

and a slightly concave base.

*Hipparion (Proboscidipparion) pater*: this three-toed horse lacks a preorbital fossa. The nasal notch is rounded, with a bottom above the middle of M2. The cheek teeth become narrow from P2 to M3 gradually, and have long and biforked plications. The protocone is small and narrowly rounded, with a flat lingual margin, and is smallest on P2 and longest on M3. The hypocone is short, the hypoconal groove is distinct, and the hypoconal constriction is weak. On an upper jaw, each hypocone is strongly constricted forming an oval shape, with a very deep hypoconal groove and constriction (Fig. 4f). This configuration is also seen on a specimen from Yushe (Qiu et al., 1987, fig. 13). On the premolars, the parastyle is wide, with two edges and a central groove, while on the molars, the parastyle is narrow with no central groove. The metastyle becomes wide only on the premolars. The labial walls of the paracone and metacone are concave, with right-angled anterior and posterior corners. The antero-exterior horn of the postfossette is longer than the postero-exterior horn of the prefossette, even on the molars. The paraconid of p2 is linguallly expanded and divided from the protoconid by marked lingual and labial constrictions; the metaconid is small and rounded, and the metastylid is large; the lingual valley is narrowly U-shaped; the labial wall of the hypoconid is flat, and the lingual wall has some plications; the entoconid is large and podiform; the postflexid is long and curved; the labial valley is deep and penetrates into the isthmus; and the pli caballinid is fine. The metastylid on p3 and p4 has some plications on its posterior wall, and its lingual end is at the same level with the metaconid; the lingual wall of the protoconid is roundly curved, developing anterior and posterior angles; the metaconid is narrowly rounded, with a wide and short neck; the metastylid is small and rounded, with a narrow and long neck; the lingual valley is narrowly U-shaped; the lingual wall of the hypoconid is wrinkled, while the labial wall is straight; the pli caballinid is narrow and long, and is located near the bottom of the labial valley; the labial valley is shallow, not penetrating into the isthmus; the entoconid is large and coracoid on p3, while it is small and podiform on p4. The double-knots on m1 and m2 are larger than those on p3 and p4, the pli caballinid is weaker, the labial valley is deep and penetrates into the isthmus, and the entoconid is small, rounded or roundly rectangular (Fig. 4h).

*Hipparion hippiodus* is a medium-sized three-toed horse, with a length of 129 mm for its lower tooth row. On the lower cheek teeth, the labial wall is convex, lacking a protostylid; the labial valley is deep, penetrating into the isthmus; and the double-knots are rounded. The paraconid and protoconid of p2 are linguallly divided; the metaconid has a coracoid anterior end; the metastylid has a short and

narrow neck, and is more linguallly shifted than the metaconid; the entoconid is coracoid; and the postflexid is long and curved. On p2 and p3, the anterior angle of the proflexid is distinct, but the posterior angle is weak; the metaconid has a long neck, and the metastylid has a narrow neck; and the pli caballinid is well-developed. On p3 and p4, the double-knots are relatively large and long, and are more linguallly prominent than is the entoconid, but are weaker than those of the Qingyang specimens (Qiu et al., 1987, fig. 52); the lingual valley is widely and deeply V-shaped; the pro- and post-flexids are narrow and long; the protoconid and hypoconid are relatively wide, closing to the width of the double-knots; the entoconid is large and nearly square. On m1 and m2, the double-knots are small and the pli caballinid is absent. The lingual wall of the protoconid of m1 is strongly concave, and the entoconid and hypoconulid are narrow and long, with a constricted base.

*Hipparion platyodus*: on the upper cheek teeth of this three-toed horse, the protocone is large and narrow, with a convex lingual wall and sharp anterior and posterior ends; the plications are medially-developed; the labial and lingual walls of the paracone and metacone are flat; the parastyle is wide, with a marked posterior edge; the mesostyle is narrow, with a higher anterior wall than the posterior wall; the hypoconal groove is deep and sharp, and lacks a hypoconal constriction; and the pli caballine is small and frequently biforked. The anterostyle of P2 is wide and short, with a rounded end; the protocone is roundly rectangular, with a flat lingual margin; the parastyle is wide, and the mesostyle is centrally-grooved. P3 and P4 are very similar to each other: the parastyle is moderately wide, is slightly wider than the high and narrow mesostyle, and the protocone is large and rounded. M1–2 have some differences from P3–4: the lingual and labial walls of the para- and meta-cones are convex, the protocone is flatter and longer, and the parastyle is narrower than the mesostyle. The parastyle of M3 is weak, and the protocone is flat and long, and is semicircular in shape (Fig. 4g).

*Hipparion licenti*: the skull of this three-toed horse has a deep preorbital fossa that is strongly retracted so that its position is high and backward, and is located above the front of the orbit; its posterior border is located slightly anterior to the anterior rim of the orbit and posterior to the level of M3, and its lower border is at the same level with the upper rim of the orbit. A vertical ridge divides the preorbital fossa into two parts: the posterior part has a clear boundary, with no trace of the fossa foramen, but the anterior part has no clear boundary so that the maxillary bone forms a depression in this position. The orbit is slightly longer than high. The lacrymal notch is obvious, but does not form a foramen.

*Shansirhinus ringstroemi*: the skull of this acerathere rhino from Duikang has well-developed flanged parietal crests that are slowly posteriorly convergent, and their posterior parts are divergent toward the lateral ends of the occipital crest, connecting its lateral margins. The parietal crests are nearly parallel to each other on the parietal area, with a minimal width of 52.8 mm between them. The mandibular symphysis has a moderate width, with a deeply concave labial surface and a shallowly concave lingual surface. The i2 are small tusks, even smaller than the i2 of the female *Chilotherium*, with a distance of 91.5 mm between them. The wearing facet of i2 is located on the postero-labial side, and the medial flanges turn upward. The nasals are long, with rough tips and a shallow and wide sagittal groove. The zygomatic arches are wide. The braincase is narrow with steep outer walls. On the upper premolars, the bridge is well-developed, the crista and crochet are slender, forming a medifossette, the parastyle is protruding, the paracone rib is absent, the connection between the protoloph and ectoloph is narrow, the protocone is strongly constricted, and the antecrochet is robust.

*Hesperotherium* sp.: the juvenile skull and mandible of this chalicothere from Duikang have DP2-4, dp2-4 and erupting M1. The nasals are wide at the back and contact with the lacrymals. The mandibular horizontal rami are shallow, and the posterior boundary of the symphysis is located before dp2. All teeth are brachyodont. DP1 and dp1 are absent. DP2 is triangular. DP3 and DP4 are quadrate. The protoconule and protoloph are developed on the upper milk-teeth. The lower milk-teeth consist of double "V". The labial cingula of the all cheek teeth are well-developed.

*Ancylotherium* sp.: the skull of this chalicothere from Duikang belongs to a juvenile individual with a cranial length of over 450 mm (Fig. 4e). The nasals are narrow, with a well-developed sagittal groove and vertical lateral surfaces. The central part of the frontal area is convex, and the maxillary face is long and flat. The preorbital fossa is rectangular and very shallow, and is located above DP4. The facial region of the lacrymal bone is approximately triangular and shallowly concave. The lower rim of the orbit is flat and the upper rim is curved. The postorbital process of the frontal bone is prominent and sharp at its tip. The supraorbital foramen is large and round. The temporal fossa is long and the zygomatic arch is thick. The occipital surface is triangular in shape, with a high central ridge. The postglenoid process is transversely flat and triangular in shape. The tympanic bulla is longitudinally extended, and is located at the interior side of the postglenoid process. The temporal condyle is flat and wide, and the pterygoid process is thin and high. The cheek teeth are high-crowned, with strong cingula. DP1 is absent. P2 is triangular in

shape, with a convex labial wall; the ectoloph is narrow, and the protoloph is slender and posteriorly oblique; the anterior cingulum becomes a broad platform; and the protocone is expanded. DP3 is nearly square, with a continuous lingual cingulum and a rounded protocone. DP4 is rectangular in shape, with a strongly wavy labial wall; the mesostyle is strongly prominent and forms a plate, but is reduced toward the root; the parastyle is markedly prominent; the para- and meta-cones do not exceed the midline; the protocone is expanded and rounded, and the hypocone is small; the protoloph is nearly transverse, and the metaloph is slightly posteriorly oblique; the crochet is slender and the cingula are well-developed. M1 is rectangular, with a marked W-shaped ectoloph; the para- and meso-styles are prominent and form plates; the para- and meta-cones exceed the midline; the protocone is a large cone, and the hypocone is weak; the protoloph and metaloph are nearly parallel to each other and are slightly posteriorly oblique; the crochet is marked; the labial cingulum is weak, but the lingual cingulum is high and thick and extends to the labial half of the anterior and posterior sides of the tooth.

*Palaeotragus microdon* is a medium-sized giraffid, represented by a skull and a maxillary from Duikang. The maxillary face is short and the orbit is vertically-positioned and oval in shape. Horns are located above the orbit, and are slender and straight, sharpening upward. The basal parts of the horns have grooves, becoming smooth in an upward direction. The lateral surfaces of the nasals are slightly convex. The upper cheek teeth are square in outline, with well-developed parastyles and mesostyles. The exterior ridge of the paracone has a marked and rounded edge, and that of the metacone is centrally-grooved. The anterior tips of the protocone and metaconule are not curved. The lingual crescent lophs are simple and lack an entostyle and lingual cingulum. The p4 has a rounded medial vertical edge, and anterior and posterior folds.

*Cervavitus novorossiae*: the antler of this deer has marked grooves and ridges on its surface. The main beam and brow tine are slightly curved. The burr is notably bulged, consisting of a series of tuberculiform nodules of different sizes. The brow tine is highly positioned above the burr, with a distance of 126 mm between them. The connection between the main beam and brow tine is weakly palmate. The brow tine has a length of 130 mm and is at a 50° angle to the main beam. The base of the main beam is oval in cross-section with a short diameter of 25 mm.

*Sinotragus* sp.: the skull of this bovid from Duikang has an angle of over 60° between facial and cranial axes. The frontal area is centrally flat and laterally curved, and lacks a supraorbital foramen. The cranial region is short and wide, with a slightly convex roof. The lacrymal fossa is large and

deep, and extends to the infraorbital foramen that is located 2.5 cm above P3. The facial region of the lacrymal bone is nearly equal to that of the zygomatic bone. The orbital rims are moderately prominent and the dentition is located in front of the orbit. The occipital surface is broad, with a distinct central crest. In ventral view, the occipital base is short and quadrangular, the sagittal groove is deep, and both of the anterior and posterior basal tuberosities are transversely prominent. The horn cores are located above the posterior region of the orbit, are moderately long, posteriorly oblique, and strongly inferiorly curved; the cross section of the base is approximately triangular, rapidly becoming superiorly narrow; the rotation is clear, about 90° in a clockwise direction (right horn); the bases of the horn cores are very close to each other, and the lower two-thirds are nearly parallel to each other on their medial sides, while the upper thirds are distinctly divergent; the lateral surface is very rough, with marked grooves on the antero-lateral side, among which a deep groove extends from the horn base to the tip; the medial surface is very flat, with many fine grooves that extend upward; the anterior edge begins sharpening from 9 cm above the horn base; the posterior edge is rounded. The cheek teeth are wide and low-crowned. The premolars are long. P3 is longer than P2, and P4 is very short, with a well-developed parastyle. The molars have well-developed parastyles, weak ribs, and frequent enamel islands between the anterior and posterior lobes.

*Gazella blacki* is a large-size gazelle with high-crowned teeth. The horn corns are robust and curved, and the horn bases are close to each other and moderately divergent and rapidly sharpened from base to tip. On the horn surface, ridges are clear, and grooves are deep and dense. The outline of the horn core base is oval in shape, with a width of 24 mm, and the longitudinal axis is slightly longer than the transverse axis. The p4 has a high metaconid, connecting the expansion of the paraconid, and both are parallel to each other, forming a U-shape. The crown height index of m1 (length/height × 100) is 109.

Several proboscideans of the Gaozhuang Fauna, such as *Mammot borsoni*, *Anancus sinensis*, and *Sinomastodon intermedius*, which lived in warm and humid conditions, have not been found in the Duikang locality or the Shilidun Fauna. Micromammals of the Shilidun Fauna have not been systematically collected and only skulls of porcupines and lagomorphs have been found until now. Two giraffids, *Palaeotragus microdon* and *Samotherium* sp., as well as chalicotheres, were found from Duikang. Chalicotheres have not been found in the Gaozhuang Fauna. All of these herbivores are typical browsers. The components of the Shilidun Fauna indicate that the environment of the Linxia Basin was a subarid steppe during the Early Pliocene.

## 5 Mio-Pliocene Boundary at the Duikang Section

Li et al. (1984) correlated the Jinglean Age, which was considered to belong to the Early Pliocene, to the Ruscinian Age of the European land mammal ages, corresponding to MN 14–15. Its mammalian localities or assemblages include Hefeng in Jingle, Shanxi, Zone II in Yushe, Shanxi, and Leijiahe in Lingtai, Gansu. The Gaozhuang Age was created by Qiu et al. (1987), but was later replaced by the Yushean Age (Qiu and Qiu, 1990). They suggested that the Early Pliocene part of the Yushean Age was represented by the Gaozhuang Fauna, corresponding to the European Ruscinian Age, and its contemporaneous mammals included the Harr Obo Fauna in Huade, Inner Mongolia, which was correlated to the fossil assemblage of the basal part of the Gaozhuang Formation, and the Bilike Fauna in Huade, which was correlated to the late Gaozhuang Fauna. Tong et al. (1995) reconfirmed the correlation of the Yushean Age to the European Ruscinian and early Villanyian ages, representing the whole Pliocene.

In 1999, the Second All-China Stratigraphic Commission (ACSC) formally proposed to establish the chronostratigraphic units of the Chinese Pliocene, the Gaozhuangian and Mazegouan stages, in which the time spans correspond to the Gaozhuangian and Mazegouan ages of the Chinese land mammal ages (ACSC, 2001). Since then, the Gaozhuangian Age (Stage) has been reintroduced. At the same time, the Mazegouan Age (Stage) was newly nominated. Deng (2006) correlated the Gaozhuangian and Mazegouan ages to the Ruscinian and early Villanyian ages, respectively.

According to the definition proposed by ACSC (2001), the Chinese terrestrial Gaozhuangian Stage of the Lower Pliocene should be correlated to the marine Zanclean Stage of the International Stratigraphical Chart, and the Gaozhuangian Age should be correlated to the Ruscinian Age of the European land mammal ages. The lower boundary of the Zanclean is situated at the upper part of Chron C3r, and is 96 ka earlier than the Thvera normal subchron (C3n.4n), with an astronomical age of 5.332 Ma in the orbitally-calibrated time scale. Its calcareous nannofossils (coccoliths) are close to the disappearance of *Triquetrorhabdulus rugosus* (base of CN10b) and the first occurrence of *Ceratolithus acutus*. GSSP of the Zanclean Stage is located in the Eraclea Minoa section on the southern coast of Sicily, Italy, at the base of the Trubi Formation (base of the carbonate bed marking the small-scale stratigraphic cycle (1), ratified by IUGS in 2000 (Van Couvering et al., 2000). The lower boundary of the Ruscinian is also at the upper part of Chron C3r, with an age of 5.3 Ma (Steininger et al., 1996). As a result, the



lower boundary of the Gaozhuangian Stage is identical with those of the Zanclean and Ruscinian, and is located at the upper part of Chron C3r, with an age of 5.3 Ma (Deng, 2006).

According to the chronostratigraphical subdivision of the Chinese Neogene (Deng, 2002, 2006), the Duikang section includes the Miocene/Pliocene boundary, i.e., the lower boundary of the Gaozhuangian Stage. The first occurrence of *Hipparion (Proboscidipparion) pater* (0.8 m above the lower boundary of the Hewangjia Formation) is a biostratigraphical marker, below which it belongs to the Late Miocene Baodean Stage, and above which it belongs to the Early Pliocene Gaozhuangian Stage.

Among the first appeared large mammals at Duikang, *Hipparion pater* is smaller in size than *H. sinense* of the Early Pleistocene. The nasals of the former are less reduced than those of the latter, the tooth crowns are lower, the plications of the fossettes are fewer, the para- and meso-styles are narrower, and the lateral walls of the lower premolars are more convex. Besides the Duikang material, *H. pater* was also found at Gaozhuang in Yushe, Shanxi, Loc. 5 in the northern region of Baode, Shanxi, and Youhe in Weinan, Shaanxi (Qiu et al., 1987). *Chasmaporthetes* first appeared during the middle Late Miocene in Europe, but appeared in Asia from the Pliocene. Besides the distribution at Duikang and Shilidun in Guanghe, Gansu, *Chasmaporthetes kani* was found at the Pliocene localities of Gaozhuang and Catacombs in Odessa, Ukraine (Qiu et al., 2004a).

Among the last appeared taxa, *Alilepus annectens* first appeared at Ertemte in Huade, Inner Mongolia, and continued into Gaozhuang in Yushe, Shanxi, and Harr Obo in Huade, Inner Mongolia (Storch, 1987; Qiu, 1987; Flynn et al., 1997). *Hipparion platyodus* appeared from the Late Miocene Baodean Age, and was distributed in Wuxiang, Shanxi, and Wudu, Gansu. *H. platyodus* is very common from the Mahui Formation to the Gaozhuang Formation in the Yushe Basin, and it may be the ancestor type of *H. houfenense* (Qiu et al., 1987).

The above-mentioned comparisons seem to show that the age of the Duikang mammals or Shilidun Fauna is slightly earlier than that of the Gaozhuang Fauna. The markers of the lower boundary of the Pliocene or Gaozhuangian Stage in the Duikang section are relatively rich. However, it is very difficult to determine the first or last appearance of a species independently. Coexistence of first and last appeared species is a good method to resolve this issue (Deng et al., 2007). Among the above-mentioned fossils, either of the first appeared species *Hipparion pater* and *Chasmaporthetes kani* combines with either of the last appeared species *Alilepus annectens* and *Hipparion platyodus*, providing an important reference to judge the

lower boundary of the Pliocene or Gaozhuangian Stage.

## 6 Magnetostratigraphy

Li et al. (1995) and Fang et al. (1997, 2003) provided paleomagnetic dates for the Linxia sequence, including the Maogou, Wangjiashan, and Dongshanding sections. Samples were taken at 0.5–1.0 or 2.0 m stratigraphic intervals, along 1 m deep trenches through the entire length of the sections. Exceptions were made for the conglomerates, where sampling intervals depended on the availability of finer-grained lenses. These sections include paleomagnetic measurements of the Liushu and Hewangjia formations.

Paleomagnetic results for the Maogou and Wangjiashan sections show that the Hewangjia Formation records four normal and three reversed magnetozones (Fang et al., 2003, fig.3). From bottom to top, the long first normal zone, which extends into the Liushu Formation, was correlated to C3An, and the long first reversed zone to C3r. The short second and third normal zones, and the long fourth normal zone, which extends into the Jishi Formation, were correlated to C3n.4n, C3n.1n, and C2An.3n, respectively. As a result, the upper part of C3r as marks of the lower boundary of the Gaozhuangian Stage, and a precise position dated 0.1 Ma earlier than C3n.4n is situated within the basal red clays of the Hewangjia Formation, with an age of 5.3 Ma. According to the paleomagnetic measurements, the Early Pliocene Shilidun Fauna, which includes the fossils from Duikang, is within C3n.4n, with an age of 5.0 Ma, corresponding to MN 14 of Europe.

## 7 Stable Isotopes

According to the age data, the lower boundary of the Gaozhuangian Stage should be well correlated to the global expansion of C<sub>4</sub> plants, which have been shown in Siwaliks, North America, and East Africa as well as Yushe, Shanxi and central Inner Mongolia in China (Hou et al., 2006; Zhang et al., 2009). On the other hand, the carbon isotopic record from analyses of fossil tooth enamel and soils from the Linxia Basin indicates that the  $\delta^{13}\text{C}$  values of tooth enamel prior to the Pleistocene display a narrow range of variation from  $-8.4\text{‰}$  to  $-12.4\text{‰}$ , with a mean  $\delta^{13}\text{C}$  value of  $-10.0\text{‰}$  (Wang and Deng, 2005). These  $\delta^{13}\text{C}$  values indicate that these various herbivores were feeding predominantly on C<sub>3</sub> plants during the late Paleogene and Neogene. The pure or nearly pure C<sub>3</sub> diet of various herbivores suggests that the ecosystems in the Linxia Basin consisted primarily of C<sub>3</sub> plants prior to  $\sim 2\text{--}3$  Ma. The  $\delta^{13}\text{C}$  values of herbivore tooth enamel from the Linxia Basin for this time interval correspond to a dietary intake of  $-22.4\text{‰}$

to  $-26.4\text{‰}$ , with a mean value of  $-24.0\text{‰}$ , which falls well within the  $\delta^{13}\text{C}$  range of modern  $\text{C}_3$  plants. The enriched  $\delta^{13}\text{C}$  values for herbivores' diets in the Linxia Basin (based on the analysis of fossil enamel) relative to the mean  $\delta^{13}\text{C}$  value for  $\text{C}_3$  plants suggest that water-stressed conditions are not a recent phenomenon in the area and probably have existed in the Linxia Basin since the Late Oligocene. The carbon isotope data from the Linxia Basin do not show a positive  $\delta^{13}\text{C}$  shift in the Late Miocene or Early Pliocene. The mean enamel  $\delta^{13}\text{C}$  value prior to 7 Ma is  $-9.9\text{‰}$  and is indistinguishable from the mean  $\delta^{13}\text{C}$  of  $-10\text{‰}$  for the period of 7.0 to 2.5 Ma.

The  $\delta^{18}\text{O}$  of tooth enamel is related to the  $\delta^{18}\text{O}$  of local meteoric water, which provides drinking water for most animals and water for plants that are consumed by herbivores. Because the  $\delta^{18}\text{O}$  of meteoric water is controlled by climatic conditions, a shift in  $\delta^{18}\text{O}$  of tooth enamel of the same species indicates a change in some aspects of regional climate. The large range of  $\delta^{18}\text{O}$  values within the horse and rhino families at a given time interval may reflect differences in the drinking and dietary behaviors of different species and seasonal variability of  $\delta^{18}\text{O}$  of local rainfall. Near the Miocene/Pliocene boundary of the Linxia Basin, the  $\delta^{18}\text{O}$  of tooth enamel from horses shifted significantly to more negative values after  $\sim 6$  Ma. This negative oxygen isotopic shift indicates changes in climate towards cooler temperatures and/or less arid conditions. Similarly, there is a significant  $\delta^{18}\text{O}$  shift towards higher values after  $\sim 7$ , which indicates a shift to warmer and/or drier conditions. The enamel  $\delta^{18}\text{O}$  values from rhinos of the Linxia Basin also show parallel shifts where there is data coverage. Most notably, the positive  $\delta^{18}\text{O}$  shift after  $\sim 7$  Ma, which is also seen in deer and bovid of the Linxia Basin, is comparable in timing and direction to the  $\delta^{18}\text{O}$  shift observed in paleosol carbonates and fossil enamel in Pakistan and Nepal (Quade et al., 1989; 1992; 1995), indicating a change in climatic conditions on both sides of the plateau at about the same time in the Late Miocene. The tooth-enamel  $\delta^{18}\text{O}$  data from the Linxia Basin show a general shift to more negative values from about  $\sim 6$  to  $\sim 2.5$  Ma, indicating a shift to cooler temperatures. This is in broad agreement with the marine  $\delta^{18}\text{O}$  and Mg/Ca records (Lear et al., 2000; Zachos et al., 2001).

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