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Late Quaternary aeolian dust input variability on the Chinese Loess Plateau: inferences from unmixing of loess grain-size records

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Abstract

The grain-size distributions (GSDs) of loess–paleosol sequences may provide valuable information on provenance, transport and paleoclimate variability, and consequently, a wide range of methods to extract genetic information from loess GSDs has been proposed. Here it is shown that a genetically meaningful decomposition of a series of Late Quaternary loess grain-size records extending across the Chinese Loess Plateau can be accomplished with the end-member modelling algorithm (EMMA). The unmixing results in conjunction with loess accumulation rate estimates reveal that two contrasting dust supply patterns were active over the Loess Plateau during the last glacial–interglacial cycle: (i) a background sedimentation pattern that was dominant during interglacial periods, especially over the central and southern parts of the Loess Plateau, is reflected by the constant flux of the fine-grained loess component, (ii) an episodic, highly variable dust input pattern, that was dominant during glacial periods throughout the Loess Plateau and noticeable during interglacial periods mainly over the northern Loess Plateau and almost disappearing over the southern Loess Plateau, is reflected in the admixture of two coarse-grained loess components. A genetic interpretation and the paleoclimatic significance of the mixing model are provided by comparison of the modelled end members with modern dust samples in terms of their GSD and flux rates.

1. Introduction

The emission, transport and deposition of aeolian dust are intimately coupled to and indicative of changes in paleoclimate. Several physico-chemical properties of dust can be used to trace the source area and to characterise the mode of transport. Many geological investigations in the loess-covered region of central China have used grain-size measurements as a basis for differentiating widespread loess and paleosol units, correlating them regionally, and relating them to the deep-sea isotope stratigraphy (e.g., An et al., 1991; Lu and Sun, 2000; Ding et al., 2002; Rokosh et al., 2003; Nugteren and Vandenberghe, 2004; Yang and Ding, 2004). Various parameters have been used to summarise bulk grain-size changes in the loess–paleosol records, and have been widely applied as paleoclimate indicators for atmospheric circulation (wind strength, aridity). Most commonly used are univariate grain-size properties such as the median or mean grain size (e.g., An et al., 1991; Derbyshire et al., 1995; Chen et al., 1997; Ding et al., 2002), clay content (<1 or $2\,\mu m$: e.g., Zhang et al., 1999; Fang et al., 2003), coarse fraction content ($>16\,\mu m$: e.g., Nugteren and Vandenberghe, 2004; $>20\,\mu m$: e.g., Zhang et al., 1999; $>30\,\mu m$: e.g., Lu et al., 1999; $>40\,\mu m$: e.g., Chen et al., 1997; $>63\,\mu m$: e.g., Ding et al., 1999), or the ratio of coarse over fine silt (e.g., Vandenberghe et al., 1997). Others used the median and maximum grain size of the quartz fraction (e.g., Porter and An, 1995; Xiao et al., 1995). Different properties are chosen to highlight the importance or to exclude the influence of various likely sedimentary or climatological processes/parameters such as

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the influence of dust input versus pedogenesis, deposition of suspended grains versus saltating grains, wind strength versus source area proximity, just to name a few.

A common feature of sediments is that they are mixtures of sediment populations derived from different sources and/or transported to the site of deposition by different mechanisms. An obvious consequence of the above is that one cannot interpret grain-size variations within loess sediments in terms of paleoclimate variation without knowledge of the (potentially varying) provenance, the dispersal pathways and the transport mechanisms of the sediments under consideration. Therefore, the fundamental problem is to determine whether the measured grain-size variation should be attributed to mixing of detritus from multiple sources, to size-selective dispersal, or to some combination of both (Weltje and Prins, 2003). An inverse model of (un)mixing would be ideally suited to obtain genetically meaningful interpretations of observed grain-size distributions (GSDs). A wide range of methods to extract genetic information from GSDs has been proposed in the literature. A brief overview of the most commonly used methods to decompose GSDs into theoretical end members (EMs) is given in Weltje and Prins (2003, submitted). In general, two different views on decomposition can be distinguished: parametric decomposition and non-parametric decomposition (Weltje and Prins, submitted). *Parametric* decomposition assumes that the EMs that make up an observed GSD are continuous unimodal distributions, which can be adequately described by analytical functions with a small number of parameters. Standard curve-fitting techniques may be used to decompose a single observed GSD into proportional contributions of analytical distribution functions belonging to a predefined class. This method cannot be used to simultaneously decompose a series of GSDs. Recent applications of parametric decomposition of Chinese loess GSDs are the papers of Sun et al. (2002), Sun (2004) and Qin et al. (2005). *Non-parametric* decomposition regards GSDs as spectra, which record a combination of some initial state modified by various processes, notably mixing and selective transport. There is no compelling reason why EMs should fit into any particular class of parametric models. Weltje (1997) has formulated a non-parametric inversion technique (the end-member modelling algorithm (EMMA)) which turned out to be particularly well suited to the unmixing of GSDs (e.g., Prins and Weltje, 1999a; Weltje and Prins, 2003, and references cited therein). End-member modelling is required to decompose GSDs into proportional contributions of an optimal set of EMs whose distributions are not restricted to a particular class. This method of decomposition needs an array of GSDs; it cannot operate on a single GSD. Recently, Vriend and Prins (2005) used the end-member modelling technique to decompose the grain-size dataset of a Late Quaternary loess-paleosol succession from the north-eastern Tibetan Plateau into a series of end member GSDs. A mixing experiment carried out with sediment standards similar to their modelled EMs indicated that their laser-diffraction particle sizer is sensitive to small variations in mixing proportions of the standards. The unmixing approach potentially enables the unravelling of sediment fluxes from multiple dust sources, opening the way to significant advances in palaeoclimatic reconstructions from loess GSD data.

The present paper provides a synthesis of the unmixing results obtained for a series of Late Quaternary loess grain-size records extending across the Loess Plateau in China. The aim is to quantify different aeolian dust components in the loess GSDs with the EMMA, and to relate the reconstructed composition, spatial-temporal distribution and flux of the modelled aeolian dust components to possible sediment transport processes and dust supply patterns. It is shown that the unmixing of loess GSD data provides an important step forward in the development of source-specific dust flux models.

2. Material and methods

At the Vrije Universiteit Amsterdam we have an extensive grain-size data set of a series of loess sections extending across the Chinese Loess Plateau. This paper discusses the modelling results obtained for four sites (Huanxian, Yanan, Luochuan and Xunyi; Fig. 1), focusing on the S0-L1-S1 loess–paleosol complex, which has been deposited during the last glacial–interglacial cycle. Following An and Lu (1984) and Kukla and An (1989), we assumed that the boundaries between the loess and paleosols are time-equivalent with the glacial–interglacial stage boundaries of the marine isotope stratigraphy (Imbrie et al., 1984; Martinson et al., 1987) (Table 1). We realise that this might not be true in detail; however, for the purpose of highlighting the glacial–interglacial variability this assumption is valid. Description of the loess sections, bulk density and raw grain-size data have been taken from Nugteren (2002) and Nugteren and Vandenberghe (2004). A Fritsch A22 Laser Particle Sizer was used to analyse the GSDs (0.15–1682 μm). Details on the laser-particle sizer and sample preparation methods are given in Konert and Vandenberghe (1997). Several grain-size statistics have been calculated with the GRADISTAT program developed by Blott and Pye (2001).

The GSD data set (5–10 cm resolution; $n = 909$) of the four sites has been unmixed with the inversion algorithm for end-member modelling of compositional data EMMA (Weltje, 1997) to construct mixing models that express the observations as mixtures of a limited number of EMs. EMMA has been designed to provide the simplest possible explanation of the observed variation among a set of compositions (e.g., GSDs) in terms of (un)mixing. In contrast to curve-fitting algorithms, EMMA does not require any case-specific assumptions, i.e., the number of EMs and their shapes do not have to be specified. EMMA does not make use of parametric GSD models corresponding to continuous functions (e.g., lognormal or Weibull