Mineral magnetic record of the Chinese loess and paleosols

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ABSTRACT

Variations in the magnetic susceptibility of the Chinese loess and its interbedded paleosols correlate strikingly well with the deep-sea oxygen isotope record. Low susceptibility values are found for the loess layers, and high values are found for the soil horizons. Two interpretative models have been advanced to account for these magnetic variations. Both of these models discount any significant in situ formation of magnetite during soil-forming periods. Instead, they infer relative concentration of detrital or atmospheric magnetite at these times. We critically examine the assumptions made in these models and, on the basis of some new mineral magnetic data and formalized magnetic flux calculations, offer an alternative explanation of the loess magnetic record. Our model identifies pedogenic formation of magnetite as the major contributor to the high magnetic susceptibility of the paleosols. The formation and preservation of this pedogenic magnetite is dependent on soil-forming conditions and hence reflects the regional climate.

INTRODUCTION

The extensive sequences of loess and interbedded paleosols in north-central China represent a detailed and quasicontinuous terrestrial record of paleoclimatic change through Quaternary time (Kukla, 1987). Deposition of the loess began 2.4 Ma, but reached its maximum spatial extent in the late Pleistocene. The sediments were deposited in arid and semiarid regions of an area trending west-east, between lat 33° and 47°N and long 127° and 75°E. In the central loess plateau, the loess and soil sequences attain vertical thicknesses >130 m. The loess deposits in this area display a clearly defined paleomagnetic polarity zonation (Heller and Liu, 1982) that extends to below the Olduvai subchron.

Studies (An et al., 1977; Heller and Liu, 1984; Kukla et al., 1988) have shown that the loess and soil units can readily be differentiated by measurements of their initial magnetic susceptibility: the susceptibility of the soils is generally higher than that of the loess by a factor of two to five. The susceptibility record is also strongly correlated with the deep-sea oxygen isotope record (Heller and Liu, 1984), indicating that deposition of dust in this area and global ice volume have both been linked to, and controlled by, changes in the general circulation of the Northern Hemisphere. The susceptibility record of the loess thus constitutes a natural archive of proxy climatic data. However, the source of the observed variations in the susceptibility signal, and the mechanism of its response to climatic forcing, are as yet poorly understood. Two interpretative models have been advanced. Heller and Liu (1986) suggested that there was relative enrichment of detrital magnetic minerals in the soils during interglacial periods, due to concentration by decalcification and soil compaction processes. Kukla et al. (1988) and Kukla and An (1989) proposed that the bulk of the susceptibility signal is contributed by subaerial deposition, from high-level transport of ultrafine particles of magnetite from distance sources. Assuming a constant rate of this atmospheric input over a time scale of several millenia, they inferred dilution of the magnetite concentration during cold and dry periods, when large amounts of local, low-susceptibility silt were deposited. In contrast, during warm and humid interglacial periods, when sedimentation rates were low, the ultrafine dust would form the dominant component of the air-fall deposits, and the magnetic concentration would thus be relatively high.

Both of these models discount the possibility of in situ authigenesis of magnetite during soil formation, a phenomenon reported for a range of contemporary soils in the humid temperate zone (e.g., Mullins, 1977; Longworth et al., 1979; Maher and Taylor, 1988; Fassbinder et al., 1990). Herein we examine the assumptions underlying the two models and, on the basis of some new mineral magnetic data, present an alternative interpretation of the loess magnetic archive.

MAGNETIC ACCUMULATION RATES

As in many soils and sediments, the magnetic properties of the Chinese loess and paleosols are dominated by the most strongly magnetic natural minerals, magnetite and maghemite. Kukla et al. (1988) have identified submicron-sized magnetite in magnetic separates obtained from loess and soil units in Luochuan. From magnetic measurements of particle size separates, they found that these submicron grains were the major contributor to the susceptibility signal. They also used a variety of analytical techniques to detect the presence of maghemite, chlorite, and hematite.

Under certain conditions, magnetic susceptibility is proportional to the magnetite concentration of a sample. This relation forms the first basic premise of Kukla et al.'s (1988) model. They dated the loess susceptibility record by matching it with the deep-sea oxygen isotope chronology of Imbrie et al. (1984) and Prell et al. (1986). Kukla et al. then sought to identify the long-term accumulation rate of the magnetic component by plotting the cumulative concentration of magnetite (as given by the susceptibility signal) as a function of time. This results in a virtually straight line plot, from which they concluded: (1) the total amount of magnetite in each of two widely separated sequences (Xifeng and Luochuan, 160 km apart) is virtually the same; (2) the rate of magnetite accumulation is almost constant throughout the Brunhes epoch; and (3) the near constancy of the magnetic sedimentation rates in differing lithologies and locations of the loess plateau identifies a depositional rather than pedogenic origin of the susceptibility signal.

The validity of these conclusions is doubtful, however, because they result from a demonstrably insensitive treatment of the susceptibility data. Because the susceptibility values oscillate in a limited way around some mean value, and because these oscillations are then compared with an increasingly large cumulative susceptibility total, the net effect is to smooth the data and remove the inherent variations in input. A useful analogue is provided by the example below, comprising some rainfall data collected from a station in Thailand over 50 yr (Fig. 1). The yearly inputs vary from 501 to 2033 mm, the standard deviation is 242 mm, and the coefficient of variation is 20%. The rate of input through time ($\delta p/\delta t$, where p is precipitation, and t is time) is not constant (Fig. 1B). However, as with the loess data, if the *cumulative* rainfall total ($\Sigma p/\delta t$) is calculated and plotted against time, a straight line results (Fig. 1A). This indicates only that there is no drastic change in the *mean* of the incoming rainfall over the monitored time period. In the same way, the susceptibility data from the loess identify variable rates of influx of magnetic minerals through time, the values oscillating from minima during glacials to maxima in interglacials around a relatively stationary mean.

These variations in magnetic mineral flux can be clearly seen when more appropriate use is made of the susceptibility data, through calculation of actual magnetic accumulation rates. As Kukla et al. (1988) have shown, there is a striking similarity between the magnetic susceptibility profiles at Xifeng and Luochuan and the deep-sea oxygen isotope record. We have used a sequence-slotting algorithm (Thompson and Clark, 1989) to match these three records in detail. The sequence-slotting algorithm provides an age at every susceptibility measurement depth. Furthermore, differentiation of the resulting age-depth information, through use of a cubic hermite function (Fritsch and Butland, 1984), allows us to produce estimates of sediment accumulation rates at each sample horizon. Multiplication of the susceptibility of each horizon with its sediment accumulation rate gives the magnetic accumulation rate. This is plotted against time in Figure 2 for the Xifeng and Luochuan profiles.

As calculated with our procedure, magnetic accumulation rates in the Xifeng and Luochuan sequences are variable through time and space. Figure 2 shows a trend of gradual increase in magnetic accumulation rates with time; clear oscillations are superimposed on this trend. Minima of magnetic accumulation rate are associated with unweathered loess, and maxima are associated with horizons of soil development. The significance of these differences between the loess units and the soil horizons is confirmed by application of a formalized Student's t-test. Where individual loess layers are internally interrupted by soil development, e.g., loess 1.SS1, the susceptibility values are moderate. Multiplication of these moderate values by the high sediment accumulation rates calculated for the loess layers then results in notably high values of magnetic accumulation rate. The records show little between-site variation for the period 0.8 to 0.35 Ma, for which the two magnetic accumulation rate curves agree remarkably well. However, from 0.35 to 0.15 Ma, the records do not match as well, and imply clear differences in magnetic accumulation rate at the two sites. These differences are most pronounced in soil units S2, S1, and S0. For example, the mean magnetic accumulation rate for the S2 horizon at Xifeng is 18.9 ±1.5, whereas at Luochuan it is 12.6 ±1.2.

CONTRASTS IN MAGNETIC MINERALOGY

A second assumption of both the Heller and Liu (1986) and the Kukla et al. (1988) models is that there are no systematic differences in the composition and grain size of the ferrimagnetic minerals in the soils and in the loess. To characterize the magnetic mineralogy of the soil and loess more fully, and thus test this assumption, more detailed magnetic measurements are required, such as the parameters listed in Appendix 1. These parameters trace the magnetic response of the sample material to a variety of applied magnetic fields. This response is mainly determined by the mineralogy, concentration, and grain-size distribution of the dominant magnetic phases (e.g., see Thompson and Oldfield, 1986; Maher, 1988). We have determined the magnetic parameters listed here for 21 loess and soil samples (provided by G. Kukla) from the Luochuan section near Potou village (Kukla and An, 1989). Figure 3 shows the lithology of the section, sample depth, and results of our remanence and susceptibility measurements.

The laboratory measurements show that susceptibility minima are associated with the least weathered loess horizons, and susceptibility maxima are associated with the most well developed soil horizons, in accord with Kukla et al.'s (1988) field measurements of magnetic susceptibility. Absolute values vary between 26 and

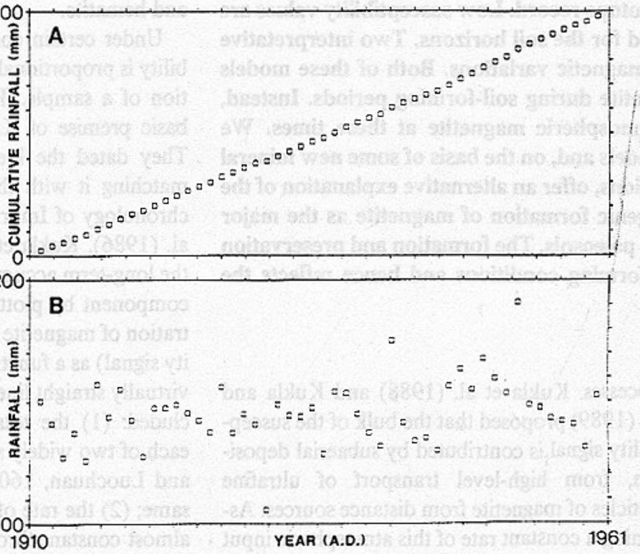


Figure 1. A: Cumulative rainfall vs. time, northern Thailand. B: Yearly rainfall for 50 yr period, northern Thailand.

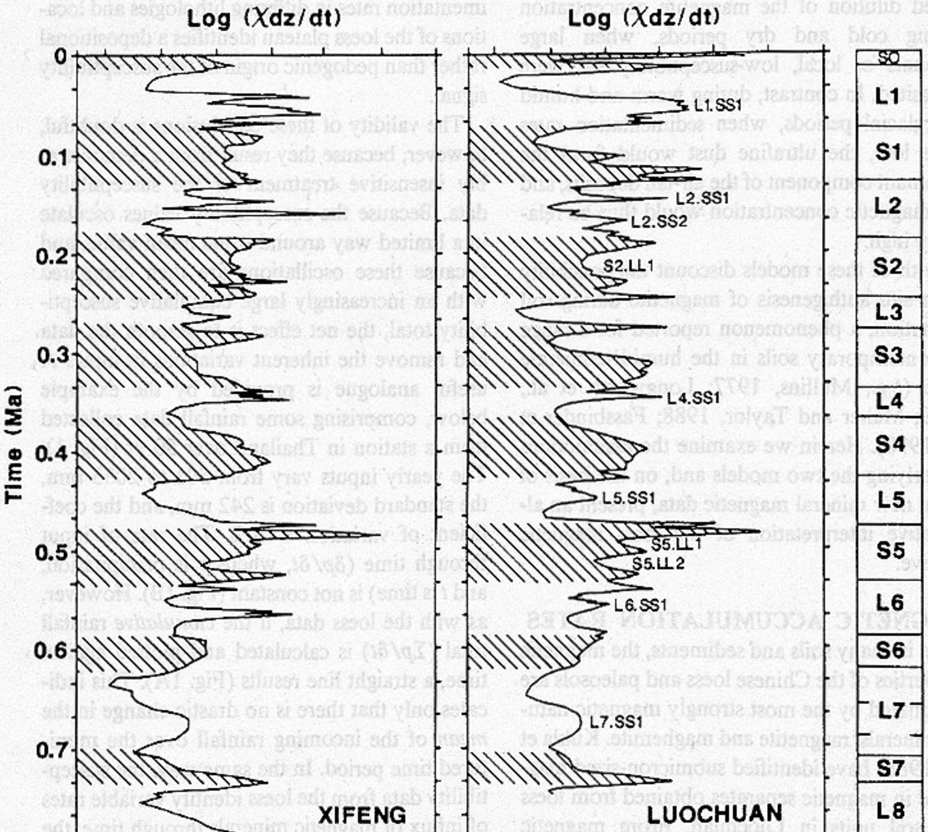


Figure 2. Magnetic accumulation rates (X dz/dt), Xifeng and Luochuan. SO = Soil 0, L1 = Loess 1, L1.SS1 = intermediate soil in loess unit.

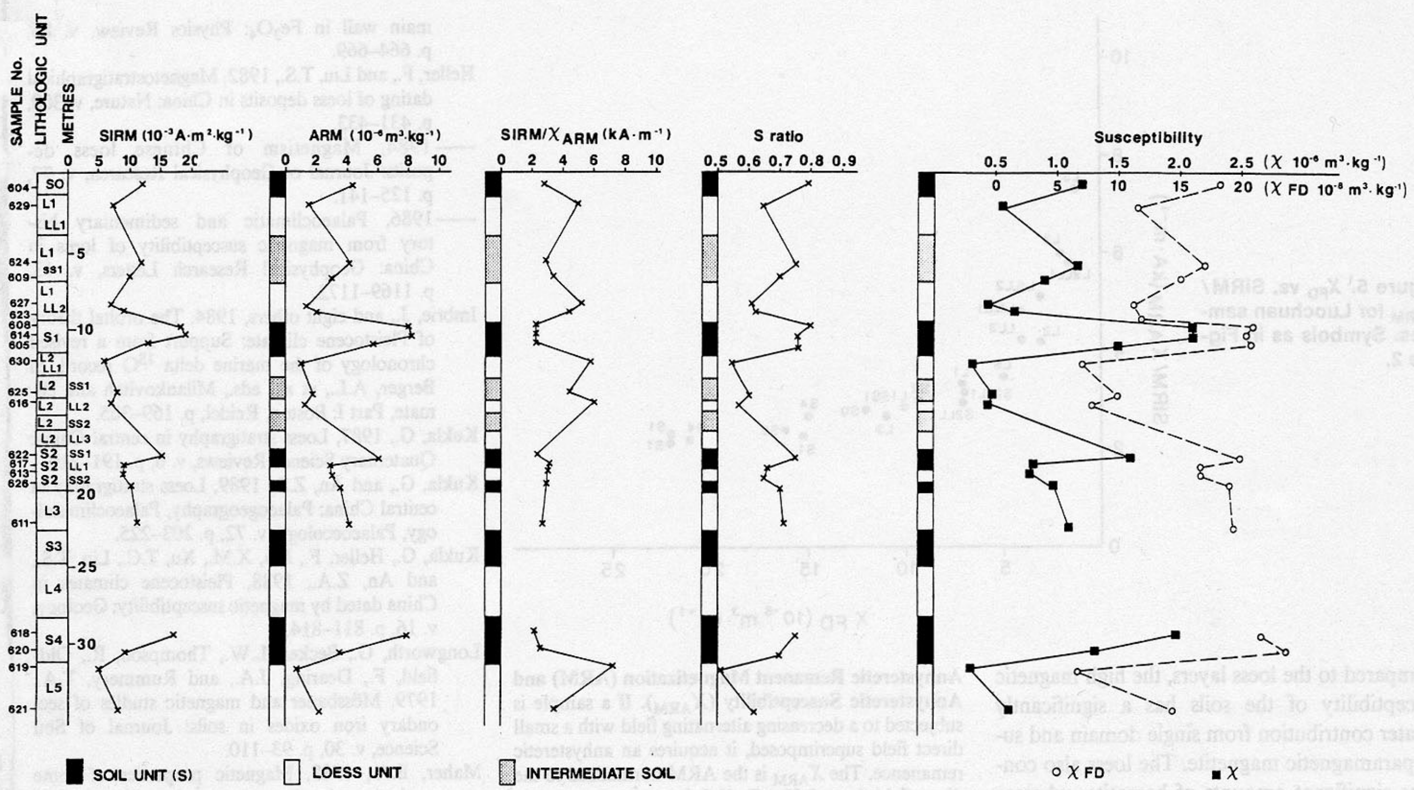


Figure 3. Lithology and magnetic remanence and susceptibility parameters obtained for 21 Luochuan samples. X_{FD} = frequency-dependent susceptibility, X = susceptibility.

$114 \cdot 10^{-8}$ m$^3 \cdot$ kg^{-1} (mean = $63 \cdot 10^{-8}$ m$^3 \cdot$ kg^{-1}) for the loess, and between 77 and 212 $\cdot$ 10^{-8} m$^3 \cdot$ kg^{-1} (mean = $145 \cdot 10^{-8}$ m$^3 \cdot$ kg^{-1}) for the soils. The remanence parameters, saturation remanence, and anhysteretic susceptibility (Appendix 1) reflect a generally similar pattern to susceptibility. These measurements indicate a mean magnetite content of between 0.08% and 0.14% by weight in the loess layers, and 0.2% and 0.32% in the soils. However, in addition to differences in magnetic concentration, the magnetic data also identify variations in the magnetic grain-size distribution of the loess and soil samples. For example, when samples contain superparamagnetic grains of magnetite (Fig. 4), their response to magnetic susceptibility measurements is dependent on the frequency of the field applied (Galt, 1952). Thus, the presence of such grains can be identified by measuring magnetic susceptibility at two different frequencies (0.5 and 5 kHz). The Luochuan samples (Fig. 3) demonstrate a direct correlation between susceptibility and frequency-dependence of susceptibility; the high-susceptibility paleosol horizons have a larger frequency-dependent component than the low-susceptibility loess layers. This suggests that the soils contain a significantly higher proportion of superparamagnetic magnetite. Further information on magnetic grain-size variation can be gained from the ratio between the anhysteretic susceptibility (X_{ARM}), and the saturation remanence (SIRM). The lower the SIRM/X_{ARM} ratio, the larger the proportion of

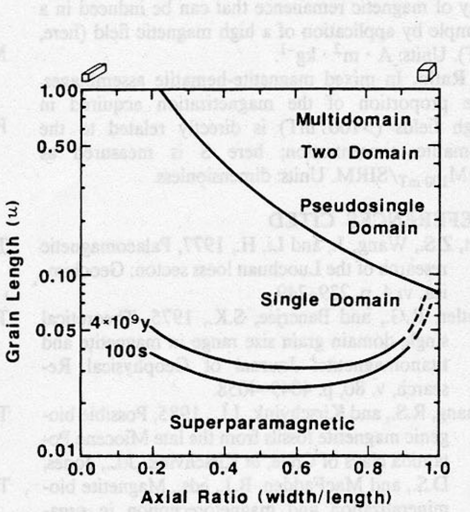


Figure 4. Domain status and grain size in magnetite; y = year, s = second (after Butler and Banerjee, 1975, redrawn from Chang and Kirschvink, 1985).

viscous, single-domain magnetite grains (grains close to the single-domain/superparamagnetic boundary at ~0.03 μm; Fig. 4) within the grain-size distribution (Maher, 1988). The SIRM/X_{ARM} ratios of the Luochuan samples (Figs. 3 and 5) vary between 2.2 and 3.2 kA $\cdot$ m^{-1} (the mean is 2.6 kA $\cdot$ m^{-1}) for the soil units; ratios for the loess layers vary between 2.7 and 7.1 kA $\cdot$ m^{-1} (the mean is 4.3 kA $\cdot$ m^{-1}). Hence, these data identify distinctive grain-size contrasts between the loess and soil layers. The soil horizons are characterized by the presence of ultrafine-grained magnetite, of single domain and superparamagnetic size (up to ~0.05 μm), whereas the loess layers contain little, if any, single-domain magnetite and only a small fraction of superparamagnetic magnetite (Fig. 5). Soil layers interrupted by loess deposition have intermediate accumulations of single domain and superparamagnetic material. Sample 611, from the base of loess unit L3 (i.e., immediately above soil S3), exhibits magnetic properties closely akin to the soil units, and thus may include local deflated soil particles.

In addition to these contrasts in the magnetite concentration and grain size, and as noted by Kukla et al. (1988), the proportion of hematite varies significantly between the loess and soil units. The S ratio (Appendix 1, Fig. 3) varies from 0.7 to 0.8 in the soils, and from 0.54 to 0.75 in the loess. Lower S ratios indicate increasing proportions of imperfect antiferromagnetic materials (such as hematite), which only acquire magnetic remanence at high applied fields.

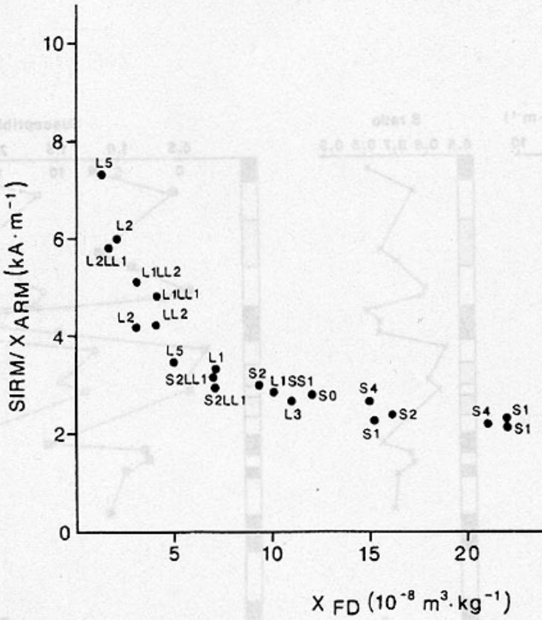
CONCLUSIONS

1. Magnetic accumulation rates of the Chinese loess and paleosol sequences vary both in time and space.

2. Magnetic accumulation rates are significantly higher in the paleosol horizons than in the loess layers.

3. There are systematic differences between the loess and soil units in both the concentration of magnetite and in the grain-size distribution.

Figure 5. X_{FD} vs. SIRM/X_{ARM} for Luochuan samples. Symbols as in Figure 2.



Compared to the loess layers, the high magnetic susceptibility of the soils has a significantly greater contribution from single domain and superparamagnetic magnetite. The loess also contains significant amounts of hematite, whereas the soils do not.

4. Given that (1) magnetic accumulation rates in the loess and paleosol sequences demonstrate significant variation, and (2) there are significant differences in the magnetic mineralogy, concentration, and grain size between the loess and soil layers, then neither the constant-influx model of Kukla et al. (1988) nor the concentration (by decalcification) model of Heller and Liu (1986) fully account for the variations in the loess and soil magnetic properties. This indicates that the underlying assumptions of these models are not entirely correct.

5. We suggest that the presence of higher concentrations of single domain and superparamagnetic magnetite in the paleosol units is at least partly due to its in situ formation during soil-forming periods. Ultrafine-grained magnetite is the characteristic product of inorganic precipitation (Maher and Taylor, 1988; Tite and Linington, 1975) and bacterial magnetosome formation (Fassbinder et al., 1990). Both of these processes are sensitive to the temperature and wetness of the soil and hence reflect the climate regime at the time of soil formation.

APPENDIX 1. MAGNETIC MINERALOGY PARAMETERS

Low-field Magnetic Susceptibility (X). The ratio of induced magnetization to applied field, a measure of the magnetizability of a sample. Units: $m^3 \cdot kg^{-1}$.

Frequency-dependent Susceptibility (X_{FD}). If susceptibility is measured in an alternating field with a low frequency (0.5 kHz), then a high frequency (5 kHz), there will be a reduced contribution to susceptibility by superparamagnetic grains (<~0.03 μm in magnetite). Thus, samples with a significant proportion of grains show frequency-dependence of susceptibility. Units: $m^3 \cdot kg^{-1}$.

Anhysteretic Remanent Magnetization (ARM) and Anhysteretic Susceptibility (X_{ARM}). If a sample is subjected to a decreasing alternating field with a small direct field superimposed, it acquires an anhysteretic remanence. The X_{ARM} is the ARM normalized to the direct field (here, 0.08 mT, 63.7 $A \cdot m^{-1}$), expressed in units of $m^3 \cdot kg^{-1}$.

Saturation Remanence (SIRM). The highest intensity of magnetic remanence that can be induced in a sample by application of a high magnetic field (here, 1T). Units: $A \cdot m^2 \cdot kg^{-1}$.

S Ratio. In mixed magnetite-hematite assemblages, the proportion of the magnetization acquired in high fields (>100 mT) is directly related to the hematite concentration; here S is measured as $IRM_{100\ mT}$/SIRM. Units: dimensionless.

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Reviewer's comment

Challenges the two current hypotheses of magnetic susceptibility variations in loess and presents new data to support the challenge.

William Ruddiman