

黄土高原三趾马红土的观察¹⁾

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摘要:讨论了黄土高原地区红粘土中脊椎动物化石的考察历史,记录了山西和甘肃“三趾马红土”地点的观察结果。红粘土广泛分布于黄土高原地区,但常被误认为是一个描述性术语,因为其中的许多沉积物既非红色,又不以粘土级颗粒为主。不少红粘土序列中含有古土壤,也含有水成沉积物。此次考察包括榆社盆地的经典地点、灵台任家沟和雷家河,以及庆阳和秦安的一些地点。讨论了在任家沟发现的化石,在玉村新发现的小哺乳动物上新五褶兔(*Pliopentalagus*)和在胡家村观察到的上新世潜穴,后两个地点都位于灵台东北面的庆阳地区。观察结果与晚中新世遍布黄土高原、很可能来自降尘的粘土级颗粒的快速堆积吻合。但在一些区域则以河流或湖泊过程为主,红粘土颗粒部分或全部被水成的粗碎屑沉积物代替,没有找到晚中新世-早上新世干旱化的证据,反而支持高生产力的湿润环境假说。局部富集的脊椎动物化石证明三趾马动物群具有很高的陆生生物量。

关键词:黄土高原,新近纪,三趾马红土,哺乳动物,沉积学

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OBSERVATIONS ON THE *HIPPARION* RED CLAYS OF THE LOESS PLATEAU

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Abstract We discuss the history of exploration of Red Clay vertebrate fossils of the Loess Plateau, and record observations on “*Hipparion* Red Clay” localities of Shanxi and Gansu provinces. Red clay is

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widespread across the Loess Plateau, but misleading as a descriptive term because many deposits are neither red nor dominated by clay-size sediment. Many red clay sequences contain paleosols, but also water-laid deposits. Our survey includes well-known localities of Yushe Basin, Renjiagou and Leijiha near Lingtai, and sites of Qingyang and Qin'an. We discuss fossils found at Renjiagou, a new discovery of micromammals (*Pliopentalagus*) from Yucun, and Pliocene burrows observed at Hujiacun, both latter localities northeast of Lingtai. Observations are consistent with a high rate of supply of clay sized particles, likely air-fall origin, throughout the Loess Plateau during the Late Miocene. In some areas where fluvial or lake processes dominate, red clay particles are replaced in part or completely by water-laid coarse-grained deposits. We saw no evidence for a dry Late Miocene-Early Pliocene, but rather hypothesize well-watered habitat of high productivity. Locally diverse vertebrate fossils attest to high terrestrial biomass for *Hipparion* faunas.

Key words Loess Plateau, Neogene, *Hipparion* Red Clay, mammal, sedimentology

1 Introduction

The late Cenozoic rocks and faunas of northern China have been the subject of considerable study during the last century due to their widespread nature and contained vertebrate fossils. Interest intensified in these fossiliferous deposits during the last quarter century with the application of modern biostratigraphic and magnetostratigraphic techniques (Tedford, 1995). Truly impressive in North China, from Shanxi to Gansu provinces, is the thick blanket of Pleistocene loess, which dates in places to about 2.5 Ma (Burbank and Li, 1985) or older. Early in the 20th century, geologists recognized that silt-sand-gravel deposits below the loess were widespread and attested to an interval of time between Early Pleistocene deposits of Zhoukoudian and Nihe-wan (faunas containing *Equus* and elephantids) and older Eocene and Oligocene strata yielding archaic elements. These later Tertiary sediments contained distinctive fossil assemblages characterized commonly by the three-toed horse *Hipparion* (now *Hippotherium* and derived subgenera) and by cervids, gazelles, and hyaenids. The ages of these intermediate faunas were considered to represent mostly Pliocene and part of Late Miocene time (Andersson, 1923), with the conclusion that deposits with fossils of earlier Miocene time had not yet been found in China. It is now understood that *Hipparion* faunas span the entire Late Miocene (6 million years) as well as Pliocene time (Zhang et al., 2002), and that the assemblages characteristic of the changed climate of the Early Pleistocene date to about 2.6 Ma.

For Andersson (1922, 1923) one key finding of his previous several years of work for the Geological Survey of China, was the ubiquitous nature of Tertiary deposits older than the Pleistocene. He characterized them mainly by the common occurrence of *Hipparion*, and noted that the sediments often included red clays. Other westerners also were conducting field observations and were impressed by the reddish fine-grained, but variable, deposits. Teilhard de Chardin (1922) noted pre-loess "terres rouges" that were found by his colleague Emile Licent to produce well preserved fossils. Zdansky (1923) conducted studies of the "*Hipparion* Lehm" (clays) of Baode. Quickly embedded in the literature, these references were rendered in English as the "*Hipparion* Clays", or the "*Hipparion* Red Clays", or "*Hipparion* Red Earth".

In ironic contrast, hipparionine assemblages came to be best known from non-red sand-silt deposits of Yushe Basin, Shanxi Province (Qiu et al., 1987). The fluvial and lacustrine Yushe sequence sets the standard for the biostratigraphy of the latest Miocene through Pliocene interval (Tedford et al., 1991). Licent and Trassaert (1935) recognized three superposed Zones represented by distinctive assemblages in the Yushe Basin. The multiple fossil horizons of the upper two Zones of Yushe Basin ultimately became the basis for the Yushean land mammal age (Qiu and Qiu, 1995; currently subdivided as Gaozhuangian and Mazegouan), which spans the entire Pliocene. This biochronology is repeatedly observed elsewhere in China and westward, and is therefore highly useful.

However, the *Hipparion* red clays remain enigmatic in their widespread nature and apparent transition with overlying loess. Indeed in recent years, loessic deposits have been noted at Lingtai and claimed to predate Pleistocene loess, not just into the Pliocene but well into the Miocene (Zheng et al., 1992; Zhang et al., 1999; Guo et al., 2001). In Gansu Province, other red deposits have been claimed to represent loess as old as the Early Miocene (Guo et al., 2002). To what degree are these ancient aeolian deposits, does this mode of deposition span a vast area of northern China during the Miocene, and what is the scale of lateral variation is observed? Through field reconnaissance in 2008, our group sought to contrast red clay deposits with the Yushe sequence, and to revisit the classic “terres rouges” of North China, especially as represented at Qingyang, the rich accumulation quarried by Licent in the 1920s. It should be noted that some of our observations have been made previously by specialist students of Neogene paleontology and geology in China. We supplement them here, largely for the international audience.

2 Yushe Basin

The Yushe sequence in Shanxi Province, specifically the deposits of the Yuncu subbasin, is well discussed by Qiu et al. (1987) and Tedford et al. (1991). Guided by one of us (Mu) we collected mammalian fossils for isotopic studies from Late Miocene and younger horizons that may provide clues to interpret degree of aridity and seasonality of moisture during the late Neogene in this area of China, on the eastern margin of the Loess Plateau. The local stratigraphic sequence is a succession of dominantly fluvial sediments spanning about 6.5 to 2 Ma. The lowest unit is the Miocene Mahui Fm., dominated by sands and gravels, fining upwards and ending with greenish thin clay units and yellow marls. The successive Gaozhuang Fm. is mostly sand in its lower half, then fining upwards with repeated cycles of cross-bedded sands to silts to purple mudstones and marls. Above this is the Mazegou Fm., which is generally finer grained, with fewer sands, again drab to purplish in color. These beds dip gently to the northwest. The superposed and horizontal Haiyan Fm. is thinner and partly lacustrine in origin, mostly silts and green clays. Being reversely magnetized, it corresponds to the early Matuyama magnetochron (Chron C2r.2r). All of these units produce fossils. The Haiyan Fm. records *Equus* assemblages comparable to the Nihewan fauna (Qiu et al., 1987; Zone 3 of Licent and Trassaert, 1935). Older units record a succession of hipparionine assemblages that demonstrate time depth of such deposits and represent Zone 1 and Zone 2 of Licent and Trassaert (1935).

While loess deposition was active to the west on the Loess Plateau, during the end of the Pliocene and the Early Pleistocene, fluvial and lake deposits (Haiyan Fm.) were aggrading in Yushe Basin. Finally, the Yushe sequence (including Haiyan Fm.) underwent erosion, and became blanketed by later Early Pleistocene red loess and overlying yellow loess. Micromammals from the red loess indicate Gongwanglingian age (Flynn et al., 1997) and indicate that by about 1 Ma, loess deposition was under way in this eastern part of the Loess Plateau.

The Yushe sequence presents a Miocene-Pliocene biostratigraphy that can be duplicated elsewhere (e. g., in Gansu Province, Zheng and Zhang, 2001). It establishes that the hipparionine faunas of the late Neogene show change over time, which is reflected in successive land mammal units. It shows further that the vertebrate assemblages are preserved in drab-colored fluvial sands and silts, hardly the “red clays” one might expect to encounter given a rich literature on “*Hipparion*” beds. Finally, it shows that fluvio-lacustrine deposition continued into the Early Pleistocene, well after red loess was being deposited to the west.

3 Gansu Basins

Lingtai (Fig. 1) is situated in the heart of the Loess Plateau in eastern Gansu very near Shaanxi Province. Near the town of Lingtai is a long section of a great pile of red clays and silts. This section is clearly what one might think of as “terres rouges”. Zhang et al. (1999) measured and studied a well-exposed section in excess of 300 m at Renjiagou. Paleomagnetic analysis shows normally magnetized sediment at the base of the section, which was interpreted as the top of chron C3Br1n, 7.25 Ma (Gradstein et al., 2004 time scale). Thus red clay and sand deposition in this section began in the Late Miocene. The top 170 m of the 300 m Renjiagou section is brownish loess with well-developed paleosols. Below that is a thick series of red clays with some soils, calcareous nodules and occasional sands. Sands increase downward, with even a few thin gravels toward the base. The beds below the brownish loess have been compared with a similar lithological succession some 300 km to the east where the Jingle Fm. (red clays) overlies the reddish, sandier Baode Fm. in Shanxi Province. The similarity is provocative, but does not demonstrate a simultaneous depositional regime all across North China. To the south of Lingtai, a study by Han et al. (2002) on pre-loess red clays argues that the “Jingle” equivalent beds of Lingtai were dominantly of aeolian origin, albeit accreted at a slow rate. Therefore, the Renjiagou red beds are generally thought of as loess-like, and aeolian deposition characterized the entire Pliocene, at least. The sedimentation rate was higher for the Pleistocene loess than the Miocene-Pliocene deposits.

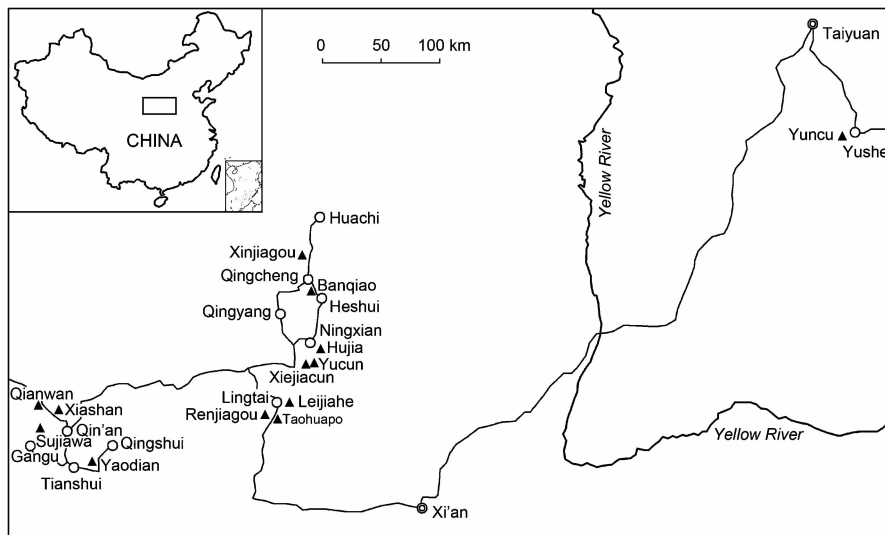


Fig. 1 Map showing location of Yushe Basin, Shanxi Province, with respect to basins and localities in Gansu Province

The contact of loess dominated by brownish paleosols and the underlying red clay is approximately the C2r/C2An (Matuyama/Gauss) boundary. Zhang et al. (1999) recovered typical Pliocene faunal elements from lower in the red clays (*Nyctereutes sinensis*, *Plesiohipparion houfenense*, *Paracamelus*, *Gazella blacki*, and *Antilospira licenti*) at a level correlated to chron C2An3n, about 3.5 Ma. They found one rodent *Chardinomys* sp., which is consistent with this. In the course of our brief survey, at about the 225 m level of the Zhang et al. (1999) section,

about 4.3 Ma on the Gradstein et al. (2004) time scale, we discovered a few small mammal remains; *Ochotona* at the small end of the size range for *Ochotona lagreli* (length of m1-3 = 3.65 mm), a leporid molar in a dentary fragment, and a siphneine rodent; cf. *Prosiphneus eriksoni* (IVPP V 18016.1-18016.3) represented by two jaws and a humerus. The humerus shows the typical burrowing morphology of zokors. Lingually, the lower molars show moderate dentine tract development (Fig. 2) and buccally, a tract barely intersects the occlusal surface at the protoconid. *P. eriksoni* is a conservative latest Miocene-Early Pliocene form known from Ertemte and Harr Obo, Nei Mongol; Zheng Shaohua identified the material without bias of knowing the provenance. These taxa are consistent with the estimated age.

The localities of Leijiahe, worked by Zheng Shaohua and colleagues over a number of years, yield a rich succession of micromammal fossils. This area is in Lingtai County, only about 20 km from Renjiagou, but lithologically quite different. The longest section is only about 65 m thick, but thought to encompass about the same time range as Renjiagou. Therefore, it is a relatively condensed section. Unlike Renjiagou, it is dominated by silty sand, laterally variable and conglomeratic in places, with varied colors and thickness from one exposure to the next. Zheng and Zhang (2001) reported a number of small mammal levels, Late Miocene to Late Pliocene. There are abundant large mammals including hipparionines in some sand units. This different mode of accumulation and fossil preservation shows that a model of uniform deposition of a thick air-fall blanket of silt does not apply here. If aeolian deposition began in North China during the Late Miocene or earlier, then the model must allow different local modes of deposition.

During our reconnaissance, we benefitted from the local skill and experience of Mr. Li Hongju (Longdong University), who led us to Xiejiacun, which empties into the Jing River. He took us to a site where a proboscidean tusk had been extracted. The tusk was found in a massive sandstone layer underlying a thick (~3—4 m) conglomerate, the latter in turn overlain by yellow loess. We found scant remains, including equid and antelope fragments, at this site. As at Leijiahe, there was no indication of red clays. Mr. Li also led us to nearby Yucun, another dominantly sand section. This exposure is used as a source of sand for construction, and produces large vertebrates. There are at least two fining-upward sequences of gravel to sand to silty sand. Sand units are on the order of 1 to 3 m thick, cross bedded or massive. Poorly sorted pebbly sands with silt produce bone, including horses and bovinds, and notably a p3 of *Pliopentalagus* (IVPP V 18017). This tooth (13 mm height, length × width = 3.25 mm × 2.80 mm), similar to material under study by Jin Changzhu, represents Late Miocene *Pliopentalagus huainanensis* or possibly a primitive population of Early Pliocene *P. dajushanensis* Tomida & Jin (2009). The single Yucun specimen is probably Late Miocene in age, but is consistent as a minor variant of the Early Pliocene species. Again, this is a *Hipparion* fauna without red clays.

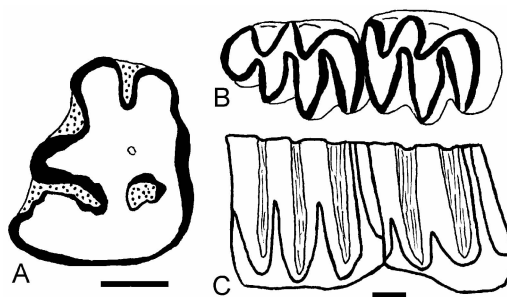


Fig. 2 Dental remains of *Pliopentalagus* cf. *P. huainanensis* (A, IVPP V 18017) and *Prosiphneus* cf. *P. eriksoni* (B, C; IVPP V 18016.1)

A. left p3 from Yucun in Qingyang showing distribution of enamel (black) and cementum (stippled); there is a small pit in the dentine posterior to the anterior reentrant; B, C. occlusal and lingual views of right m1-m2 from Renjiagou, near Lingtai; scales = 1 mm

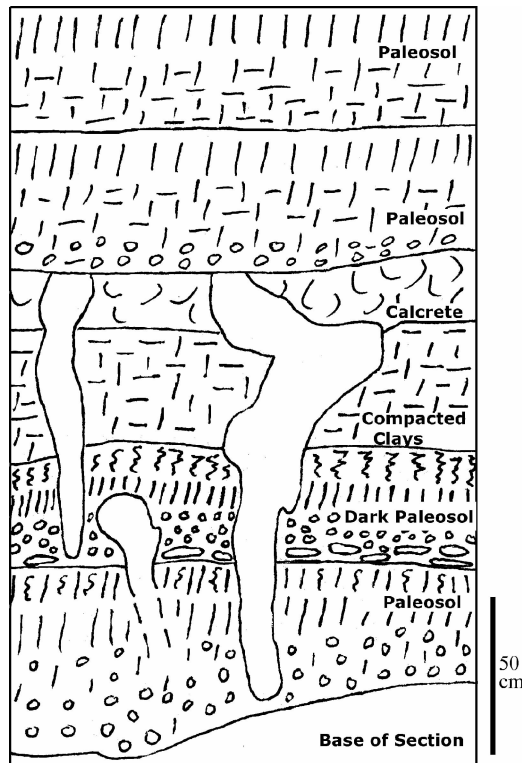


Fig. 3 Section at Hujiacun with multiple paleosols intersecting resistant, filled burrows, probably dug by the zokor *Mesosiphneus*

Northeast of Lingtai, near Ningxian, Gansu, Mr. Li (joined by Prof. Zhou Tianlin) guided us to a valley exposing a thick accumulation of brown silts. This is the general area that has yielded small mammals previously (Zhang, 1999), which indicate Early Pliocene age. Taxa include a derived species of *Pseudomeriones*, a zokor close to *Mesosiphneus praetingsi*, *Paralactaga* cf. *P. anderssoni*, and *Ochotona lagreli*, and these correspond to microfaunas of Yushe Basin that date to ca. 4 Ma. The origin of the brown silts may be primarily aeolian with possible fluvial contribution of fine grained overbank deposits and considerable organic content. This lithology differs from that of the contemporaneous Jingle Fm. A striking aspect of the brown silts in Hujiacun gully is prominent, mature paleosols, some exceeding 20 cm in thickness. Time for development of paleosols attests to substantial hiatuses in deposition. There are well developed burrow systems, primarily vertical shafts, representing the fossorial behavior of, most likely, the zokor *Mesosiphneus*. Shaft diameters are typically 4 ~ 5 cm, but some expand to >10 cm, where nesting or food storage

chambers were located. We reproduce here a section exposing burrows (Fig. 3). Vertical shafts penetrate well over a meter deep, through several paleosols. They appear to begin at a horizon that at some point (perhaps later in time) became calcified as calcrete.

Exposures near Qingyang, north of Ningxian, are the classic “terres rouges” that yielded a rich *Hipparion* fauna to the efforts of Emile Licent in the 1920s. Qiu et al. (1987) revised the systematics of horses from Qingyang and Yushe. Qingyang (“King-Yang-Hsien”) became Zdansky’s locality 116w, from which a hyaenid fossil became the type specimen of *Chasmaporthetes exitelus* Kurtén & Werdelin, 1988. This is also the type locality of the gerbil *Pseudomeriones abbreviatus* (Teilhard de Chardin, 1926), an occurrence not duplicated there by modern field collection. We relocated the fossil bed by using Licent’s field notes, transcribed as a long set of volumes of limited publication, a copy of which is preserved in the IVPP archives. Licent’s journal refers to the old “Qingyang” now known as Qingcheng; present day Qingyang is a new city. The long Xinjiagou, a stream followed by Licent, is the key; loess lies on Mesozoic rock for much of its way, but upstream there is intervening reddish sand. Near the village Yinpingcun, the section is just as Licent describes it: a massive well-sorted sand body, light brick-red in color and over 10 m thick. One to two meters above its base is a bone bed, 0.5 m thick, with fossil mammals dense enough for quarrying, as did Licent, and as do dragon bone hunters today. J G Andersson may have also quarried there, augmenting the Lagrelius Collection. At the base of the bone bed occurs a silty-sand unit with small bone that could be productive if washed. The “*Hipparion*” fauna of Qingyang evidently occurs in water-laid sand and silt, possibly with a

wind-blown dust component. The age of this locality is not yet precisely determined, but Qiu et al. (1987) compared the horses from Qingyang to those from localities of Baode that are dated to about 6.5 to 7.2 Ma (Zhu et al., 2008).

From easternmost Gansu, we drove west to Qin'an, north of Tianshui. Qin'an is a vast basin with many areas already known to produce fossils. IVPP, under the leadership of Liu Liping, has developed an ongoing research program to develop a continuous fossil sequence spanning the entire Miocene epoch. Superposed vertebrate horizons could offer a new level of precision in defining and understanding Chinese mammalian biochrons. Guo et al. (2002) previously studied a 22 m. y. section (near Qianwan) interpreted as mainly aeolian in origin. Its paleomagnetic dating is supported by several consistent small mammal fossil assemblages. The length of the section is impressive and thought to represent nearly continuous, if slow, sedimentation. In one 253 m section, 231 reddish layers show soil structures and are associated with carbonate nodules, and are interpreted to represent paleosols that developed subaerially. The section is taken to indicate a moderate rate of loess deposition back to its 22 Ma base. A high rate of sediment accumulation began about 3.5 Ma and lasted to present. How much of the earlier Miocene sediment originated as air fall silt is controversial (we observed what we thought were pond marls and green clays). Although Qiang et al. (2011) call for early desertification of this region, Alonso-Zara et al. (2009) interpret early Late Miocene sediments as mudflat-lacustrine, rejecting an aeolian environment of deposition, but supporting a semi-arid habitat for the region at that time.

In Tianshui we visited the Yaodian section of Li et al. (2006). This 240 m section is Late Miocene in age, correlated to chrons C3An.2n to C5An.2n, about 6.5 to 12 Ma. A rich fauna containing *Hipparion weihoense* occurs at about 10.5 Ma. The top units are clearly dominated by lake deposits; reddish-brown mudstones with yellowish calcareous mudstones and greenish marlites, thinly bedded. Alternating red and green clays (previously compared to 'zebra beds' of Linxia Basin) attest to a long, continuous interval of lacustrine environment (interpreted to span 9.2 to 7.4 Ma). Lower sediments show a fluvial regime, with a cluster of cross bedded sands at about 11.5 to 10.4 Ma. Generally, these become finer upward and the section becomes dominated by mainly overbank deposits of red-brown silts with yellowish marlites and some paleosols. Li et al. (2006) interprets basal units to represent floodplain overbank deposits, and these include pond deposits, periodically evaporated, and reminiscent of upper units. The "*Hipparion* fauna" in the Yaodian section is one that clearly does not occur in loess, and is not representative of the classic red clays. It would be useful to analyze lateral variability of deposits to compare with Guo's section.

Sujiawa in Gansu presents another red silt sequence that includes minor amounts of fine sands without evident lake deposits. This thick accumulation seems to reflect the widespread, but not universal, occurrence of fine-grained to sandy Miocene deposits on the Loess Plateau. It has yielded fossil material of a *Hipparion* red clay assemblage.

4 Discussion

In China, Neogene fossil vertebrate deposits are often referred to in a shorthand fashion, which is useful in a general context, but of limited descriptive power. The adjective for assemblages is often derived from a dominant faunal element, as is the case for the Middle Miocene *Platybelodon* fauna or the Pleistocene *Equus* fauna. As noted above, Chinese "*Hipparion* faunas" occur from about 11 Ma to the Late Pliocene. Obscured by this broad designation is that the infrequently sampled early "*Hipparion* faunas" (early Late Miocene) and Pliocene assemblages, are distinct from the widespread late Late Miocene, Baodean age faunas. This is rectified in part by applying different mammal units for them: the revival of Bahean as a mammal

unit for earlier *Hipparion* assemblages (Zhang et al., 2002; Deng, 2006), and Yushean (Qiu and Qiu, 1995) for Pliocene assemblages, which is further subdivided by Qiu et al. (in press).

“*Hipparion*” faunas occur in many sedimentary settings of varied lithology, clay to sand, deep red to drab buff or gray or green. Below the widespread Pleistocene loess of the Loess Plateau many locations display deep red color clays that are Pliocene in age. Examples are the Jingle Formation of Shanxi Province and the Lantian Formation of Shaanxi Province. In many areas, red, fine-grained sediments extend into the Late Miocene, and the silt particles are of aeolian origin (Lu et al., 2001; Han et al., 2002; Miao et al., 2004). Kaakinen (2005) shows this style of sedimentation to commence about 6.8 Ma at Lantian, and confirms that the sedimentary regime is consistent with aeolian transport, at that early date, albeit with minor fluvial components low in the Lantian Formation. The dating by Zhang et al. (1999) for Lingtai is similar; there the section above the 7 Ma sand and pebble-bearing layers is dominantly fine red clays. Other localities across the Loess Plateau also indicate aeolian transport of red clays after about 7 Ma (Ding et al., 1998; Guo et al., 2001). Although “*Hipparion*” red clays are widespread, they are not universal, the antithesis being the Yushe sequence that is dominated by drab-colored fluvial sands and silts.

The Loess Plateau is vast, spanning 1000 km of central China. Variation across this region includes relatively greater fluviolacustrine influence on the environment of deposition in the western part, the Longzhong Basin. Eastward, the Ordos platform is dominated by clay sized particles and a more obvious aeolian source of fine sediment since the Late Miocene (Song et al., 2007). Yushe Basin, in the extreme east of the Loess Plateau, is exceptional because tectonism controlled its depositional regime. Down dropping of the Yushe half-graben allowed coarse fluvial sediments to dominate any clays provided aerially to the system.

Although northern China Late Miocene deposits are variable in color and sedimentology, Late Miocene “terres rouges” are widespread. One research question concerns why they are frequently but not universally encountered. Another factor is the spotty distribution of the fossil occurrences in the red clays. These deposits may be unfossiliferous through most of their thickness, but have rich local concentrations of bone, as is the case at Qingyang and other Baodean age accumulations. Interpreting these observations depends on how Late Miocene paleohabitat of the Loess Plateau is reconstructed. Earlier prevailing views of mainly dry continental habitat for the Loess Plateau have been challenged by new analyses of mammalian fossils and paleofloras. Hypsodonty changes indicate a moist Loess Plateau during the Late Miocene Baodean Age (Liu et al., 2009) and paleofloras argue strongly for wetter-than-present Miocene conditions (Liu et al., 2011). Passey et al. (2009) find evidence from stable isotopes of fossil teeth for a humid monsoon forest environment during the Miocene-Pliocene transition in North China.

Our paleoenvironmental model of red clay deposition and fossil preservation hypothesizes that the Miocene of eastern Asia, an area greater than the Loess Plateau, experienced considerable air fall dust accumulation. Red silts, aeolian in origin, were widely available to most sedimentary systems and supplied a component to the sediment record, unless coarser sand dominated and fluvial action carried the silt downstream. The rate of sedimentation was probably high in the Pleistocene, 60 m/m. y. for the loess at Lingtai (Zhang et al., 1999), but lower during the Miocene and Pliocene, 10 to 30 m/m. y. for the Jingle red clay (Zhu et al., 2008). Given aeolian deposition, all areas would have been aggrading, unless they were near water courses. Probably much of the loess plateau was of low relief, and depressions, or waterholes, would have been attractive to vertebrates, large and small, herbivores and carnivores. Probably also in a moist habitat, vegetation growth was highly productive, keeping pace with aggradation. This scenario, then, suggests that depressions in the landscape would be natural sites of accumulation and preservation of bone, most elements dissociated, but occasional articulations preserved. Around waterholes, bone concentration over years could have been great. Trampling

would break, but also reorient bones from the horizontal, explaining occasional vertical elements. Trees at such sites would hold predatory birds, which could be the concentrating source for microfaunal elements. This is a scenario of accretion of fauna over time, years to tens of years at single sites, perhaps longer. It is not a catastrophic scenario. Taphonomic field data can be expanded to test the model.

An important ecological role may have been played by fire. Ecologists have noted that wildfires functioned to maintain widespread grasslands of the Late Miocene (Keeley and Rundel 2005). Fifty km northeast of Yushe (Cheng et al., 2011), surface fires were an aspect of the Taigu Basin ecology during the Pliocene. The great role of fire in the ecosystem stands out when considering a high-biomass scenario in which significant fuel was continually generated due to rapid growth, and fire maintained open habitat.

Wind-blown red clay deposits appear to have accumulated in Late Miocene settings when other sediment sources were not available. In Gansu Province, we observed vertebrate-bearing sands and silts, mottled or drab yellow and gray in color at various locations, including Leijiahe and Yucun. How can airborne loess be so dominant in one area and absent 20 km away? Our model sees loess deposition as dominant only where the depositional regime was slow-current. Where coarser sediment was available and higher flow rates dominated, as at Leijiahe, the aeolian red clay comprised a minor component in the accumulation.

As the Neogene of China has become known better, Miocene red clays significantly older than the “*Hipparion* red beds” have been identified. Some of these, as in the Qin’an Basin or at Lanzhou, are also dominantly red and show an aeolian contribution to the fine grained component. Whether such deposits of Early Miocene age truly represent loess is debatable, but they show that dust was a sediment source in northern China throughout the Neogene. Aeolian sediment does not necessarily invoke desertification. On the contrary, the high diversity of Loess Plateau *Hipparion* faunas stands witness to productivity and high biomass. Rather than representing catastrophic assemblages, we think that aeolian deposition in combination with floodplain aggradation was the norm across North China. Fine-grained sediment accumulated rapidly on low-relief surfaces, burying abundant faunal remains at water holes that naturally attracted vertebrates.

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