Paleo-environmental study on the growth of magnetotactic bacteria and precipitation of magnetosomes in Chinese loess-paleosol sequences

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Abstract 405 samples were collected from L_5-S_5-L_6 in consideration of obvious variations in susceptibility of the geological sections, which are section Xifeng in Gansu Province and section Duanjiapo in Shaanxi Province for study of magnetotactic bacteria (MB) and magnetosomes (MS) in Chinese loess-paleosol sequences. MB in each sample were observed by TEM after being cultured under 8—18℃, room temperature (RT), 25℃, 26℃ and 30℃ conditions. In general, MB are distributed widely in loess-paleosol sequences, fewer in loess layers with predomination of vibriod in shape. However, there are more MB in paleosol layers with morphological varieties such as roddish, vibriod and occasionally approximately coccus. The magnetosomes (MS) in MB of paleosol are usually arranged in chains along the cells. It was also found that MB growth and MS formation are associated with the environment in which MB live. It can be inferred from the distributions of MB and MS that the paleoclimates fluctuated during the formation of loess-paleosol sequences in the Chinese Loess Plateau. The climate became gradually warmer but displayed more frequent fluctuations from the northwest to the southeast of the Plateau .

Keywords: **loess-paleosol sequences, magnetotactic bacteria (MB), magnetosomes (MS), paleoeclimate, Section Xifeng, Section Duanjiapo.**

Susceptibility of Chinese loess-paleosol sequences has been taken as one of the proxies of paleoclimate and paleoenvironment[1,2]. From the points of view of physical and chemical aspects, the main hypotheses pertaining to the mechanism of the paleosol magnetism enhancement are (i) “the dilution theory” proposed by Kukla et al.[3], holding that an increase in flux of weakly magnetic dusts during loess accumulation will dilute the density of strongly magnetic materials, and as a result the susceptibility of loess will be lowered and (ii) the “pedogenesis theory” represented by Mayer et al. and Verosub et al., supposing that the amount of superfine strongly magnetic mineral produced by pedogenesis be the major cause of paleosol magnetism enhancement[4—7].

It is discovered by Jia et al. that the susceptibility of Chinese loess-paleosol sequences is associated with the TOC (total organic carbon) content[8,9]. Then MB and MS, which are widely distributed in marine, lacustrine and fluvial sediments[10,11], have also been found in S_0 to L_2 layers of profile Duanjiapo [12—14]. The distribution of MB and MS in loess-paleosol sequences shows basic consistence with the susceptibility, as is evidenced by fewer MB and MS in loess layers and more MB and MS in paleosol. This discovery opens up a new way to study the enhancement of paleosol magnetism and the genesis of the superfine magnetic materials in loess sections. In addition, because of the sensitivity of MB growth to climatic fluctuation and environmental change, abundant information will be developed for the study of Quaternary climate evolution on the Chinese Loess Plateau. So, on the basis of the previous work, we chose section Xifeng and Duanjiapo and collected samples from L_5-S_5-L_6 layers to study the MB distributions and MS formation and then to discuss the paleoclimatic and paleoenvironmental information developed from them.

1 Samples and analysis

(i) Geological settings and sampling. The section Xifeng (simplified as X hereafter) is located in the central part of the Loess Plateau where the climate is relatively cold and dry (about 10℃ modern annual temperature (MAT) and about 561 mm modern annual precipitation (MAP)), while the section Duanjiapo (D in short hereafter) is located in the southeastern part of the plateau, where is relatively warm and wet (about 12℃MAT and about 620 mm MAP)[15]. In addition, Section X is relatively abundant in element S but poorer in Fe_2O_3.

A total of 405 samples were collected from the top of L_6 up to L_1 at intervals of 5—20 cm for the susceptibility measurement (Bartington Model MS2, fig. 1). Then the layers L_6-S_5-L_5 with obvious variations in susceptibility were chosen for collecting lump samples, numbered XL_6, XS_{5-3}, XS_{5-2}, XS_{5-1}, XL_5, DL_6, DS_{5-3}, DS_{5-2}, DS_{5-1}, DL_5.

(ii) Experiments and observations. Experiments were carried out as illustrated below for study of the distributions of MB and MS, as well as their contributions to the susceptibility in section X and D. First, MB in each sample (triplicate) were cultured under RT and 26℃ and then were observed under TEM (H-7000FA Type and JEM-1010 Type) respectively after being collected by a specific magnetic method. MB in the samples from layer S_{5-1} were subsequently cultured under various temperature conditions (8—18℃, RT, 25℃, 30℃) for observation of the MB growth and MS formation and their associations with temperature.

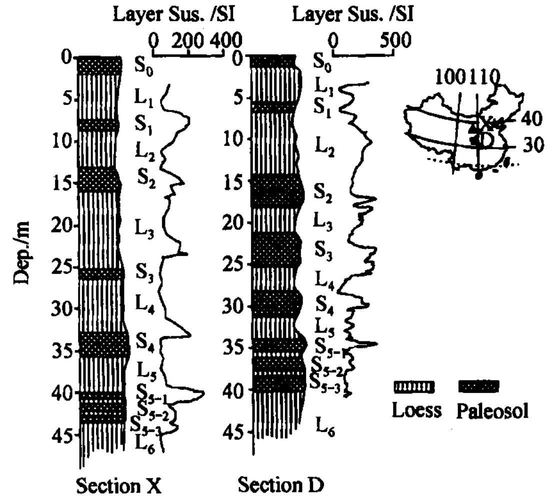

Fig. 1. Sketch map of sample localities and loess sections. X, Section Xifeng; D, Section Duanjiapo; Dep, Depth; Sus., susceptibility; L, loess; S, Paleosol.

2 Results and discussion

(i) Distributions of MB in the loess sections and the paleoenvironmental significance. As observed under TEM, MB in loess-paleosol sequences are roddish, vibrioid and occasionally approximately coccus and spirillum morphol- ogically, usually 1—3 μm in size. However, some roddish MB longer than 4 μm can be occasionally found in paleosol samples (table 1). Only a small amount of MB were found in loess with vibrioid predominant (fig. 2(b)), especially in Section X which has recorded a relatively cold and dry climate. Obviously more MB were observed in paleosol with great varieties in shape, such as roddish, vibrioid and occasionally coccus (fig. 2(e)) in DS_{5-2}.

Table 1 MB in loess-paleosol sequences enriched under RT condition

Items		Section X		Section D	
		loess[b)]	paleosol[c)]	loess[b)]	paleosol[c)]
Shape[a)]		thick-walled vibrioid, roddish	roddish, vibrioid	vibrioid, roddish, spirillum (fig. 2(c))	roddish, vibrioid, coccus
Length/μm		1—3	1—3, occationally >4	1—3	1—3
Length/width		>2 slightly	2—4	>2 slightly	3±, ≈1 to coccus
MS	No. (grains)	<3 generally	>6	⩾3, vesicles	>6, fewer in coccus (2—4)
	Arrangement	usually at one end of cells	in chains (single or double)	at one end or in chains	chains, irregular in coccus

1, In order of importance; 2, L_6, L_5; 3, S_{5-3}, S_{5-2}, S_{5-1}.

The habits of MB, the hydrophilic microbe, are closely related to their living environments, reflected by the amount, sizes and morphologies of MB and grains, sizes and shapes of the contained MS [11,16]. It is shown by the results of MB cultured at various temperatures (table 2) that more MB were observed in both XS_{5-1} and DS_{5-1} at 25℃, predominated by roddish in shape (fig. 2(h), (i)). However, when the temperature is lower (8—18℃), MB in both samples become obviously fewer and mostly slender-long vibrioid morphologically. When the temperature rises to 30℃, more roddish MB are found in XS_{5-1}. It can be seen from the above results that MB of a certain shape usually

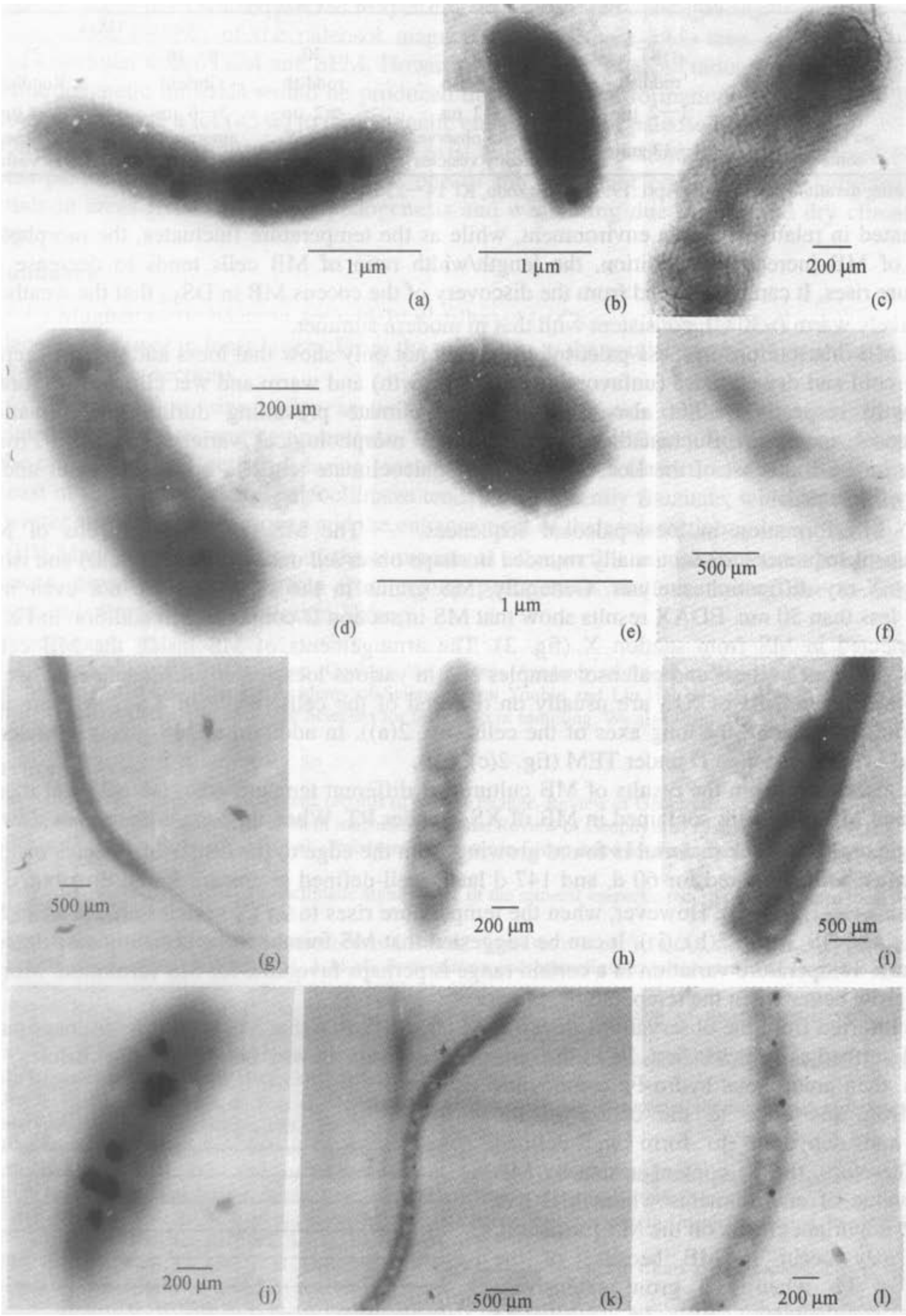

Fig. 2. MB in Chinese loess-paleosol sequences. (a) MB in the fifth layer of paleosol of section X (XS_{5-1}); (b) MB in the fifth layer of loess of section X (XL_5); (c) spirillum MB in the fifth layer of loess of section D (DL_5); (d) roddish MB in the fifth layer of paleosol of section D (DS_{5-1}); (e) roughly coccus MB in the fifth layer of paleosol of section D (DS_{5-2}); (f) MB in the fifth layer of paleosol of section X (XS_{5-1}) for EDAX analysis; (g) long vibrioid MB in XS_{5-1} enriched at 18℃ (h) roddish MB in XS_{5-1} after being enriched at 25℃; (i) roddish MB in DS_{5-1} after being enriched at 18℃; (j) MB bearing amorphous bearing material in DS_{5-1} after being enriched at 18℃ for 60 d; (k) MB in DS_{5-1} and the contained MS grains after being cultured at 8—18℃ for 147 d; (l) local magnification of (k).

Table 2 MB in paleosol enriched at different temperatures

Samples	XS_{5-1}				DS_{5-1}	
T(℃)	8—18	RT	25℃	30	8—18	25
Shape	vibrioid, roddish	roddish	roddish	roddish	vibrioid	Roddish
Length	3—5 μm	1—2 μm	≈2 μm	≈2 μm	3—6 μm	2—3 μm
MS	no MS observed some vesicles	4—13 grains	no MS observed, many vesicles	no MS observed	amorphous grains	no MS observed, many vesicles

Culturing duration, Dec. 1998—Apri .1999, Guangzhou, RT 14—25℃.

predominated in relatively stable environment, while as the temperature fluctuates, the morphological varieties of MB increase. In addition, the length/width ratio of MB cells tends to decrease as the temperature rises. It can be deduced from the discovery of the coccus MB in DS_{5-2} that the weather then was relatively warm (>30℃), consistent with that in modern summer.

The MB distributions in loess-paleosol sequences not only show that loess and paleosol represent relatively cold and dry climates (unfavorable to MB growth) and warm and wet climates (favorable to MB growth) respectively, but also show that the climate prevailing during the formation of loess-paleosol sequences fluctuated, reflected by the morphological varieties of MB. From the northwest to the southeast of the Loess Plateau, the paleoclimate tends to become warmer and more frequently fluctuated.

(ii) MS formation in loess-paleosol sequences. The MS contained in cells of MB in loess-paleosol sequences are sectionally rounded in shape observed under TEM (fig. 2(a)) and isotropic shown by X-ray diffraction analysis. Generally, MS grains in the same cell are not even in size, generally less than 50 nm. EDAX results show that MS in section D contain Co in addition to Fe, while S was detected in MS from section X (fig. 3). The arrangements of MS inside the MB cells are somewhat different in loess and paleosol samples and in various loess-paleosol sequences as well. For example, MS in the MB of XL_5 are usually on one end of the cells, while in XS_{5-1}, MS are always arranged in chains along the long axes of the cells (fig. 2(a)). In addition to MS, many vesicles were also found in MB of section D under TEM (fig. 2(c), (d)).

It is discovered from the results of MB cultured at different temperatures (table 2) that more and well-defined MS grains are contained in MB of XS_{5-1} under RT. When the temperature goes down to 8—18℃, amorphous black material is found growing from the edge to the center of vesicles inside MB of DS_{5-1} after being cultured for 60 d, and 147 d later, well-defined grains are found distributed along the long axis (fig. 2(j), (k)). However, when the temperature rises to 25℃, vesicles are found in MB of both XS_{5-1} and DS_{5-1} (fig. 2(h), (i)). It can be suggested that MS formation be certainly associated with temperature. Temperature variation in a certain range is perhaps favorable for MS formation. Moreover, MS may grow better when the temperature is lower.

It is inferred from the observations under TEM (fig. 2(j), (k)) that MS formation in loess-paleosol may be described as follows: first, Fe in the environment finds its way into "magnetic vesicles" inside MB cells, then amorphous hydro-Fe compounds "grow" from the edge to the center of the vesicles and dehydrate to form well-defined grains. Therefore, the Fe content usable by MB and pH value of environments where MB live may have important effects on the MS formation. Vesicles may occur in MB because of the shortage of Fe when MB grow extensively without supplements of Fe. Alkaline environments could be more favorable to the deposition and dehydration of the iron-bearing compounds, making them transform from amorphous to crystalline.

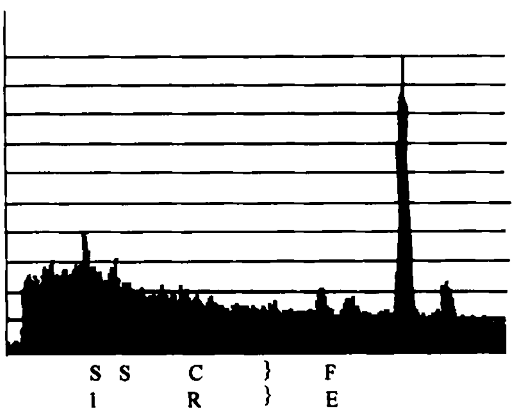

Fig. 3. EDAX spectrum map of MS in MB from XS_{5-1}.

There has long been a controversy about the origin and compositions of superfine magnetic materials in loess-paleosol sequences. Mayer et al.[4—7] proposed "pedogenesis" superfine magnetite as the main cause (>90%) of the paleosol magnetic enhancement after they examined samples from section Luochuan under TEM and SEM. However, Hanjiamao et al.[17] thought that no large amount of superfine magnetic minerals would be produced during paleosol formation and the grains less than 50 nm do not contribute a lot (<5%) to the magnetic enhancement of paleosol.

Our experimental results show that there exist biogenetic superfine magnetic materials (that is MS) in loess-paleosol sequences. MS could be one of the important components of superfine magnetic materials in areas free from strong pedogenesis and weathering due to cold and dry climate, such as Xifeng.

3 Summary

(i) Magnetotactic bacteria are widely distributed in Chinese loess-paleosol sequences with more in paleosol and fewer in loess layers. From the northwest to the southeast of the Loess Plateau, MB tend to increase in loess sections.

(ii) The amount, size, shape as well as the characteristics of the contained MS in MB are associated with climates and environments. The distribution of MB in loess-paleosol sequences shows that the climates were fluctuated during loess-paleosol sequence formation. From the northwest to the southeast of the Loess Plateau, paleoclimates tended to frequently fluctuate, which is maybe associated with winter and summer monsoons and the enhancement of their interactions.

(iii) Magnetosomes are one of the components of superfine magnetic materials in loess-paleosol sequences, especially in areas free from strong pedogenesis and weathering due to cold and dry climates, as is the situation in Section Xifeng.

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