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Magnetoclimatology: Teleconnection between the Siberian loess record and North Atlantic Heinrich events

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ABSTRACT

New environmental magnetic data from loess and paleosol successions in outcrops in the upper reaches of the Ob River drainage, southern Siberia, track the major climatic variations over the last glacial-interglacial cycle. Profiles of magnetic susceptibility and alternating deposition of loess and soil-formation events correspond to oxygen isotope stages 1–5. The magnetic-susceptibility data, in association with the stratigraphic succession, confirm that the wind-vigor magnetoclimatological model is a viable alternative to the classic pedogenic model. Interpretation of magnetic-susceptibility data from loess-paleosol successions must therefore consider eolian dynamics, available source materials, and transport directions, in addition to pedogenic processes. Rapid magnetic fluctuations are also observed. These are identified—for the first time in Siberian records—as the signature of the abrupt cold pulses responsible for the Heinrich layers in North Atlantic marine sediments. The data thus form a component of climatic teleconnections across the Northern Hemisphere, allowing correlations to be made among (1) Siberian magnetic susceptibility stratigraphy, (2) data recorded from other loess-paleosol successions in China, European Russia, Europe, and North America, (3) North Atlantic ice-rafted detritus, and (4) sea-surface temperatures derived from molecular stratigraphy of marine sediments off the northwest coast of Africa.

Keywords: loess, Siberia, paleoclimate, magnetic susceptibility, Heinrich events.

INTRODUCTION

Recent years have seen a vigorous international effort to understand Earth's climate and to document its fluctuations, both in the short term and over the long run. In the Northern Hemisphere, some of the most fruitful natural archives for this endeavor have been the thick deposits of loess and interstratified paleosols in several key areas in Eurasia (e.g., Liu, 1991; Velichko, 1990; Rutter et al., 1996; Chen et al., 1997; Chlachula et al., 1997, 1998; Tsatskin et al., 1998; Boenigk and Frechen, 2001; Horváth, 2001; Terhorst et al., 2001; Gunster et al., 2001) and North America (e.g., Begét et al., 1990; Maat and Johnson, 1996; Mason, 1998; Johnson and Willey, 2000; Mason and Kuzila, 2000). The detailed records presented by these successions potentially allow recognition of climate shifts that can be correlated across the entire hemisphere.

The use of magnetic susceptibility (MS) as a proxy for climate change is now firmly established, but two competing models have emerged that give rise to opposing magnetoclimatological signatures. In the celebrated loess sections in north-central China, it has been convincingly demonstrated that the warm, moist conditions prevailing during interglacial periods give rise to magnetic enhancement due to the iron oxide particles that are created during soil production (pedogenesis) and preserved in the fossil soils (paleosols) found at the appropriate stratigraphic levels (Heller and Liu, 1984; Maher and Thompson, 1992; Verosub et al., 1993; Han and Jiang, 1999; Deng et al., 2000). In contrast, the pristine air-fall dust that composes the intervening loess layers remains relatively unchanged and retains its low magnetic susceptibility. This pedogenic model, with MS maxima associated with paleosols, has been applied to loess-paleosol successions elsewhere (e.g., Heller and Evans, 1995; Maher, 1998; Tsatskin et al., 1998) and is sufficiently robust that several authors (e.g., Heller et al., 1993; Maher and Thompson, 1995; Han et al., 1996; An and Porter, 1997) have attempted to deduce quantitative estimates of paleoprecipitation throughout the last glacial-interglacial cycle.

At Kurtak (91.4°E, 55.1°N, Yenisei River valley, Siberia), a 34 m profile (Chlachula et al., 1997, 1998; Matasova et al., 2001) manifests MS maxima in cold oxygen isotope stages (OISs) 2 and 4 (represented by loess) and minima in warm OISs 3 and 5 (represented by paleosols). This type of ''inverted'' signature was originally identified in Alaska (Begét and Hawkins, 1989), where it was attributed to the ability of stronger, and more frequent, winds to entrain dense iron oxide particles and transport them to depositional sites downwind. Subsequent investigations in Alaska and Siberia, where MS minima are associated with paleosols, have suggested that this wind-vigor

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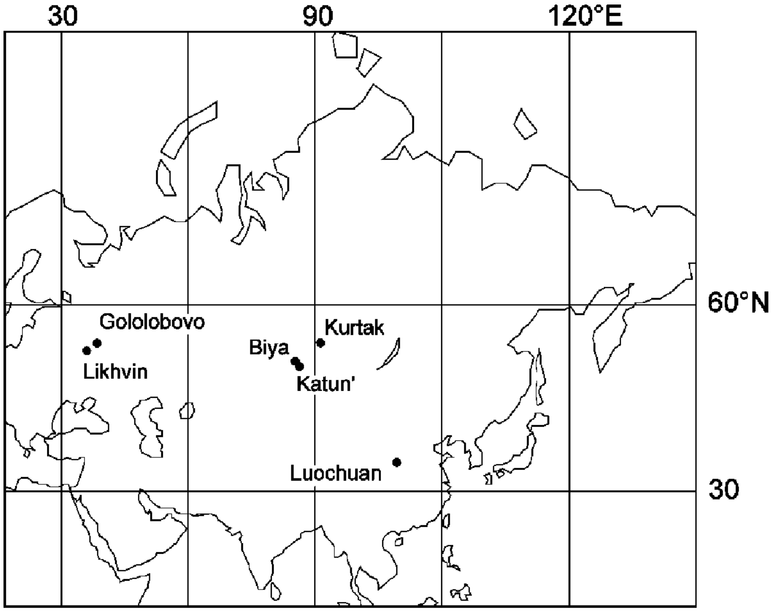

Figure 1. Location map indicating sites mentioned in text.

model may be more generally applicable to other loess-paleosol sequences (Evans, 2001). Thus, interpretation of the significance of MS fluctuations cannot proceed in isolation from consideration of the modes of deposition of loess in each succession, including potential differences in the available minerals in the source area (e.g., Liu et al., 1999; Han and Jiang, 1999).

BIYA AND KATUN' VALLEY SECTIONS

Loess deposits in Siberia cover, with variable thickness, an area >700,000 km^2. The successions, notably that exposed at Kurtak, contain paleosols that can be correlated to OISs 3 and 5 (Chlachula et al., 1997, 1998; Fig. 1). The chronology is based on comparisons between numerous well-dated loess and paleosol sections found in parts of the Russian Plain, south of Moscow (Velichko, 1990; Little, 2002), and throughout the Chinese Loess Plateau (Liu, 1991; Sun et al., 1998; Rutter et al., 1996). Common to all these is a well-developed modern soil (OIS 1) over relatively thick units of loess deposited during OISs 2 and 4, indicating colder climates. Warming trends are noted in the loess of OIS 3. In many successions, one or more soils are present. In the central Russian Plain, well-dated sections are found at Likhvin (36.3°E, 54.1°N) and Gololobovo (38.6°E, 55.1°N), where two soils are present in OIS 3 (Velichko, 1990; Little, 2002). Elsewhere, OIS 3 is marked by textural variations, finer grains indicating warmer periods (Rutter et al., 1996). In China, many sections are well dated, and OIS 3 is represented either by two soils or by two units of finer-textured loess (Sun et al., 1995). At Kurtak, the major section contains several soils in OIS 3 (Chlachula et al., 1997). This supporting evidence leaves little doubt that the stratigraphic assemblages described herein represent OISs 1, 2, 3, and 4.

For the investigation reported here, several hundred samples were collected from two loess and paleosol sections in the valleys of the Biya and Katun' Rivers, the major tributaries of the Ob (Fig. 1). After removal of surface material and preparation of clean vertical faces, samples were removed in 8 cm^3 plastic boxes at stratigraphic intervals of 5 cm. Susceptibility was measured in the laboratory on a Bartington MS2B susceptibility meter using the standard low-frequency setting (470 Hz). The resulting magnetic profiles from the two sections are shown in Figure 2. The longer profile (Biya River) can be readily interpreted in terms of the wind-vigor model and tied to the classical oxygen isotope chronology. Abrupt changes occur at the 1-2, 2-3, and 3-4 stage boundaries. The 4-5 boundary is less clear, and additional field research and analyses are in progress to clarify its characteristics. Within this broad stratigraphic framework, it is possible to identify shorter-wavelength features that we correlate to the Heinrich events (H1–H6) seen in marine cores from the North

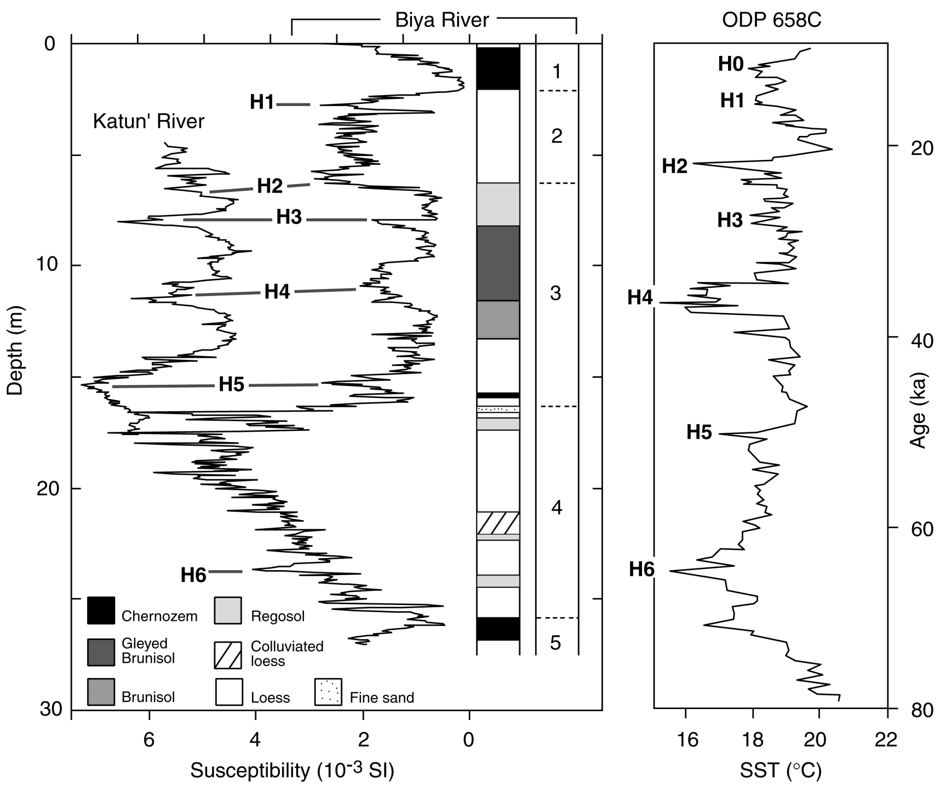

Figure 2. Magnetic-susceptibility profiles at sections on Biya River (85.3°E, 52.6°N; 541 samples) and Katun' River (85.8°E, 52.2°N; 237 samples). Values on abscissa are reversed following common practice of plotting warm (interglacial) features to right and cold (glacial) features to left. Biya data are plotted correctly, but Katun' data are shifted 3.75 × 10^{-3} units to left to avoid overlap. Panel on extreme right shows sea-surface temperature (SST) reconstruction obtained from alkenone measurements on phytoplankton remains (molecular stratigraphy) in marine sediments recovered from Ocean Drilling Program (ODP) Site 658C (18.6°W, 20.7°N) off northwest coast of Africa (modified from Zhoa et al., 1995).

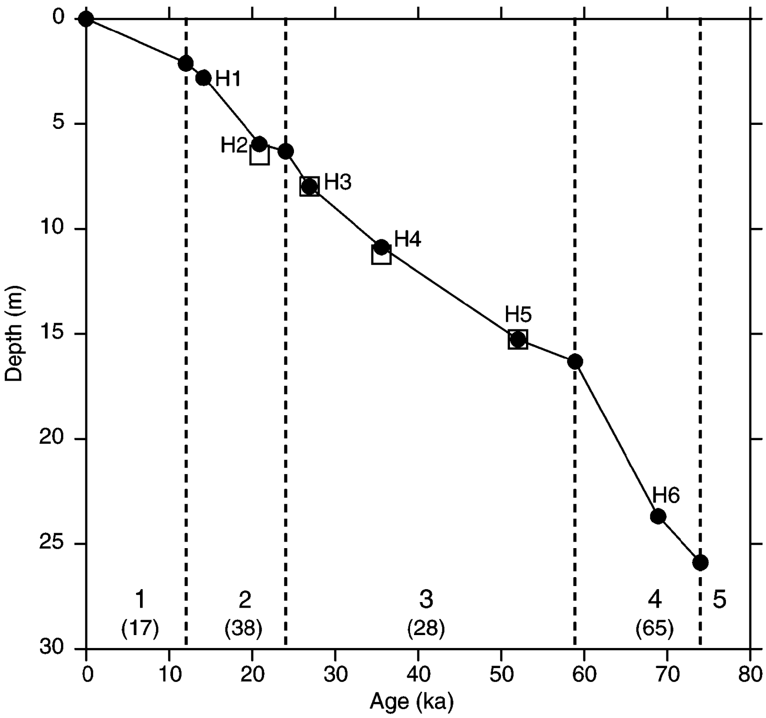

Figure 3. Chronostratigraphic summary based on ages of oxygen isotope stage boundaries and Heinrich events (Bradley, 1999, Tables 6.2 and 6.6). Circles—Biya River site; squares—Katun' River site. For each isotope stage at Biya site, average sediment-accumulation rate (in centimeters per thousand years) is shown in parentheses.

Atlantic (Heinrich, 1988). Four of these events (H2–H5) can also be identified in the Katun' River section, ~50 km to the southeast. To our knowledge, this is the first time that such millennial-scale climatic features have been recognized in the vast area of loess deposits in Siberia.

Because the ages of the isotope stage boundaries and the Heinrich events are reasonably well defined (Bradley, 1999), a combined chronology can be constructed for the Biya River section, as illustrated in Figure 3. Despite minor fluctuations, a regression line through the complete ensemble fits very well ($R = 0.9891$) and implies an overall average sediment-accumulation rate (SAR) of 32 cm/k.y. However, separate regression lines through isotope stages 2, 3, and 4 yield meaningful variations with significantly higher average rates in cold stages. The average SARs are as follows: stage 2, 38 cm/k.y. ($R = 0.9872$); stage 3, 28 cm/k.y. ($R = 0.9915$); and stage 4, 65 cm/k.y. ($R = 0.9944$). Stage 1 has no internal points because H0, the only potential Heinrich event, cannot be reliably identified in these sections. Nevertheless, the assumption that sedimentation has continued throughout the Holocene yields an acceptable average of 17 cm/k.y. These SAR values indicate that the 5 cm sample spacing corresponds to ~290, 130, 180, and 80 yr in stages 1, 2, 3, and 4, respectively.

Higher SAR values during cold stages imply high rates of eolian transport and sediment influx, as would be expected from increased wind vigor. The average SARs we obtain for stages 2 and 4 (0.38 mm/yr and 0.65 mm/yr, respectively) are comparable to rates of accumulation in eolian environments where periodic moistening of the surfaces leads to more effective adhesion (Mason, 1998; Catto and Bachhuber, 2000). For stage 3, the estimated SAR of 0.28 mm/yr reflects the combination of eolian deposition and soil formation. Rates of soil accumulation are less than those for eolian sedimentation because sediment is strongly compacted during pedogenesis due, in large measure, to significant organic input. In stage 1, pedogenic processes appear to dominate, and the SAR is only 0.17 mm/yr.

IMPLICATIONS

The correlations just outlined imply that climate over central Asia during the last glacial cycle responded to the same abrupt atmospheric cooling events that launched armadas of icebergs into the North Atlantic. We argue that, during these short cold (Heinrich) interludes over the Laurentide ice sheet and the North Atlantic, atmospheric conditions over Siberia were also colder and generally stormier. The increased magnetic susceptibility that is the hallmark of the North Atlantic Heinrich layers is due to a higher content of magnetic ice-rafted detritus produced by glacial action from the North American craton. In a similar manner, the short-period MS peaks in our Biya and Katun' valley sections are due to increased entrainment of dense iron oxide grains resulting from elevated wind vigor.

We also note that the Atlantic cold-water pulses involved in the Heinrich events traveled southward in the Canaries Current and caused abrupt sea-surface temperature changes off the northwest coast of Africa (Zhoa et al., 1995). These correlate particularly well with our Siberian magnetoclimatological data, as shown in Figure 2. Similar correlations have also been made between the North Atlantic region and the Chinese Loess Plateau (Porter and An, 1995; Rutter et al., 1996), where Heinrich events have been identified on the basis of grain-size analyses. In both studies, magnetic susceptibility was also measured, but the published profiles show no evidence of the Heinrich events that are so clearly seen in the grain-size data. Chen et al. (1997) reported a similar investigation from the western Chinese Loess Plateau where they also found evidence for Heinrich events in grain-size and calcium carbonate–content variations. However, their high-resolution MS profile shows no such evidence, recording instead what they interpret as the warm interstadials (Dansgaard-Oeschger cycles) manifested as oxygen isotope fluctuations in the Greenland ice cores. The marked contrast between these Chinese studies and our Siberian data can be explained in terms of the different applicable magnetoclimatological models. In China, MS variations are primarily due to precipitation-driven pedogenesis controlled by the southeasterly summer monsoon, whereas in Siberia, loess magnetism is largely controlled by the wind-vigor model. It appears that where wind vigor is the controlling factor, short cold intervals, such as Heinrich events, can be captured magnetically. Where pedogenesis is the dominant magnetoclimatological factor, the magnetic signature of such cold pulses is too subtle and can only be revealed by time-consuming grain-size and/or chemical analyses.

Our new Siberian data are from sites ~2500 km to the northwest of the Chinese Loess Plateau and much farther from the Atlantic Ocean. By investigating different climate proxies, the various studies succeed in complementing each other in the overall goal of understanding past climatic variability as encoded in the geologic record. In particular, the identification of similar features in all these regions argues strongly for the reality of millennial-scale climate events that extended across the Northern Hemisphere and perhaps were global in extent.

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