that all three subgroups have a similar origin and were driven by high-pressure cells as described already by Liu et al. (1985) and later by e.g. Nugteren and Vandenberghe (2004). The preference for deposition of one of the three subgroups is probably determined by slightly differing wind energy, and thus transport capacity, influenced by the local topographical setting and surface conditions, rather than by different transport distances.

The fine-grained loess type 1.c (modal diameter ranging from 4 to 22 µm) may be subdivided in two subtypes: a first one (1.c.1) with a modal size of c. 19 µm (16-22 µm) and a second one (1.c.2) with modal peak around 4 µm (2–11 µm). Its interpreted depositional mode is as background dust transported in high-suspension clouds over long distances and outside the influence of monsoonal winds (Zhang et al., 1994, 1999; Prins et al., 2007; Vriend et al., 2011), and incorporated in the high-level westerlies (Pye and Zhou, 1989; Pye, 1995; Sun D. et al., 2002, 2008). The transport capacity differs as a function of the grain size explaining the difference in deposition of 1.c.1 or 1.c.2. It follows that the grain size of this loess type is slowly decreasing with transport distance, altitude and lower wind velocity (e.g. Rea et al., 1998; Ruth et al., 2003; Crouvi et al., 2008; Stuut et al., 2009; Lin et al., 2016). Exceptionally, this dust type is deposited as a unimodal fraction (e.g. in Red Clays: Vandenberghe et al., 2004), but mostly it occurs in combination with the medium-to-coarse silt fraction 1.b. It is deposited continuously over time but is relatively dominant in warm conditions when winter monsoon impact was relatively weak, such as during interglacials and interstadials and in Red Clays (Prins et al., 2007; Vandenberghe et al., 2004, 2006; Vriend et al., 2011).

Specific grain-size properties of pedogenic (illuviation) clay:

Pedogenic ‘clay’ consists essentially of clay minerals. Traditionally, these clay particles were categorized in the <2 µm grain-size fraction as measured by the pipette method. Due to their platy shape the Stokes settling velocity is retarded in comparison with sphere-shaped grains of equivalent diameter. Konert and Vandenberghe (1997) demonstrated that such ‘clay’ particles have a length of up to 5.5 or 8 µm in reality as measured by the laser diffraction method. This effect is nicely illustrated by Sun et al. (2006) who compared paired grain-size distributions of weathered bulk samples of windblown dust (containing high amounts of pedogenic clay particularly in Red Clays and palaeosols) and isolated quartz samples from the same samples after chemical removal of the clay minerals (thus containing only the windblown dust without pedogenic clay) (Fig. 2A). Their results show a clear bimodality in the bulk grain-size distribution with one peak at c. 4-8 µm, next to another modal peak at c. 26-42 µm, in contrast to the single-mode composition of c. 26-42 µm of the pure quartz samples. Similar experiments on weakly weathered loess do not show any shift in modal size after the chemical pre-treatment since the relative amount of clay particles is insignificant. It means that the weakly weathered loess shows relatively coarse mean grain sizes both with and without chemical pre-treatment which are exactly coinciding with an original typical loess, while the finer average size of the bulk weathered samples (without chemical pre-treatment) is due to admixture with clay minerals. Similar results were obtained in experiments by Feng et al. (2014) in Chengdu clay (modal size of bulk sediment is 5-15 µm but is 20-50 µm for quartz sediment). Also Ma et al. (2014) and Zeeden et al. (2016) derive that the 2-10 µm fraction in SE European, Chinese and Australian loess is closely related to the degree of pedogenesis. In contrast, traditional pipette grain-size analysis is masking this phenomenon of fine-grained silt occurrence due to pedogenesis, since clay minerals –due to their platy shape- are 'measured' as <2 µm by this method (Konert and Vandenberghe, 1997). Finally, it should be mentioned that in the case of weathered loess deposits, this pedogenic clay was included previously within type 1.c.2 (Vandenberghe, 2013).

It may be concluded that the finest background dust component 1c.2 (modal value c. 4-11 µm) is only slightly coarser grained than the pedogenic clay (modal value <8 µm) and largely overlapping in size. This makes it difficult to distinguish pedogenetic clay from background dust solely by grain size, thus needing specific pedogenic characteristics (e.g. Zeeden et al.,2016; Yang et al., 2016) or specific analyses (cf. Sun et al., 2006; Schulte and Lehmkuhl, 2017). But in general, discriminating between these two sediment types and their associated processes has to be supplemented by other sediment properties, for instance, the presence/absence of weathering traces as evidenced by macroscopic field or/and micromorphological observations and geochemical and mineralogical analysis (e.g. Zeeden et al., 2016). Two examples from C. China illustrate this phenomenon. The first one is from a loess deposit at Hu Jia Wan (Hanzhong basin) in Fig. 2B: besides a fraction of distinct medium silty loess in both samples, the fraction with mode c. 8 µm in sample (a) may be partly a pedogenic clay since macroscopically a strongly weathered soil is present (see lower half of photo), but mixed up with background dust (since that fine-silt fraction also occurs in layers without macroscopic soil formation at that site (sample (b) in upper half of photo:) and elsewhere (Prins et al., 2007). The second example is from the Huang He valley described by Wang et al., submitted (Fig. 2C). It shows a facies with fine-grained silt that has a modal size of 10 µm, which is very similar to a primary background loess (type 1.c) mixed with a small amount of clay. However, it is in fact clearly a deposit sorted out from suspended fluvial sediment as is evident from the sedimentary structure with fine lamination with ripple crossbedding covered by clay drapes, thus clearly a fluvially reworked loess.

Lake infill by (reworked) loess

Silt-sized deposition in lakes may have two main sources (Fig. 3A). At first, there is direct aeolian deposition from suspension in the air by dustfall. Secondly, the same material may be supplied to the lake from areas around the lake by erosion processes such as surface runoff or channel flow, occasionally mass flow along the lake margin, resulting in secondary deposition. In both cases the aeolian origin may be demonstrated by geochemical signatures and quartz surface texture analysis next to grain-size texture (e.g. Guo et al. 2001; Fan et al. 2006; Licht et al 2014). It is striking that the original modal grain size of the windblown sediment is preserved after deposition in a lake or pool so that individual grain-size populations are easily identified in lakes (e.g. Munroe et al., 2015). It does not matter whether that supply is of primary or secondary origin. The different kinds of original aeolian populations can still be recognized, from the coarse populations 1.b to the background dust 1.c, even when mixed up to a certain degree with locally eroded material. Many examples may be found as in Tertiary tectonic basins, for instance at Shuiwan in the Xining basin of west China (Fig. 3Ba-d; Licht et al. 2014) and the Bogota basin in South-America (Torres et al., 2005), and in

Quaternary lakes of different origin, for instance in Inner Mongolia (Xiao et al 2014) and west China (Liu et al, 2016).

Apart from this typical aeolian signature, very fine clay (1-2.5 µm) is generally deposited in the standing water of ephemeral or perennial lakes (e.g. Torres et al., 2005; Lebbink, 2010; Xiao et al. 2012; Dietze et al., 2012; Wang et al., 2013; Brunck et al. 2016; Liu et al. 2016). This very fine fraction (labelled within type 2.b by Vandenberghe, 2013) is primarily a function of the deposition process in the lake, i.e. the settling or dispersion in standing water. Such processes may occur in all kinds, depths and sizes of lakes including endorheic lakes in tectonic basins and lakes on floodplains such as abandoned channels or backswamps (see below). Rather exceptionally, it occurs as a unimodal grain-size distribution of 1-2.5 µm, as illustrated in Fig. 3Be. It may contain all kinds of grain shapes: from spheroids and cubic blocks to fragmented platy shapes.

As the process of hydrodynamic settling is a reworking process of the material supplied to the lake, there must be an original source sediment that has been sorted out to constitute the population with a grain size of 1-2.5 µm. It must be a sediment that contains that very fine-grained population whether primary or secondary in origin. Candidates are obviously the background dust (1.c, primary as well as secondary) and the pedogenic sediment (Fig. 3C). Theoretically, decomposition of windblown clay aggregates (Qiang et al., 2010 and references therein) could also be a source for this component in the lake, although their existence is disputed (e.g. Lin et al., 2016).

Finally, Sun D. et al. (2002, 2011), confirmed by Ma et al. (2014), interpret a grain-size endmember with a modal size of about 0.2-0.4 µm as being of chemical or biochemical origin, produced within the lake and/or of detrital, pedogenic origin. It is not sure, however, that the latter component would be equivalent to the 1-2.5 µm fraction reported here because, as discussed above, (pedogenic) clay minerals have a dominantly larger grain size. Also, a measurement error is not excluded.

A particularly illustrative example of deposition in a large subsidence area occurs in the Xining basin (Licht et al. (2014) and Lebbink (2010), see Figs. 1 and 3B). A late Eocene facies of mud and gypsum deposition, occasionally in combination with locally mm-scale laminated sedimentary structures, points to a playa lake environment, more particularly the distal part of the mud flat (Abels et al. 2011) in generally arid conditions (Schreiber and Tabakh, 2000). The succession of an original far-distance wind supply followed by deposition into a shallow lake may fit to all grain-size characteristics of this facies during alternating relatively wet (gypsum formation saline playa lake, perennially inundated) and dry periods (subaerial mudflat environment under (episodic) inundated conditions) (cf. Reinhardt and Ricken, 2000 and Abels et al., 2011).

In most cases (illustrated in Fig. 3B), decomposition of the grain-size distribution of lake sediments shows the presence of distinctly individual components with typical grain-size characteristics (Lebbink , 2010; Torres et al., 2005; Liu et al., 2016). It is striking that in all lake analyses until now there is not any measured gradual transition in grain size of these individual components from the lake margin to the center of the lake. General and gradual hydrodynamic sorting during transportation in the lake, as supposed by Xiao et al. (2012, 2015), would result in a gradual shift of the modal grain sizes of the individual components, both spatially and vertically. However, hydrodynamic sorting does exist as is obvious from the settlement of the heaviest endmember (often fluvial) around the lake margin, while the finer-grained endmembers are transported farther away into the lake until the water has come to a complete standstill and the finest material can settle down. Thus, the coarser, sandy grain-size endmembers may be deposited preferentially around the lake margins and consequently the sediment in the lake may become depleted partly or completely from those fractions in the lake centre. The combined sedimentary processes explain this sedimentary facies called 'lacustro-aeolian' (facies 2.b) by Vandenberghe (2013). In fact, one could consider the process of progressive endmember separation as a kind of hydrodynamic sorting, in contrast to a gradually decreasing bulk mean grain size. Finally, a rather uniform grain-size pattern in the lake could be favored by a large lake size or by relatively intense primary dust fall directly from the atmosphere, or both (e.g. Licht et al., 2014).

Since original grain sizes of the primary material are preserved after transport to and deposition into the lake, it is not always possible to distinguish between primary (direct airfall) and secondary (reworked) deposition. Mostly the lake environment should be easily identified by the presence of the very fine fraction of 1-2.5 µm, even in small amounts or as a unimodal population, as a unique characteristic of lake deposition. Additional arguments for a lacustrine origin may be provided by specific sedimentary structures that are caused by water flow and by paired proxy indicators, such as high organic matter and carbonates content (An et al., 2012). Also, the presence of organic material and/or lacustrine fauna and flora, the geochemical composition including isotopic signature and solute precipitation and the clay mineralogy may be helpful (e.g. Matter and Tucker, 1978).

Alluvial deposition:

The process of sedimentary reworking of primary, windblown loessic material (types 1.b and 1.c) by river erosion and their subsequent, secondary redeposition on floodplains or alluvial fans leads to various degrees of modification of the original loess grain-size distributions more than by lacustro-aeolian depositional processes (Figs. 4A and B). These sediments were expressed as fluvio-aeolian facies 2.a by Vandenberghe (2013). Similar to the lacustro-aeolian facies, it is again striking that the reworking of primary aeolian deposits does not fundamentally change the modal size of the main component of the original aeolian facies with diameters between 25 and 65 µm (1.b) or 2-22 µm (1.c). Typical for the fluvio-aeolian sedimentation in comparison with the primary loess, however, is the addition of coarse-grained sediment eroded from a sandier substratum by water flow or surface runoff before the sediment was deposited on the floodplain, at least on condition that such sand grains are present in the substratum. The eroded sediment may be re-deposited by flooding events preferentially in abandoned channels, pools or depressions. In addition, clay particles (supplied as previously eroded products) may settle down in the standing water of those pools or lakes on the floodplains. By this addition of clayey material alluvial deposits bear similarity with the lacustro-aeolian facies. It means that the alluvial environment should be recognized additionally, and apart from the coarse-grained admixture, by the humic character of the reworked loess, small sedimentary structures due to water flow (e.g. laminar structure or even small ripples) and remnants of flora and fauna that live around or in the temporary pools or swamps.

Thus, characteristically the main component of a fluvio-aeolian deposit in catchments with a loessic substratum is formed by the original material, in this case the aeolian silt-sized component. In comparison with the latter original loess, a certain amount of coarse-grained material (coarse silt and sand) is added together with a certain amount of clay. The fluvio-aeolian and lacustro-aeolian facies may look similar, but apart from different sedimentary structures, there is also a difference in grain size. Generally, the sorting of the fluvio-aeolian facies is poorer than that of the lacustro-aeolian facies because the former facies contains simultaneous admixture of coarse and very fine material, in contrast to the latter facies that contains either admixture with coarse material (near to the lake boundary) or very fine material (in the lake centre). Thus, it is in fact the spatial scale that causes this difference: lakes are generally much larger than the pools or depressions in floodplains. Interfingering may occur especially in deltaic settings in lakes with oscillating water level.

Some illustrative examples of admixture with coarse sediment in fluvio-aeolian deposits are given in Figs. 4 and 5. Fig. 4A concerns the Holocene floodplain of the Geul river, a small tributary of the Maas river in the southernmost Netherlands (described in detail by De Moor et al., 2008 and Vandenberghe et al., 2010). This alluvial plain is still nowadays regularly flooded (annually to bi-annually). At such occasions, extended but shallow sheets of water invade the alluvial plain. The surface sediments of the catchment consist for a large part of Pleistocene primary loess. As is recognized in present-day conditions (e.g. Rommens et al 2005; Notebaert et al 2011), the loessic substratum was eroded during the Holocene by runoff along the valley slopes and supplied towards the rivers for further transport in suspension. Those loessic sediments, preserving largely their original grain-size distribution pattern during fluvial transport, were re-deposited on the alluvial plain during the waning stages of flooding events, i.e. when the transport capacity of the flooding water has decreased (Rommens et al., 2005). But not only these Quaternary cover sediments were eroded, also sediments from the Tertiary sandy subsoil are (were) removed by both slope processes and river erosion and subsequently transported by the river, partly as bed sediment, partly as near-bottom suspension. These sandy sediments could also reach the floodplain, probably concentrated in channel-like positions, during high-stage flows and were re-deposited rapidly when flooding power decreased. As visible in Fig. 4A, their grain-size distribution reaches a modal peak of c. 250 µm in the Geul catchment. In that example, the clay admixture is almost absent. This contrasts with the examples from the Minino site in the upper reach of the Volga catchment north of Moscow (Fig. 4B; Vandenberghe et al., 2010). Both samples show a distinct supplement of clayey sediment. The swampy depositional conditions were further illustrated by the high humic content (Gracheva et al., 2015). In addition, sandy admixture is also distinct in the sample OM-2a resulting in a trimodal grain-size distribution and a very poor sorting of that sample. These are typical examples globally occurring in positions on top of fluvial gravel and at the transition to overlying primary aeolian loess as, for instance, in China (e.g. Pan et al., 2009; Vandenberghe et al., 2011; Wang et al., submitted).

A more complex mode of deposition occurs at the Hu Jia Wan section in the Central Chinese Hanzhong basin (Fig.2B; Wang et al., in prep.). The grain-size distribution of the palaeosol (sample a) shows the typical pattern as described for weathered primary loess deposits with maxima in the silty loess fractions at c. 29 and c. 8 µm (see discussion above). In contrast, the sample of the unweathered loess (sample b) contains strikingly more sand (c. 21%), which is very high for a medium-sized primary loess (e.g. Vandenberghe et al., 1985; Nugteren and Vandenberghe, 2004; Bokhorst et al., 2011; Liu et al., 2017submitted). In addition, this latter unweathered loess deposit is clearly finely laminated with alternations of coarse-grained layers even containing occasionally small-pebble strings. Thus sample b is considered as a flood sediment or resulting from surface wash on top of a river plain and resembles the Geul and Minino sites. Macroscopically visible soil formation reflects temporary subaerial exposure with pedogenic clay admixture in both the alluvial plain (sample a) and the primary loess (sample b) (as discussed above).

To complete this overview, we may mention at last a separate category of sedimentary facies which is due to aeolian reworking of floodplain sediment and redeposited at short distance on that floodplain. In fact, it may be considered as a primary aeolian deposit and occurs often as a sheet of coarse-grained loess (e.g. Prins et al., 2009; Vriend et al., 2011) and identified as facies 1.a by Vandenberghe (2013). However, it may also be expressed as river dunes on that floodplain. A high number of such dunes consisting of medium-to-coarse-grained sand have been described as they were blown up from sandy river braidplains, but are not considered here. However, also the fine-grained alluvial plains, may function as source area for such river dunes of variable size and shape (e.g. Wang et al., submitted). Particle transport on the floodplain is dominantly by saltation or in suspension clouds very near to the surface (De Ploey, 1977). Practically, the mean grain size does not change much from the source area to the dune accumulation site (Fig.5), showing that the wind energy is less determining for the grain size of the dune than the characteristics of the source area.

Synthesis and conclusions

It appears possible, to a large extent, to differentiate between individual primary and secondary aeolian depositional environments based on their respective grain-size characteristics. Firstly, in comparison with direct dust fall, sedimentary reworking does not modify substantially the original modal grain size of the windblown sediment, which thus still remains recognizable after reworking. Secondly, the reworking processes that modify the original aeolian signature may be of different nature, each of them leaving a characteristic imprint on the grain-size distribution. In lacustrine environments, it is found that the settling of sediment in standing water is in general responsible for the addition of fine-grained clay (1-2.5 µm). In the fluvial environment, the erosion of underlying or adjacent basin marginal sediment by flowing water with relatively high energy leads often to the addition of sediment that is coarser grained (coarse silt and sand) than the original aeolian dust. But, this erosion may also entrain clay particles for redeposition in the standing water of pools or shallow lakes on the floodplain. In this way, the alluvial sediments may show the addition of both kinds of admixtures, thus finally leading to the poorest sorting of reworked loess deposits. The alluvial setting is in general more energetic than the lacustrine one. However, the distinction between the grain-size characteristics of fluvio-aeolian and fluvio-lacustrine sediments may be vague in specific settings, as lake margins. In the latter case, a distinction between both kinds of sediment is hardly possible by grain-size discrimination and other characteristics (e.g. sedimentary structures, fauna, flora) are needed.

The effects of weathering or soil formation may be least diagnostic in grain-size. The clay minerals may have grain diameters that are relatively large in their pristine shape (3-8 µm) or smaller when (partly) broken down. Consequently, both in-situ weathered and reworked loess may sometimes be difficult to distinguish from primary background dust of 4-10 µm. This illustrates that specific grain-size populations cannot in all cases represent specific (primary or secondary) aeolian processes or deposits. Sediment sorting processes of different origin might lead to grain-size distributions that are very similar. Therefore, genetic interpretations of different kinds of loess and loess-like depositions have to be based on all available sedimentological and geomorphological information as derived from field observations and supplementary sediment analyses (Figs.2B, 2C and 5) as reported e.g. by Vandenberghe (2013) and Lehmkuhl et al. (2016).

Figure captions:

Fig. 1 Examples of typical grain-size distribution curves of primary loess. Fig. 1A is a loess type 1.b.3 with modal size of c. 28 µm from Ruma in Vojvodina, Serbia (Vandenberghe et al., 2014); Fig. 1B is a loess type 1.c.2 with modal size of c. 6 µm from the Red Clay at Xifeng (Vandenberghe et al., 2004).

Fig. 2A Illustrations of the impact of removal of pedogenic clay from windblown loess, paleosols and Red Clay respectively (from Sun et al 2006); S1 is a palaeosol, L9 is a loess layer and RC1 is a Red Clay from the Lingtai section.

Fig. 2B Site Hu Jia Wan (Hanzhong basin, C China). In addition to admixture with sand, both samples are dominated by silty loess (sample a: type 1.b.3, modal size c. 29 µm; sample b: type 1.b.1, modal size c. 42 µm). Both samples contain also a fraction with mode at c. 8 (range 2-14) µm. The latter component is probably a mixture of background dust (type 1.c) and pedogenic clay in a (strongly) weathered palaeosol. The presence of pedogenic sediment is confirmed by macroscopic soil formation (facies visible in lower half of photo), while the presence of background loess is manifested by the fact that this grain-size fraction also occurs in sediments that are not affected by pedogenesis (facies visible in upper half of photo). Thus, sample 'a' resembles a (strongly) pedogenically weathered loess, while sample b shows the characteristics of only slightly weathered loess. Vertical lines in graph are at 5, 29 and 42 µm.

Fig. 2C Sediment settled from fine-grained fluvial suspension as manifested by the sedimentary structures, but with a grain size that is very similar to a primary background loess (type 1.c) or lacustro-aeolian loess (as suggested by the small admixture with settled clay of 1-2 µm). Site Jing Shan (Huang He terrace (N36°26'29,976'', E104° 25' 38,628''), described by Wang et al. (submitted).

Fig. 3A Simple and generalized sketch of sedimentary processes in the filling of topographic depressions or lakes by fine-grained sediments resulting in the formation of a lacustro-aeolian loess facies (2.b). zone a: poorly sorted near-shore sedimentation consisting of a considerable sand population supplied as bedload by rivers and surface runoff mixed up with other silty and clayey components, zone b: bimodal mixture of silty material supplied from the land as derived (suspended) loess and settled very fine clayey material due to lake settling, zone c: unimodal very fine settled clay in standing water, zone d: poorly sorted alluvial loess. In all zones sediments may be mixed up with direct airfall dust (primary loess).

Fig. 3B Examples of grain-size distribution curves of primary loess deposited in a lacustrine setting, a tectonic depression of Eo-Oligocene age in western China Shuiwan section; described by Lebbink, 2010 and Licht et al., 2014): Figs. 3Ba and 3Bd are mixtures of windblown loess types 1.b and 1.c without lacustrine clay; Fig. 3Bb is a mixture of windblown loess type 1.c and fine-grained lacustrine clay 2.b; Fig. 3Bc is a mixture of windblown loess types 1.b and fine-grained lacustrine clay 2.b (be aware of the different scales at the x-axis). Fig. 3Be represents a family of grain-size distribution curves from the Xining basin at Shuiwan (west China; Lebbink, 2010) with unimodal very fine-grained clay 2.b deposited in standing water (9 ϕ= c. 2 µm).

Fig. 3C Illustration of the provenance of the fraction 1-2.5 µm from other fine-grained sediments as Red Clay and aeolian background dust.

Fig. 4A Typical grain-size distribution curve of alluvial loess deposits (type 2.a) in the Geul floodplain (southern Netherlands) showing bimodality caused by admixture of bedload to the reworked loess (from De Moor et al., 2008).

Fig. 4B Alluvial loess in the Dubna alluvial plain, a small tributary of the Upper Volga about 100 km north of Moscow, illustrating the very poor sorting due to admixture of bedload (sand) and settled fine clay to the original suspended loess (from Vandenberghe et al., 2010).

Fig. 5 Example of a dune sand (SC B'1), blown up from the underlying floodplain sediment (SC A1) on a Huang He terrace at Shichuan described by Wang et al. (submitted) (N36° 09' 04,272'', E103° 59' 23,97'').

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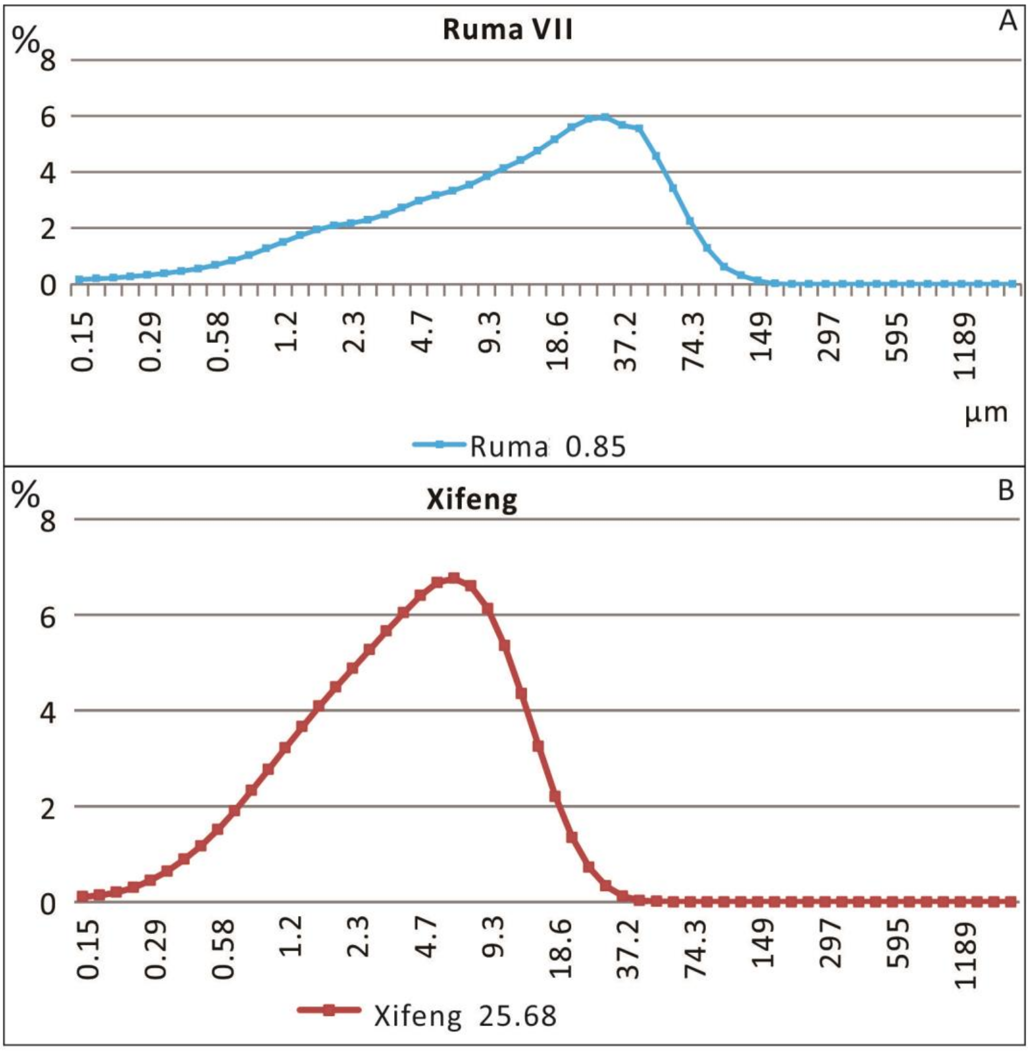
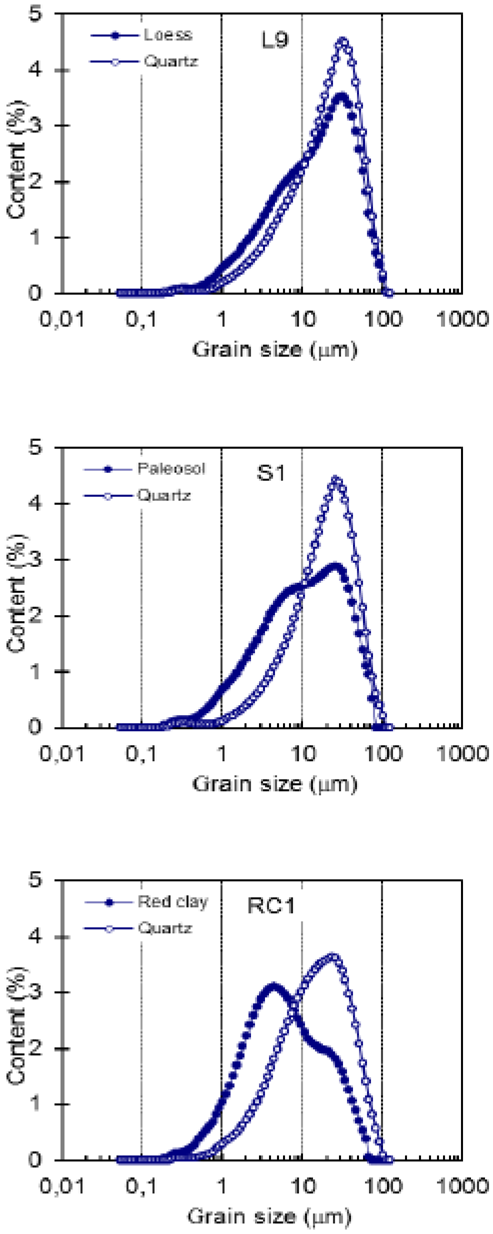


Ruma VII
A
%
8
6
4
2
0
0.15
0.29
0.58
1.2
2.3
4.7
9.3
18.6
37.2
74.3
149
297
595
1189
µm
Ruma 0.85
Xifeng
B
%
8
6
4
2
0
0.15
0.29
0.58
1.2
2.3
4.7
9.3
18.6
37.2
74.3
149
297
595
1189
Xifeng 25.68

Fig. 1



5
4
3
2
1
0
Content (%)
Loess
Quartz
L9
0,01
0,1
1
10
100
1000
Grain size (μm)
Paleosol
Quartz
S1
Red clay
Quartz
RC1

Fig. 2a

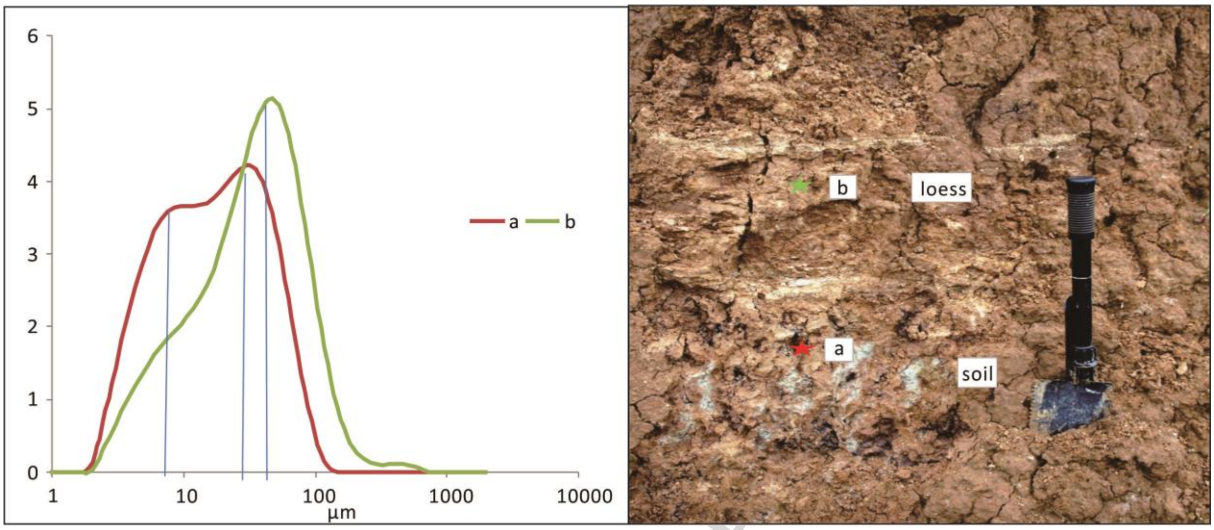


Fig. 2b

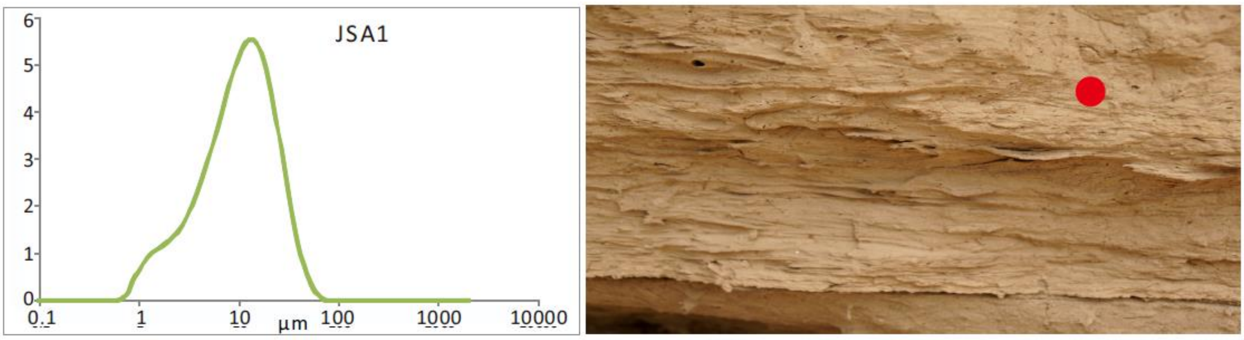


Fig. 2c

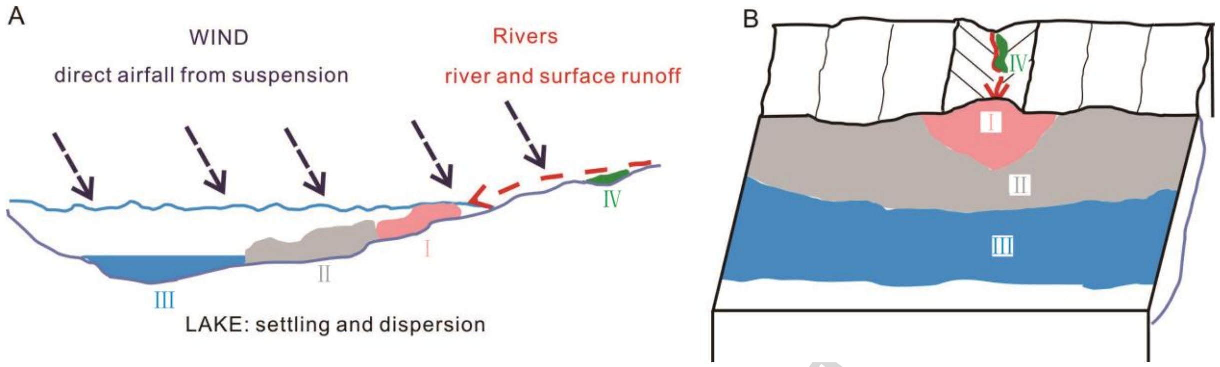

A
WIND
direct airfall from suspension
Rivers
river and surface runoff
I
II
III
IV
LAKE: settling and dispersion
B
IV
I
II
III

Fig. 3a

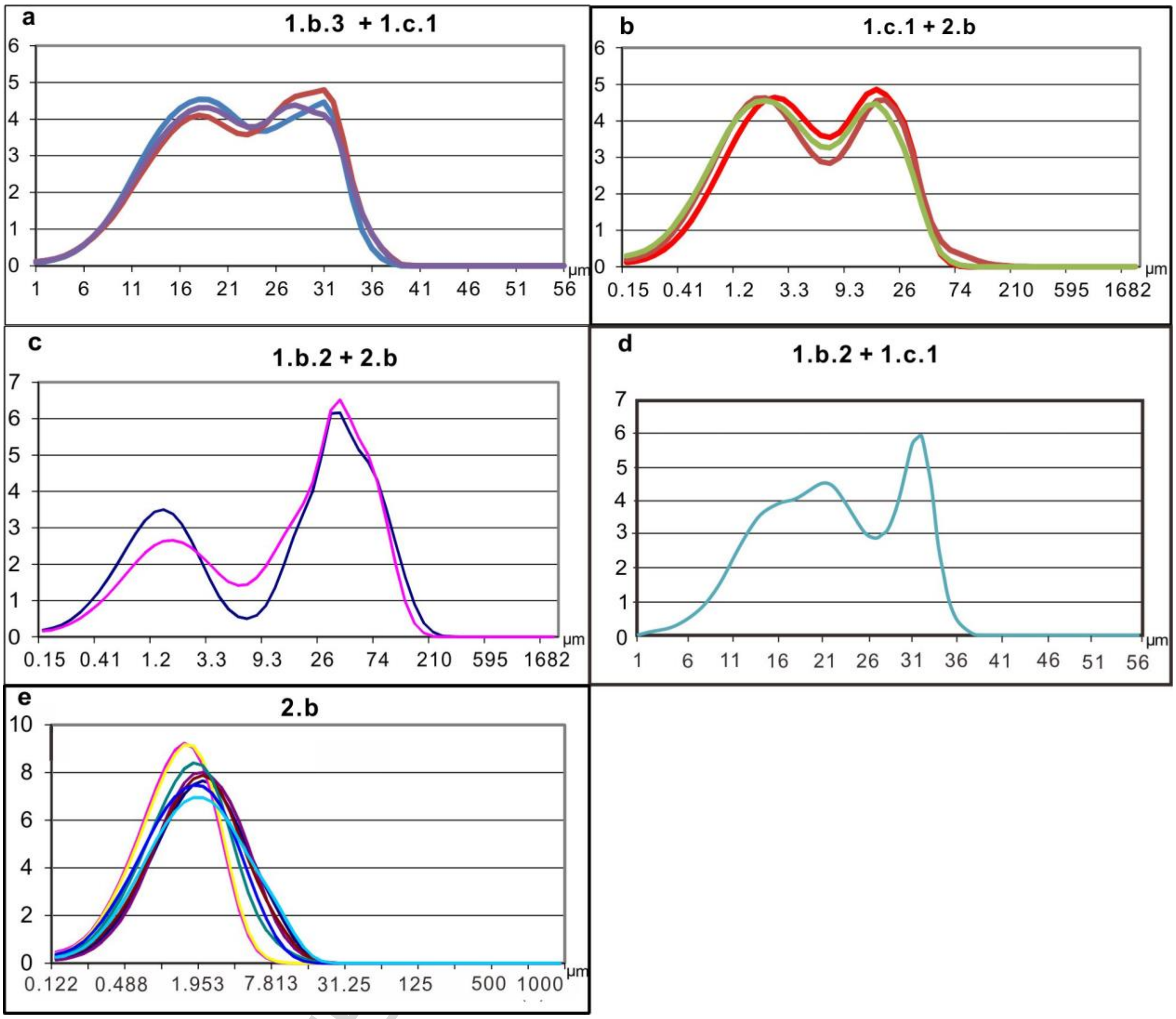


Fig. 3b

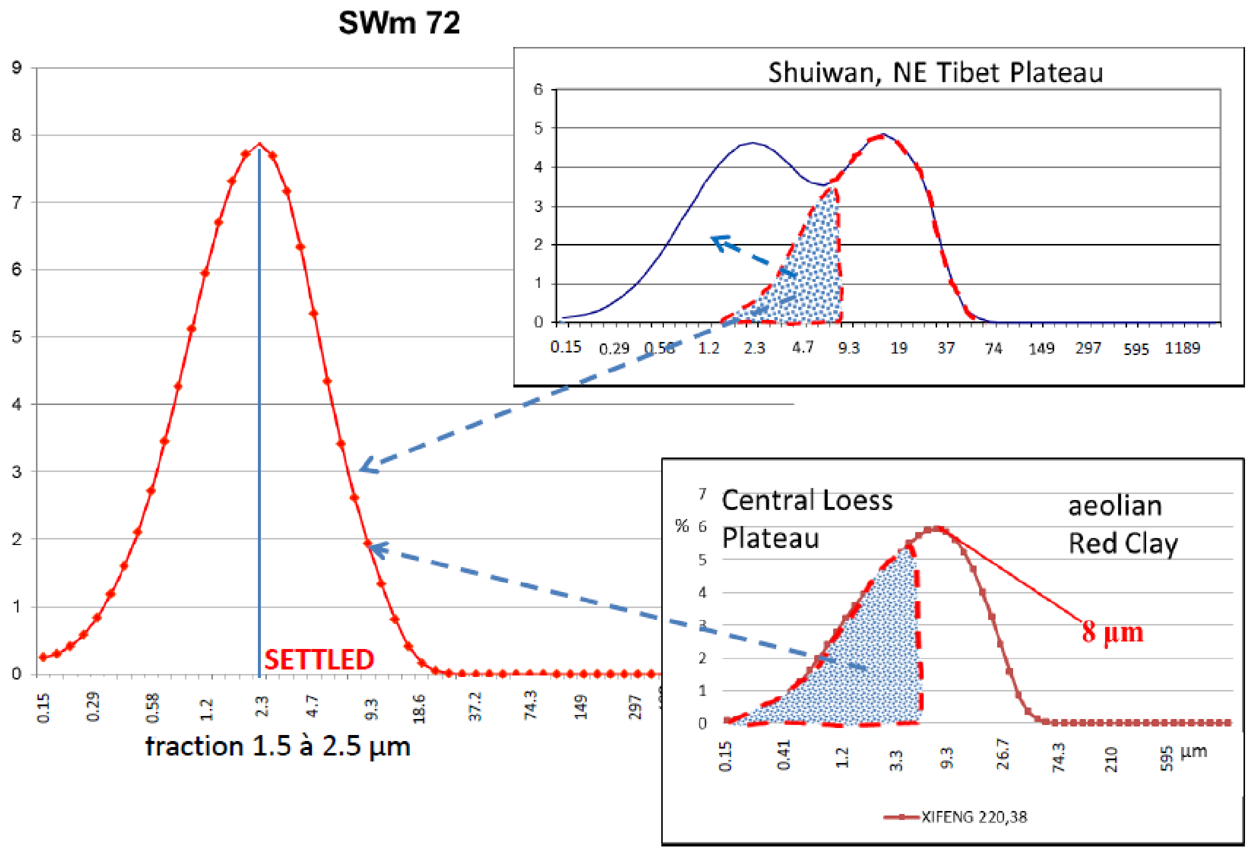

SWm 72
SETTLED
traction 1.5 à 2.5 µm
Shuiwan, NE Tibet Plateau
Central Loess
Plateau
aeolian
Red Clay
8 µm
XIFENG 220,38

Fig. 3c

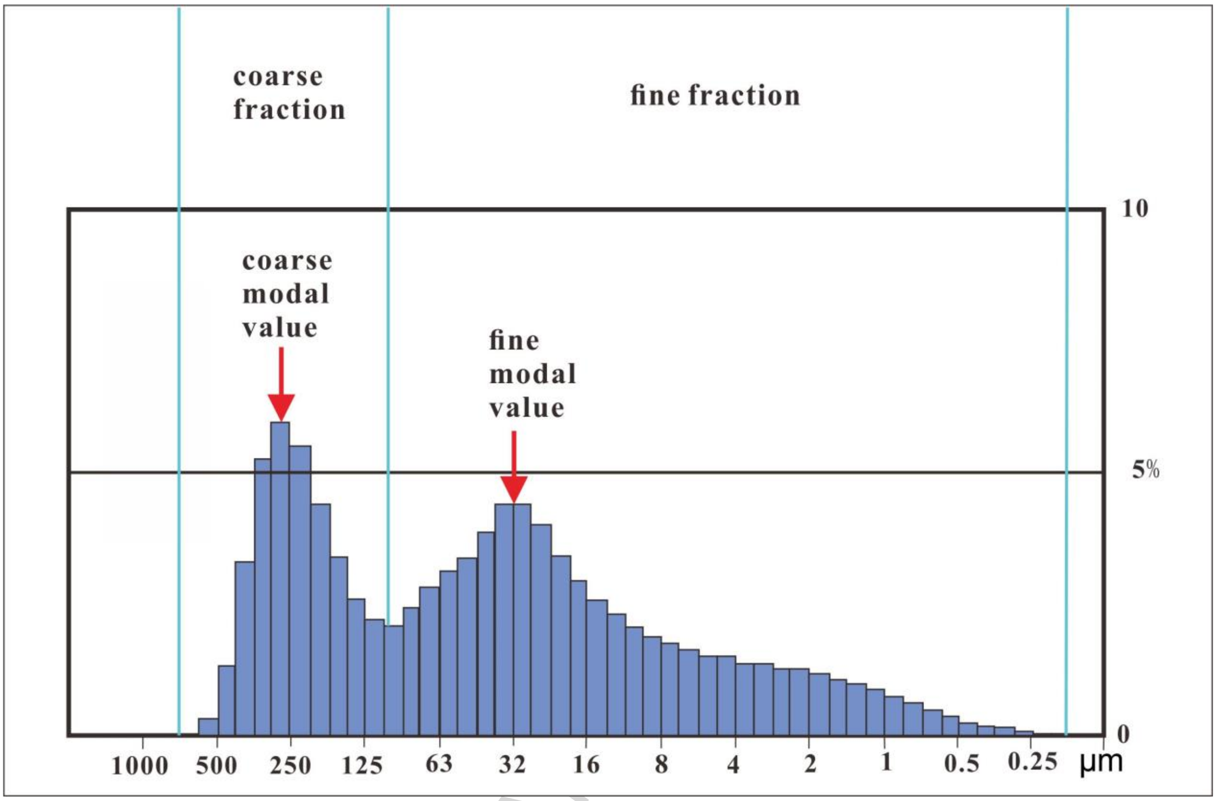
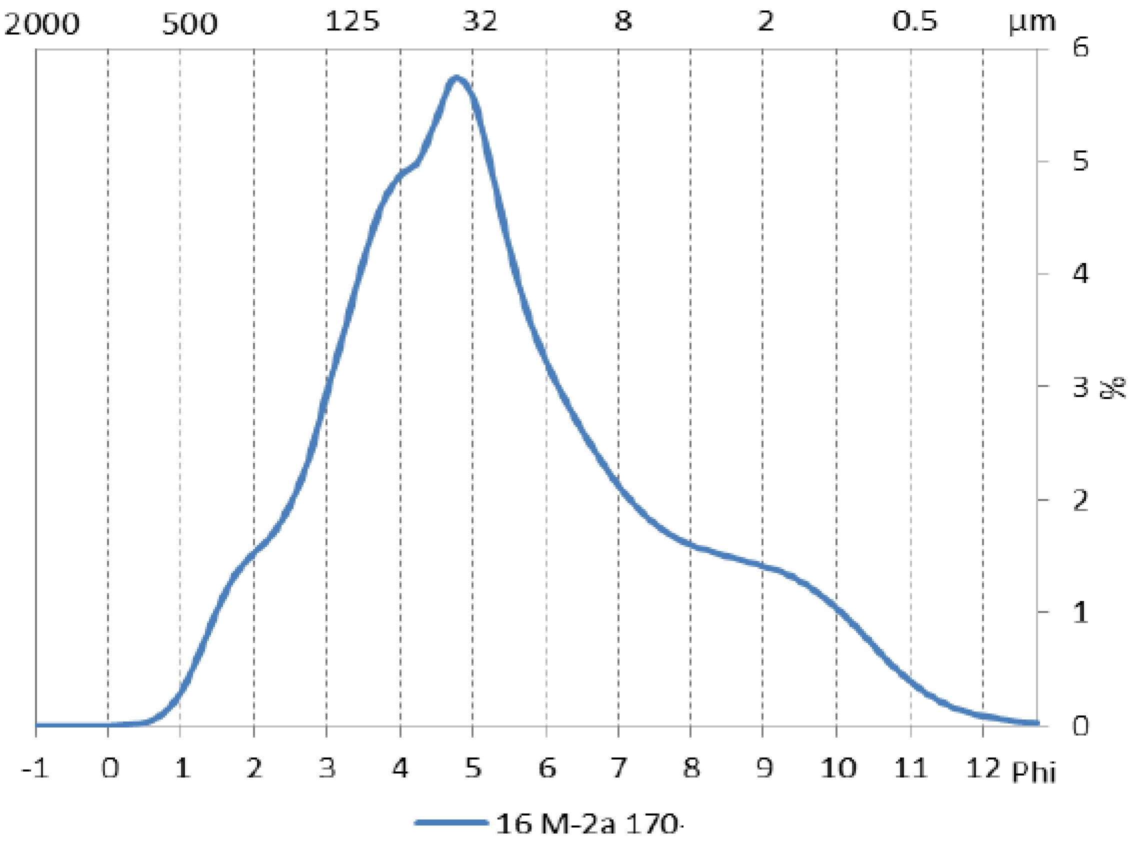

coarse
fraction
fine fraction
coarse
modal
value
fine
modal
value
10
5%
0
1000
500
250
125
63
32
16
8
4
2
1
0.5
0.25
μm

FIg. 4a



2000
500
125
32
8
2
0.5
µm
6
5
4
3
2
1
0
%
-1
0
1
2
3
4
5
6
7
8
9
10
11
12
Phi
16 M-2a 170-

Fig. 4b

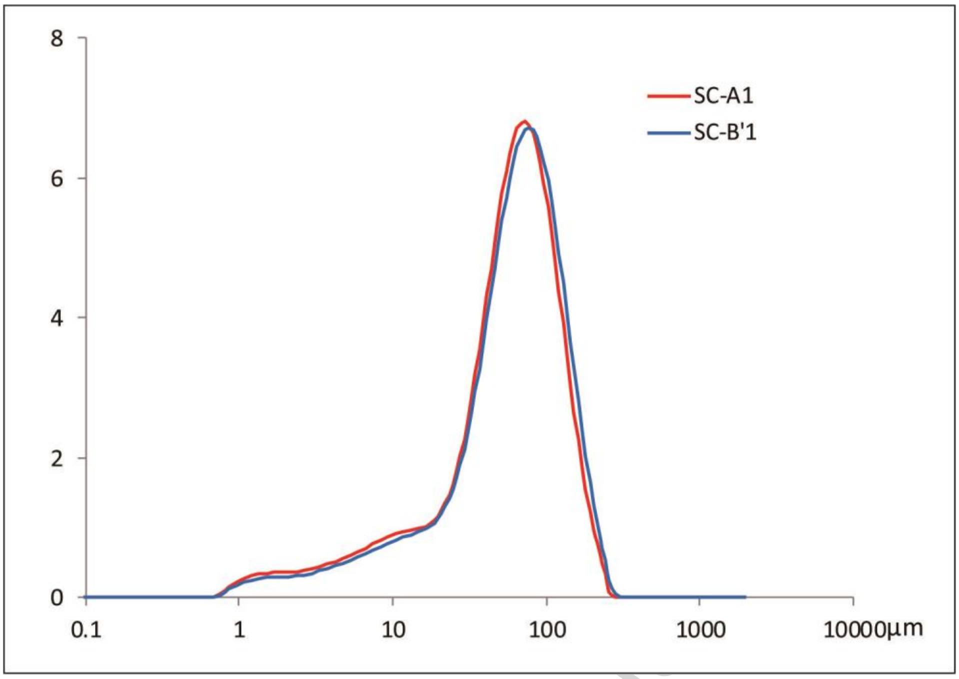


Fig. 5