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Magnesium isotopic variations in loess: Origins and implications

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ABSTRACT

Loess deposits serve as important continental archives for studying Quaternary climatic variations and for estimating the average chemical composition of the upper continental crust. Here, we report high-precision Mg isotopic data for 19 loess samples from China, Argentina and Europe, which were previously used to estimate the composition of the upper continental crust. The results show that global loess samples have heterogeneous Mg isotopic compositions, with $\delta^{26}\text{Mg}$ (per mil deviation of the $^{26}\text{Mg}/^{24}\text{Mg}$ ratio from the DSM3 standard) values ranging from -1.64‰ to $+0.25\text{‰}$ and a weighted average of -0.89‰ , which is lighter than both crust and mantle silicates. MgO content and $\delta^{26}\text{Mg}$ of loess positively correlate with $\text{CaO}/\text{Al}_2\text{O}_3$ ratio, suggesting a two-component mixing between carbonates and secondary silicate minerals. The large variation in Mg isotopic composition of loess results from a combination of factors, including source heterogeneity, eolian sorting during transport of the loess and chemical weathering during formation of the loess deposit. Our results suggest that Mg isotopic composition of loess has potential to be a proxy indicator to characterize the paleoclimatic change, but may not represent the average Mg isotopic composition of the upper continental crust due to mixing, sorting of isotopically distinct components and isotope fractionation during loess deposit formation.

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1. Introduction

Knowledge on the Mg isotopic composition of the upper continental crust is crucial for understanding interactions between the crust and mantle and constraining global Mg cycles. The Mg isotopic composition of the upper continental crust estimated from granites, loess, shales and upper crustal composites is highly heterogeneous, with $\delta^{26}\text{Mg}$ varying from -0.52‰ to $+0.92\text{‰}$ (Shen et al., 2009; Li et al., 2010; Liu et al., 2010), and on average heavier than the mantle, which has a relatively homogeneous Mg isotopic composition (i.e., $\delta^{26}\text{Mg} = -0.25 \pm 0.07\text{‰}$, Teng et al., 2007, 2010a; Handler et al., 2009; Yang et al., 2009; Bourdon et al., 2010; Chakrabarti and Jacobsen, 2010; Liu et al., 2011; Huang et al., 2011; Pogge von Strandmann et al., 2011; Xiao et al., 2013). The highly variable Mg isotopic composition of the upper continental crust is mainly attributed to the lithological complexity of the continental crust and Mg isotope fractionation during low-temperature water–

rock interactions (Tipper et al., 2006, 2008; Pogge von Strandmann et al., 2008, 2012; Li et al., 2010; Teng et al., 2010b; Wimpenny et al., 2010, 2011a; Huang et al., 2012; Opfergelt et al., 2012). These make accurate estimates of the average Mg isotopic composition of the upper continental crust challenging.

Loess is a good proxy for constraining the average composition of the upper continental crust due to the fact that loess is formed by particles from a large area of exposed crust and undergoes limited chemical weathering during its formation (e.g., Goldschmidt, 1922; Taylor et al., 1983; Gallet et al., 1998; Barth et al., 2000; Peucker-Ehrenbrink and Jahn, 2001; Hattori et al., 2003; Teng et al., 2004; Hu and Gao, 2008; Park et al., 2012). Furthermore, loess–paleosol sequence preserves a terrestrial record of environmental changes during the Quaternary (Heller and Liu, 1984; Liu and Ding, 1998). A number of proxy indicators, including magnetic susceptibility, grain-size distribution, mineral composition, and geochemical signature have been employed to characterize paleoclimatic changes during the Quaternary (Heller and Liu, 1984; Bronger and Heinkele, 1990; An et al., 1991; Ding et al., 1994; Liu and Ding, 1998; Chen et al., 1999; Guo et al., 2000; Wang et al., 2007; Liang et al., 2009). Large isotope fractionation during low-temperature water–rock interactions and limited fractionation during igneous differentiation (Teng et al., 2007, 2010a;

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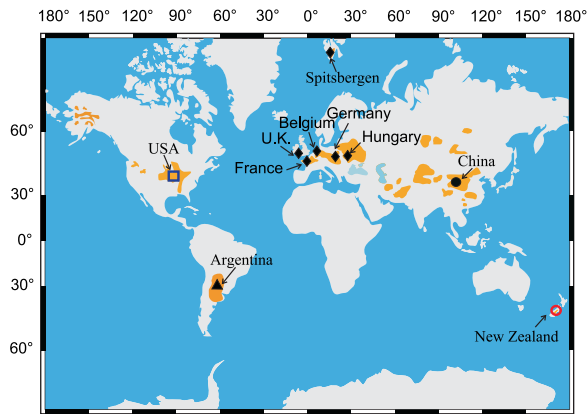


Fig. 1. Map showing the world distribution of loess deposits and sampling localities (modified after Pécsi, 1990). Loess samples from Argentina, Europe, and China measured in this study are marked as black solid triangles, quadrangles and circles, respectively. Open squares and circles stand for the previously studied loess samples from the USA and New Zealand (Li et al., 2010).

Liu et al., 2010) make Mg isotopes a potentially powerful tracer of chemical weathering, which exerts a fundamental role in regulating the global carbon cycle, and in turn controls the Earth's climate (Berner et al., 1983). Hence, studies of Mg isotopic composition of loess may potentially shed light on the average Mg isotopic composition of the upper continental crust and paleoclimatic change (Wimpenny et al., 2011b).

To date, limited Mg isotopic data of loess have been reported and they display large ($> 1\%$) variations (Young and Galy, 2004; Li et al., 2010; Immenhauser et al., 2010; Wimpenny et al., 2011b). The detailed mechanisms that control Mg isotopic variations in loess are still unclear, and systematic investigations of the major loess deposits of different continents are needed. Here, we analyzed Mg isotopic compositions of well-characterized loess samples from the major loess deposits in the world (Europe, China and Argentina, Fig. 1) (Taylor et al., 1983; Gallet et al., 1998; Jahn et al., 2001; Peucker-Ehrenbrink and Jahn, 2001; Teng et al., 2004) to (1) determine the general factors controlling Mg isotopic composition of loess, (2) discuss possible application of Mg isotopic geochemistry of loess as a tracer of paleoclimatic change, and (3) investigate whether Mg isotopic composition of loess can be used to evaluate the average isotopic composition of the upper continental crust. Our results demonstrate that the Mg isotopic composition of loess has potential as a tracer for reconstructing paleoclimatic change, but is not suitable for estimating the average Mg isotopic composition of the upper crust due to isotope fractionation during eolian sorting, chemical weathering and dilution by carbonates.

2. Samples

Loess is an eolian deposit of silt-sized clastic particles, which is formed essentially by mechanical erosion of large geographical areas in arid and semiarid climate (Bryan, 1945; Smalley, 1966; Liu, 1985; Pécsi, 1990; Pye, 1995; Smalley et al., 2011). Owing to the difference in the surficial geology and the effectiveness of sediment mixing processes in the individual source region, mineral compositions of loess vary greatly within different regions (Pye, 1995). In general, the dominant minerals in loess are silt-sized quartz, feldspar, carbonate minerals, clay minerals and heavy minerals (Liu, 1985; Pécsi, 1990; Eden et al., 1994; Gallet et al., 1998). The ternary diagram, i.e. $(\text{Na}_2\text{O}+\text{K}_2\text{O})-(\text{MgO}+\text{CaO})-(\text{Al}_2\text{O}_3+\text{Fe}_2\text{O}_3)$, has been used to reflect the relative abundance of silt-sized feldspars and micas, carbonates and clay minerals in loess (Muhs

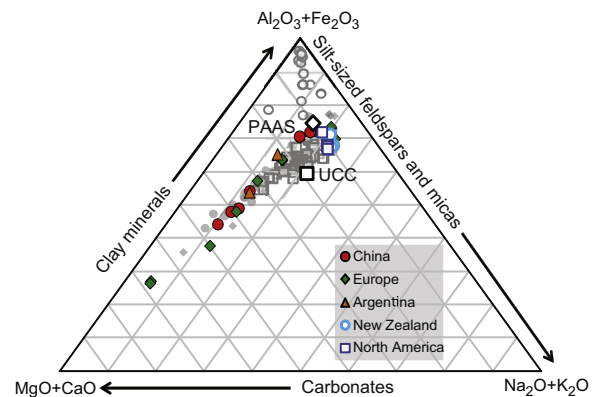


Fig. 2. The ternary diagram showing the relative abundances of carbonates ($\text{MgO}+\text{CaO}$), clay minerals ($\text{Al}_2\text{O}_3+\text{Fe}_2\text{O}_3$) and silt-sized feldspars and micas ($\text{Na}_2\text{O}+\text{K}_2\text{O}$) in loess samples in this study (bigger color icons) and previous studies (smaller gray icons) as well as post-Archean Australian average shale (PAAS, Taylor and McLennan, 1985; McLennan, 2001) and the upper continental crust (UCC, Rudnick and Gao, 2003). The Chinese loess data are from Taylor et al. (1983), Gallet et al. (1996), Ding et al. (2001) and Jahn et al. (2001). The Argentinean loess data are from Gallet et al. (1998). The European loess data are from Gallet et al. (1998). The New Zealand loess data are from Graham et al. (2001) and Li et al. (2010). The USA loess data are from Muhs et al. (2008) and Li et al., (2010). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

et al., 2008). Relative to silt-sized feldspars and micas, carbonates and clay minerals are main components of global loess, with loess plotting between clay minerals ($\text{Al}_2\text{O}_3+\text{Fe}_2\text{O}_3$) and carbonates ($\text{MgO}+\text{CaO}$) on a trajectory pointing away from carbonates toward clay minerals (Fig. 2).

Nineteen loess samples from 8 localities on three continents were investigated here (Fig. 1). The chemical compositions of these loess samples cover the compositional ranges of global loess (Fig. 2), suggesting that our samples have good representativeness for the global loess. Among these samples, 10 were collected from Europe covering most of the western part of the continent, including Belgium, France, Germany, Hungary, the United Kingdom and Spitsbergen (Svalbard), seven were from the Chinese Loess Plateau, and two were from Pampean, Argentina. Detailed descriptions on these samples have been presented in previous studies (Taylor et al., 1983; Gallet et al., 1998; Jahn et al., 2001). Thus, only a brief description is given below.

2.1. European loess

Ten samples from Europe that were previously used to estimate the composition of the upper continental crust (Taylor et al., 1983; Gallet et al., 1998) were studied here. Four samples were collected from France: samples NS4 and NS6 (Nantois section, Brittany), sample PR (Port-Racine section in Normandy), and sample HOT (Gallet et al., 1998). Two samples (K1 and K2) were from the Kaiserstuhl section, Rhine Valley, Germany (Taylor et al., 1983). One peculiar loess sample (SCIL) was collected from Scilly Islands, UK, and dated to be 18 ka (Gallet et al., 1998). Sample K14 was collected from the Kesselt section in Belgium and sample H was from Hungary. One Holocene loess sample (LO94) was collected from the Adventdalen valley on Spitsbergen Island in Svalbard, Norway, where loess was generally produced through the combined erosive powers of salt and ice smashing in addition to abrasion to the underlying bedrocks by glacial erosion (Bryant, 1982; Gallet et al., 1998).

The European loess samples are dominated by quartz, calcite, clay minerals, muscovite, chlorite-vermiculite, and micas (Swineford and Frye, 1955). The two samples from Kaiserstuhl, Rhine Valley, Germany, have high carbonate content, but other

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