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Cave deposits from Luotuo Hill, Northeast China: A geochronologically calibrated mammalian biostratigraphic standard for the Quaternary of Eastern Asia

Over the past decade, much welcome progress has been made concerning research on the Quaternary biostratigraphy and geochronology of East Asia. On behalf of our colleagues, we express sincere gratitude to the journal *Quaternary International*, for having played a pivotal role in these developments by providing an essential platform to disseminate new evidence and new perspectives, through the publication of two thematic special issues (Jin et al., 2014a; Wang et al., 2017a) aside from numerous independent papers. The two aforementioned special issues focused on the most diverse and fascinating Pleistocene fossil faunas containing, of all the intriguing ancient species, *Gigantopithecus* and hominins, discovered from the Quaternary cave sites in the Guangxi Zhuang Autonomous Region of southernmost China, especially from Chongzuo Municipality in the Zuojiang River area. There have been at least 6 new *Gigantopithecus* layers and several important hominin sites with associated diverse faunas dated from the Early to Late Pleistocene from the Chongzuo area, including the Baikong fauna (~2.2 Ma BP), Yanliang fauna (~2.0 Ma BP), Juyuan fauna (~1.8 Ma BP), Sanhe fauna (1.2–1.6 Ma BP), Queque fauna (~1.0 Ma BP), Hejiang fauna (400–320 ka) and Zhiren fauna (116–106 ka); all these faunas are respectively eponymous of the karst cave sites in Guangxi from which they were discovered (Jin et al., 2014b; Sun et al., 2014; Zhang et al., 2014, 2016; Cai et al., 2017; Wang et al., 2017b).

Compared to these great advancements on the Quaternary biostratigraphy and geochronology in southern China, briefly aforementioned, it is also inspiring that rich fossiliferous deposits dated to the late Cenozoic have been recently discovered from Jinyuan Cave at Luotuo Hill, an extremely large-sized cave site situated within in the Dalian Puwan Economic Zone of Dalian Municipality, Liaoning Province in northeast China (Jin et al., 2021).

The Jinyuan Cave site at Luotuo Hill, initially discovered in 2013, is enormous in size with a sedimentary thickness of over 40 m. Systematic excavations at Jinyuan Cave conducted by the Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences (IVPP, CAS) during the past few years have yielded abundant, diverse and well-preserved vertebrate fossils from multiple fossiliferous layers. Based on faunal analysis conducted by Jin et al. (2021), the fossil assemblages from Jinyuan Cave have been divided into four successive faunas that span the Late Cenozoic (ca. 3.60–0.35 Ma): the Wanghai fauna from upper faunal unit (Middle Pleistocene, 0.78–0.35 Ma), the Jinyuan upper/lower fauna from middle-lower faunal unit (Early Pleistocene, 2.60–0.78 Ma) and the Luotuoshan fauna of the bottommost faunal unit (Late Pliocene, 3.60–2.60 Ma). Accordingly, the mammalian faunal evolution of Jinyuan Cave has also been divided into four temporal stages from the Late Pliocene to the Middle Pleistocene (Jin et al., 2021). The paleoecology of the Jinyuan Cave fossil assemblage has been reconstructed to focus on three signature taxa (*Paracamelus gigas*, *Proboscidipparion sinense* and *Equus*) of Jinyuan lower fauna (~1.8 Ma BP) (Fig. 1).

The diverse fossil assemblages from Jinyuan Cave provide an outstanding opportunity to conduct multidisciplinary studies combining traditional paleontology, paleoanthropology, geochronology, and paleoenvironmental sciences. The present special issue reports on the progress of the Luotuo Hill research program and on investigations in other areas of China, even northeastern Asia (e.g., Heilongjiang, Zhoukoudian, Guangxi, Guizhou, and the Russian Far East) that have important contributions to offer. A total of 12 papers are presented, with 8 of them focused on new findings from Jinyuan Cave of Luotuo Hill.

The multidisciplinary nature of the research is reflected in the different aspects of the featured contributions within this special issue: community-level faunal analysis, systematic paleontology and paleoanthropology, geochronology, and paleoenvironmental reconstructions using data derived from stable isotopes, palynology, and geochemical analyses of the deposits.

The first two papers in this issue lay the groundwork for the geochronology and paleoenvironment of the Jinyuan Cave. The chronological sequence of Quaternary terrestrial mammalian faunas has long been acknowledged as an indisputable scientific fact that provides critical information about the evolutionary history of mammals, regional biostratigraphy and paleoenvironmental changes. Ge et al. (2021, this volume) reports on a thick and nearly-continuous cave sedimentary sequence from the Jinyuan Cave, Luotuo Hill containing four mammalian faunas ranging from the Late Pliocene to the late Middle Pleistocene. The detailed paleomagnetic measurements and U-series determinations date the upper and middle-lower units of the Jinyuan Cave sedimentary sequence from ~2.2 Ma to ~0.35 Ma. Our results suggest that the development and infilling of the Jinyuan Cave deposits were closely associated with the tectonic evolution of the Bohai Basin, including the subsidence of that basin and uplift of surrounding mountains, such as Luotuo Hill. Taken together with large mammalian faunas from both south and north China. Ge et al. (2021, this volume) suggest that these mammalian faunas were slightly reduced in diversity during the Middle Pleistocene Transition period (MPT; 1.2–0.5 Ma) than in the earlier and later Pleistocene, indicating dramatic climatic and environmental variation during the MPT in northern China may have reduced taxonomic abundance and diversity of those mammalian assemblages. The markedly warmer and more humid interglacial climates that followed in monsoonal East Asia provided an ecological niche for the evolution and migration of these mammalian faunas, and resulted in

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an increase in abundance and diversity of mammals in East Asia.

Shen et al. (2021, this volume) conducts a palynological study of a long section (~2.2–0.35 Ma) of sediments in the Jinyuan Cave to identify the history of vegetational succession in the area and undertake paleoclimatic reconstruction. The pollen evidence from the Jinyuan Cave suggests that the climate during the Early and Middle Pleistocene was featured by a trend of cooling and drying, with obvious fluctuations. Temperate broad-leaved forest occurred from ca. 2.2 to 1.87 Ma, indicating a relatively warm and humid climate. There was a marked cold and dry period from 1.87 to 1.82 Ma, and the vegetation changed to coniferous and broadleaved mixed forest, which developed from 1.82 to 1.76 Ma. Forest-steppic habitats dominated the whole MPT period, and the climate became colder in the later stage. The period from 0.59 to 0.35 Ma witnessed the expansion of steppe, implying a colder and more arid climate. The combination of vegetation types with faunal communities shows that the warmer and more humid climate in the early stage of the Early Pleistocene corresponds well to the presence of a variety of relatively thermophilic species. During the MPT, the dominance of forest steppe probably prompted the flourishing of grassland-adapted animals. In the Middle Pleistocene, the steppe vegetation expanded further, coinciding with the appearance of typical animals adapted to arid grassland. The strong correspondence between vegetational and faunal suggests that the vegetational shifts may have played an important role in forcing the adaptive change of the fauna.

The next set of contributions focuses on the new paleontological discoveries from Jinyuan Cave's various faunal units.

Horse evolution during the Plio–Pleistocene has been considered of great importance in the study of biostratigraphic correlation, biogeographic dispersion and adaptation on a nearly global scale. Sun et al. (2021a, this volume) describes the *Hipparion* specimens including maxillary, mandible and cheek teeth of *H.* (*Proboscidipparion*) *pater*, *H.* (*Pr.*) *sinense* and *H.* (*Plesiohipparion*) *shanxiense* from the middle-lower and bottom faunal units of Jinyuan Cave (Late Pliocene and Early Pleistocene), representing the easternmost records of *Hipparion* (sensu lato) in China. Importantly, the *H.* (*Pr.*) *sinense* and *H.* (*Pl.*) *shanxiense* found from different faunal units in Jinyuan Cave correlate biochronologically to other important hipparionine-bearing localities in China, from early to late stages of Early Pleistocene. The two species of *Hipparion* exhibit significance on biostratigraphy and could be regarded as a mark for the beginning of Quaternary in Northern Eurasia, like *Equus* (sensu lato).

Another important contribution by Sun et al. (2021b, this volume) conducts study on a well-preserved cranial remain of *Equus qingyangensis* from the Jinyuan upper fauna (1.6–1.2 Ma) of Jinyuan Cave, the youngest known occurrence of this species. Based on the morphological comparison among specimens from Jinyuan Cave, Nihewan and Bajiazui (Qingyang, Gansu), the first and last occurrences of *E. qingyangensis* provide a different argument from previous recognition of this species as one of the earliest species of *Equus* (sensu lato) in Eurasia. In addition, a second immigration event of *Equus* from North America to northern China across the Bering Land Bridge, influenced by significant environment changes, is also hypothesized based on the study of Sun et al. (2021b, this volume).

The giant short-faced hyena, *Pachycrocuta brevirostris*, was the largest and most spectacular bone-cracking hyena that ever existed. This prodigious carnivore, extensively distributed across Eurasia during the Early and Middle Pleistocene, is an important fossil species for understanding the biochronological and paleoecological context of habitats that early humans in Eurasia inhabited. It is thus timely that Liu et al. (2021) thoroughly described a well-preserved cranium of the giant short-faced hyena (IVPP V26310) from the lower faunal unit of Jinyuan Cave (the Jinyuan lower fauna; Jin et al., 2021) belonging to the early Early Pleistocene (1.77–1.86 Maet al., 2021, this volume), and meticulously compared the new specimen with relevant materials from both Europe and Asia. 1) V26310, with the estimated basicranial length of around 332 mm, probably represents the largest *Pachycrocuta brevirostris* known to date; 2) V26310 is almost identical to the holotype from Sainzelles (France) in both morphological and morphometric aspects, and thus referable to the nominotypical form *P. b. brevirostris*, previously only widely recognized in the European record; 3) these giant hyenas, distributed throughout Eurasia could be further classified into different populations or subspecies, nevertheless, those subspecies are reinterpreted as the chronological rather than the geographic ones, i.e., they practically constitute an ancestor-descendant sequence or clade; 4) the nominate subspecies *P. b. brevirostris* probably first originated Northeast Asia, and then dispersed into Europe as open steppic habitats further expanded. A hypothesis of "out of Northeast Asia" is proposed for *P. b. brevirostris* by Liu et al. (2021).

Among the living members of the Order Carnivora, the marten *Martes* is one of the most widespread genera and probably has the longest evolutionary history, and yet its fossil record is only scantily known, especially with respect to crown-group species of martens. The paper by Jiangzuo et al. (2021, this volume) describes a new fossil species, *Martes crassidens* sp. nov. from the Jinyuan lower faunal unit belonging to the early Early Pleistocene (~1.8 Maet al., 2021, this volume). By extensive comparisons of living and Plio-Pleistocene species of *Martes*, the new species is identified as the earliest member of the Holarctic marten group, providing important chronological baseline for the

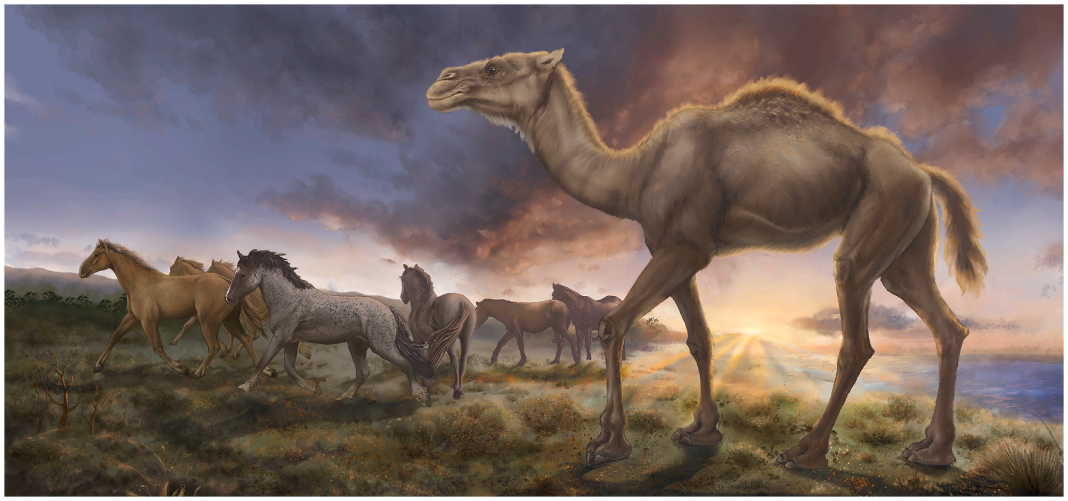

Fig. 1. The paleoecological reconstruction of Jinyuan Cave at Luotuo Hill, Northeast China, focusing on the three signature ungulate taxa (*Paracamelus gigas*, *Proboscidipparion sinense* and *Equus*) of Jinyuan lower fauna (~1.8 Ma BP). This painting was drawn by Miss Xiao-cong Guo (IVPP, CAS).

diversification of crown-group martens.

As established environmental indicator taxa, the fossil record of zokors (Myospalacinae, Rodentia) is characterized by rapid evolutionary rates, quantifiable evolutionary trends, and sensitivity to environmental changes, and hence particularly helpful in Late Cenozoic biostratigraphic correlations of Northeast Asia. Qin et al. (2021, this volume) describes a new fossil species, *Episipheneus dalianensis* sp. nov. based on the cranium and mandible materials from the lowermost fossiliferous deposits (Luotuoshan fauna of the Late Pliocene, 3.6–2.6 Ma) of the Jinyuan Cave. As the first discovery of fossil Myospalacini from Northeast China, *E. dalianensis* sp. nov. is the earliest and most primitive species of the genus, indicative of a Northeast Chinese origin for this lineage.

The contribution by Y.H.S. Yang et al. (2021, this volume) describes and analyze a collection of new specimens referred to the Eurasian giant beaver (*Trogontherium cuvieri*), which were collected from five different layers of the Lower to Middle Pleistocene of the Jinyuan Cave of Luotuo Hill. *T. cuvieri* shows remarkable resilience, with records spanning most of the Early and Middle Pleistocene, through numerous dramatic climatic oscillations. However, the macro-morphological characteristics of *T. cuvieri* through time lack salient signals of a trend in adaptive modification, and instead suggest a remarkable case of stasis. What is the secret behind *T. cuvieri*'s success? Y.H.S. Yang et al. (2021, this volume) performed a statistical analysis of dental stereomicrowear from these giant beaver remains. The result shows that *T. cuvieri* populations from different chronofaunas had significantly different foraging ecologies, suggesting that plasticity in feeding ecology to be an important mechanism for the evolutionary adaption of the giant beaver through time.

The following paper by Stidham et al. (2021, this volume) deals with a complete bird skull unearthed from the upper faunal unit at Jinyuan Cave, the Middle Pleistocene Wanghai fauna (Jin et al., 2021; Ge et al., 2021, this volume). The fossil skull attributable to the common raven (*Corvus corax*) is the oldest and possibly largest known raven skull, and it preserves features which suggest that it is more closely related to living ravens in Asia than to populations elsewhere. The raven likely served as a scavenger near the cave, and the fossil was found south of where the species occurs today in China, suggesting that the raven's geographic distribution changed as the result of climatic shifts in the Pleistocene.

The final paper from this issue which concerns traditional descriptive paleontology is contributed by Lu et al. (2021, this volume), reporting the first discovery of a fossil wolf from Eurasia that is assigned to the dire wolf (*Canis dirus*), a signature species from the mammal faunas of Late Pleistocene North America, but a lineage never hitherto known from the Old World. The new specimen is a mandibular fragment, uncovered from the Late Pleistocene sediment of the Songhua River near Harbin in Heilongjiang Province, Northeast China. The co-occurring mammal fossils indicate that the dire wolf dispersed into Eurasia via the Bering Land Bridge and coexisted with the typical *Mammuthus-Coelodonta* Faunal Complex in Late Pleistocene. Lu et al. (2021, this volume) compared the niche distribution of medium and large-bodied carnivores from Asia and North America by using body mass as an indicator. The result suggests that there is a niche overlap between the Asian dire wolf and the now-extinct Chinese spotted hyena (*Crocuta crocuta ultima*). Therefore, Lu et al. (2021, this volume) propose that the interspecific competition may be the key ecological factor that the dire wolf thrives in North America but is rare in Eurasia.

Studies of stable isotopic signatures from mammalian fossils have long been used to inform on a region's paleoclimate and paleoecology. The contribution by Ma et al. (2021, this volume) presents the new results of stable isotope analyses on a set of mammalian remains from the Late Pleistocene*Mammuthus-Coelodonta* Faunal Complex in Northeast Asia, comparing samples from the Yanjiagang Paleolithic site in Heilongjiang Province, Northeast China, and those from Geographical Society Cave in the nearby Russian Far East, to reveal the foraging ecology of this iconic ancient fauna in Northeast Asia. Combing ZooMS and radiocarbon dating results, Ma et al. (2021, this volume) reveal an intriguing and unique scenario in Northeast China during Marine Isotope Stage (MIS) 3, where the comparably thermophilic *Bubalus* was a member of the *Mammuthus-Coelodonta* Faunal Complex.

The next paper is related to the progress in paleoanthropology. The Tianyuan Cave in Zhoukoudian is a famous hominin fossil-bearing site dated to 42–39 ka BP. Wei et al. (2021, this volume) report new discoveries of Tianyuan 1 individual, one of the earliest anatomically modern humans discovered in East Asia. The internal structural analysis of the Tianyuan 1 right and left humeri supports a hypothesis whereby the individual was right-handed. The regional cortical reinforcement in the right humerus of Tianyuan 1 individual may be related to the increased unilateral physical activity of the right arm. Unlike the lower humeral asymmetry of recent human agriculturalists, the relatively higher bilateral asymmetry, combined with the relatively larger femoral robusticity, indicate that Tianyuan 1 lived an activity lifestyle compared to the agriculturalists investigated in this study. The study by Wei et al. (2021, this volume) also indicates that the bilateral asymmetry of humeri may be more informative for discriminating between fossil and recent modern human samples than cortical thickness or rigidity values in only one side.

More and more modern human fossils have been recovered in the cave sediments in Southwest China during recent years. However, it is still a challenge for archaeologists and geologists to understand the environment of the ancient humans based on palynological evidence, due to the ambiguous significance of pollen records for paleo-vegetation in cave sediments. In the concluding paper from this issue, Q.J. Yang et al. (2021, this volume) present pollen data from surface samples collected from inside and outside several caves in southwestern China (Guangxi and Guizhou), with the aim of assessing the utility of fossil pollen spectra from cave sediments for vegetation reconstruction. The results indicate that pollen spectra from within the sack-shaped caves, and from the front and middle of a long, narrow caves can be reliably used for paleo-vegetation reconstruction. Wind is the major transport medium for the pollen entering caves and cave geometry is likely to be responsible for the observed spatial distribution of pollen concentrations in caves. The gradient in pollen concentration between the entrance and the rear is observed in long, narrow caves, but this pattern isn't found in sack-shaped cave.

The well-stratified fossiliferous deposits of the new discovered Jinyuan Cave site, bearing very little discontinuation in the sedimentation sequence from top to bottom, covers a scientifically significant faunal and sedimentary sequence stretching from the Late Pliocene to the Middle Pleistocene, with reliable geochronological data and detailed paleoenvironmental information. It marks the first discovery of 'Villafranchian' large mammalian faunas from Northeast China. The successive faunas from Jinyuan Cave at Luotuo Hill hold enormous potential as a Plio-Pleistocene mammalian biochronological standard for Northeastern China, even Eastern Asia, just like the Yushe and Nihewan Basins both also located in northern China. It is very much appreciated that *Quaternary International* continue to provide a strong platform for assembling, understanding, and exchanging important perspectives on Quaternary geochronology and biostratigraphy in Eastern Asia.

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