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Plagioclase sub-species in Chinese loess deposits: Implications for dust source migration and past climate change

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ABSTRACT

Plagioclase mineral sub-species in the Lingtai Section in central Chinese Loess Plateau are examined using Mineral Liberation Analyzer techniques, showing that loess and paleosol samples exhibit similar patterns in terms of plagioclase feldspar sub-species content. This suggests that both loess and paleosol units have preserved their primary Ca-bearing plagioclase compositions of loess source regions. Weighted average CaO (%) in Ca-bearing plagioclase lies within a narrow range and is equivalent to the average plagioclase composition for upper continental crust. This fact supports the hypothesis that Chinese loess deposits are the result of a thorough mixing of dust sources. The sum of Ca-bearing plagioclase content exhibits a general increasing trend superimposed by glacial–interglacial oscillations. In combination with observed plagioclase data in the deserts, the variations of Ca-bearing plagioclase minerals might be used as a proxy for dust source migration and climate changes in the loess source regions. Furthermore, linear relationship between lithogenic magnetic susceptibility (MS) component input and contents of Ca-bearing plagioclase in loess units revises a MS proxy for reconstructing paleo-monsoon precipitation history. The revised MS and plagioclase sub-species records help in understanding the mechanism of glaciation across northern Tibetan Plateau.

Introduction

The climate of the past 500 ka has been characterized by the waxing and waning of global ice-sheets within a marked 100 ka cyclicity, as seen from Antarctic ice-core (Petit et al., 1999) and marine isotope records (Lisiecki and Raymo, 2005). These significant changes in ice-sheet amplitude either directly influenced Chinese loess deposits, as shown by loess deposits (glacials) with intercalated paleosols (interglacials) (Bloemendal et al., 1995), or modulated climates in the loess source regions in the Asian interior, through the influence of the Siberian–Mongolian Anticyclone (Hao et al., 2012). To assess better proxies for climate change with regard to Chinese loess deposits, it is necessary to differentiate changes in dust sources during times of high sedimentation (unaltered loess) versus times of low sedimentation (paleosols). However, the influence of glacial–interglacial climates on loess provenance remains poorly understood, as previous contradictory results attest (Gallet et al., 1996; Xiao et al., 2012). Based on zircon U–Pb ages, Che and Li (2013) suggested that the differences in zircon ages between interglacial paleosols and glacial loess were insignificant (Che and Li, 2013). Their results are supported by heavy mineral assemblage studies, which have revealed that no provenance shift occurred between the glacial and interglacial times (Nie and Peng, 2014). In contrast, studies of the physical parameters of fine-grained quartz using electronic spin resonance and crystallinity indices suggest that the predominance of loess sources varied significantly from interglacials to glacial times (Sun et al., 2008). We developed a new proxy for shifts in loess provenance by analyzing temporal changes in plagioclase feldspar mineral sub-species in loess deposits.

After quartz, plagioclase feldspar is the most abundant mineral series in the upper continental crust (Nesbitt and Young, 1984), and occurs commonly in igneous and metamorphic rocks. Plagioclase sub-species include albite < oligoclase < andesine < labradorite < bytownite < anorthite in increasing order of CaO content. The chemistry of Ca-bearing plagioclase can be used as an indicator of mineralogical maturity because anorthite molecules in plagioclase tend to be unstable during long-term exposure to chemical weathering. If plagioclase particles contain appreciable amounts of anorthite molecules, sediments are most probably not mature; such identification can prevent the misinterpretation of the presence of multi-cyclic materials (Pittman, 1970). The total anorthite molecule content and the sum of Ca-bearing plagioclase sub-species can therefore be used as reliable source tracers. For example, the chemical composition of Ca-bearing plagioclase has been used as an indicator of provenance changes in Tertiary sandstone sedimentary environments (Pittman, 1963, 1970; Trevena and Nash, 1979, 1981).

Chinese loess deposited during the Pleistocene also contains multiple plagioclase mineral sub-species. Previous studies using X-ray powder diffraction (XRD) measurements have indicated that there is a subtle difference between glacial and interglacial plagioclase contents for the last glacial–interglacial cycle (Jeong et al., 2008). However, a

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quantitative XRD method cannot satisfactorily establish anorthite molecule percentages in plagioclase. A scanning electron microscope combined with energy-dispersive X-ray spectroscopy (SEM-EDX) allows the statistical analysis of a limited number of 100–150 plagioclase particles. Using this technique, Jeong et al. (2008) estimated that 32% of the grains analyzed in one interglacial sample could be classified as plagioclase, and 20.5% in one glacial sample (Jeong et al., 2008). However, the technique has two limitations: (i) the counted number of particles is so limited that it reduced the accuracy of the calculated weighted average plagioclase values (AN); and (ii) it is difficult to detect rare plagioclase sub-species such as oligoclase, andesine, labradorite and bytownite in loess samples. We analyzed plagioclase sub-species in loess samples using a Mineral Liberation Analyzer (MLA), an automated point-counting technique (Fandrich et al., 2007). This technique, combined with energy-dispersive X-ray spectroscopy (EDS), allowed us to estimate precisely the content of each sub-species of plagioclase, principally because a larger number of granular particles could be analyzed, ranging from 10,000 to 40,000. We focused on: (i) long-term changes in plagioclase sub-species in loess deposits over the past 0.5 Ma; (ii) differences in plagioclase sub-species between glacial loess and interglacial paleosol layers; and (iii) the relation between plagioclase chemical composition and particle size distribution. Based on these observations, we further assessed the technique's potential for tracing glacial–interglacial scale changes in provenance.

Materials

The thick eolian deposits on the Chinese Loess Plateau (CLP) are located downwind from the arid regions of northern and northwestern China. These thick, continuous deposits thus provide a rare opportunity to explore past changes in provenance. The Lingtai Section (35°04′N, 107°39′E) is situated in the central CLP (Fig. 1). This profile has been described in detail in previous studies (Ding et al., 1999). Magnetic susceptibility (MS) and quartz mean grain size records for the Lingtai Section have been measured previously (Chen et al., 2006). The Lingtai Section's chronological framework is based on a paleomagnetic reversal sequence (Ding et al., 1999). A chronology is established for this section by correlating the sequences with the benthic $\delta^{18}O$ stack LR04 (Hao et al., 2012: Fig. 1).

Fourteen samples from the Lingtai Section from S0/L1 to S4/L5, covering the past 500 ka, were selected for mineral composition analysis. The sampling selection of these layers was based on minimum glacial and maximum interglacial MS values along the profile to better represent glacial–interglacial changes (Fig. S1). To avoid excluding the most significant changes between glacial–interglacial times, we selected two samples for each of glacial loess profiles L2, L4 and L5, and the interglacial paleosol S4. This sampling density was deemed sufficient for the clarification of glacial–interglacial variations in plagioclase minerals.

Methods

To obtain silicate minerals in the silt-size fraction, each of the subsamples was pretreated by adding 0.5 mol/l HCl to remove carbonate, then subjected to dispersal using ultra-sonic vibration for 30 min. Samples were then sieved using distilled water through mesh sizes 75 and 28 μm to obtain silt-sized particles. However, since the mesh size of 28 μm (500 mesh per inch) could easily be blocked by particles, we measured the true size range for the extracted particles using the SEM. This showed particles ranging between 5 and 75 μm, although clay-sized particles (<5 μm) were largely removed. Dried samples weighing 0.5 g were placed in 2.5 cm diameter round rubber mold. 20 ml resin and 5 ml hardener were added to form a hardened block. The solidified round block was then ground and polished to be ready for MLA measurement.

The MLA system consists of a specially-designed software package and a standard modern SEM fitted with an EDS analyzer. We used a Quanta 650 MLA loaded with a Philips SEM and double Bruker EDS. The maximum number of particles to be measured was set to 40,000 to be statically valid. We set the minimum particle identification area at 100 pixels (~1 μm^2). A micron-scale resolution could therefore be used for identifying single particle textures.

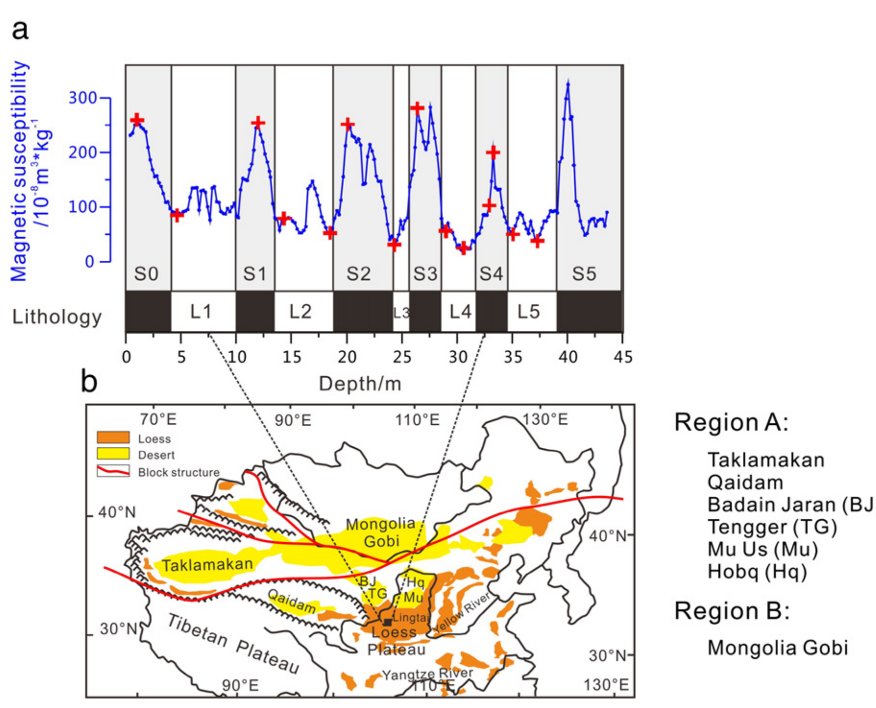

Figure 1. a) Stratigraphy (Ding et al., 1999) and MS records (Chen et al., 2006) of the loess–paleosol sequence at Lingtai in the central CLP. Paleosol units are in black. Red crosses indicate the locations of samples prepared for MLA measurement. b) The geographical setting of the loess source regions. The relevant principal deserts, or *gobi*, extend from northern China to southern Mongolia. A and B are the two mineralogical regions. The two distinct mineralogical regions are separated by tectonic block structure.