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Comments on "Origin of the magnetic susceptibility signal in Chinese loess"☆

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In their QSR Rapid Publication, Origin of the magnetic susceptibility signal in the Chinese loess, Meng *et al.* (1997) claim that:

1. The presence of magnetic material in vegetation is demonstrated by (a) experiments in which high magnetic susceptibility values were obtained for burnt and peroxidised leaf and leaf litter samples from Southeast England, and (b) an association between increased magnetic susceptibility values and vegetational debris in modern Chinese dust in the summer months.
2. Hence, decomposition of vegetation is an important contributor to the magnetic susceptibility of the palaeosols of the Chinese Quaternary loess/soil sequences.
3. Fine grains of ferrihydrite may be responsible for enhancement of the magnetic susceptibility signal in both decomposed plant tissue and modern Chinese dust.
4. The origin of the magnetic susceptibility signal in the Chinese loess remains poorly understood.

Here these claims are examined in turn.

(1a) The experiments reported by Meng *et al.* on leaves and leaf litter samples from SE England demonstrate only that prior to the experiments, the samples did not contain detectable amounts of magnetic material. After burning and peroxidation of the samples, they did. These results demonstrate that iron compounds present in the samples were altered by the experimental procedures. It is well established that heating of Fe-containing samples (i.e. as here, by burning or via the endothermic heating of the peroxide treatment) can transform non- or weakly-magnetic iron compounds into strongly magnetic ones (e.g. Le Borgne, 1960; Longworth *et al.*, 1979; McClean and Kean, 1993).

It is, in fact, very difficult to identify unequivocally the presence of biogenic magnetic material in plant tissues. First, leaves and leaf litter often carry or even entrain strongly magnetic pollution particles, produced by heating of iron impurities during fossil fuel combustion (Plate 1 and e.g. Hunt, 1986). Second, magnetic measurements of 'non-polluted' leaves and twigs give rise to values very close to detection limits (e.g. they are often less magnetic than the polystyrene sample holder).

(1b) The association between increased amounts of vegetational debris in the modern Chinese dusts collected in summer months and apparently higher magnetic susceptibility values strongly suggests that the dusts contain windblown topsoil. No meteorological data are given by Meng *et al.* but the dominant surface wind direction in this region during the summer months is the SE monsoon (Fig. 2a). Conversely, in winter, the NW monsoon is

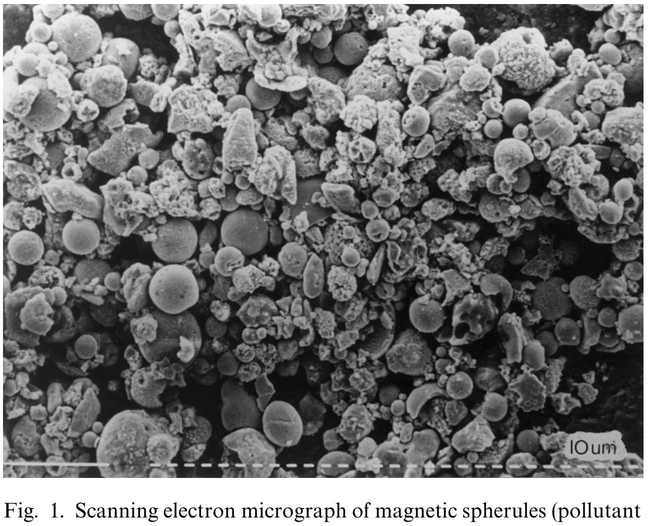

Fig. 1. Scanning electron micrograph of magnetic spherules (pollutant particles), deposited on a surface soil sample (from Maher, 1998).

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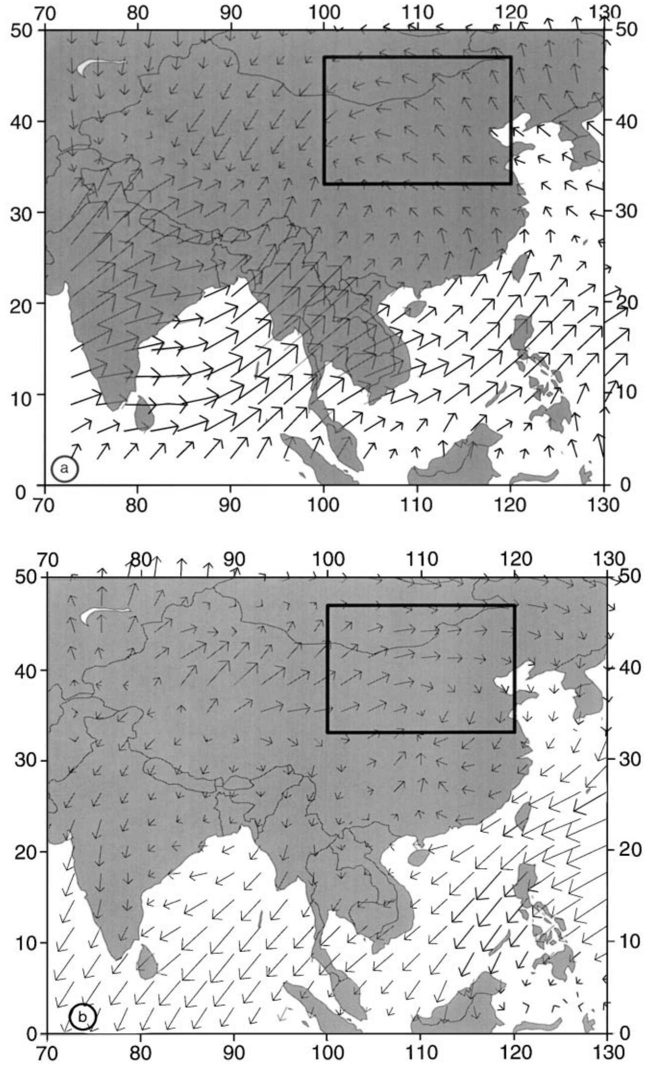

Fig. 2 Surface wind vectors in the Asian region during (a) the summer monsoon; (b) the winter monsoon (Hall *et al*., 1996). The box marks the area of the Loess Plateau.

Fig. 3. The bare and erodible surface soils of the Chinese Loess Plateau, following harvest in September 1990 near Luochuan, central Loess Plateau area.

Fig. 4. Dust fall in Xi'an city, September 1990.

dominant (Fig. 2b). Hence, it is probable that topsoil from the upwind (SE) area of the Loess Plateau, presently subject to severe soil erosion due to intensive agricultural activity (Figs. 3 and 4), is contributing to these modern summer dust samples. Across the area upwind (in summer) from Lanzhou, the susceptibility of the eroding Holocene topsoil varies from ~ 100 to 180×10^{-8} m^3 kg^{-1}. Magnetic susceptibility values might be expected to be lower when winter winds blow dust from the NW deserts, as suggested by the data of Meng *et al.*

It is, however, difficult to evaluate the magnetic susceptibility data presented by Meng *et al.*; there is no information on sample mass, dust collection methods, intra-monthly variability or sample blank values. The absence of any frequency-dependent susceptibility data suggests that the sample masses are low and hence that the measured susceptibility values are similarly rather low.

2. As discussed previously in the scientific literature, organic matter decomposition *does* play an essential role in the formation, in soils, of the strongly magnetic (ferrimagnetic) minerals, magnetite (Fe_3O_4) and maghemite (γFe_2O_3). Thompson and Maher (1995) explicitly identify a direct link between soil magnetic susceptibility and organic content: they suggest rapid increases in magnetic susceptibility values, in tandem with, and partly controlled by, rapid increases in organic carbon content of soils (i.e. within ~ 10–10^3 years).

Organic matter transfers iron from weathering subsoil layers to the biologically active topsoil (e.g. Rode, 1970; Maher, 1984). It is also the energy source for the iron-reducing bacteria (e.g. Lovley *et al*., 1987) which, during soil wetting and drying cycles, provide the Fe^{2+} required for formation of magnetite—a mixed Fe^{2+}/Fe^{3+} iron mineral (Maher, 1991). It has been estimated that 10 g of iron-reducing bacterial cells can produce over 1 kg of magnetite (Frankel, 1987). Given that magnetite concentrations in plant tissues are barely measurable, the flux of magnetite arising via bacterial decomposition of organic

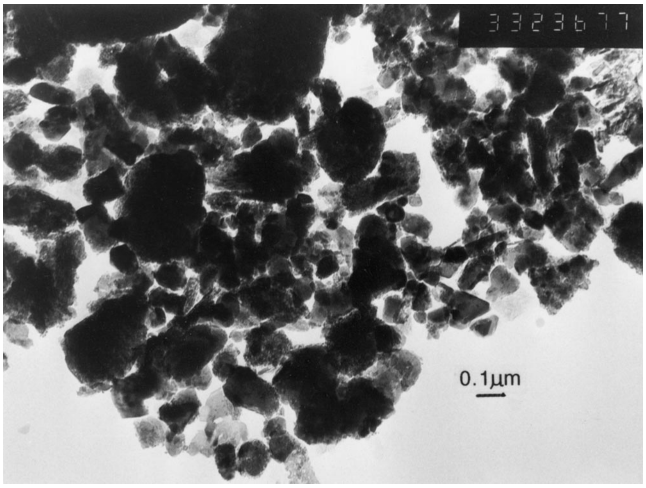

Fig. 5. Transmission electron micrograph of ultrafine ferrimagnets from palaeosol S_1, Chinese Loess Plateau. Note the very variable grain size ($\sim$1–100 nm), indicating *extracellular* precipitation, and clustering of the finest particles around larger grains. Such grains make up $\sim$99% of the ultrafine magnetic fraction and contribute $\sim$90% of the magnetic susceptibility signal (Maher and Thompson, 1992).

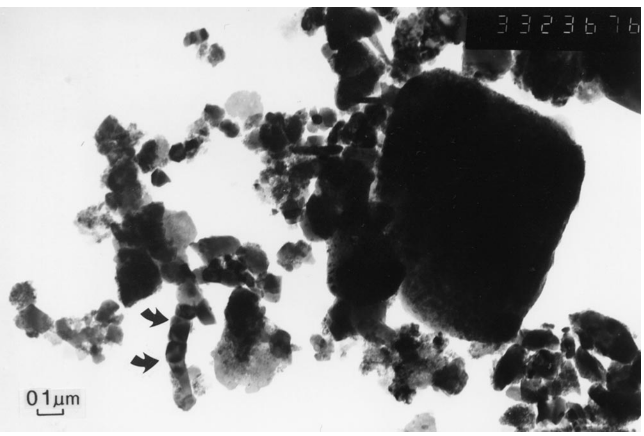

Fig. 6. Transmission electron micrograph of unidimensional, ultrafine ferrimagnets from palaeosol S_1; these crystals are formed intracellularly by magnetotactic bacteria. Such biogenic grains constitute $<1\%$ of the ultrafine magnetic fraction.

matter is likely to be orders of magnitude greater than that from direct biogenic sources.

3. Ferrihydrite is a weakly magnetic (paramagnetic) iron oxyhydroxide, with a magnetic susceptibility value of $40 \times 10^{-8}\,m^3\,kg^{-1}$ (compared with a value of $56{,}500 \times 10^{-8}\,m^3\,kg^{-1}$ for magnetite, Maher, 1984, 1998). Contrary to Meng *et al.*'s suggestion, ferrihydrite grains will not contribute to enhanced magnetic susceptibility values in soil, plant tissues or dust. (The spherical particles shown in Meng *et al.*'s micrograph C and referred to as ferrihydrite closely resemble the magnetic pollutants shown here in Fig. 1).

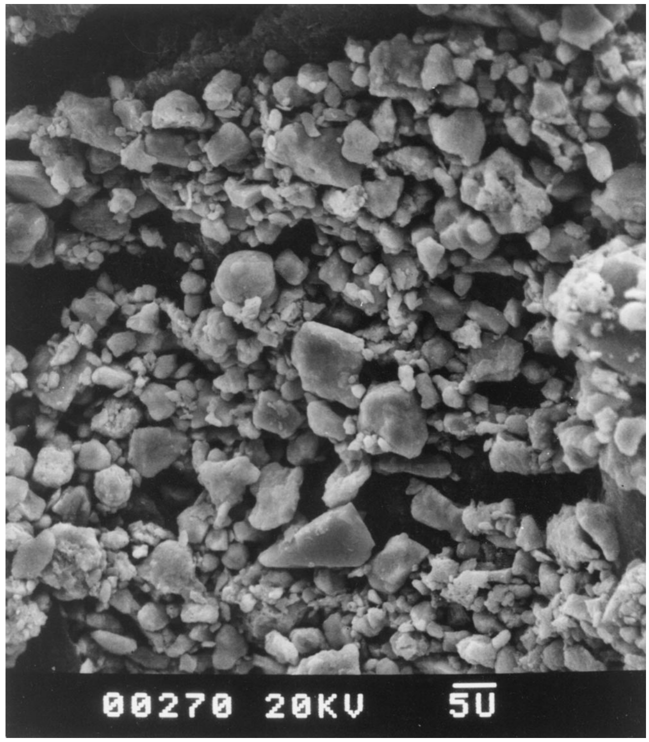

Fig. 7. Scanning electron micrograph of the 'coarse-grained' magnetic fraction from palaeosol S_1. From X-ray diffraction, these windblown detrital grains are a mixture of magnetite, titanomagnetite and haematite.

4. On the basis of their claims, Meng *et al.* state that the origin of the magnetic susceptibility signal in the Chinese loess remains 'poorly understood'. An alternative view is that its origin has been well defined by detailed magnetic, mineralogical and microscopic analyses.

Enhanced magnetic susceptibility values in the Chinese palaeosols arise from distinctively ultrafine crystals, of very variable size (1–100 nm), of magnetite and maghemite, residing in the <2 μm fraction of the soils and incipient soils (Fig. 4). A *non*-biogenic source is indicated by the uncontrolled crystal size, reflecting precipitation within the soil matrix rather than within organic cells. These particles are least abundant in pristine loess and increasingly abundant in increasingly well-developed palaeosols. None of the micrographs of Meng *et al.* are of sufficient magnification to resolve these crystals, which are well-dispersed throughout the soil matrix. A minor number of the ultrafine grains ($<1\%$) have been formed intracellularly by magnetotactic bacteria (Fig. 5). There is a 'background' magnetic component in both the loess and the palaeosols: detrital windblown grains of magnetite, maghemite and titanomagnetite, magnitudes larger in size than the pedogenic precipitates (Fig. 6). The concentration of this component in the loess and soil layers is virtually constant and contributes a magnetic susceptibility value of $\sim 30 \times 10^{-8}\,m^3\,kg^{-1}$ (as seen in the least-weathered loess layers).

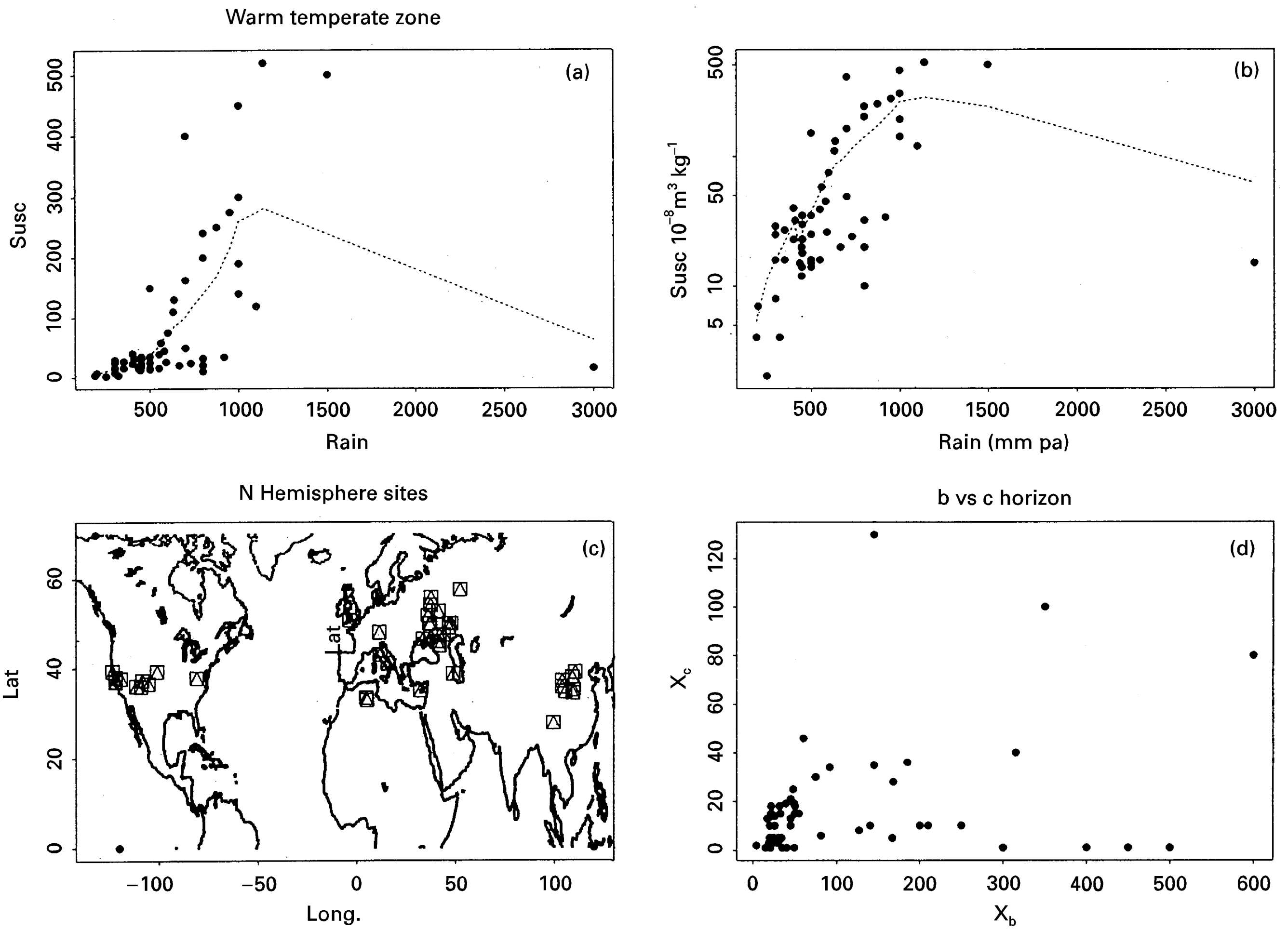

Fig. 8 (a), and (b) Pedogenic magnetic susceptibility versus rainfall for a range of Northern hemisphere sites (c) in the temperate zone (from Maher and Thompson, 1995). Little pedogenic magnetite formation occurs under dominantly oxic, low-rainfall conditions; increasing rates of magnetic formation occur as soil wetting and drying cycles occur under moderate rainfall totals. Excessively high rainfall ($\gtrsim$1500 mm pa) is associated with decreasing magnetic susceptibility values, as soils become leached and too acidic for magnetite formation. (d) Note the lack of correlation between susceptibility values of the soil substrate and the B horizon, indicating authigenesis of magnetite within the soil profile rather than inheritance of a detrital component.

Studies of modern soils show that ultrafine ferrimagnetic crystals form *in situ* in well-drained, moderately buffered, non-burnt soils with even minor Fe content (e.g. Maher, 1984). Within such soils, rainfall induces temporary anoxia in the soil micro-environment, enabling metabolism of organic matter by Fe-reducing bacteria. Upon re-oxidation, the Fe^{2+} excreted by the bacteria can combine with Fe^{3+} from reactive iron oxides, especially fine-grained or poorly crystalline species, to precipitate as the strongly magnetic, mixed Fe^{2+}/Fe^{3+} compound, magnetite. There is strong correlation between annual rainfall and the pedogenic magnetic susceptibility of well-drained, not too acid soils, up to a maximum rainfall value of $\sim$1500 mm pa (Fig. 8). Such a relationship would not be expected if other soil-forming factors, such as time, were more significant. It is interesting to compare these magnetic data with the data of Folkoff (1987), in his study of the effects of climate on B horizon pH in soils sampled across the full climate range of the USA. Of a host of climatic and soil factors (e.g. annual rainfall, annual potential evapotranspiration, actual evapotranspiration, leaching and moisture indices, A and B horizon soil textures), the factor with the highest explanatory power ($R^2 = 0.77$) was found to be annual rainfall. The dominance of this particular factor is due to its over-riding control of soil moisture.

In summary, the hypothesis of *pedogenic magnetite formation* is widely accepted because (a) it can account for the observed changes in magnetic concentration and grain size in the Chinese loess and soil units, (b) it is supported both by magnetic synthesis experiments in the laboratory and modern soil data (Fig. 8 and caption), and (c) it predicts a direct, testable correlation between rainfall and soil magnetic properties (Fig. 8a and b).

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