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Review Article

A review of the Cenozoic biostratigraphy, geochronology, and vertebrate paleontology of the Linxia Basin, China, and its implications for the tectonic and environmental evolution of the northeastern margin of the Tibetan Plateau

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ABSTRACT

Thick successions of middle and late Cenozoic sedimentary rocks occur in the Linxia Basin of China. These deposits comprise an archive recording spatiotemporal patterns of mountain uplift, erosion, basin deformation, and associated changes in the monsoon, as a result of the growth of the northeastern Tibetan Plateau. The Linxia Basin is also world famous for its abundant and diverse vertebrate fossils that shed light on Cenozoic terrestrial ecosystem evolution; however, previous studies of these important fossils have been beset by issues related to commercial excavation and associated difficulties in ascertaining provenance, with many specimens in private collections. Despite years of intensive studies by geologists from Lanzhou University and vertebrate paleontologists from the Institute of Vertebrate Paleontology and Paleoanthropology (IVPP), aspects of basin stratigraphy and chronology still remain controversial. The heart of these controversies often revolves around questions of imprecise fossil provenance and related casual references of fossils as age tie-points, different interpretations of lithostratigraphic units at different localities across the basin, and ultimately different age determinations. In this special issue, entitled *Biostratigraphy, Chronostratigraphy and Vertebrate Paleontology of the Linxia Basin,* we report the findings of an IVPP project, funded by the Chinese Academy of Sciences, which addresses these controversies, proposes a new age model for basin, and develops understanding of the fossil assemblages. In this introduction to the special issue, we review the tectonic context for basin evolution and chronology as well as lithostratigraphy, paleoenvironments and climates. While issues of provenance remain challenging and will continue to burden Chinese vertebrate paleontologists into the future, our findings shed new light on the vertebrate paleontology of the Linxia Basin, and unique circumstances in which it developed.

1. Introduction

Located in the foothills of the northeastern margin of the Tibetan Plateau, the Linxia Basin (Figs. 1, 2) is one of the most significant continental basins for understanding late Cenozoic mammals, tectonic history, and paleoenvironments in Central Asia, and has been intensively studied for over 30 years. Vertebrate paleontology has played a large role in these studies due to the extraordinary accumulation of well-preserved fossils. Spanning Oligocene to early Pleistocene ages, astonishing quantities of fossil vertebrates have been amassed, such as hundreds of skulls and jaws of the *Chilotherium* rhinoceros and the strange-horned *Hezhengia* antelopes, and dozens of skeletons of the shovel-tusked *Platybelodon* "elephant" forming a complete growth series from infants to old adults. In addition to mammals, the rich fossil assemblages of the Linxia Basin include snakes (Shi et al., 2023) and birds (Li et al., 2022; Musser et al., 2019). With stunning discovery comes the darker side of market forces—the vast majority of the fossils have been acquired through private collectors, either directly from local fossil

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dealers or illicit markets. Commercial motives are behind the remarkable rate of discoveries, both in exquisitely preserved specimens and extremely rare finds that are not seen elsewhere in China (e.g., Qiu Z -X et al., 2014; Qiu Z -X et al., 2007). So many fossils were discovered in so short a time that an entire generation of Neogene mammalian vertebrate paleontologists, primarily from the Institute of Vertebrate Paleontology and Paleoanthropology (IVPP), was trained either entirely or partly on the Linxia Basin fossils with several dissertations and monographs based on them (e.g., Qiu Z -X et al., 2004; Shi, 2012; Wang and Qiu, 2018).

Two influential scientists have played an especially pivotal role. From as early as 1965, Zhanxiang Qiu (we invert Chinese names for western readers) at the IVPP initiated paleontological explorations of the Linxia Basin, focusing on the descriptions of the fossils and their chronology (Qiu Z -X et al., 1987, 1988, 1990). Beginning in early 1990s, Jijun Li and his students from Lanzhou University, plus their colleague, Zugang Gu, also from the Lanzhou University, used the Linxia Basin to explore their ideas of stepwise uplift of the Tibetan Plateau in the late Neogene and its environmental implications (Gu et al., 1995; Li et al., 1996b; Li et al., 1995). Controversies between these two groups soon arose over fossil identifications, localities, lithostratigraphic units and, importantly, age relationships. Suspicions were raised over the provenance of fossil collections, often lacking due to private acquisition. During the last 20 years, both groups have attempted to address early mistakes and to bring to bear latest concepts and methodologies. Nevertheless, certain issues are difficult to resolve, such as specimen provenance and interpretations based on magnetostratigraphy, and arguments are sometimes acrimonious (but usually private).

In 2017, a five-year grant from the Chinese Academy of Sciences was secured by the IVPP to study fossils and their age relationships in Linxia Basin. As largely envisioned by principal investigator, Zhanxiang Qiu, a renewed push was made to address the controversies. Major objectives included searching for small mammal assemblages to securely date key strata, lithostratigraphic and biostratigraphic correlations, as well as multiple new magnetostratigraphic studies. Now at the conclusion of this grant (unfortunately COVID-19 prevented a full execution of the project), it seems an opportune time to bring together the project's results and present a preliminary synthesis. This Virtual Special Issue (VSI) in the journal of *Palaeogeography, Palaeoclimatology, Palaeoecology* serves this purpose (Table 1). Here we attempt an overview of the geologic history of Linxia Basin, its tectonics, paleoenvironments, and its unique circumstances in the development of vertebrate paleontology.

2. Tectonic settings, basin history, and lithostratigraphy

2.1. Linxia Basin tectonics and uplift of Tibetan Plateau

Conveniently located just a few hours of drive from the City of Lanzhou, Jijun Li and his Lanzhou University colleagues chose the Linxia Basin as an ideal region that contains a thick succession (~1600 m) of middle and late Cenozoic sediments preserving rich assemblages of fossil mammals (Li et al., 1996b; Li et al., 1995). Such a record, they argued, could rival the classic Siwalik sequence from Pakistan (Barry et al., 2013) and help to establish a model for the timing and style of uplift of the Tibetan Plateau. This goal came to encompass a series of basins in the northern Tibetan Plateau to demonstrate their hypothesis of stepwise uplift in the late Cenozoic (8 Ma initial uplift followed by accelerated rises at 3.6 Ma, 2.6 Ma, 1.8–1.7 Ma, 1.2–0.6 Ma and 0.15 Ma) of the northern Tibetan Plateau (Li et al., 2014). Many of the inspirations of this line of thought came from early study of Yellow River terraces in Lanzhou and Linxia basins where major conglomerates (as a prime example, the Jishi conglomerate) indicate increased sedimentary rates and mountain uplift in Qilian Mountains and Linxia Basin (Li et al.,

Fig. 1. Example of Linxia Basin exposures near the basin center looking toward the northwest. Alternating red and white beds at the top of the section (upper right) is the Dongxiang Formation (late middle Miocene), a prominent marker bed used for correlations in this part of the basin. Exposures here are excellent and continuous, although not very fossiliferous, in contrast to more peripheral areas in the basin, where the majority of the fossil-rich beds is exposed although vegetation can obscure many sections. Photo by Deng Tao. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

1996a; Li et al., 1997b). While the notion of thick conglomerates signaling mountain uplift has been challenged by alternative climate-induced global phenomena (Molnar, 2004; Zhang et al., 2001), data increasingly suggest that from the onset of the early Cenozoic India-Eurasia collision, northern Tibetan Plateau (including Linxia Basin) was already active although thousands of km away from the collision zone, i.e., it experienced long-distance transmission of strain as opposed to progressive outward deformation (see Basin chronology in Section 2.2).

Tectonically, the Linxia Basin was bounded by the eastern tip of the

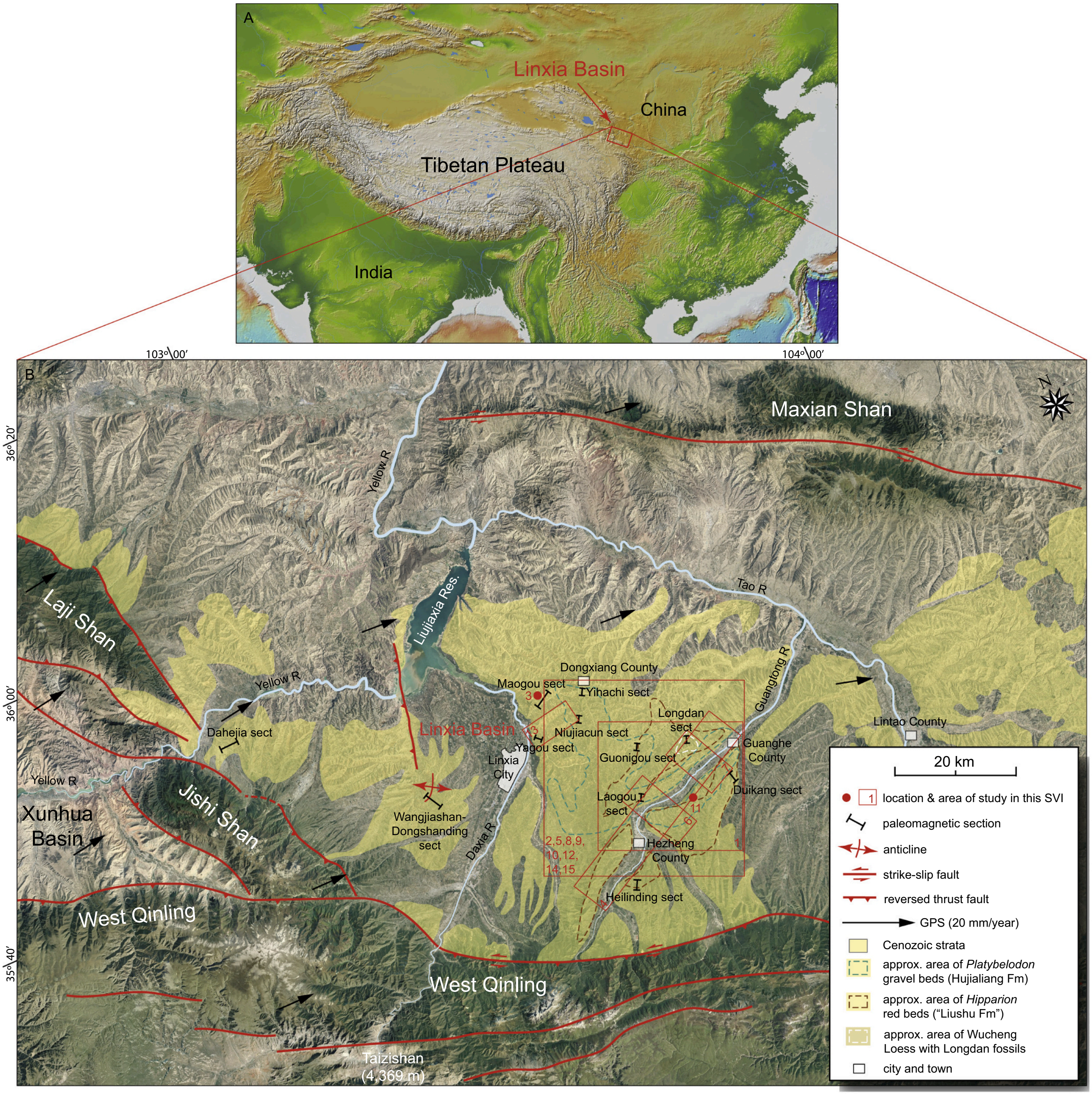

Fig. 2. Key studied sites in the Linxia Basin discussed in this VSI. A, Location of the Linxia Basin at the northeastern edge of Tibetan Plateau; topographic map generated by GeoMapApp version 3.5.1 (Ryan et al., 2009); B, Satellite image of Linxia Basin area obtained from Google Earth (Google Earth Pro (Version 7.3.6.9345), Google Earth Pro, 2023). Movements for select GPS stations (black arrows, typically <10 mm/year in Linxia Basin) are based on Gan et al. (2007) as plotted in Guo et al. (2018:fig. 1). Major basin-bounding faults and Cenozoic strata are adopted and modified from those by Li et al. (1996b), Clark et al. (2010), Hough et al. (2011), Lease et al. (2011, 2012), Saylor et al. (2017), Guo et al. (2018), and Wei et al. (2023). Approximate areas where the *Platybelodon*-producing Hujialiang Fm crops out (green dash lines) was based on Zheng et al. (2023:fig. 1c), and areas for the *Hipparion* red beds (“Liushu Fm”) (brown dash lines) based on Deng et al. (2013:fig. 9.1), and areas for the Longdan Fauna-producing Wucheng Loess (white dash lines) was based on Qiu Z -X et al. (2004:fig. 1). Numbers in red adjacent to solid red circles and rectangles refer to the following articles in this VSI (see Table 1): 1, Aiglstorfer et al. (2023); 2, Deng et al. (2023); 3, He et al. (2023); 4, Hou and Zhang (2023); 5, Jiangzuo et al. (2023); 6, Liu et al. (2023); 7, Ma et al. (2023); 8, Qiu Z -X et al. (2023); 9, Qiu Z -D and Li (2023); 10, Qiu Z -D et al. (2023); 11, Shi et al. (2023); 12, Shi (2023); 13, Sun et al. (2023); 14, Wang S -Q et al. (2023); 15, Zheng et al. (2023). For full colour reproduction, the reader is referred to the web version of this article. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Summary of 15 papers (in alphabetic order) that comprise this Virtual Special Issue. The locations for each (numbers on left column) is shown in Fig. 2.

No.	Papers in this Special Virtual Issue	Title	Main theme
1	Aiglstorfer et al. (2023)	Miocene Moschidae (Mammalia, Ruminantia) from the Linxia Basin (China) connect Europe and Asia and show an early evolutionary diversity of a today monogeneric family	Systematics, zoogeography
2	Deng et al. (2023)	Rhinocerotoid fossils of the Linxia Basin in northwestern China as late Cenozoic biostratigraphic markers	Biostratigraphy
3	He et al. (2023)	Cenozoic tectonosedimentary evolution of the Linxia Basin, northeast Tibetan Plateau based on an analysis of detrital zircon provenance	Sediment sources, tectonic history
4	Hou and Zhang (2023)	A biostratigraphic and palaeoecological study of late Cenozoic kubanochoeres from the Linxia Basin, Gansu Province, China	Systematics, ecology
5	Jiangzuo et al. (2023)	Chronological framework and palaeoecology of Carnivora from the Linxia Basin, China	Systematics, ecology, environments
6	Liu et al. (2023)	Cosmogenic nuclide chronological constraints on the late Cenozoic strata of the Linxia Basin, northeast Tibetan Plateau	Age constraints
7	Ma et al. (2023)	Dietary niche reconstruction of Pliocene and Pleistocene Equidae from the Linxia Basin of northwestern China based on stable isotope analysis	Stable isotopes, horse diet
8	Qiu Z -X et al. (2023)	Stratigraphic context of Oligocene to Pliocene mammal-bearing deposits in Linxia Basin, Gansu Province, China: a historical review and a discussion of ongoing controversies	Overview of study history in Linxia Basin
9	Qiu and Li (2023)	Miocene squirrels from Linxia Basin, Gansu, China; paleoenvironmental and palaeoecological implications	Systematics, ecology, environments
10	Qiu Z -D et al. (2023)	Middle Cenozoic micromammals from Linxia Basin, Gansu Province, China, and their implications for biostratigraphy and palaeoecology	Systematics, biostratigraphy, ecology,
11	Shi et al. (2023)	Evolutionary and biogeographic implications of an erycine snake (Serpentes, Erycidae, Eryx) from the Upper Miocene of the Linxia Basin, Gansu Province, China	Systematics, zoogeography
12	Shi (2023)	Fossil bovids from the Linxia Basin of Gansu Province, China, and their implications for regional biostratigraphy, palaeogeography and palaeoecology	Biostratigraphy, zoogeography, ecology
13	Sun et al. (2023)	Magnetostratigraphy of the Oligocene and Miocene of the Linxia Basin, northwestern China	Magnetostratigraphy, geochronology
14	Wang S -Q et al. (2023)	Gomphotheres from Linxia Basin, China, and their significance in biostratigraphy, biochronology, and paleozoogeography	Biostratigraphy, zoogeography
15	Zheng et al. (2023)	Revised magnetostratigraphy of the Linxia Basin in the northeast Tibetan Plateau, constrained by micromammalian fossils	Magnetostratigraphy, geochronology

Laji Shan and Jishi Shan (=Leiji Shan) to the west, the West Qinling to the south, and Maxian Shan to the north (Figs. 1, 2). The eastern boundary of the basin is poorly defined. Of these, the Laji-Jishi Shan and West Qinling seem to play a much larger role in controlling the basin sedimentation.

By 2010 a US-Chinese collaboration co-led by Peter Molnar and Peizhen Zhang on the outward growth of northeastern Tibetan Plateau was initiated. Teams from multiple US and Chinese institutions worked on several basins and mountain ranges. Naturally, existing works on geology and paleontology in Linxia Basin played an important role in the formulation of their new ideas. At the conclusion of these efforts, Yuan et al. (2013) summarized a major framework regarding the tectonic history of northeastern Tibetan Plateau: 1, deformation of the northern Tibetan Plateau began from the beginning of India-Eurasia collision; 2, the style of early deformation in northeastern Tibetan Plateau is primarily a north-south shortening, locally in the form of West Qinling, Laji Shan, and Maxian Shan thrust faults; 3, a major re-orientation from N-S crustal shortening to *E*-W growth and eastward extrusion during the Miocene, with exhumation of Jishi Shan. The following is a brief review.

2.1.1. West Qinling frontal fault and early flexural basin

The West Qinling is the oldest structural element surrounding the Linxia Basin (Yuan et al., 2013:fig. 4), but is the least studied. It includes a pre-Paleozoic through Mesozoic complex history of shifting terranes (Zheng et al., 2010). An apatite (U—Th)/He age of ~45–50 Ma for middle or late Eocene activation of the West Qinling Fault suggests rapid exhumation of the West Qinling in the form of a major thrust fault (Clark et al., 2010). Direct dating of reverse faulting in the West Qinling range front yielded a similar age of 50 ± 8 Ma (Duvall et al., 2011). No study so far, however, is able to substantiate an Eocene age of initial deposition, although thick sequences of tilted, folded, and faulted conglomerates are exposed in Yatang Reservoir area and in the Taizi Shan Reserve at the southern edge of Linxia Basin (Fig. 3). Based on a magnetic section at Heilinding, Fang et al. (2016) assigned a middle Oligocene (~29 Ma) age for commencement of basal conglomerate deposition at the northern edge of the West Qinling. Given that the oldest Linxia Tala Formation at Maogou section, is Oligocene in age, it seems safe to assume that West Qinling had started to shed sediment into the Linxia Basin at least by then.

About 170 km further east, Wang X -X et al. (2023) presented apatite fission-track thermochronology in the Wushan Basin, an intermontane basin at the northeast margin of the West Qinling. They estimate a Paleocene initial exhumation of the basin as a result of far-field stress propagation of the northeastern Tibetan Plateau. If this is true, a similarly old onset of Linxia Basin shortening is also expected.

By late Pleistocene time, the West Qinling Fault shows a low rate (<3 mm/yr) of left-lateral strike-slip faulting (Chen and Lin, 2019), as is consistent with modern GPS movement directions that are roughly parallel to the West Qinling Fault (Fig. 2). Eastward extrusion of the Linxia block seems to be the main mechanism to accommodate the growth of the Tibetan Plateau. Therefore, the West Qinling frontal fault has either changed from a thrust fault during the early to middle Cenozoic to a strike-slip fault more recently or it could have been active as a transpressional fault throughout the Cenozoic.

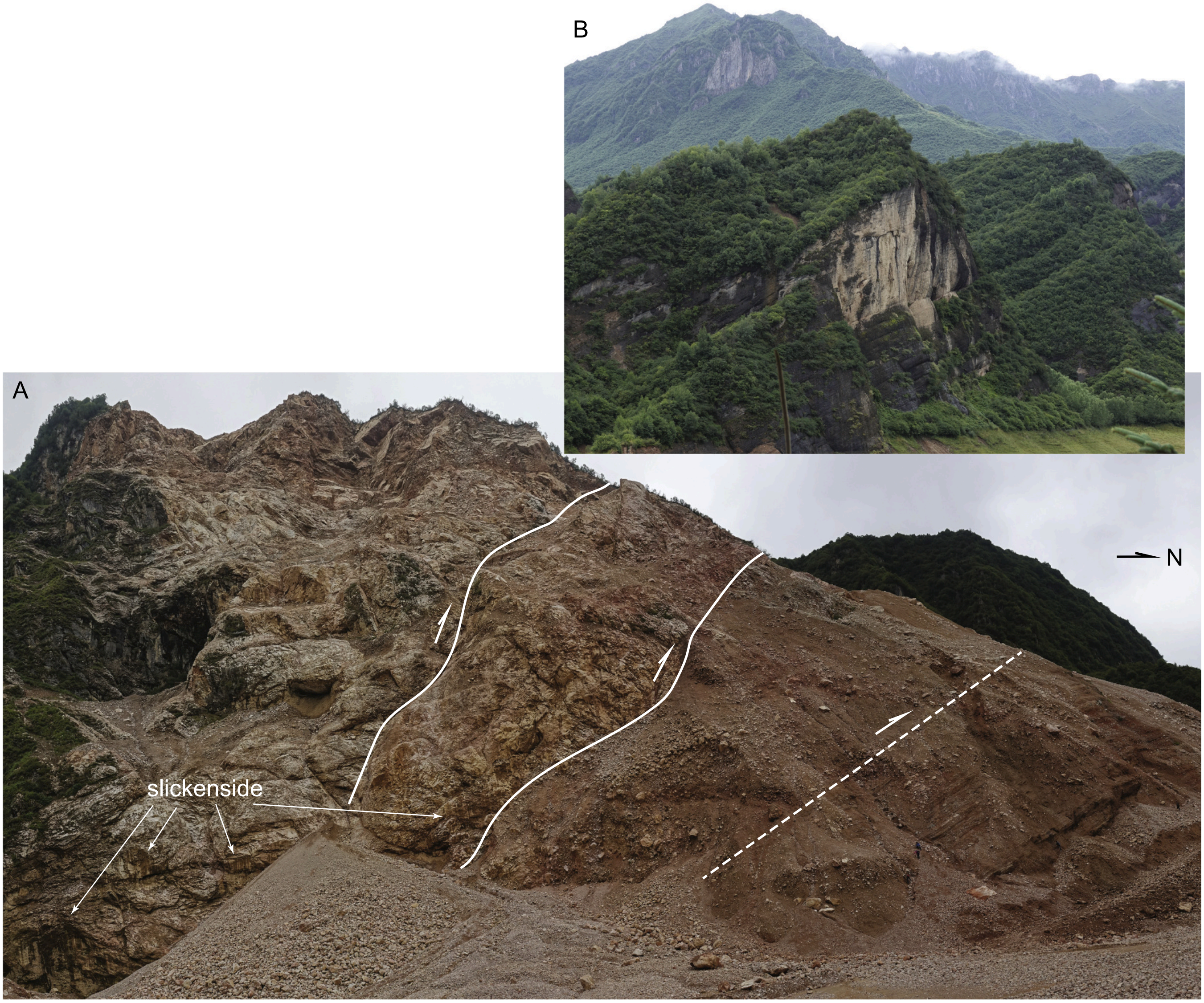

Fig. 3. West Qinling faults were widely assumed to be active since the Eocene, but to date the age of the basal conglomerates is poorly constrained. A, West Qinling frontal thrust faults at a limestone quarry in Taizi Shan Nature Reserve; red basal conglomerates to the right of photograph form a broad anticline extending toward north (outside of the photograph); nearby exposures (not shown in the photo) show signs of strike-slip motion, i.e., the West Qinling frontal fault has transformed to a transpressive fault, presumably coinciding with eastward extrusion and exhumation of the Jishi Shan (see Fig. 4); photo taken by Xiaoming Wang at 35°16′52”N 103°16′13″E (elevation 2003 m) on August 21, 2019; people in distance serving as scales. B, exposures of a massive conglomerate at Yatang Reservoir, presumably related to early uplift of the West Qinling, but it has not yet been dated; photo looking to the east and taken by Xiaoming Wang at 35°18′24”N 103°09′26″E (elevation 2533 m) on August 25, 2019. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.1.2. *Laji-Jishi Shan uplift and Xunhua-Linxia basin segmentation*

In contrast to great antiquity for the West Qinling orogen and its early influence on Linxia Basin formations, the Laji-Jishi Shan to the west of the basin was much younger, reflecting a pattern of outward growth of the northeastern Tibetan Plateau (Yuan et al., 2013). Using $\delta^{18}O$ isotopes, lithostratigraphy, and magnetostratigraphy, Hough et al. (2011) proposed a single integrated Xunhua-Linxia Basin during early Miocene (20–16 Ma) along the paleo-Yellow River. $\delta^{18}O$ isotopes were similar across the entire Xunhua-Linxia Basin (Fig. 4). By middle Miocene, around 16–11 Ma, a marked change in $\delta^{18}O$ isotopes indicates a shift to more arid conditions on the Xunhua side. This was interpreted to be the result of surface uplift of the Jishi Shan and the subsequent blocking of moisture from the easterly summer monsoons on the Linxia side. Since 11 Ma, the oxygen stable isotopes have remained fundamentally modern, i.e., a dry Xunhua Basin persisted due to the rain shadow effect of the Jishi Shan (70.1–61.8 cm/yr modern precipitation in Linxia Basin in contrast to 41.0–26.6 cm/yr in Xunhua Basin).

Based on apatite (U—Th)/He and apatite fission-track ages for thrust-related exhumation, Lease et al. (2011) further restricted the uplift of Jishi Shan to ~13 Ma, and its sedimentary response to 12–9 Ma (Lease et al., 2012), which is consistent with that deduced from $\delta^{18}O$ isotopes (Hough et al., 2011). In a more integrative approach, the segmentation model of the Xunhua-Linxia Basin was further refined by Saylor et al. (2017) through detrital zircon geochronology and flexural modeling. Initial segmentation began with the onset of exhumation of the Jishi Shan around 14.7–13.1 Ma. This low relief, proto-Jishi Shan (0.3 ± 0.1 km) disrupted eastward-flowing drainage but was not sufficiently high to make great difference in moisture circulation. By 9.3 Ma, the paleo-Yellow River breached the Jishi Shan dam, reintegrating the drainage system. Continued uplift of the Jishi Shan created greater relief of 0.8 ± 0.2 km by 8 Ma, which was sufficient to cause a rain shadow effect as recorded by $\delta^{18}O$ isotopes. Most recently, a magnetic study in a Hongzhuang section in eastern Xunhua Basin suggests an early Oligocene through middle Miocene age for deformation and if correct, this

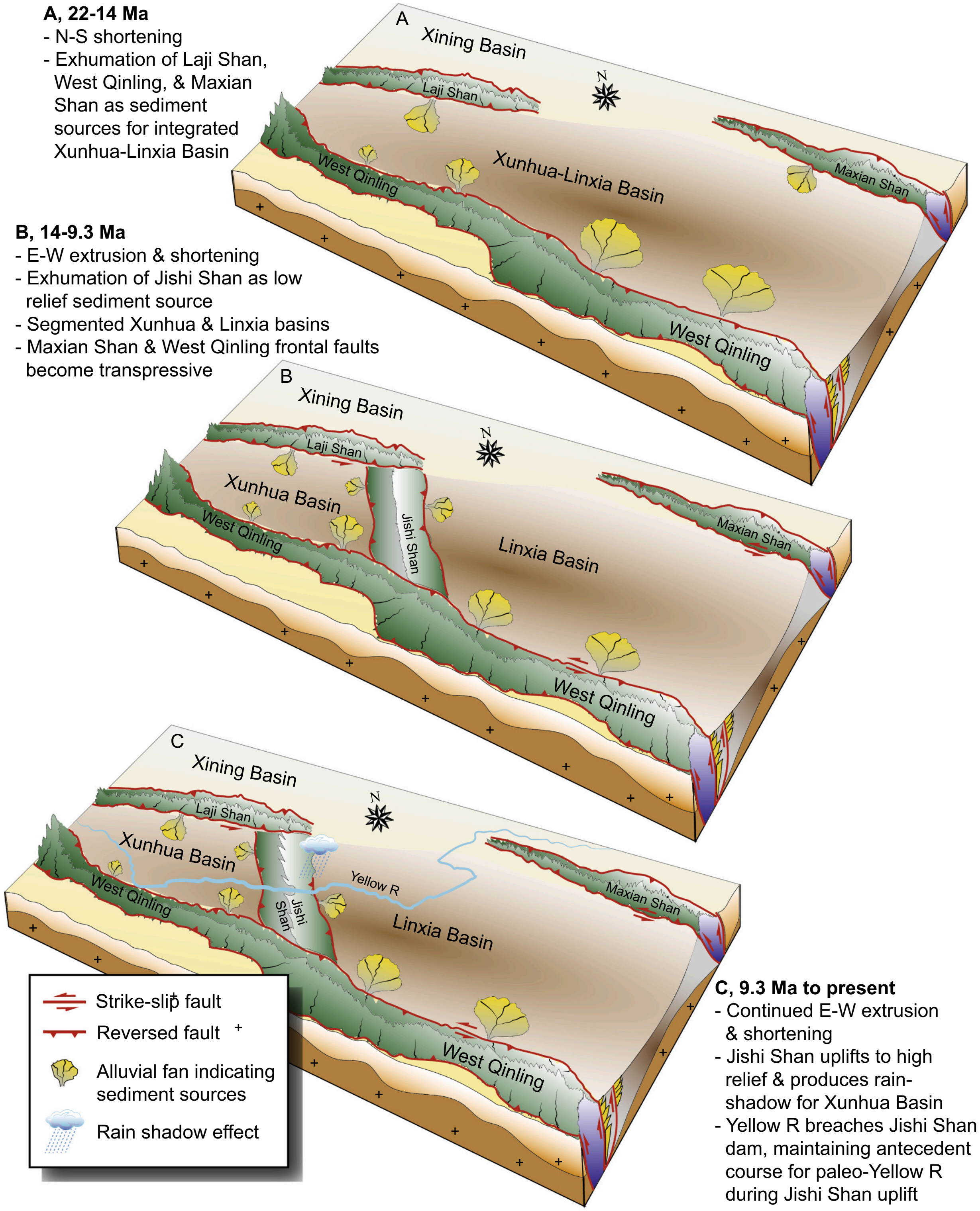

Fig. 4. Diagrams illustrating the evolution of segmentation of an integrated Xunhua-Linxia Basin during the Neogene. Modified from Saylor et al. (2017:fig. 14), and incorporating results from Hough et al. (2011), Lease et al. (2011, 2012), Yuan et al. (2013), and He et al. (2023).

predates the Jishi Shan uplift, as seems to be shown by its climate record (magnetic susceptibility) being mostly influenced by global temperature, not regional tectonics (Li et al., 2023).

Critically, these studies were all based on Fang et al. (2003) age models from Wangjiashan and Maogou sections. The new age model proposed in this special issue (Sun et al., 2023; Zheng et al., 2023), if integrated with these studies, will likely require review of the sequence of events.

2.1.3. *Maxian Shan sinistral transpressive fault*

The Maxian Shan received little attention in terms of its Cenozoic history. Lack of reports on fossil occurrences in Cenozoic sediments abutting the Maxian Shan makes it difficult to evaluate its role in Linxia Basin formation. Movements of modern GPS stations are largely to the east (Fig. 2). This is consistent with strike-slip motion for the Maxian Shan based on a seismic profile study from West Qinling to the Haiyuan Fault (Guo et al., 2016). Field observations of fault slickensides further confirm the strike-slip nature of Maxian Shan Fault (Guo et al., 2018). A rotation of the Linxia block of 5.1° ± 2.6° (Dupont-Nivet et al., 2004) to 10° (Fang et al., 2003) may also be consistent with strike-slip tectonics. Yuan et al. (2013: fig. 4), however, envisioned a Paleogene initiation of reverse faults along Maxian Shan, with these faults becoming strike-slip faults during the Neogene (at around 12 Ma), based on a marked regional shift from compressive to transpressive tectonics (indicated by the Jishi Shan orogen, see above). During the early Miocene, the Maxian Shan region was a sediment source for up to 43% of the Maogou section in Linxia Basin (He et al., 2023).

2.1.4. *Foreland basin model*

Based on progressively shorter thicknesses of the Wangjiashan, Maogou, and Dongxiang sections, Fang et al. (2003) first recognized the Linxia Basin as a flexural basin. Although they did not explicitly specify whether the Laji-Jishi Shan or West Qinling frontal faults were responsible for the basin flexure, by referring to the "southwest" as the source of sediments, they seem to suggest Jishi Shan as the main frontal thrust that caused the flexural deformation. In their analyses of Nd isotopes and trace elements, Garzione et al. (2005), however, implicated sedimentary sources from older rocks in the West Qinling orogenic belt.

Fang et al. (2016) more forcefully argued their flexural model. This time, however, they envisioned a predominantly N-S flexural model (see also Khan et al., 2023). In order to demonstrate this, they used two new magnetostratigraphic sections at Heilinding and Guonigou. The selection of these two sections from near the West Qinling range front was used to demonstrate an earlier N-S shortening and thrusting of the West Qinling. However, despite noting a paleocurrent shift from a mostly eastward direction before 13 Ma to northward after 13 Ma, they proposed decreased subsidence of the West Qinling.

Saylor et al. (2017) further refined Linxia Basin flexural subsidence, using a Monte Carlo inverse flexural model to reconstruct Jishi Shan relief, concentrating on the impact of the Jishi Shan exhumation and its climatic implications (Fig. 4). This modeling suggests that before 13 Ma, Jishi Shan had a modest relief of about 300 m relative to the newly divided Xunhua and Linxia basins on either side, an elevation enough to segment the Xunhua-Linxia basin but not enough to cause major climatic differentiation. By 9.3 Ma, the Jishi Shan topographic relief reached ~800 m, enough to cause a marked drying of the now isolated Xunhua Basin.

2.1.5. *Provenance of sediment sources*

Garzione et al. (2005) tackled the sedimentary sources for Linxia Basin. They sampled the then known magnetic sections at Wangjiashan and Maogou for Nd isotopes and trace elements. Although interpretation of their results was not definitive, as the mixing of fine-grained loess complicated the picture, they could identify sediment contributions from older rocks in the West Qinling orogenic belt.

Using apatite (U—Th)/He (AHe) and apatite fission track (AFT) ages for low-temperature thermochronology, Lease et al. (2011) differentiated discrete growth of the Laji Shan ~22 Ma and the Jishi Shan at 13 Ma, indicating a change in thrust orientation from northward to eastward. A follow-up study by Lease et al. (2012) on the magnetostratigraphy of the Xunhua Basin suggested that a large component of the sedimentary rocks of 24–21 Ma came from the Laji Shan, which must also have been a source for the Linxia Basin as well. Age distributions from source terranes indicate a marked shift from Qinling-sourced sedimentation from the beginning of the Xunhua-Linxia integrated basin, to Laji Shan-sourced sediments at 22.5–19 Ma, and finally to Jishi Shan-sourced sediments (indistinguishable from those of the Laji Shan) at 14.5–11.5 Ma, although West Qinling continued to supply sediment as well during this time (Lease et al., 2012:fig. 11). A similar style of basin deformation was also reported in Guide and Gonghe basins further to the west (Craddock et al., 2011), as summarized in Yuan et al. (2013).

More recently, Fang et al. (2016) proposed a similar shift within Linxia Basin before and after 13 Ma, noting a change in paleocurrent directions within their studied sections and river systems. However, their flexural model calls for a rapid rise of the West Qinling with increased thrust load as an overall response to the NE Tibetan uplift, i.e., assigning a lesser role for the Laji-Jishi Shan as a source area. In this new iteration, Fang et al.'s foreland basin model gave much greater importance to the West Qinling as a sedimentary source.

Using detrital zircon geochronology to engage questions of sediment provenance in the western Linxia Basin (Wangjiashan and Maogou sections), Saylor et al. (2017) arrived at a more complex picture of sediment provenance. They detected a predominantly Qinling and Songpan-Ganzi flysch complex (Weislogel et al., 2010) as the main source of sediments before 14 Ma. From 13.1 to 8 Ma, uplift of the Jishi Shan cut off the previous flow; sediments came from the north-northwest (Maxian Shan, Riyue Shan, and Laji Shan). From 8 to 4.5 Ma, Jishi Shan was the dominant sediment source for western Linxia Basin.

In this special issue, based on their detrital zircon U—Pb age analysis, He et al. (2023) worked on the Maogou section using the latest age model of this issue (Zheng et al., 2023). Sediments earlier than 27.8 Ma came from multiple regions, including East Kunlun Shan, Qilian Shan, and Songpan-Ganzi terranes, in addition to West Qinling. By early Miocene, the northern mountains, such as Laji Shan and Maxian Shan, were the major sources, suggesting that an integrated Xunhua-Linxia basin was not yet broken up. The Jishi Shan became increasingly important and by 11.6 Ma signaled the segmentation of the Xunhua-Linxia basin.

2.2. *Basin chronology and magnetostratigraphy*

Despite the tectonic upheaval in the Tibetan Plateau and surrounding regions, there is a conspicuous shortage of volcanism in much of mainland East Asia during the Cenozoic. As a result, mammalian fossils often provide the only dating, however imprecise, for continental basins of East Asia through much of the 20th century. For many continental basins, early paleontologic explorations often provide the first hint of the age of basin formation, and play a role in the initial understanding of geologic history. This is true of the Linxia Basin as well. Qiu Z -X et al. (2023) summarize the history of basin chronology, with a critical evaluation of the controversies. We highlight some salient points.

Under the leadership of Jijun Li (later succeeded by Xiaomin Fang at Institute of Tibetan Plateau Research), geologists at the Lanzhou University chose the basin to develop ideas about stepwise uplift of the Plateau in the late Cenozoic. The vast fossil collections (see below Section 3) were naturally brought into play, both for chronologic constraints and their environmental implications. However, questions related to fossil provenance continue to be contentious.

Fang et al. (1997) published gypsum fission-track dates for red beds in Wangjiashan and Maogou sections, but these did not endure. Since the 1990s, magnetostratigraphy as constrained by fossil mammals has become an ideal combination for refined age determination. With increasing Chinese funding, no fewer than 10 paleomagnetic sections have been published in Linxia Basin (Fang et al., 2003; Fang et al., 2016; Li et al., 1997a; Li et al., 1997b; Li et al., 1995; Sun et al., 2023; Wu et al., 2017; Zhang et al., 2021; Zhang et al., 2019; Zhang et al., 2020; Zheng et al., 2023) (Fig. 2), in addition to 3 in Quaternary loesses (Qiu Z -X et al., 2004; Zan et al., 2018a; Zan et al., 2018b). While the unsparing efforts by Lanzhou University and Institute of Tibetan Plateau Research have made the basin intensely studied magnetically, an unfortunate lack of collaborative efforts with the paleontologists continued due to institutional barriers. Many sections lack credible fossils to test the magnetic correlations. For sections with vertebrate fossils as tie points, there are still questions regarding either the provenance or identification (see Vertebrate Paleontology in Section 3). As a result, many of the published magnetic sections are still controversial, although the chronology in the basin center is improving, including works in this issue (Sun et al., 2023; Zheng et al., 2023).

As a summary of the latest multidisciplinary efforts in litho-, bio-, and magnetostratigraphy, we present Fig. 5 to allow a limited sense of lateral variation in lithology and sedimentation. We choose sections with good chronologic constraints by vertebrate fossils with known provenance (mostly faunas of small mammals, plus the Longdan Fauna). The fine-grained red beds in the basin center (Maogou and Yagou sections; two left columns in Fig. 5), where most of the lithological units were named, have seen the greatest improvements in our understanding of chronology (Sun et al., 2023; Zheng et al., 2023). Sediments that are between the basin center and periphery (three right columns in Fig. 5), such as the majority of fossil localities along the north and south banks of the Guangtong River region, still lack a good chronologic framework, although a number of small mammal faunas discovered in recent years (Qiu Z -D and Li, 2023; Qiu Z -D et al., 2023) should test magnetic correlations in the future. This area likely continue to be controversial, with the “Liushu” and Hewangjia formations still poorly defined lithologically and many published large mammals lacking credible provenance. To avoid fueling controversies about some of these strata, we left some of the previously published magnetic sections with poor fossil

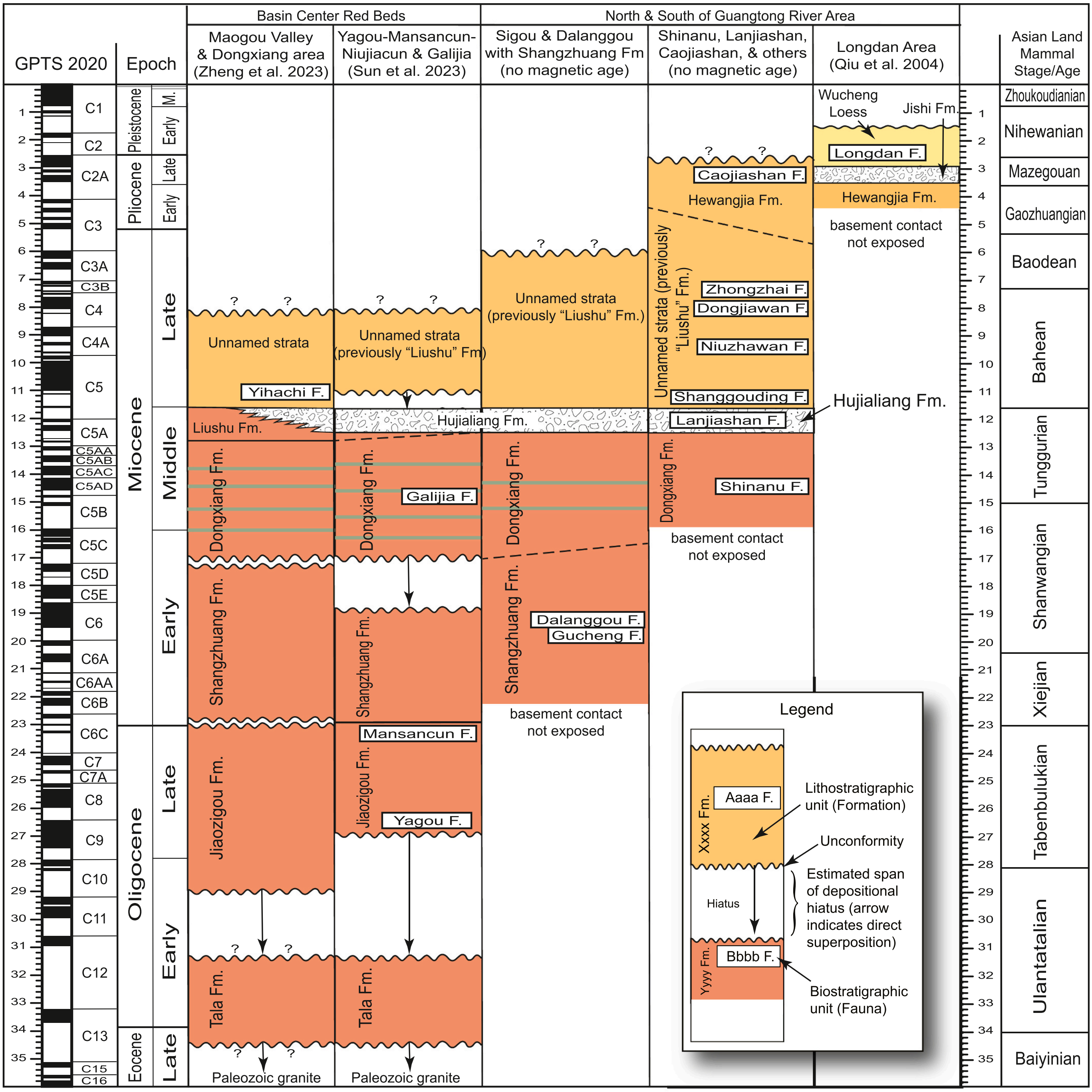

Fig. 5. Thematic summary litho- and biostratigraphy of Linxia Basin based largely on papers published in this VSI. Magnetostratigraphic and chronological controls for Maogou and Yagou valleys (left two columns) are based on papers in this VSI (Sun et al., 2023; Zheng et al., 2023), and those for Guangtong River area (third and fourth columns) are still poorly defined and largely based on fossil mammals, such as Qiu Z -D and Li (2023) and Qiu Z -D et al. (2023). See Basin chronology section (2.2) for additional explanations.

documentation (or no fossils) as in need of future work (e.g., the popularly cited Wangjiashan section of Fang et al., 2003; Fang et al., 1997; Li et al., 1997a) and the Heilinding section of Fang et al. (2016). The latter have been used for studies on paleoenvironment (see Paleoenvironment and climate in Section 4), but their chronology may need review.

2.2.1. Early basin chronology

Using Ar-dating of fault clays and low-temperature thermochronometry, Duvall et al. (2011) proposed middle Eocene (50 ± 8 Ma) faulting of the West Qinling, continuing into the Miocene. Rapid exhumation beginning at ~45–50 Ma for the West Qinling was also indicated by apatite (U—Th)/He ages (Clark et al., 2010), suggesting long distance transmission of strain from the plate boundary and early uplift of the northeastern Tibetan Plateau. Early purported Eocene basin formation is in contrast to the fact that the earliest fossils from the Tala Formation are probably no older than middle Oligocene (Wang B -Y and Qiu Z -X, 2023)—leaving a major gap of 15–20 million years.

That gap might be filled by a recent study. Mainly based on geomagnetic reversal patterns, Feng et al. (2022) correlated their Dahejia (DHJ) section on the western edge of the Linxia Basin to Eocene about 54–40 Ma. This estimate lacks fossil or other constraints.

At the West Qinling range front, thick conglomerates are best seen at the Taizi Shan Nature Reserve and Yatang Reservoir (Fig. 3). These range front basal conglomerates may be associated with thrust faults (Fig. 3). We are not aware of any study on these strata, but based on changes in apparent dips, the basal conglomerates seem to represent a series of growth strata.

In this special issue, Sun et al. (2023) published a new Yagou section that they interpreted to be as old as 34 Ma in the basal Tala Formation, although for this great age to be correct, a long span of missing sediments of about 5 million years must exist. Great antiquity for early onset of basin sedimentation is also implied by Zheng et al. (2023) reanalysis of the Maogou section (see Section 2.2.3).

2.2.2. Wangjiashan-Dongshanding-Dayuanding section

Initially worked by Lanzhou University colleagues (Fang et al., 2003; Fang et al., 1997; Li et al., 1997a; Li et al., 1995), this is one of the earliest published magnetic sections, and for some time the only section in western Linxia Basin. The Wangjiashan section came to dominate for its western location and presumed long, continuous strata, in addition to being the type section of the Linxia Fm. Six fossiliferous horizons are placed within this section. From top down, these are: *Equus* Fauna in Dongshan Fm (this formation does not appear elsewhere in the basin), *Hipparion* Fauna in Hewangjia Fm, two Longguang faunal horizons in Liushu Fm, and two Sigou faunal horizons in Dongxiang Formation. Critically, only the Longguang Fauna (from the Longguang Village in Yinchuanxiang) is close to the Wangjiashan section; the Sigou Fauna is about 40 km away in Guanghe County. Therefore, most of the purported fossil tie points are dependent on lithostratigraphic correlation, which, by Fang et al. (2016) own flexural models, can be diachronous. In recent years, Fang et al. (2016) completely reinterpreted their magnetic correlation of the Wangjiashan section from 2 to 11+ Ma (Fang et al., 2003; Fang et al., 1997) to a much longer duration of ~1.7–21+ Ma, illustrating the uncertain nature of correlation schemes.

2.2.3. Maogou and nearby sections

Because the Maogou section can be observed to directly overlie granitic basement, the section was initially believed to span ~4+ to 29+ Ma (the longest time span of any Linxia Basin section) although it is only about 450 m long due to its basin-center location with more fine-grained red beds (Fang et al., 2003; Fang et al., 1997; Li et al., 1995). Lithostratigraphically this is the most crucial section as many (but not all) formation names are derived from here, including one named by Qiu Z -X et al. (1990). However, despite its over-arching historical importance, the Maogou section similarly suffers from a shortage of reliable fossil tie points in its relatively poorly fossiliferous, fine-grained red beds. Similar to the Wangjiashan section, all of the initially cited faunas within the Maogou section are dozens of km away from the Maogou section — Longguang (Wangjiashan), Sigou (north bank of Guangtong River), and Shanzhuang (south bank of Guanghe River) — creating a false sense of paleontologic control that does not exist.

One small fauna in Jiaozigou Fm described by Qiu Z -X et al. (1990) (roughly equivalent to Zhongzhuang Fm of Li et al., 1995) is close enough to the Maogou section to offer some age control. Qiu et al., however, initially underestimated the age relationship as early Miocene due to an error in recognition of proboscideans, which should not have appeared in the Oligocene.

To mitigate the above deficiency of biostratigraphy in the Maogou section, Zhanxiang Qiu and his colleagues initiated a campaign in 2017–2019 to search for fossils, especially small mammals, within or adjacent to the Maogou area. Toward that end, a substantial improvement is achieved, as described in this special issue. This includes the Yagou and Mansancun faunas (Qiu Z -D et al., 2023; Wang B -Y and Qiu Z -X, 2023; Wang B -Y et al., 2023) in the Jiaozigou Fm, the Galijia Fauna (Qiu Z -D and Li, 2023; Qiu et al., 2023) in the Dongxiang Fm, the Yihachi Fauna (Qiu Z -D and Li, 2023; Qiu Z -D et al., 2023) in the “Liushu” Fm.

Importantly rich small mammals of the Yihachi assemblage offer excellent biochronologic control (Qiu Z -D and Li, 2023; Qiu Z -D et al., 2023). A 50-m magnetic section was obtained, yielding an age of 10.8–11.6 Ma, and permitted the identification of subchrons (“tiny wiggles”) with dense magnetic sampling (Zhang et al., 2021). Such high-resolution chronology illustrates an ideal combination of magnetostratigraphy and biochronology given favorable circumstances.

In coordination with the paleontologists, a paleomagnetic team has restudied the Maogou section (Zheng et al., 2023). Zheng et al.’s new magnetostratigraphy suggests ~29 Ma for the base of the Jiaozigou Fm. Unfortunately, they omitted the older Tala Fm because of its lack of fossil constraints. The ~50 m Tala Fm was known to span multiple magnetochrons based on Fang et al. (2003) earlier work, and as such the Maogou section possibly begins well into the late Eocene, substantially older than 29 Ma, as also implied by Sun et al. (2023). Zheng et al.’s terminal age for Maogou section is 11.6 Ma based on their new interpretation of the Liushu Fm, substantially older than the 4.3 Ma in Fang et al. (2003). Additionally, three sections in parallel to the Maogou section were published: Yagou, Mansancun, and Niujiacun (Sun, 2014; Sun et al., 2023), which favored an interpretation of early Oligocene (~34 Ma) onset of basin sedimentation.

2.2.4. Heilinding-HZ and Guonigou sections

To work out their N-S basin shortening and flexure, Fang et al. (2016) chose the Heilinding section, complemented by two (HZT and HZ) nearby drill cores, near the foreland thrust fault and Guonigou section for an intermediate basin setting. Two mammal faunas are found in the Heilinding section, a late Miocene *Hipparion* fauna and a middle Miocene *Platybelodon* fauna.

Using their foreland basin model, Fang et al. (2016:fig. 8) proposed diachronous occurrences of the observed zebra beds (alternating red and white bands in a lacustrine sequence, as is typical of Dongxiang Fm). While their zebra beds in the foredeep Heilinding are correlated to forebulge Maogou sections, a similar zebra bed in the transitional (foreslope) Guonigou section was projected to fall in the underlying Shangzhuang Fm.

2.2.5. Laogou and Duikang sections

For much of the past 30 years, the large number of middle Miocene *Platybelodon* fossil sites and late Miocene “*Hipparion*” fossil sites along the Guangtong River were not the focus of magnetic studies. The sheer numbers of fossils mined by for-profit collectors, often lacking provenance data (see Vertebrate Paleontology in Section 3), and a large body of literature describing the fossils but giving only cursory treatments to stratigraphy, have become a source of confusion. In addition, the status of the "Liushu" and "Hujialiang" rock units are in question (see Sections 2.3.1 and 2.3.2). As constraints Zhang et al. (2019, 2020) constructed the Laogou and Duikang magnetic sections, which, unfortunately, were not discussed in this special issue.

2.2.6. *Cosmogenic nuclide dating*

In this VSI, Liu et al. (2023) attempted radiometric cosmogenic nuclide dating using ^{26}Al/^{10}Be and ^{10}Be/^{21}Ne burial methods. They arrived at an age of 11.70 ± 0.17 Ma for the "Liushu Fm", 3.06 (+0.36/−0.31) Ma for the Hewangjia Fm, and 2.50 (+0.20/−0.18) Ma for the Jishi Fm. Unfortunately, their "Liushu" and Hewangjia formations seem largely chosen for the late Miocene and Pliocene fossils that they contain, rather than properly defining what "Liushu Fm" really represents (Section 2.3 below). For example, they sampled the graded section at Hualin onsite museum in southern Linxia Basin as their "Liushu Fm" without stating how these beds relate to other late Miocene strata (their age of 11.70 Ma precedes *Hipparion* immigration) or to the Hewangjia Fm (sampled from the village of Hewangjia, far away from the Hualin section).

2.3. *Lithostratigraphy*

The preliminary lithostratigraphic division devised by the Gansu Regional Geological Survey Team (1965) based an informal system of Linxia Formation members I—IV on strata of the Wangjiashan area. When teams from the Lanzhou University began to contemplate formal establishment of lithological nomenclature, they chose the Maogou section along an *E*-W ridge west of Dongxiang County seat. This section has both advantages and disadvantages. Good exposures from the basement to the top of the section make the Maogou section easy to examine and its basin center location also features a relatively stable depositional environment, allowing easy correlation with strata from nearby washes (Fig. 1). However, the mostly red beds in Maogou section are also not very fossiliferous and far from the fossil-producing sites along Guangtong River (Fig. 2), making it difficult to develop true fossil tie points.

With the exception of a name change from Zhongzhuang Fm to Jiaozigou Fm, due to priority (Qiu Z -X et al., 2023), much of the original lithostratigraphic nomenclature by Li et al. (1995) endured (Fig. 5). But their Liushu Fm is problematic, as well as the new Hujialiang Fm (=Laogou Fm) proposed by an IVPP group (Deng, 2004; Deng et al., 2004a; Deng et al., 2004b). Qiu Z -X et al. (2004:fig. 1) and Deng et al. (2004b:fig. 1) presented the most detailed geologic map of Linxia Basin, but the mappable units are greatly simplified from Li et al. (1995) original scheme. In light of the new stratigraphic model presented in this VSI, many of the units need to be remapped, especially the "Liushu: and "Hewangjia" formations (see Sections 2.2.3 and 2.3.3 below). We highlight the following three units because they contain the vast majority of vertebrate fossils. Uncritical use of these formation names continues not only to confuse concepts in lithostratigraphy and chronology but also to cause practical ambiguities by researchers who must confront the issues.

2.3.1. *Hujialiang Fm Controversy*

A conglomerate and sandstone, best-developed along the Guangtong River, is known to produce a middle Miocene *Platybelodon* fauna (blue dash line in Fig. 2). Deng et al. (2004a,b) named this gravel bed Laogou Fm, with the type section selected at Laogou in Sanhexiang area, but soon renamed it Hujialiang Fm due to conflict with an existing name (Deng, 2004). Their concept is that this massive gravel bed is sandwiched between the underlying purple red mudstones of Dongxiang Fm and overlying brownish yellow mudstones of Liushu Fm. Deng et al. noted its occurrence in the Maogou as well as Wangjiashan sections.

Fang et al. (2016:90) remarked that the Hujialiang conglomerates vary laterally as fluvial lenses, and as such, are difficult or impossible to trace in basin-wide lithostratigraphy. Conceptually, for a dynamic foreland basin model, they claimed a "pervasive ignorance of stratigraphic diachroneity, sedimentary facies influence and its temporal-spatial variation" (Fang et al., 2016:79–80). Fang et al. thus argued against the use of Hujialiang Fm as a formal lithostratigraphic unit, preferring to include it within Dongxiang Fm as a lateral facies variant.

As high-energy fluvial deposits, conglomerates do occur in multiple horizons, especially toward the periphery of the basin. It is thus a legitimate question whether or not the *Platybelodon*-producing gravel beds can be consistently recognized throughout the basin, as Fang et al. (2016) noted.

To meet this challenge, Zhanxiang Qiu and his colleagues embarked on an ambitious field program in 2017–2019 to trace the Hujialiang gravel beds both along the Guangtong River, where the majority of the *Platybelodon* assemblages were found, and further north to near the Maogou section itself. In a series of maps and stratigraphic columns (Zheng et al., 2023:figs. 1-3), the Hujialiang gravel beds were physically traced through an area of around 30 × 30 km, covering much of the fossil-producing region (green dashed areas in Fig. 2). They identified the *Platybelodon* gravel beds throughout the region, tracing them all the way to within 1 km of the Maogou section (the gravel bed nearly pinches out), lending credence to the Hujialiang Fm as a distinct, mappable lithological unit from the basin center toward the periphery.

To further refine the age relationship, Zheng et al. (2023) re-studied Maogou magnetic section gave a thin gravel bed ($<$10 m), the putative Hujialiang Fm, an age of 12.8 Ma (C5Ar.2r), in contrast to 11.5 Ma in Laogou section and 12.5–11.1 Ma basin wide (Zhang et al., 2019). Zheng et al. (2023) further extrapolated the Hujialiang Fm to chrons C5r.2n–C5Ar.2r (~11.6–12.8 Ma). Their new concept of the Hujialiang Fm laterally transitioning into Liushu Fm at basin center, is very different from the original concept as a discrete chronologic unit between Dongxiang and Liushu formations (Deng, 2004). Lithostratigraphically and chronologically, the Hujialiang/Liushu Fm hypothesis has become considerably more specific in this new formulation, and can be tested in future studies.

Based on the above, one can naturally ask the following questions. Is the Hujialiang Fm tectonically induced due to uplift of the surrounding mountains or is it a climatic phenomenon due to increased precipitation? If the Hujialiang gravels are sheet-like, why is it not well represented near the basin periphery at the Heilinding section (Fang et al., 2016)?

2.3.2. *Problems with Liushu Fm*

Li et al. (1995) originally defined the Liushu Fm as a brownish yellow mudstone above their Dongxiang Fm. Their early magnetic correlations suggest a late Miocene age (Fang et al., 1997). Unfortunately, the Liushu Fm began to bear a chronologic connotation and was equated to late Miocene, regardless of location and stratigraphy. In practice, Liushu Fm (and also Hewangjia Fm, another problematic term) was widely used for *Hipparion* faunas in much of the literature.

East of the type Liushu Fm, Yihachi small mammals and magnetostratigraphy yielded an age of latest Middle Miocene to earliest Late Miocene, upsetting the previous concept. This seems to suggest that the Liushu Fm and Hujialiang Fm are approximately contemporaneous, as different depositional facies (Qiu Z -X et al., 2023; Zheng et al., 2023). If this is correct, the large areas along Guangtong River where large mammal "*Hipparion*" faunas mostly occur (brown dashed lines in Fig. 2) are left with no formal formational name as a lithologic unit, a problem left unresolved in this special issue. Colleagues from the IVPP tentatively treat strata along Guangtong River as "Liushu Fm" in contrast to beds in the type section at Maogou. This provisional measure highlights problems with existing nomenclature and awaits future resolution.

2.3.3. *Problems with Hewangjia Fm*

Originally called Wangjiashan Fm for the Wangjiashan section (Li et al., 1995), this lithostratigraphic unit was soon renamed Hewangjia

Fm, in the Chinese version of Li et al. (1996b), because Wangjiashan Fm was pre-occupied (no mention was made in the same paper in English; Li et al., 1996a). Defined as a sequence of fluviolacustrine mudstones and sandstones containing large quantities of carbonate nodules, this 60-m thick bed also supposedly produced *Hipparion richthofeni* and *Chilotherium* rhinoceros (Li et al., 1995:52). These fossils were originally mentioned by the Gansu Regional Geological Survey Team (1965) from their type section of Member IV in Linxia Fm in the Wangjiashan section. As was the view 50 years ago, the entire Linxia Fm was considered Pliocene in age based on the presence of *Hipparion*. Given the lack of detailed documentation and changing concepts, the survey team's age assignment and its paleontologic basis are outdated. Unfortunately, all subsequent study has inherited this problematic Pliocene determination, bestowing uncertainty for high units in the Wangjiashan section as Hewangjia Fm (Qiu Z -X et al., 2023). The Hewangjia Fm was subsequently paleomagnetically dated to 6.0–4.48 Ma at Wangjiashan section (Fang et al., 2003; Fang et al., 2016; Li et al., 1997a), 6.0–4.34 Ma at Maogou section (Fang et al., 1997), and 6.5–4.1 Ma at Heilinding section (Fang et al., 2016), but was considered non-existent in the Maogou section by Zheng et al. (2023).

Despite the paleontologically poorly documented fossil assemblage from the beginning, the concept of Hewangjia Fm was widely misused for any strata that carry a vague notion of Pliocene age, paleontologically or otherwise. This means that Hewangjia Fm is equated to early Pliocene, regardless of actual sedimentary character. As in "Liushu Fm" (see above), the Hewangjia Fm needs revision, a task not undertaken in this special issue.

3. Vertebrate paleontology

3.1. For-profit collections

Known for its eye-opening riches of vertebrate fossils, the Linxia Basin exploded onto the paleontologic scene during the past 30+ years due to a unique combination of circumstances. China and surrounding countries have a long history of consuming "dragon bone" as an ingredient in traditional medicines, which was well documented by ancient compilations on herbal medicines (e.g., Li, 1596). The western science of paleontology, as introduced to China in the 1800s, has long taken advantage of the commercial availability of fossils sold in Chinese pharmacies (Owen, 1870) or as charms or trophies much earlier in India and Tibet (Wang et al., 2020). By early 1900s, several Chinese late Cenozoic basins were known to produce great quantities of fossil vertebrates through commercial mining, such as well-documented sites as Zhoukoudian (Beijing), Nihewan (Hebei), Baode (Shanxi), and Yushe (Shanxi).

Although commercial "dragon bone" production in Linxia Basin started relatively late, in the 1970s, and was initially modest (Qiu Z -X et al., 2023), it quickly surpassed all other basins in expoitation in a short time. For-profit mining of fossils at a time of rapid transition to a

Fig. 6. Tunnels and fossils from Linxia Basin. A, a typical working tunnel at Yinshanhe (LX0044 locality), Bantu, Nalesi with apparently on-going excavations (note fresh dirt track for transport of sediments from the cave); B, Qiu Zhanxiang (right) examining mixed "dragon bone and teeth" in the courtyard of Zhao Yongchang's family home; this is a typical result in early commercial excavations that sold fossils by weight, i.e., specimens were hastily broken into pieces during excavations and no or minimal attempt was made to salvage the complete specimens; C, a block of intact specimens in their original preserved context; this block was excavated while supervised by the Zhao family, after instruction about the scientific value of preserving original juxtapositions of bones for taphonomical research; D, a skull of *Canis* from Longdan in Zhao family collection; note the notation of private numbering system of Zhao family locality #38 (later catalogued as LX0010 locality in Deng et al., 2013:appendix) in the lower tunnel levels (Chinese word "lower" next to "38"); black ink pen for scale. Photos are by Xiaoming Wang during 2000 summer field season.

market economy for the country quickly saturated illicit domestic and international markets (Wang, 2013). Fueling this development is an explosive growth of Chinese scientific enterprise as well as bourgeoning natural history museums throughout the country this century.

By early 2000s, "dragon bones" as a traditional medicine sold by the weight at an affordable price (from under 1 Yuan/kg in early 1980s to over 10 Yuan/kg in early 2000s) have been largely replaced by fossil trade for display (Qiu Z -X et al., 2004), along with a thriving market for forgery (Deng, 2011). Deep tunnels were dug by hand that follow fossil-rich layers for hundreds of meters horizontally (Fig. 6). Local villagers, typically in groups of 5–10, excavated the tunnels by lantern during off seasons of crop production (Qiu Z -X et al., 2004:8). In recent years, crack down of illicit trade in international markets, increasing demand by domestic museums, and great wealth of private Chinese collectors have combined to drive a thriving domestic market while the importance of international markets diminishes. While unique specimens can still be found in international markets (e.g., Galiano et al., 2022), domestic markets probably make up the bulk of trade in recent years.

3.2. Mitigation of private collections

A major feature of Cenozoic mammals as compared, for example, to Paleozoic fishes and Mesozoic dinosaurs and birds, is the density of fossil records, which as such, often play a prominent role in biostratigraphy and biochronology. In addition to the intrinsic anatomical values for each fossil, Cenozoic mammals frequently play an important function in their contextual relationships as index fossils for geologic ages and local correlations. The inevitable loss of provenance in commercially mined specimens thus greatly diminishes their scientific value. This is especially true for fossils that are produced from a basin spanning the last 30+ million years.

With the large-scale involvement of the IVPP in Linxia Basin fossil vertebrates, Zhanxiang Qiu devised a method for mitigating the lack or poor documentations of provenance (Qiu Z -X et al., 2023). He engaged a prominent local fossil dealer, Mr. Zhao Yongchang (and his three sons), to keep track of localities, as well as excavate blocks of fossils *en masse* (rather than cutting them down to smaller pieces) to preserve their taphonomic context (Fig. 6C). Zhao implemented a locality numbering system, designating specific man-made tunnels with fossils (most tunnels are horizontal and follow productive layers, which, with few exceptions, are mostly flat-lying in Linxia Basin) (Fig. 6D). The tunnel entrances, lithologic characters, and stratigraphic context were later verified by paleontologists from the IVPP. This initial effort captured up to 87 Zhao family localities, which were later catalogued into an IVPP system that contains information about their nearest villages and GPS locations (Deng et al., 2013:appendix).

Despite the above mitigating efforts, however, many fossils acquired from other dealers lack contextual information. As a result, much controversy and uncertainty about many of the specimens persists and casts a shadow over the full scientific value of the specimens.

3.3. New museums and fossil protection

Given a broader background of a thriving infrastructure in China, a similar boom was seen in establishment of new museums, as exemplified by the Hezheng Paleozoological Museum (HPM). Zhanxiang Qiu played a pivotal role in the original philosophy and implementation of this museum, which opened to the public in 2003 (Fig. 7A–C). Initially based largely on a collection acquired from the Zhao family (see Section 3.4.3), the Museum rapidly expanded to phase II and III constructions as well as additional acquisition from local collectors. In addition to the HPM, another onsite facility was built at Hualin, where fossils are displayed in situ as preserved in strata (Fig. 7D).

While the new museums are major boosts to local tourism, challenges remain in fostering a healthy, sustainable development of a natural history museum. At the most fundamental level, recruitments of young professionals with curatorial and other scientific expertise are much needed given a prevailing culture of young college graduates reluctant to settle in small cities and remote towns. Perhaps equally challenging, the new museums must also face the tasks of integrating the privately collected fossils in a way that allows an appropriate evaluation of their provenance data, or lack thereof, while recognizing that some exquisite fossils have intrinsic anatomical value.

Recently government-sanctioned protective areas were also established (Fig. 8), with earlier national law protecting fossils in China (Liston, 2014; Liston and You, 2015; Stone, 2010b), offering hopeful signs that the pillage of fossils will subside. As far as we are aware, no data evaluate the effectiveness of the new measures.

3.4. Evaluating provenance of fossils

Given the above problems in specimens from private collections, it is reasonable to ask how much can the published fossils be trusted in terms of their provenance? For those who have not worked in Linxia Basin, this can be a difficult question to answer. We provide a rule-of-the-thumb guidance about level of confidence in provenance, but when in doubt, ask museum professionals.

3.4.1. Small mammal faunas are reliable

As a rule, small mammal teeth typically require screen washing and are too small to be noticed by village collectors in dark tunnels (exceptions include skulls of zokors, beavers, bamboo rats and rabbits that are large enough to be found by hand excavations and to be sold in open markets). An increasing number of small mammal faunas are published, including several in this special issue and elsewhere (Qiu Z -D and Li, 2023; Qiu Z -D et al., 2023; Wang B -Y et al., 2023; Wang B -Y and Qiu Z -X, 2023). While their age relationship can always be debated, as in all stratigraphic paleontology, their provenance is generally not questioned.

3.4.2. Longdan Fauna in Wucheng Loess is well constrained in biostratigraphy

A large collection of early Pleistocene mammals has benefited from the mitigating efforts of Zhanxiang Qiu (see Section 3.2.). Near the Longdan village, early Pleistocene Wucheng Loess contains two fossiliferous layers, separated by a few m of paleosol strata. As mentioned above, specimens obtained by the Zhao family came with separate designations of "upper" and "lower" strata (Fig. 6D). Magnetically, these two strata fall within the early Matuyama reversed chron (2.15–2.58 Ma) (Qiu Z -X et al., 2004), making the Longdan Fauna well-constrained chronologically.

For a relatively restricted occurrence (geographically and stratigraphically, see small area, white dashed line in Fig. 2), successful mitigation efforts plus detailed documentation by Qiu Z -X et al. (2004) have combined to make the Longdan Fauna one of the best outcomes for vertebrate paleontology in an active dragon-bone trading region. Individual specimens are recorded in a system of 13 "localities" (tunnel entrances), and for all practical purposes, the details in locality and stratigraphic information can rival those documented by professional paleontologists. This success is also one of the reasons that an early monographic treatment of all Longdan large mammals was carried out without the usual concerns about biostratigraphy in dragon bone hunting regions (Qiu Z -X et al., 2004).

3.4.3. Zhao family collection has some degree of provenance control

Besides the above example of the well constrained Longdan Fauna, the Zhao family has recorded a system of up to 87 "localities" throughout the Linxia Basin, as suggested by Zhanxiang Qiu (see above). These localities are catalogued into an IVPP locality system of "LX" numbers (Deng et al., 2013:appendix). Individual localities were field-verified by IVPP staff, recording GPS, lithology, and fossils recovered in discarded sediments. Specimens that are so-recorded also have some

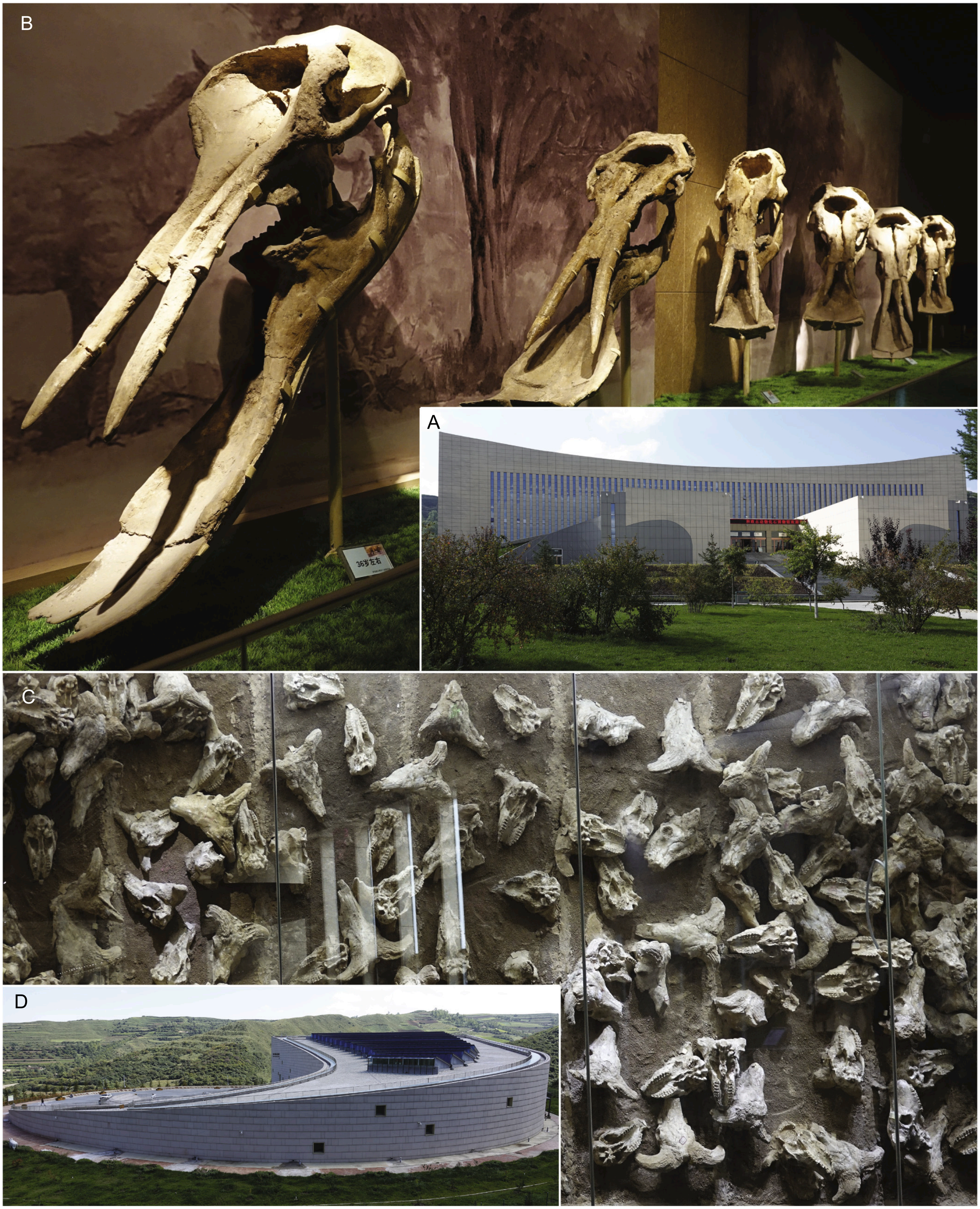

Fig. 7. Boom in museum construction and tourism, featuring the rich heritage of Linxia Basin fossils. A, Hezheng Palaeozoological Museum, shown in one of three phases of constructions; B, an exhibit of six complete individuals of the shovel-tusked elephant *Platybelodon*, forming an ontogenetic series not seen elsewhere, from Hezheng Palaeozoological Museum; C, a display panel of dozens of skulls of *Hezhengia bohlini*, a peculiar sheep-sized antelope (previously believed to be a distant relative of *Obivos*) most abundantly represented from Linxia Basin, made available due to commercial trades, from Hezheng Palaeozoological Museum; D, Hualin On-site Fossil Protection Building, an exhibit facility specializing in displays of in-situ excavations and preservation of Linxia Basin vertebrate fossils. Photos by Xiaoming Wang during 2017 field season.

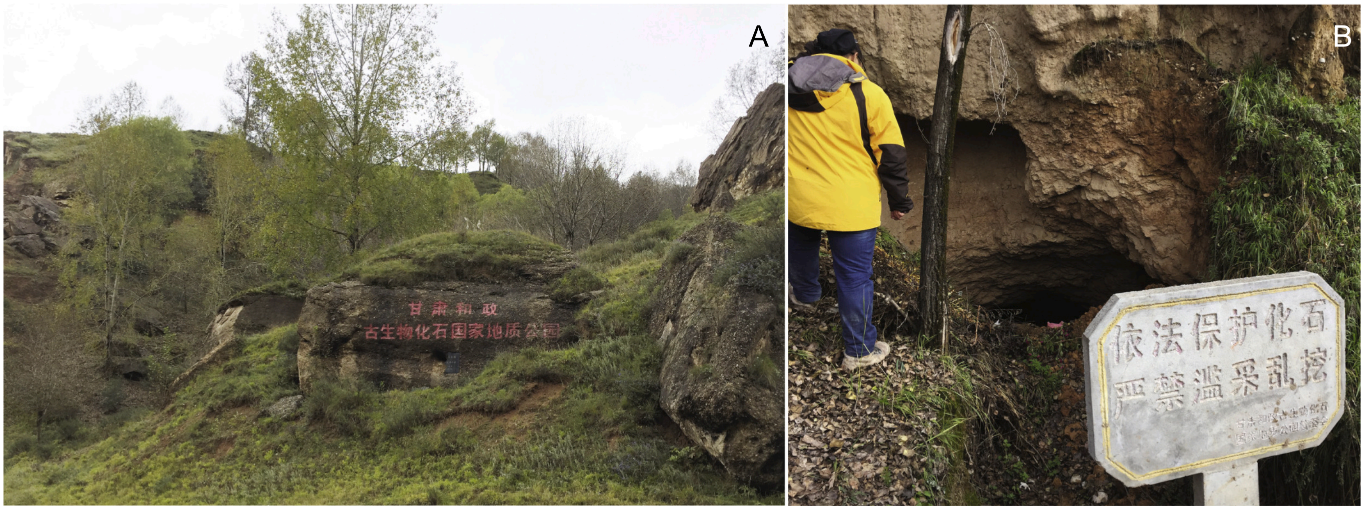

Fig. 8. Protective measures of vertebrate fossils were implemented during the 2010s. A, establishment of a geological park at the village of Hougou; red letters engraved on rock cliff reads "Fossil Protection National Geological Park, Hezheng, Gansu" in Chinese; B, a concrete fossil protection plaque posted at an abandoned tunnel entrance (person for scale) (the sign reads "Fossils protected by the law; illegal excavation strictly prohibited" in Chinese) in Yangjiashan area. Photos by Xiaoming Wang during 2018 field season. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

level of assurance about their provenance, even though exact location within a given tunnel is not known. In addition, as in professional collections, the lithology and biostratigraphy can be independently examined by future researchers, assuming the tunnel entrances are representative of the rest of the tunnel.

A substantial proportion of the Zhao family collection was acquired by the Hezheng Palaeozoological Museum numbering >1000 good specimens. Unfortunately, there is also a large number of fossils from different dealers acquired by the Museum. Many of the latter have minimal documentation and/or questionable provenance.

3.4.4. *The rest*

We have even less confidence in provenance for fossils that do not fall into the above categories. The nationwide boom in museum construction in the last 20 years feeds into the illicit market (Wang, 2013). As a result, many specimens in new museum collections were purchased in recent years. Since vertebrate fossils are state property and trading in the open markets is not legal (but rarely monitored), one can assume that dealers do not have the incentive to reveal locality information. Furthermore, many fossils have passed through the hands of successive dealers and small shops, making information about provenance even less certain each time fossils change hands.

Fossil forgery, also rampant in Linxia Basin materials, can fool the professionals (Deng, 2011; Stone, 2010a). Typical forgeries involve embellishment of less than perfectly preserved specimens or dramatization of specimens by adding components to tell enticing stories (such as placing bones of prey into the mouth of carnivorans). These are so prevalent that it must be profitable to add forged parts, and as a result, almost every collection that we are aware has some examples of forgeries.

3.5. *Suggestion for professional paleontologists*

Given the above questions regarding provenance of vertebrate fossils from Linxia Basin, it is especially important that professional paleontologists document published specimens in great detail. Full disclosure will benefit science in the long run, as is shown in the Longdan Fauna (Qiu Z -X et al., 2004). We also recommend that researchers fully disclose their privately acquired specimens and related information regarding provenance, however unsanguine the acquisition process might be. This will help future researchers to properly evaluate levels of confidence in locality information.

4. Paleoenvironment and climate

The location of Linxia Basin not only permits explorations of change in the northeastern Tibetan Plateau, it also provides key data for evaluation of the shifting monsoon climates with associated vertebrate fossil records. A variety of paleoenvironmental studies have been conducted by researchers and collaborators from the Lanzhou University and Institute of Tibetan Plateau Research, and by IVPP. However, since most of them (except those on mammalian dental enamel and loess studies on boreholes) use age models based on paleomagnetic studies from Fang et al. (1997, 2003, 2016), the conclusions about the timing of change need to be adjusted in light of the new age models. This is especially true for the upper part of the Maogou section, where the age interpretations differ substantially (see Basin chronology in Section 2.2).

4.1. *Stable isotopes in sediments*

Dettman et al. (2003) measured $\delta^{18}O$ in sedimentary records of the Wangjiashan and Maogou sections. Based on the age model of magnetic sections (Fang et al., 2003; Li et al., 1997a), they found a major shift of $\delta^{18}O$ toward more positive direction at 12 Ma, which was interpreted to represent a reorganization of atmospheric circulation patterns along the northeastern margins of the Tibetan Plateau. Dettman et al.'s data became the basis of subsequent interpretations on precipitation records due to basin segmentation (Hough et al., 2011; Saylor et al., 2017) (see Foreland basin model in Section 2.1.4).

Fan et al. (2007) used organic carbonates and C/N ratios to characterize lake environments. They found severe aridity from 9.6 to 8.5 Ma. A Sr record from the Heilinding section also indicates a weakened weathering in paleosols, signaling an increase of sedimentation rates at ~8.6 Ma (Yang et al., 2016).

4.2. *Stable isotopes in mammalian dental enamels*

Taking advantage of the large fossil collections, Biasatti et al. (2010, 2018) examined dental enamels from mammalian herbivores (mostly horses and rhinoceros, but taxa were not further identified within family). They found that C_3 vegetation dominates the diets of these herbivores until about 2–3 Ma, in agreement with records in the interior Tibetan Plateau where vegetation was nearly uniformly C_3 (Wang et al., 2013; Zhang et al., 2012). Only during the Quaternary, a mixed diet of C_3/C_4 was detected. To examine in more detail niche partitioning of

Linxia Basin horses, Ma et al. (2023) further identified horse specimens down to species and showed strong differentiation in diets, but all consumed C_3 vegetation.

4.3. Other records

From the plant perspective, pollen records were among the first to be used as a proxy for environment and climate. Based on pollens from the Maogou section, Ma et al. (1998) found a general trend toward colder and dryer conditions, as tropical elements reduced through time. Chen et al. (2018) isolated starch granules from dental calculus of Linxia Basin rhinoceros, suggesting main diets of shrub leaves (such as Caprifoliaceae) and walnut tree leaves (Juglandaceae). Wang et al. (2022) analyzed lipid biomarkers from the Maogou section and observed an aridification event at 8.5 Ma but the age model based on Fang et al. (2003) must be updated in light of new information published in this special issue.

As to sedimentology, grain size analysis by Fan et al. (2006) from the Dongxiang, Liushu, and Hewangjia formations in the Wangjiashan and Maogou sections found that increasing proportions of the fine-grained sediments were eolian in origin, a popular view in Chinese loess research community at the time (Guo et al., 2001; Guo et al., 2002). However, the age model for these sections was substantially different from those presented in this special issue (Zheng et al., 2023), and many of their conclusions, if still correct, need to be readjusted.

Another attempt at loess studies was made for boreholes from Nalesi and Guonigou sections (Zan et al., 2018a; Zan et al., 2018b). Mature methods using magnetostratigraphy and magnetic susceptibility yielded a record of Pliocene to early Pleistocene (3.7–2.4 Ma), that was consistent with those from elsewhere on the Chinese Loess Plateau. Such a record is independent of previous age models in Maogou and Wangjiashan, and also consistent with Longdan paleontologic work (Qiu Z -X et al., 2004). Grain size analysis of these two sections confirms that the spatial pattern of modern East Asian winter monsoon was in place since the late Pliocene.

Wu et al. (2017) examined the hematite content and sediment redness in a new drill hole at Heilinding HZ-2 section, 206 m deeper than the previous HZ-1 drill core (Fang et al., 2016), reaching the late Oligocene to early Miocene part of the section. They used this record as a proxy for monsoon climate as affected by tectonism. They observed a close link between climate in the Linxia Basin during the late Oligocene through early Miocene and global temperature trends.

Most recently, Khan et al. (2023) used rock magnetic susceptibility and other records to analyze the early and middle Miocene part of the Heilinding section. They envisioned an extensively waterlogged depositional environment during the Middle Miocene Climatic Optimum, locally equivalent to their Shangzhuang Fm, and as such, the paleoenvironment in northeastern Tibetan Plateau was largely influenced by global climate during the middle Miocene.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The research described in the article depends on no new data.

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