Biostratigraphic, chemostratigraphic, and magnetostratigraphic study across the Paleocene-Eocene boundary in the Hengyang Basin, Hunan, China

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ABSTRACT

The Lingsha Formation of the Hengyang Basin, Hunan, China, is one of two currently known sites thought to preserve sedimentary rocks spanning the Paleocene-Eocene boundary in Asia. The formation includes two fossiliferous intervals: the upper, yielding about 12 mammalian species, and the lower, yielding one mammalian and one reptilian species. To constrain the temporal correlation of the Lingsha Formation faunas, we collected samples for isotopic and paleomagnetic analysis in three measured stratigraphic sections tied to the fossil sites. The isotopic and paleomagnetic results demonstrate that the transient carbon isotope excursion that marks the Paleocene-Eocene boundary as currently advocated is present in the upper Lingsha Formation. The fauna from the upper Lingsha Formation occurs within the excursion interval, and is thus of earliest Eocene age. It is correlative with the Wasatchian-0 faunal zone in the Bighorn Basin, Wyoming, to within ~10^4 yr. Cluster analysis demonstrates compositional ties between the upper Lingsha fauna, the fauna from the Bumban Member of the Naran Bulak Formation, southern Mongolia, and the fauna from the Wutu Formation, northeastern China. These faunas form a cohort separated from earlier faunas by turnover at the ordinal and familial level, and from subsequent faunas by generic-level turnover. The discovery of a hyaenodontid in the Nomogen Formation of Inner Mongolia indicates that hyaenodontid creodons may have appeared first in Asia and then spread to North America at the Paleocene-Eocene transition.
INTRODUCTION

The late Paleocene through early Eocene has been identified as a period of significant global climate and biotic change. Paleoclimatographic records from deep-sea cores (late Paleocene through early Eocene) indicate the existence of a short-term (100–200 k.y.) climatic anomaly superimposed on a longer-term (5–7 m.y.) change in global climate (Kennett and Stott, 1991, among many others). Both long- and short-term changes involved the warming of deep sea and high-latitude surface water, as well as negative shifts in δ13C values of marine carbonates (Thomas and Shackleton, 1996). Coincident changes in temperature (Koch et al., 1995; Wing et al., 1991; Wolfe, 1994), equability (Wing and Greenwood, 1994), and carbon isotopes (Koch et al., 1992, 1995) in the continental record suggest significant climatic change across the entire globe through the late Paleocene-early Eocene (Initial Eocene Thermal Maximum, [IETM]). The unique character, global synchronicity, and preservation of the short-term carbon isotope shift in terrestrial and marine sections has led to its use as a chronostratigraphic marker (e.g., Koch et al., 1992; Cojan et al., 2000) and to the proposition that the isotope excursion be used to define the Paleocene-Eocene boundary (Koch et al., 1992). In the Holartic continents, the modern mammalian orders, Perissodactyla, Artiodactyla, and Primates sensu stricto, made their first appearances in the fossil record during the Paleocene-Eocene (Clarkforkian-Wasatchian) transition. The abrupt appearance of these new orders of mammals in North America, Europe, and Asia (Beard, 1998; Clyde and Gingerich, 1998; Gingerich, 1989; Gunnell, 1999; Hooker, 1996, 1998; Meng and McKenna, 1998; Ting, 1998), and a large-scale benthic marine faunal turnover (Thomas and Shackleton, 1996), suggest a significant reorganization in the biosphere (McKenna, 1998).

Due to a series of important discoveries of Paleocene and early Eocene fossil mammals, Asia has increasingly been considered the source of immigrants of several mammalian orders to North America and Europe (Beard, 1998; Beard and Dawson, 1999; Dashzeveg, 1988; Krause and Maas, 1990; Sloan, 1987; South China “Red Beds” Research Group, IVPP, 1977; Zhai, 1978). However, the Asian record across Paleocene-Eocene boundary is poorly understood when compared to records from its Holartic neighbors, North America and Europe. Asian Cenozoic deposits are virtually restricted to continental rocks, and the age of most mammal-bearing strata is unconstrained radioisotopically. As such, fossil mammals have long been the primary tool for stratigraphic correlation and subdivision of Cenozoic strata. The Asian Paleocene and early Eocene faunas have been divided into a series of land mammal ages from oldest to youngest: The Shanghuan, Nongshanian, Gashtan, and Bumbanian Asian Land Mammal Ages (ALMAs) (Li and Ting, 1983; Russell and Zhai, 1987; Ting, 1998; Tong et al., 1995). The faunas thought to represent the latest Paleocene and early Eocene have been grouped within the Gashtan and Bumbanian respectively, but precise biostratigraphic correlation of the postulated Asian Paleocene and early Eocene faunas to those of North America and Europe has not been achieved. The Gashatan is suggested to correlate to the Clarkforkian North American Land Mammal Age (NALMA) by Meng et al. (1998) and Ting (1998), and to correlate with the latter half of the Tiffanian NALMA and early part of the Clarkforkian NALMA by Wang et al. (1998) and Beard (1998). The Bumbanian is suggested to correlate to the Wasatchian NALMA by Dashzeveg (1988), Russell and Zhai (1987), and Ting (1998), and to correlate to the pre-Wasatchian, based on the Wutu fauna, Wutu Basin, Shaingdong, by Beard (1998). To provide better evidence for intercontinental correlation, we conducted a chemostratigraphic and magnetostratigraphic study of the Lingcha Formation, Hengyang Basin, Hunan, China, one of only two currently known Asian localities with a continuous Paleocene-Eocene sedimentary record (the other being the Nement Basin, Mongolia). Here we report results that demonstrate the presence of the Paleocene-Eocene boundary carbon isotope excursion in the Lingcha Formation, use quantitative biostratigraphic methods to place this excursion within the broader context of Asian Paleocene-Eocene mammalian faunal turnover, and explore the implications of these results.

HISTORY OF WORK IN THE HENGYANG BASIN

The Hengyang Basin is located in the south-central part of Hunan Province, China (21°05′N, 112°57′E, Fig. 1). It is roughly square, with an area of ~5200 km² (Liu and Fu, 1986). The basin is bounded by the Heng Shan mountain on the north, and by hills of late Paleozoic rocks on the south near Layiang city (Young et al., 1938). To the east are ridges of early Paleozoic rocks, and westward lie the mountain ranges near the cities of Hengyang, Shaoyang, and Changning. The basin is drained by the Hsiang River and its two major tributaries, the Laishui on the east and the Chengshui on the west. The basement of the Hengyang Basin is composed of Proterozoic and early Paleozoic low-grade metamorphic rocks and late Paleozoic limestone, which crop out around the basin (417 Geological Team, 1979). Cretaceous rocks are widely distributed in the basin, whereas the early Tertiary rocks are mainly in the northeastern part of the basin.

The discoveries of early Paleogene mammalian fossils in Hengyang, Hunan, come from extensive geological investigations of the “Red Beds,” the widely distributed late Mesozoic and early Cenozoic terrestrial rocks of southern China. The red beds of Hunan were carefully investigated by C.C. Tien, H.C. Wang, and Y.T. Hsu in 1932 (Tien et al., 1933). They distinguished two sets of red beds in the surveyed areas. The older set was named the “Hengyang Red Beds” or “Hengyang Sandstone” and considered to be Eocene in age; the younger was named the “Tanshii Red Beds” and suggested to be Miocene. By 1936, however, Tien had come to consider that the “Tanshii Red Beds” were most probably Eocene, based on the “plants in association with fishes,” and that the “Hengyang Red Beds”
were Cretaceous (Tien, 1936, p. 462). To prove the age of the two red beds of Hunan, C.C. Young, M.N. Bien, and Y.Y. Lee took three trips in 1938 to several basins of central Hunan (Young et al., 1938). The first fossil mammal, a left dentary with m/3, was found in the "Hengyang Red Beds" from the Hengyang Basin. The identity of this specimen is discussed below with reference to new materials. Young (1944) reported this single find and proposed that the "Hengyang Red Beds" from which the fossil came were middle Eocene in age. However, he also pointed out that this "does not necessarily mean that the whole formation is middle Eocene in age" (Young, 1944, p. 3).

Increasingly detailed studies of the red beds in the Hengyang Basin have been made since the 1960s. Survey of industrial mineral resources of the red beds called for a reliable stratigraphic framework. This was achieved mainly through biostratigraphic study of invertebrate, vertebrate, and pollen fossils. The invertebrate paleontologic and palynologic research was carried out by the Hubei Geological Institute, Hubei Geological Bureau, Hubei Petroleum Team, Hunan Petroleum Team, and Nanjing Institute of Geology and Paleontology, Chinese Academy of Sciences. Research on ostracodes by S.Z. Guan (1979, 1989) and Liang and Zhang (1984), on Cretaceous pollen by Z.L. Zhang (1979),
on Cretaceous freshwater lamellibranchiata by R.J. Zhang (1979), on Eocene plants by H.M. Li (1965), and on stratigraphy by J.M. Hu and D.M. Zeng (1980), J.J. Zhang (1982), and C. Chu (1986) has all been important for the development of a basic stratigraphic framework. In addition, paleomagnetic analysis has been carried out on Cretaceous rocks, but only a brief report has been published (Hsu et al., 1990).

Study of fossil vertebrates has led to major progress in defining the early Tertiary strata of the Hengyang Basin. This research has been carried out by the Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences (IVPP), since the early 1970s. In 1974 and 1976, a team led by Z.X. Qiu and C.K. Li found five new species of fossil mammals from the localities −15 km southwest of Hengdong, a small town in the northeastern part of the Hengyang Basin (Fig. 1). The name “Lingcha Formation” is given to the fossil-bearing strata by Li et al. (1979, p. 77). They further subdivided the fossil-bearing strata into an upper fossil layer, yielding six mammalian species and representing early Eocene (no later than the Cuisian European Land Mammal Age [ELMA], probably equivalent to the Sparnacian ELMA), and a lower fossil layer, yielding one mammalian species and probably representing the earliest Eocene (perhaps correlative with the fauna from the Naran Bulak Formation of southern Mongolia) (Li et al., 1979, p. 78). J.J. Zheng, X.S. Huang, and others investigated the fossil localities later in 1978, and proposed that both upper and lower fossil layers are probably earlier Eocene in age and may be comparable to the Graybullian subage of the Wasatchian NALMA in North America or Sparnacian ELMA in Europe (Zheng and Huang, 1984, p. 202). However, Li and Ting (1983, p. 40) considered that the lower fossil layer of the Lingcha Formation may be Paleocene based on occurrence of Archaeolamba sp. To further enlarge the collections and establish the age of the fauna, C.K. Li, S.Y. Ting, and others worked there from 1982 to 1986. S.Y. Ting, J.L. Li, and others collected more fossils, including new species, in these localities in 1987. These six years of field work in the 1980s, as well as work by Y.Q. Wang and Y.M. Hu during the early 1990s, have tremendously improved both the quality and quantity of collections from the Hengyang Basin (Li and Ting, 1983, 1985; Li et al., 1989; Ting, 1993, 1995; Ting and Li, 1984, 1987).

**SYSTEMATIC PALEONTOLOGY**

New material bearing on the identity of the specimen reported by Young (1944) is described here:

Class Mammalia Linnaeus, 1758  
Order Perissodactyla Owen, 1848  
Family incertae sedis  
Propachynolophus hengyangensis  
(Young, 1944; Li et al., 1979)

This species is represented by the type specimen, a fragmentary mandible with a left m3 (IVPP V-214), the first mammalian fossil found in the basin. The species was first identified as ?Adapidium sp. (Young et al., 1938, p. 268) and then assigned to Propalaeotherium, a European equid (Young, 1944). It was reassigned to the genus Propachynolophus, another European equid, when additional material, a partial left mandible with the alveoli of p2 and deeply worn p3-m2 (IVPP V-5349), was found (Li et al., 1979, p. 74).

The new material described here is a single left m3 (IVPP V-7453; Fig. 2), −12.5 mm long and 5.5 mm wide. This specimen is slightly longer and narrower than the type specimen, but similar to the latter in basic morphology; both m3s are rectangular. The protoconid and the metaconid are conical and connected by a crest. The metastylid is well developed, but not separated from the metaconid. The metalophid (= cristid obliqua, Hooker, 1989) extends from the middle of the posterior wall of the protolophid (= protocristid, Hooker, 1989), labial to the metaconid. The third lobe of the m3 in both the type specimen and IVPP V-7453 is characterized by a closed, circular basin. The hypoconulid is not distinct. The new specimen differs from the type in having higher, more acute protolophid, hypolophid, and metalophid. The new specimen is referred to this species mainly based on morphological similarity, especially the characteristic third lobe of the m3.

The species Propachynolophus hengyangensis, previously identified as an equid, has long been thought to be related to a counterpart taxon in Europe. The type specimen of this species was referred to the European equid genus Propalaeotherium, based mainly on “the general structure of the tooth (which) fits well with that of Palaeoatherium sinensis” (Young, 1944, p. 2). It was reassigned to the genus Propachynolophus, based on similarities in the size, structure of the lower molars, and degree of molarization of the premolars to those of Propachynolophus maldani (Li et al., 1979, p. 74). These authors also pointed out that the larger size and the weaker cingulum of P. hengyangensis represent more advanced features, and that the lesser molarization of p3 represents a primitive feature (Li et al., 1979, p. 74).

Both the type and new specimen are about a fourth larger than P. maldani and smaller than Propachynolophus gaudryi. The most noticeable differences distinguishing P. hengyangensis from P. maldani and P. gaudryi are in the third lobe of m3. The third lobe of the m3 in P. hengyangensis is characterized by a closed circular basin; however, the third lobe of m3 in P. maldani and P. gaudryi is composed mainly of a crest connecting the middle of the posterior wall of the hypolophid to the hypoconulid. The crest then turns lingually to meet the entoconid, which is the condition commonly seen in the primitive equids. P. hengyangensis also differs from P. maldani and P. gaudryi in having a more lophodont protolophid and metalophid, and metalophid more labially connected with the posterior wall of the protolophid, instead of with the metastylid as in the latter species.

Compared with early tapiroids, P. hengyangensis is about the same size as Cardiolophus radinskyi and smaller than Homo-
Danjiangia pingi (Wang, 1995), clearly shows the cranial and dental features of early chalicotheres, and indicates that a long diastema between p1/1 and p2/2 occurred in early chalicotherium forms. The long diastema before p2/2 and either lack of p1/1 or having reduced p1/1 in P. hengyangensis allies this species with early chalicotherium. Comparing P. hengyangensis and ropalaeotherium sinense with D. pingi, we find further striking similarities in dental morphology. P. hengyangensis is similar to D. pingi in basic dental features, especially the closed lobe of m3/3, but differs from the latter in having a slightly smaller metastylid. The lower m3/3 of P. hengyangensis is more similar to that of Propalaeotherium sinense. Propalaeotherium sinense is about the same size as D. pingi and P. hengyangensis. It is similar to D. pingi in basic dental morphology, but differs from the latter in having a more developed mesostyle on the upper molar and advanced lower p3/3. We consider that Propachynolophus hengyangensis, Danjiangia pingi, and Propalaeotherium sinense may represent a new group closely related to the basal chalicotheres.

HENGYANG BASIN FAUNAS

Collections from the Hengyang Basin now include (classification based on McKenna and Bell, 1997):

Upper Lingchha Formation

Class Mammalia Linnaeus, 1758
Order Cimolestida McKenna, 1975
  Family ?Micropternodontidae Stirton and Rensberger, 1964
  Hsiangolestes Zheng and Huang, 1984
  Hsiangolestes youngi Zheng and Huang, 1984 (see Ting, 1995; Ting in preparation)
Family Cimolestidae Marsh, 1889
  Naranius Russell and Dashzeveg, 1985
cf. Naranius infrequens Russell and Dashzeveg, 1985 (see Ting, 1995; Ting in preparation)
Order Insectivora gen. et sp. nov. (see Ting, 1995; Ting in preparation)
Order Mixodontia Sych, 1971
  Family Eurymylidae Matthew, Granger and Simpson, 1929
  Matutinia Li, Chiu, Yan, and Hsieh, 1979
  Matutinia nitidulus Li, Chiu, Yan, and Hsieh, 1979
  (see Li et al., 1979; Ting, et al., 2002)
Order Acreodi Matthew, 1909
  Family Hapalodectidae (Szalay and Gould, 1966) Ting and Li, 1987
    Hapalodectes Matthew, 1909
    Hapalodectes hengangensis Ting and Li, 1987 (see Ting and Li, 1987)
  Family Mesonychidae Cope, 1875
    Dissacus Cope, 1881
    Dissacus sp. n. (Ting and Wang, in preparation)
Order Pantodonta Cope, 1873
  Family Coryphodonidae Marsh, 1876

Figure 2. Propachynolophus hengyangensis, left m3/3 (IVPP V-7453), occlusal view, scale = 1 cm.
Limuping, and is composed of red mudstone intercalated with sandstone. The lower Lingcha fauna is found in the middle of the section. Although section 2 can not be directly correlated into section 1, bedding orientations along the south limb of the fold are broadly consistent and local topography is precisely known, so a simple trigonometric projection can be used to make an approximate correlation between these two sections. Such a projection indicates that section 2 correlates to the ~350 m level in section 1. Section 3 (284.4 m thick) is from Tianzhifen to near Jixianwan, and is also composed of sandstone intercalated with red mudstone. Mammalian fossils, found between the 255 and 257 m levels, are considered equivalent to those found at the top of section 1 and grouped with the upper Lingcha fauna. An unidentified turtle was found at 204 m within section 3.

**Magnetostratigraphy**

Paleomagnetic samples were collected from all three of the local stratigraphic sections measured in the Lingcha Formation in an effort to provide independent chronostatigraphic constraints on fossil and isotopic samples collected from this area. One hundred and fifty oriented samples of red mudstone and sandstone were extracted from 31 sites. Sampling resolution was necessarily coarse due to patchy exposures. Samples were analyzed at the paleomagnetics laboratory at University of California, Santa Cruz, using thermal demagnetization. Most samples showed very to moderately stable demagnetization behavior and were characterized by 2–3 components of magnetization. All specimens carried a low-temperature component (<300 °C unblocking temperature) that exhibits random directions suggesting that it is a viscous overprint. A handful of samples also exhibited an intermediate temperature component (300–600 °C unblocking temperature) of unknown origin. Most specimens exhibited a strong high-temperature component characterized by unblocking temperatures of 670–690 °C, indicating a hematite remanence carrier. This high-temperature characteristic component exhibits antipodal directions with an average declination/inclination of 10.4/26.2° (N = 118, α = 4.6°) when all reversed samples are inverted. This component also passes the reversal test at 99% confidence limit and is not significantly different from the expected Paleocene-Eocene direction for this location on the South China Block (Dec = 3.3°, Inc = 27.5°, α = 10.2°, reference pole from McElhinny and McFadden, 2000). We interpret this component to be an early chemical remanent magnetization associated with syndepositional oxidation of these fine-grained terrigenous sediments. Although the beds are gently folded into a syncline, the fold test is equivocal with the best sites (N ≥ 5, K ≥ 50) showing maximum clustering at ~70% unfolding but a 95% confidence interval that includes 100% unfolding (and excludes 0% unfolding) using the parametric bootstrap (Tauxe and Watson, 1994). This result could indicate a synfolding magnetization but is more likely due to the small difference in bedding orientation be-
between limbs and/or the existence of a small unaccounted vertical axis rotation.

Sites were split into two groups (alpha and beta) depending on their reliability and plotted against stratigraphic position (Fig. 3A). Alpha sites (shown as closed symbols in Figures 3 and 4) are the most reliable sites and have 4 or more stable samples that are significantly clustered at $p < 0.01$ (using the Watson, 1956, test for randomness). Beta sites (shown as open symbols in Figures 3 and 4) are characterized by 3 or more stable samples significantly clustered at $p < 0.05$ or two samples significantly clustered at $p < 0.01$. Samples that exhibited stable demagnetization but were not included in these sites are also used to help confirm the pattern of polarity changes. Section 1, which is the longest section, shows a total of 4 polarity intervals, with the upper Lingcha faunal horizon falling in a long reversed zone at the top of the section. Section 2 and 3 each exhibit two polarity zones, with rocks of reversed polarity overlying normal polarity rocks (Fig. 3A).

**Carbon isotope stratigraphy**

The carbon isotope composition of authigenic carbonate precipitated within ancient soils (paleosols) is indirectly determined by the isotopic composition of atmospheric CO$_2$. During

![Figure 3](image-url)
photosynthesis, plants assimilate carbon from the atmosphere with an approximately consistent fractionation relative to atmospheric CO$_2$ (e.g., Bocherens et al., 1993; Arens et al., 2000). Within soils, gaseous CO$_2$ is typically a mixture of atmospheric carbon dioxide and CO$_2$ produced during respiration in plant roots and microbial degradation (two nonfractionating processes). The mixing of CO$_2$ within soils and fractionation of carbon isotopes during soil carbonate precipitation have been investigated (Cerling et al., 1991), and the δ$^13$C values of soil carbonate precipitating more than ~30 cm below the soil surface typically reflects the carbon isotope composition of soil vegetation, and thus that of atmospheric CO$_2$.

We collected and determined the stable isotope composition of 32 paleosol carbonates from 15 levels within sections 1 and 3. In the laboratory, carbonate nodules were polished flat on a lapidary wheel using 600-grit silica carbide powder, washed, then dried in a low-temperature oven. Samples (~100 μg) were drilled from the polished surfaces under a binocular microscope using a mounted dental drill. Micritic carbonate was sampled exclusively; care was taken to avoid sampling sparry phases that might represent diagenetic, rather than pedogenic, conditions. Where possible, two samples were drilled from each of two nodules from each carbonate-bearing horizon in each measured section. Samples were roasted in vacuo at 400 °C for 1 hour to remove organic contaminants. These were analyzed using a Micromass Optima or Prism gas-source mass spectrometer, following reaction with 100% phosphoric acid at 90 °C, with the aid of an automated Isocarb device. Isotope ratios are reported in permil (‰) units as δ$^13$C or δ$^18$O, the deviation of the isotope ratio of a sample from that for a standard (V-PDB). δ = (R$_{sample}$/R$_{standard}$ − 1) × 1000, where R = $^{13}$C/$^{12}$C or $^{18}$O/$^{16}$O.

Analytical precision, based on repeated analysis of an in-house standard, was better than 0.1‰ for both carbon and oxygen. All data are presented in Appendix 1 (Tables A1 and A2).

The δ$^13$C values of multiple samples from individual nodules and of multiple nodules from a single sampling level are tightly clustered. The average range of values from multiple samples of a single nodule is 0.3‰ (n = 26), and the average range of multiple nodules from a single level is 0.6‰ (n = 13).

The average carbon isotope composition of paleosol carbonates from each sampling level in local sections 1 and 3 is shown in Figure 3B. Values from both sections are nearly constant at approximately −7‰ through most of the sampled interval. Each section, however, includes one or more levels characterized by significantly lower δ$^13$C values. In section 1, a single level at 548 m contains nodules with an average δ$^13$C value of −12.5‰.

In section 3, the carbonate nodule δ$^13$C values decrease from 238 m to 272 m, reaching a minimum of −12.7‰, and then rebound slightly at the top of the section.

Composite section

We use a combination of field observations, isotopic data, and paleomagnetic data to correlate the three measured sections into a single composite section (Fig. 4). The similar composition and lithostratigraphic association of the upper Lingcha fauna from sections 1 and 3 suggests that these horizons may be correlative. This correlation is supported by the dramatic decrease in paleosol carbonate δ$^13$C values associated with the upper Lingcha faunal horizon in these two sections. Both of these sections also preserve a normal to reverse polarity transition that lies ~180 m below the level characterized by the upper Lingcha fauna and carbon isotope excursion. This suggests very similar sediment accumulation rates for these two sections. Based on this evidence, we correlate the 548 m level of section 1 and the 272 m level of section 3 and correlate the remainder of these sections by assuming equal sedimentation rates. The short stratigraphic interval represented by section 2 also appears to preserve a reversal from normal to reversed polarity, although sampling is relatively poor. Section 2 is estimated to correlate to the ~350 m level in section 1 using trigonometric projection. This lies within the interval of the uppermost normal to reversed polarity transition in section 1, suggesting that the reversals in these two sections are correlative. This defines a ~40 m interval within the composite of sections 1 and 3, within which section 2 likely correlates. In the absence of other constraints, we correlate section 2 to the middle of this interval.

Figure 4 presents our composite carbon isotope and paleomagnetic stratigraphy, with all values projected on the section 1 stratigraphic scale. The composite section shows two well-determined magnetic polarity zones and a dramatic shift in paleosol carbonate δ$^13$C values. The only known decrease in the carbon isotope composition of pedogenic carbonate during the Cenozoic that approximates the magnitude and abruptness of that seen in the record from Hengyang occurs during the Paleocene-Eocene boundary carbon isotope excursion, and we correlate the Hengyang excursion with this event. This correlation is supported by the association of the isotopic excursion with a fauna having early Eocene affinities, the existence of a typical Paleocene taxon from a level 180 m below the excursion, and the stratigraphic position of the excursion within an interval of reversed polarity. We place the Paleocene-Eocene boundary (54.97 Ma, Wing et al., 1999) at 516 m in the Hengyang Basin composite section, the first level producing unusually low δ$^13$C values. Given this identification, and with reference to correlated marine Paleocene-Eocene boundary sections (Kennett and Stott, 1991), we correlate the uppermost reversed polarity interval within the Hengyang composite section to chron C24r of the most recent Geomagnetic Polarity Time Scale (Cande and Kent, 1995), and the underlying normal polarity interval to chron C25n (Fig. 4). The age of the C25n/C24r boundary has been estimated to be 55.7 Ma in marine sections (Cande and Kent, 1995). Below the 275 m level, the pattern of polarity reversals is too poorly resolved to allow confident identification of magnetostratigraphic units.

Our chemostratigraphic and magnetostratigraphic results allow us to correlate the Hengyang Basin faunal horizons directly to the early Paleogene biostratigraphy of North America.
Figure 4. Composite carbon isotope and magnetic stratigraphy of the Hengyang Basin Paleocene-Eocene boundary interval. Composite stratigraphy represents data from local sections 1 (diamonds), 2 (circles), and 3 (squares) projected on the section 1 stratigraphic scale. Open and closed symbols for paleomagnetic data are as in Figure 3A. Magnetic chron assignments are made with reference to marine Paleocene-Eocene boundary sections (e.g., Kennett and Stott, 1991). The Paleocene-Eocene boundary is placed at the base of the carbon isotope excursion, and assigned an age of 54.97 Ma after Wing et al. (1999). The age assignment for the C25n/C24r magnetic reversal is an estimated age for this reversal in marine sections. The stratigraphic and temporal range of the Gashatan (Gash) and Bumbian (Bumb.) Asian Land Mammal Ages (ALMAs) are constrained by the lower and upper Lingcha faunal horizons (LC-L and LC-U, respectively); the Gashatan-Bumbian boundary lies within the interval labeled “Unconstrained.” Position of the Tiffanian (T), Clarkforkian, and Wasatchian (Wa) North American Land Mammal Ages (NALMAs) are after Bowen et al. (2001) and the compilation of Gingerich (2001). (Reprinted with permission from Bowen et al., 2002. Copyright 2002, American Association for the Advancement of Science).

(Bowen et al., 2002). The upper Lingcha fauna occurs between ~15 m above the Paleocene-Eocene boundary and the carbon isotope minimum at 548 m. In the Bighorn Basin of Wyoming, the first occurrence of Wasatchian mammals is ~2 m above the carbon isotope minimum (Bowen et al., 2001). The Hengyang Basin δ¹³C record is poorly resolved relative to that from the Bighorn Basin, however, and we present the conservative interpretation that the upper Lingcha fauna is of earliest Eocene age and is time-correlative with the earliest Wasatchian equivalent on a scale of ~10⁴ yr (Fig. 4). The lower Lingcha fauna, found within meters of the C25n/C24r reversal, is of late Paleocene age and can be correlated to the earliest subzone of the Clarkforkian North American Land Mammal Age (Cl-1, Figure 4).

Faunal analysis

In order to place the chemostratigraphic and magnetostratigraphic correlation points in the Hengyang Basin within the broader context of Asian early Paleogene mammalian faunal turnover, we correlate the lower and upper Lingcha fauna in the Hengyang Basin to other Asian Gashatan-Bumbian faunas (see Appendix 2). Faunal similarity was determined using a commonly employed clustering technique (Meng and McKenna, 1998). A similarity matrix (19 localities x 91 taxa) was built from presence/absence data at the generic level using Dice coefficients. We then clustered the faunas by reordering the similarity matrix using unweighted pair-group clustering (arith-
metric means) within the SAHN (Sneath and Sokal, 1973) mod-
ule of the NTSYSpc computer program (Rohlf, 2000). The pro-
gram can find alternative trees when there are ties in the input
matrix.

The results show that the upper Lingcha fauna most closely
resembles the fauna from the Bumban Member of the Naran Bul-
ak Formation, and shares secondary compositional affiliation
with the fauna from the Wutu Formation (Fig. 5). The Wutu fauna
(or faunas) includes both advanced taxa, such as Homogalax
wuttensis (Chow and Li, 1963), and primitive taxa, such as
Chronolestes simul and Carpocristes oriens (Beard and Wang,
1995), and the stratigraphy of this locality must be further exam-
ined to ensure that this collection is not significantly time-
averaged. Correlation of this fauna must further be considered
preliminary, because only ~1/3 of the taxa (11 of 31 taxa) in the
Wutu fauna have been studied and published so far (Tong and
Wang, 1998). Given our current level of knowledge, however,
these three faunas share only broad compositional ties with
Gashatan and other Bumbanian faunas. We suggest that they
might represent a cohort of earliest Bumbanian faunas of transi-
tional composition. The presence of a transitional fauna near the
Paleocene-Eocene boundary in North America has also been
demonstrated (the Wa-0 fauna of Gingerich, 1989). Faunas tradi-
tionally assigned to the Gashatan ALMA cluster within a discrete
group, indicating significant compositional similarities between
them. As expected, the lower Lingcha fauna clusters within the
Gashatan cluster, where it is most closely allied with another low-
diversity fauna containing Archaeolambda (a fauna from the
Shuangtasi Fin, Tongling Basin, Anhui Province, China).

The association of the upper Lingcha fauna with the Paleo-
cene-Eocene boundary carbon isotope excursion in the Hengyang
Basin allows us to correlate the Paleocene-Eocene boundary be-
low (or within) the basal Bumbanian faunal cohort. Thus, the
analysis suggests that most or all Bumbanian faunas are of Eocene
age. Further, if any Bumbanian assemblages prove to be of late
Paleocene age, the stratigraphic coincidence of the lower Lingcha
fauna with the C25n/C24r magnetochron boundary suggests that
no Bumbanian fauna is older than the 55.7 Ma age of that rever-
sal, and that no Bumbanian fauna correlates before the latter part
of the C1-I subzone of the Clarkforkian NALMA (Fig. 4).

The cluster analysis highlights the substantial faunal
turnover separating the Gashatan and Bumbanian ALMAs. Ex-
cept for a single mixodont species, Eomylus zhigdenensis, we have
not found any Gashatan species that occurred in the Bum-

![Figure 5. Cluster analysis of Gashatan-Bumbanian faunas (based on genera). Clustering coefficient provides an index of the compositional similarity of any two faunas (higher coefficient indicates greater similarity). Faunas discussed in the text include the lower (LC-L) and upper (LC-U) Lingcha faunas, the Bumban fauna (BB) from the Bumban Member of Naran Bulak Formation, Nemegt Basin, Mongolia, the Wutu fauna (if a single entity) (WT), Shangdong Province, China, and the Nomogen + Bayan Ulan fauna (NM), near Erlian, Inner Mongolia, China. See Appendix 2 for the names of other faunas.](image-url)
Biostratigraphic, chemostratigraphic, and magnetostratigraphic study, Hengyang Basin

Only four Gashatan genera, belonging to Arctostylopida, Mesonychidae, Pantodonta, and Insectivora, survived at the beginning of the Bumianian. Additionally, the families Isectolophidae (Perissodactyla), Chipattimyidae (Rodentia), Ommomidae (Primates), Hapalodectidae \(^1\) (Acreodi), and Hyopsodontidae ("Condylarthra") made their first appearance at the beginning of the Bumianian. The cluster analysis also indicates a substantial faunal turnover between the basal Bumianian cohort and subsequent Bumianian faunas. Faunal turnover across this interval is almost complete at the generic level, but does not include the substantial replacement at higher taxonomic levels that characterizes the Gashatan-Bumianian boundary.

The extant mammalian orders Perissodactyla, Primates, and Artiodactyla, and the extinct family Hyenaenodontidae (Creodonta) first appeared in North America at the beginning of the Wasatchian NALMA. Because our results indicate that all Gashatan faunas are of Paleocene age, the recent discovery of a new hyenaenodontid species, *Protlimnocyon chowi*, in the Gashatan Bayan Ulan fauna, Inner Mongolia (Meng et al., 1998), indicates that Hyenaenodontidae was present in Asia during the Paleocene, and most likely spread to North America during the Paleocene-Eocene transition (also see Bowen et al., 2002). Reports of a possible perissodactyl in the Bayan Ulan fauna (Meng et al., 1998) may also indicate that the order Perissodactyla (or at least their sister-group) occurred first in Asia, though the stratigraphic position of this specimen relative to the rest of the Bayan Ulan fauna needs to be further examined (Jin Meng, 2002, personal commun.).

ACKNOWLEDGMENTS

This project was funded by National Geographic Society Grant 6528-99. We greatly appreciate the support of the Society. Our special thanks go to the Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences, and the Hengdong County Office, Hunan, China, for their arrangements and aid in the field. Yuanqing Wang and Yuan Wang’s work was also supported by the Major Basic Research Project of Ministry of Science and Technology, China (G2000077700). G.J.B. was supported by the National Science Foundation Graduate Research Fellowship program. We thank Dr. Judith A. Schiebout of Louisiana State University for her help and support, especially in providing the NTSYS computer program for cluster analysis, and Prof. Chunxue Li, Jiajun Zheng, Yongsheng Tong, Xueshi Huang, Jingwen Wang, and Jinhong Li of IVPP for discussion. Dr. John Flynn of Field Museum of Natural History helped to organize the project during a 1997 Penrose Conference in New Mexico. Shuhua Xie of IVPP assisted the field work, Rob Coe of the University of California, Santa Cruz, facilitated paleomagnetic analysis, Paul White of Louisiana State University helped with the cluster analysis, and Mary Eggert of Louisiana State University helped draft the figures. Priscilla McKenna helped with the paleontological collecting. Ruth Hubert of LSU Geoscience Associates read the manuscript. This paper benefited from reviews by Kenneth Rose and Jonathan Bloch. We express our sincere thanks to all of them.

APPENDIX I. STABLE ISOTOPE DATA

| TABLE A1. STABLE ISOTOPE DATA FROM HENGYANG BASIN SECTION 1 |

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| TABLE A2. STABLE ISOTOPE DATA FROM HENGYANG BASIN SECTION 3 |

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\(^1\) Zhang et al. (1979) reported *Hapalodectes* sp. from the Lannikeng Member of Chijiang Formation (Nongshanian ALMA), Chijiang Basin, Jiangxi, China. The specimen is a fragmentary mandible with left p3 and right of p4 (IVPP V-5038). The authors assigned it to *Hapalodectes* because of its small size and laterally compressed teeth with acute cusps. Ting and Li (1987) suggested that this species might be a mesonychid. We do not include this potential occurrence of *Hapalodectes* in our analysis, as the evidence to support the classification of this specimen is questionable.
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## APPENDIX 2. FAUNAL LISTS

### Gashatian Land Mammal Age

**ST (Shuangtasi Group, Xuancheng Basin, Anhui)**
- *Hsiuanannia maguenisi*, *Dissacuus magushanensis*, *Bothriostylops progressus*, *Archaeolambda yangtzeensis*, *Wanotherium xuanchengensis*, *Harpyodus progressus*, *Palaeostylops iturus*, *Wanostylops youngi*

**PH (Pinghu Fm., Chijiang Basin, Jiangxi)**
- *Prodinoceras lacustris*

**LC-L (Lower part of Lingcha Fm., Hengyang Basin, Hunan)**
- *Archaeolambda* cf. *plancanina*

**TL (Shuangtasi Fm., Tongling Basin, Anhui)**
- *Bothriostylops progressus*, *Archaeolambda* sp. cf. *A. yangtzeensis*, *Guachilambda zhaii*

**TS (Tujinshan Fm., Jiashan Basin, Anhui)**
- *Sinonyx jiashanensis*, *Sinonyx zhaii*

**TZ (Taizicun Fm., Turfan Basin, Xinjiang)**

**DB (Dabu Fm., Turfan Basin, Xinjiang)**
- *Coryphodontidae*, *Prodinoceras xinjiangensis*

**NM (Nomogen Fm.; former Bayan Ulan plus Nomogen Fm., Erlian, Inner Mongolia)**

**BT (Bugin Mem. of Naran Bulak Fm., Bugin Tsav Basin, Mongolia)**
- *Khychina elongata*, *Archaeolambda trofinovi*, *Prodinoceras sp.*

**ZG (Zhigden Mem. of Naran Bulak Fm., Nemegt Basin, Mongolia)**
- *Ernanodon* sp., *Amar eleator*, *Archaeolambda planicanina*, *Prodinoceras martyr*, *Gashatostylops macrodon*, *Arctostylops sp.*

**NR (Naran Mem. of Naran Bulak Fm., Nemegt Basin, Mongolia)**
- *Prionessus lucifer*, *Prionessus sp.*, *Sinopia sp.*, *Eurymylus laticeps*, *Eomylus zhigdenensis*, *Oxyena sp.*, *Archaeolambda planicanina*, *Coryphodont tsaganensis*, *Prodinoceras martyr*, *Gashatostylops macrodon*, *Pseudictops lophiodon*, *Dissacus indigens*, *Pachyaena nemegetica*, *Palaeostylops iturus*, *Khychina elongata*

**GS (Member I of Gashato Fm., Ulun Nur Basin, Mongolia)**

### Bumabanian Land Mammal Age

**LC-U (Upper part of Lingcha Fm., Hengyang Basin, Hunan)**

**BB (Bumban Mem. of Naran Bulak Fm., Nemegt Basin, Mongolia)**
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Hsu, Vindeff, Ge, Tong Ming, Baksi, Ajoy K., Fan, Li Min, and Liu, Jan, 1990, Late Cretaceous magnetostatigraphy from a red basin in central China and a preliminary radiometric date for the K-N (Cretaceous Normal) superchron: American Geophysical Union 1990 fall meeting, Abstracts, v. 71, p. 1298.


