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The geochemistry of loess: Asian and North American deposits compared

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ABSTRACT

Loess is widely distributed over Asia and North America and constitutes one of the most important surficial deposits that serve as terrestrial records of the Quaternary. The oldest Pleistocene loess in China is likely ~2.6 Ma, thus spanning much or all of the Pleistocene. In North America, most loess is no older than the penultimate glacial period, with the exception of Alaska, where the record may go back to ~3.0 Ma. On both continents, loess deposits date primarily to glacial periods, and interglacial or interstadial periods are represented by paleosols. Both glacial and non-glacial sources of silts that comprise the bulk of loess deposits are found on both continents. Although loess has been considered to be representative of the average upper continental crust, there are regionally distinctive compositions of loess in both Asia and North America. Loess deposits in Asia from Yakutia, Tajikistan, and China have compositionally distinct major element compositions, due to varying abundances of silicate minerals, carbonate minerals, and clay minerals. In North America, loess in the Mississippi River valley, the Great Plains, and Alaska are also distinguishable with regard to major element composition that reflects highly diverse source sediments. Trace element geochemistry (Sc-Th-Zr and the rare earth elements) also shows regional diversity of loess bodies, in both Asia and North America. On both continents, most loess bodies show significant contributions from later-cycle, altered sedimentary rocks, as opposed to direct derivation from igneous rocks. Further, some loess bodies have detectable contributions from mafic igneous rocks as well as major contributions from average, upper-crustal, felsic rocks. Intercalated paleosols in loess sections show geochemical compositions that differ significantly from the underlying loess parent materials. Ratios of soluble-to-insoluble elements show depletions in paleosols due to chemical weathering losses of calcite, dolomite, plagioclase, mica, apatite, and smectite. In Asia and North America, the last interglacial paleosol is more weathered than equivalent modern soils, which could be due either to a climate that was warmer and more humid, a longer period of pedogenesis, or both. In Asia, early Pleistocene loess and paleosols are both more weathered than those from the middle and late Pleistocene, forming prior to a mid-Pleistocene aridification of Asia from uplift of the Tibetan Plateau. Understanding the geochemistry of loess and paleosols can tell us much about past atmospheric circulation, past temperature and moisture regimes, and even tectonic processes.

1. Introduction

Loess is aeolian sediment that is one of the most important surficial deposits on the surface of the Earth. As used in this paper, loess can be defined as silt-dominated sediment that has been entrained, transported, and deposited by the wind and is recognizable in the field as a distinct sedimentary body. It occupies an intermediate position in a continuum of aeolian sediments, with an average particle size that is smaller than windblown sand (2–0.05 mm), but coarser than aerosolic dust (typically < 10 µm). Commonly, loess contains 60–90% silt-sized (50–2 µm diameter) particles, supplemented with small percentages of sand (> 50 µm) and clay (< 2 µm).

Through a century and a half of research, loess has come to be regarded as one of the most important archives of Quaternary climate change, particularly on the continent of Asia. Combined with intercalated paleosols (buried soils), loess provides one of the most complete terrestrial records of interglacial-glacial cycles. Loess is also distinctive in that it provides a direct record of atmospheric circulation. Thus, given favorable circumstances, loess can be used to reconstruct synoptic-scale paleoclimatology over millennial timescales, a significant attribute for Quaternary sediments. Further, unlike many Quaternary deposits, loess can be dated directly using methods, such as luminescence geochronology, that require only the sediment itself. Thus, the combination of loess deposits and intercalated paleosols provides a highly valued source of Quaternary paleoclimate information. In some regions, such as China, the record is long enough that inferences about Tertiary paleoclimate can even be made.

Loess can be recognized in the field as a distinctive sedimentary body, although its thickness is highly variable, from a few centimeters to several hundred meters in thickness. Indeed, variability of loess

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thickness is one of its advantages as a paleoclimate indicator, as paleowind directions can often be inferred from loess thickness trends (see examples in Muhs, 2013a, 2013b). Loess deposits are commonly draped over preexisting landforms as a mantle, with thickest accumulations in protected, low-lying areas or on broad, flat, stable upland divides. Thinnest accumulations of loess typically occur on narrow, rounded hillcrests. Loess is found as the uppermost surficial sediment over large areas of Asia, Europe, North America, South America, and New Zealand and covers smaller areas of Australia and Africa.

In this review, the geochemistry of loess is examined, with a focus on Asian loess deposits compared to those of North America. Interestingly, during a major part of the Quaternary, during times of glacially lowered sea levels, Asia and North America were connected as a contiguous landmass. Asian scientists, and particularly Chinese geologists, have been pioneers in studies of the geochemistry of loess. Early recognition of the importance of geochemistry to loess interpretations in China was made by Wen Qizhong, Diao Guiyi, Sun Fuqing, and Yu Suhua, who characterized the major and trace element geochemistry of these deposits in Liu's (1988) comprehensive volume on the loess of China. Subsequent loess researchers in Asia have followed this tradition of using geochemistry in interpretations of loess origins and paleoclimatic significance. North American loess researchers have been slower to utilize geochemical tools in their studies, but sufficient data now exist to make some useful comparisons with results derived from studies in Asia.

Two broad themes will be addressed in this review. The first is that geochemistry can be a powerful tool in understanding loess origins. The igneous and sedimentary petrology communities have used both major element geochemistry and trace element geochemistry (including the rare earth elements, REEs) in trying to understand the genesis and compositional evolution of rocks. Applications of geochemical methods to loess research naturally follow the approaches that have been taken by sedimentary petrologists, but such efforts would not be particularly useful were it not for the years of careful geochemical studies of igneous rocks by the petrology community. An attempt is made here to illustrate how some relatively simple geochemical analyses can yield much potentially useful information about how loess forms. Understanding how loess is derived (its provenance) and spatial trends in its geochemical properties reveal much about paleoclimate during times of dust entrainment and transport.

The second theme that is addressed is the stratigraphic complement to the first: the origin and paleoclimatic significance of buried soils (paleosols) that represent stable land surfaces when pedogenesis was dominant between times of loess accumulation. Geochemistry of paleosols, particularly when combined with mineralogical analyses, can give important clues about the duration of pedogenesis, the prevailing climate at the time of soil formation, and sometimes even the type of vegetation that occurred during such times.

2. Geography and geologic setting of loess deposits

2.1. Geography of loess in Asia

Loess is widespread over much of Asia, particularly in Russia, China, and a number of countries in Central Asia (Fig. 1). In the Asian portion of Russia, loess is extensive in central Siberia and its depositional history has been reviewed by Chlachula (2003). Farther to the northeast, loess is also found along the Lena River in Yakutia (Péwé and Journaux, 1983). Based on mapping by Velichko et al. (1984), loess is also likely extensive along the Arctic Ocean coast of Siberia, but further studies are needed in this remote region to understand its true distribution. Loess in Central Asia is found primarily in five countries: Tajikistan, Kyrgyzstan, Turkmenistan, Uzbekistan and Kazakhstan. The loess in Tajikistan is the most studied and best understood, primarily from work by the late A.E. Dodonov and his colleagues (see review by Dodonov, 2007). Smaller areas of loess occur in Iran, Afghanistan, Pakistan and northern India (see Ahmad and Chandra (2013) for an example of the latter), but their spatial extent is known only approximately.

Without question, the most accurately mapped and best-studied loess deposits are in China, due to the pioneering efforts of T.S. Liu. Loess is found in several parts of China (Fig. 2). The largest contiguous area, and that which has received the most study, is the dissected Loess Plateau in the central part of the country, between approximately 95°E and 110°E longitude and centering on ~38°N latitude (Figs. 2–4). In the

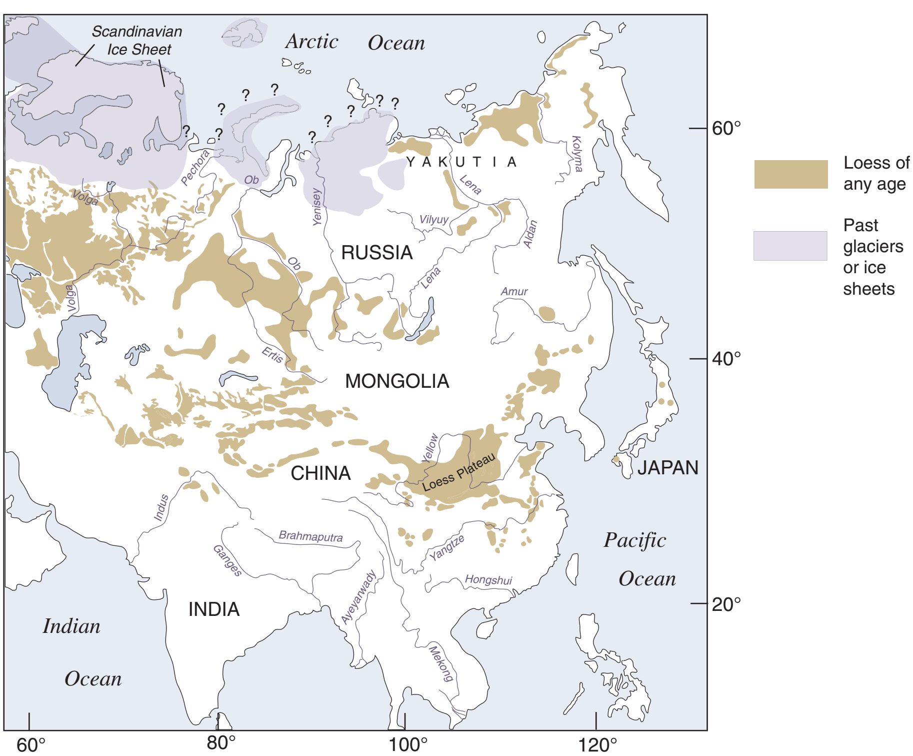

Fig. 1. Distribution of loess in Asia, compiled from Velichko et al. (1984, 2006), Liu (1988), Rozycki (1991), Dodonov (2007), and Frechen et al. (2009). Note: loess is also reported for Japan (Watanuki et al., 2005; Matsu'ura et al., 2011), but distribution maps are not shown in those reports.