

**MAGNETIC SUSCEPTIBILITY VARIATIONS IN LOESS SEQUENCES  
AND THEIR RELATIONSHIP TO ASTRONOMICAL FORCING**

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The long, well-exposed and often continuous sequences of loess found throughout the world are generally thought to provide an excellent opportunity for studying long-term, large-scale environmental change during the last few million years. In recent years, the most fruitful loess studies have been those involving the deposits of the loess in China. One of the most intriguing results of that work has been the discovery of an apparent correlation between variations in the magnetic susceptibility of the loess sequence and the oxygen isotope record of the deep sea. This correlation implies that magnetic susceptibility variations are being driven by astronomical parameters. However, the basic data have been interpreted in various ways by different authors, most of whom assumed that the magnetic minerals in the loess have not been affected by post-depositional processes. Using a chemical extraction procedure that allows us to separate the contribution of secondary pedogenic magnetic minerals from primary inherited magnetic minerals, we have found that the magnetic susceptibility of the Chinese paleosols is largely due to a pedogenic component which is present to a lesser degree in the loess. We have also found that the smaller inherited component of the magnetic susceptibility is about the same in the paleosols and the loess. These results demonstrate the need for additional study of the processes that create magnetic susceptibility variations in order to interpret properly the role of astronomical forcing in producing these variations.

The Chinese loess plateau stretches from 35°N to 40°N and from 100°E to 115°E and covers an area of 500,000 sq. km. The loess deposits are typically 150 m thick, and they appear to represent continuous deposition of wind-blown, silt-sized material during the past 2.4 million years. The source of this material is believed to be glacial outwash in the regions to the west and north of the plateau (Kukla and An, 1989). More importantly, the loess sequence contains many interbedded paleosols which attest to the existence of significant and cyclic climatic fluctuations. The most recent, comprehensive description of the units of the loess sequence is that of Kukla and An (1989), who recognized six stratigraphic units. From youngest to oldest, these are the Holocene

Black Loam Formation, the Malan Formation, the Upper Lishi Formation, the Lower Lishi Formation, the Wucheng Formation, and the Pliocene Red Clay.

On the basis of paleomagnetic studies (Heller and Liu, 1982; Kukla, 1987), the contact between the Wucheng Formation and the Red Clay layer has been dated at 2.4 million years, and the Brunhes/Matuyama, Olduvai event and Jaramillo event have each been identified in the sequence.

One of the primary parameters that has been used in the study of the loess/paleosol sequence has been magnetic susceptibility. Because the magnetic susceptibility of the loess is low while that of the paleosols is high, this parameter is considered an effective proxy for the quantitative study of the climatic fluctuations recorded by the loess/paleosol sequence (Heller and Liu, 1984; 1986).

The first comprehensive study of magnetic susceptibility variations in the loess/paleosol sequence was that of Heller and Liu (1984) who pointed out that there appeared to be a strong correlation between the magnetic susceptibility record and the oxygen isotope record of deep-sea cores from the equatorial Pacific Ocean. The relationship was further explored by Kukla *et al.* (1988) who published detailed magnetic susceptibility records from the loess/paleosol sections at Xifeng and Luochuan. These authors presented data to support their belief that the time required for the deposition of a particular loess unit was directly proportional to the product of the thickness of the unit and its magnetic susceptibility. They used this idea to construct a time scale that was independent of the oxygen isotope curve. On this time scale, the variations in magnetic susceptibility corresponded very closely to the variations in the oxygen isotope record from the deep sea, implying an interdependence among the rate of influx of loess, the volume of land-based ice, and the global climate. Additional evidence for astronomical forcing of the magnetic susceptibility record was provided by Wang *et al.* (1990).

A key component in the model used by Kukla *et al.* (1988; 1990) to account for the magnetic susceptibility variations was the assumption that the source of the magnetic susceptibility signal was a constant "rain" of ultrafine magnetic grains, carried into the upper atmosphere from volcanic eruptions and other unspecified processes. Kukla *et al.* further assumed that after these grains had been incorporated into the loess sequence during deposition, they remained inert and unaltered by post-depositional processes. The loess, on the other hand, was assumed to be essentially non-magnetic, and the modulation of the magnetic susceptibility signal was interpreted as a measure of the extent to which the magnetic "rain" had been diluted by loess. Thus, during glacial times, when the climate was cold and dry, the barren outwash plains could be easily eroded by aeolian processes, the rate of loess deposition would be at a maximum, and the magnetic susceptibility signal would be at a minimum. During interglacial times, when the climate was warm and humid, vegetation and soil moisture would tend to stabilize the outwash plains, loess deposition would be a minimum, and the magnetic susceptibility would be a maximum.

The model of Kukla *et al.* (1988; 1990) differs from that of Heller and Liu (1984) who suggested that the magnetic susceptibility values in the paleosols reflected a concentrating of the magnetic minerals by decalcification and soil compaction. Both models discounted any post-depositional alteration of the magnetic carriers. This fundamental assumption has been questioned by Zhou *et al.* (1990), Maher and Thompson (1991), and Zheng *et al.* (1991) who showed that there were significant differences between the rock magnetic properties of the magnetic minerals in the loess units and those in the paleosol units. These differences implied that there were differences in both the magnetic mineralogy and the grain size of the magnetic minerals in the two units. Maher and Thompson (1991) also raised questions about the methods that Kukla *et al.* used to demonstrate that the rate of accumulation of magnetic minerals had been constant. Zhou *et al.*, Zheng *et al.*, and Maher and Thompson all concluded that pedogenic processes had probably been important in the development of the magnetic susceptibility record of the paleosols.

We have obtained direct evidence that the magnetic susceptibility signal of *both* the loess units and the paleosols is due primarily to magnetic minerals formed by pedogenic processes. This conclusion is based on the studies of samples from ten loess/paleosol pairs from the classic section in Luochuan. The samples were provided to us by George Kukla of the Lamont-Doherty Geological Observatory, and they encompass the entire loess/paleosol sequence. Their designations, stratigraphic positions and approximate ages are shown in Table 1.

For each sample, we measured a variety of rock magnetic properties both before and after extraction with citrate-bicarbonate-dithionite (CBD). In this procedure, samples are subjected to sodium dithionite and bicarbonate, a strong buffered reductant, in the presence of sodium citrate, a chelating agent (Singer and Janitzky, 1986). The procedure was developed by Mehra and Jackson (1960) as a means of removing iron oxides from clay samples being prepared for X-ray diffraction analysis. The procedure was subsequently adopted by soil scientists as part of the standard chemical technique for characterizing the iron components of a soil. With that technique, extraction procedures involving pyrophosphate, oxalate and CBD are used to determine the amount of iron in organic, amorphous and crystalline phases, respectively. In recent years, we have used the CBD extraction technique in our studies of magnetic susceptibility enhancement in soil chronosequences in California (Singer and Fine, 1989; Fine *et al.*, 1989; Singer *et al.*, 1992). That work has shown that that CBD extraction is particularly effective in removing pedogenic magnetic grains (primarily maghemite) and that it leaves untouched essentially all of the magnetic grains that were inherited from the soil parent material (primarily magnetite and hematite). This selectivity has recently been confirmed by Mossbauer spectrometry (Singer *et al.*, 1991).

For untreated samples from the loess plateau, our rock magnetic measurements are fully consistent with those reported by Maher and Thompson (1991) and by Zhou *et al.* (1990). For example, the magnetic susceptibilities of the paleosols are as much as twenty times larger than

those of the corresponding loess samples (Table 1). Differences between loess and paleosol sample pairs are also noted in the frequency dependence of the magnetic susceptibility (which is a measure of the concentration of ultrafine grained, superparamagnetic particles), in the S-ratio (which is a parameter related to hematite concentration), in the ratio of saturation isothermal remanent magnetization to anhysteretic remanent magnetization (which is a measure of the relative abundance of single domain grains) and in the ratio of magnetic susceptibility to anhysteretic remanent susceptibility (which is related to mean magnetic grain size).

After CBD treatment, both the loess and the paleosol samples lose a significant percentage of their magnetic susceptibility (Table 1). These losses average 65% for the loess samples and 90% for the paleosol samples. Because the magnetic susceptibilities of the untreated paleosol samples are five to ten times greater than that of the untreated loess samples, the absolute decreases in magnetic susceptibility are much greater in the paleosols than in the loess units (Figure 1). Furthermore, after CBD treatment, the magnetic susceptibilities of the loess samples and the paleosol samples are about the same, regardless of the age of the samples (Figure 1). Several other rock magnetic properties also show decreases after CBD treatment with largest changes again occurring in samples from the paleosols (Figure 2). For a few rock magnetic properties, the values from the paleosol and loess samples move in opposite directions after CBD treatment. Furthermore, we have found a close relationship between magnetic susceptibility and dithionite-extractable iron (Figure 3), providing additional evidence of the importance of pedogenesis in determining the magnetic susceptibility of paleosols and loess.

Based on our work on the soil chronosequences in California, we interpret the CBD soluble fraction in the loess and paleosol samples as the pedogenic fraction, and the CBD insoluble fraction as the inherited fraction. This indicates that a significant portion of the magnetic susceptibility signal of both the loess samples and the paleosol samples is pedogenic in origin. The fact that pedogenesis is important in producing the magnetic susceptibility signal in the paleosols was suggested by Zhou *et al.* (1990), Maher and Thompson (1991) and Zheng *et al.* (1991). However, none of these groups postulated that pedogenesis could account for almost all of the magnetic susceptibility signal in the paleosols, and none of them proposed that pedogenesis would be important in the loess units as well. This latter observation gives us an entirely new perspective on the paleosol/loess sequences. In the conventional view, paleosol units are considered to have resulted from very different processes than those that produce the loess units. From our results, it seems that the same pedogenic processes might have been operating during times of loess deposition and paleosol formation but these processes were more intense during the former than during the latter.

Our results also show that other earlier inferences about the nature of the magnetic susceptibility signal were probably also wrong. For example, Maher and Thompson suggested

that the pedogenic component of the magnetic susceptibility was probably carried by magnetite while our data strongly support the conclusion that maghemite is the primary magnetic mineral. More importantly, our observations provide no support for the concept of an inert, ultrafine magnetic "rain" diluted to varying degrees by non-magnetic windblown silt, as proposed by Kukla *et al.* (1988; 1990). In fact, if the nearly constant residual magnetic susceptibility that we observe in both the paleosol and loess samples after CBD treatment is an exogenous magnetic component, it implies that the loess was accumulating at a same rate during glacial and interglacial stages and that the differences between paleosols and loess are due entirely to the degree of pedogenesis.

At present time, we are not prepared to argue the merits of this or any other explanation of our results. What we will argue is that we have shown that there is a clear need for a better understanding of the nature and origin of the magnetic susceptibility signal in the Chinese loess/paleosol sequence. This need is more than just a minor problem, of interest to a small group of rock magnetists. As noted above, the loess/paleosol sequences in general, and the Chinese sequences in particular, are considered the best recorders of terrestrial climate change during the last 2.4 million years. Almost exclusively, this change is being studied using magnetic susceptibility as a proxy indicator of paleoclimate. In fact, using assumptions about the magnetic susceptibility signal that our research has now shown to be incorrect, other workers have already developed an elaborate model for climate changes in Asia and the western Pacific. The model attributes these changes to astronomically-driven fluctuations in the summer monsoon that are modulated by uplift of the Tibetan plateau (Kukla, 1987; An *et al.*, 1991).

While certain aspects of this model may ultimately prove to be correct, the model itself cannot be validated until its underlying assumptions are based on the proper paleoclimate interpretation of the magnetic susceptibility record. Our work has shown that this interpretation must address the pedogenic nature of the magnetic susceptibility signal. This requirement also applies to loess/paleosol sequences elsewhere that are also being interpreted as records of terrestrial climate change.

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Table 1. Paleosol and Loess Samples from Luochuan, China.  
(Samples provided by George Kukla.)

Position	Depth m	Age <sup>†</sup> ka	Magnetic susceptibility	
			Pre-CBD	Post-CBD
			SI x 10 <sup>-8</sup> m <sup>3</sup> kg <sup>-1</sup>	
S1	10.0	128	227.5	22.7
L2-LL1	12.5	174	11.4	8.1
S3	24.0	328	223.3	19.7
L4	26.0	357	57.2	18.6
S5	36.5	614	283.3	11.4
L6	42.0	652	59.7	13.7
S7	52.0	726	81.1	15.3
L8	52.5	?	58.5	15.0
S8	54.5	737	129.5	15.0
L9	57.5	834	26.9	15.3
L14	76.0	?	53.7	11.2
L15	78.5	1172	23.0	14.4
WS1WL1	86.0	1316	132.9	13.9
WS1SS1	86.5	?	86.2	14.3
WS1SS1	87.5	?	84.6	14.1
WS2SS2	99.0	1566	102.5	15.0
WL2LL2	101.0	1695	54.9	12.8
WS3LL1	107.5	1939	45.0	13.0
WS3LL1	109.0	1939	49.9	9.4
WL4LL3	134.0	2342	37.1	11.2
RsSS1	136.0	>2342	168.7	14.3

<sup>†</sup> Age from Kukla (1987) Table 5.

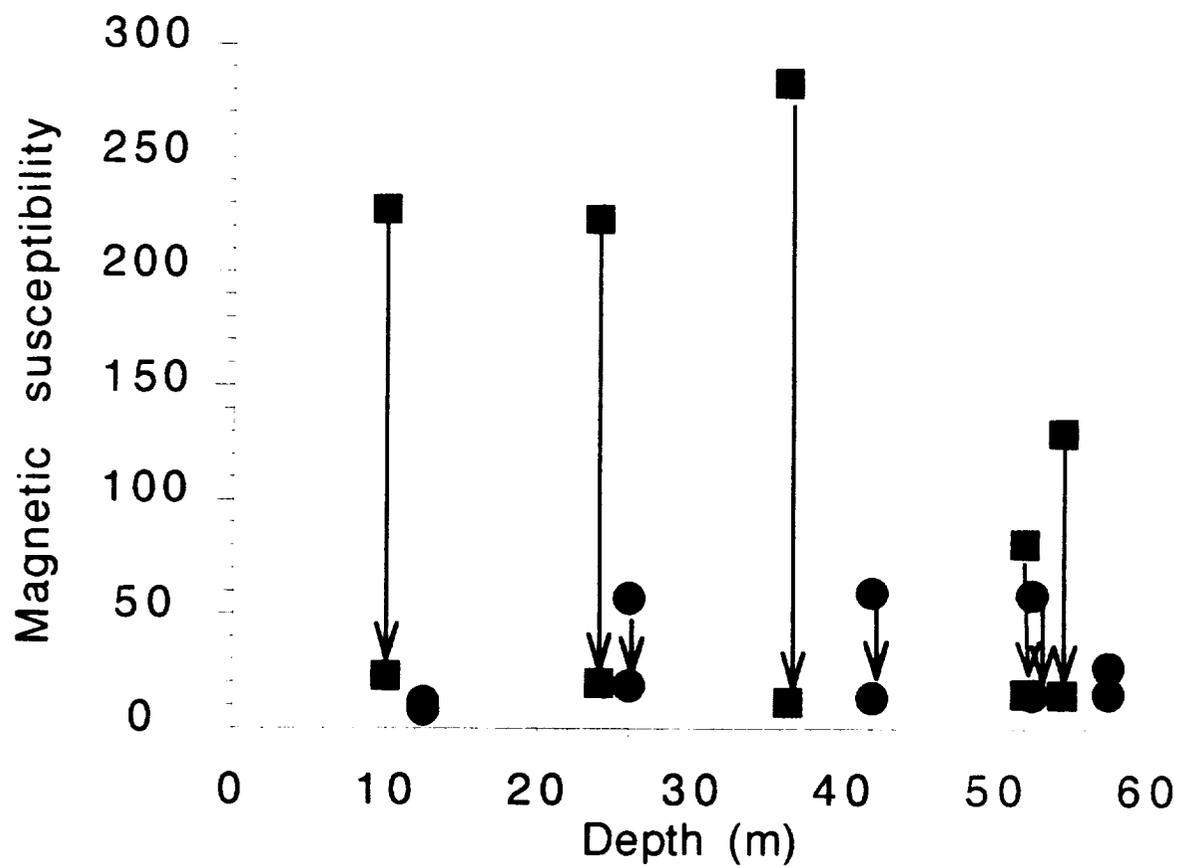


Figure 1. Effect of CBD treatment on magnetic susceptibility of some paleosol and loess units from the Lishi Formation, Luochuan, China. Squares are paleosol units; circles are loess units. Arrows indicate change upon CBD treatment. The post-CBD values for both paleosols and loess units are about the same.

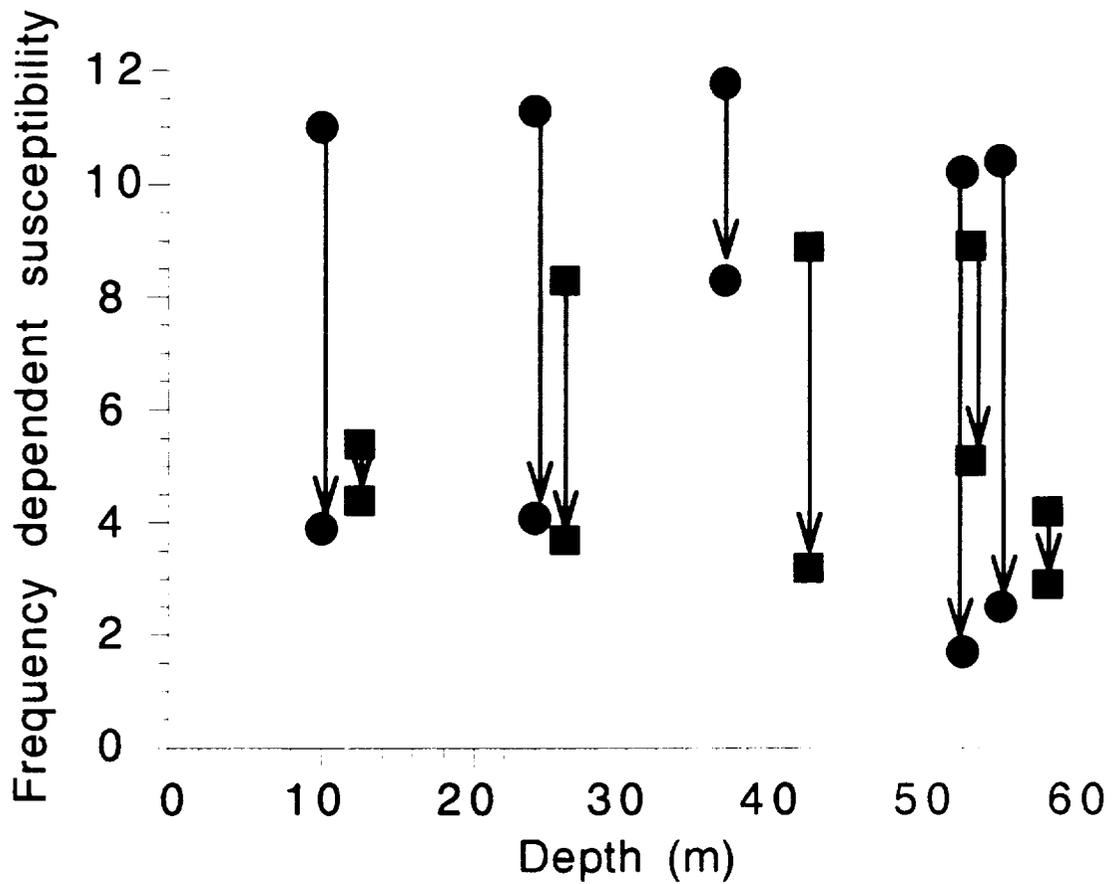


Figure 2. Effect of CBD treatment on the frequency dependence of the magnetic susceptibility of some paleosol and loess units from the Lishi Formation, Luochuan, China. Squares are paleosol units; circles are loess units. Arrows indicate change upon CBD treatment. The post-CBD values for both paleosols and loess units are about the same.

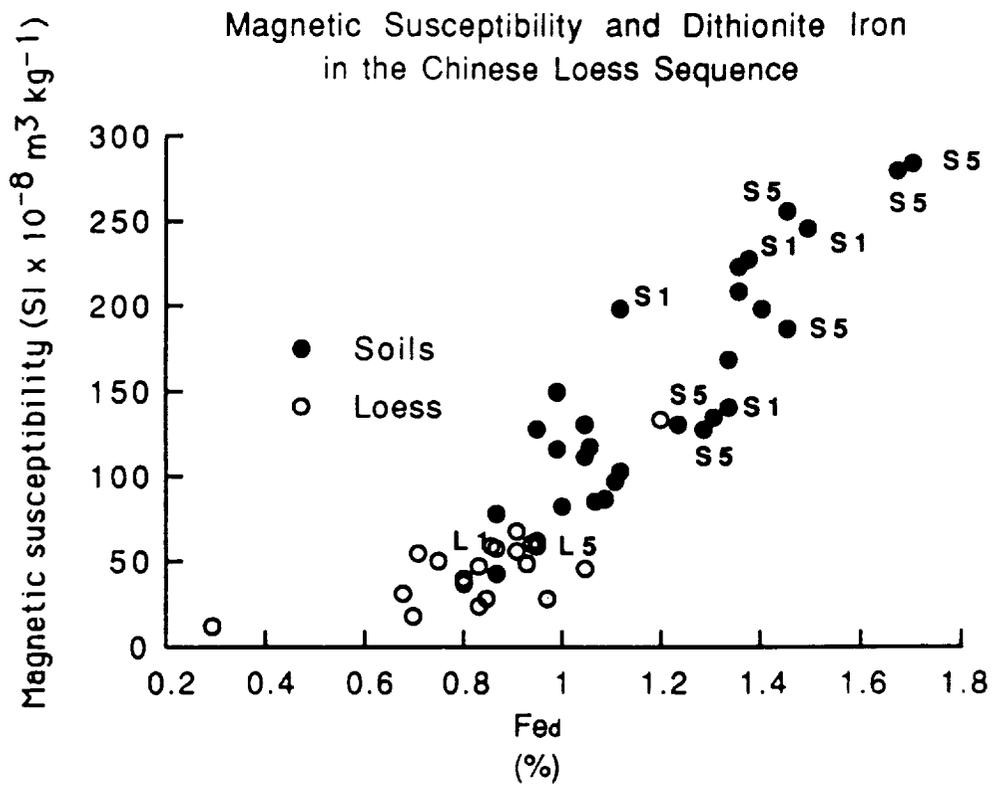


Figure 3. Relationship between dithionite extractable iron and magnetic susceptibility of some paleosol and loess units.