Vertebrate fossils on the roof of the world: Biostratigraphy and geochronology of high-elevation Kunlun Pass Basin, northern Tibetan Plateau, and basin history as related to the Kunlun strike-slip fault

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ABSTRACT

The Kunlun Pass Basin, at the foothill of Yuzhu Mountain (6224 m asl and the highest peak of the Kunlun Range), records Plio-Pleistocene fine-grained sediments sandwiched between glacial moraines. We document a new vertebrate fossil assemblage, the Yuzhu Fauna, with 16 mammal and 2 fish species that provide insights into basin chronology as well as the paleoenvironment adjacent to alpine glaciations in the Pliocene, in which the mammals and fishes lived. The Yuzhu Fauna consists of the following eight small mammals: Petenymia sp., Aepyopus sp., Nanocricetulus mongolicus, cf. Orientalomys sinensis, Mimomys n. sp., Prophineus cf. P. eriksoni, Ochotona minor, Ochotona cf. O. lagreli, and eight large mammals: Rhinocerotidae indet., Hipparion (Abyssonippid), Pater, Qurliqinoria sp., Bovidae indet., cf. Panthera blytheae, Hyaeninae indet., Vulpes qiuzhudingi, and aff. Actomeles sp. Two cyprinid fishes are also included: Gymnocypris sp. and Triplophyssa sp. The Yuzhu Fauna has a distinctly early-middle Pliocene appearance, substantially earlier than previous age estimates, sharing broad similarities with vertebrate fossil assemblages from North China in general and the Zanda Fauna in southern Tibet in particular, including three carnivores (Vulpes qiuzhudingi, cf. Panthera blytheae, and aff. Actomeles sp.), one artiodactyl (Qurliqinoria), and at least two rodents (Aepyopus and Prophineus) and a lagomorph (Ochotona). We re-interpret published magnetostratigraphy to arrive at a correlation of the Yuzhu Fauna to the lower part of Chron 2Ar (Gilbert Chron 2.1–3.6 Ma), and the entire basin sequence spanning part of chron 1n through 3n, i.e., −4.9–0.5 Ma. Our revised magnetic age for the Kunlun Pass Basin strata implies a slip rate of 7.2–6.1 mm/year along this part of the Kunlun Pass strike-slip fault system, much slower than its modern rate of offset.

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investigations for its tectonic, seismic, zoogeographic, paleoaltimetry, and paleoenvironmental implications (e.g., Qian et al., 1982; Wu et al., 1982; Kidd and Molnar, 1988; Qian and Zhang, 1997; Cui et al., 1998b, 1999; Lin et al., 2002; Song et al., 2005; Wang et al., 2008; Wang and Chang, 2010, 2012).

Following an initial report of a three-toed horse (*Hipparion*) metapodial (Qian and Zhang, 1997), we have searched for vertebrate fossils in the basin since 2003. Inclement weather being a constant threat, collection of fossils was painstakingly slow. Nonetheless, after eight field seasons, a low diversity faunal assemblage, here named the Yuzhu Fauna, from the Kunlun Pass Basin is emerging with 16 mammal taxa and 2 fishes. With the exception of the fishes, all mammals are represented by fragmentary remains with small sample sizes. Although much remains to be learned of individual taxa, the specimens at hand are sufficient to advance ideas about geochronology, which in turn has important implications in the tectonics, zoogeography, and paleoenvironment of the Kunlun Pass Basin.

2. Material and method

With rare exceptions, all large mammal fossils and fishes were collected by surface prospecting. Fossil small mammals, however, were obtained by wet screen-washing, usually by shipping matrix to Beijing for processing. Approximately six tons of matrix have been processed. Members of our field team had prospectuated much of the exposures of the Qiangtang Formation along the Qinghai-Tibetan railroad and state highway G109 (shown in Fig. 1B). All fossil sites were recorded by standard GPS. Most of the fossil sites in Fig. 1B produce isolated specimens, and screen-washing was done in KL0402, 0605, and 0607 localities. We measured one section that passes through KL0402 and 0605 (as well as several other fossil sites), in an attempt to correlate our fossil sites with previously published magnetic section (Fig. 2A, B) (Song et al., 2005).

All vertebrate fossils are deposited at the Institute of Vertebrate Paleontology and Paleoanthropology (IVPP), Chinese Academy of Sciences, Beijing, China. Our usage of the Plio-Pleistocene boundary at
2.6 Ma follows a recent decision by the International Commission on Stratigraphy (Gibbard et al., 2010; Pillans and Gibbard, 2012). Abbreviations: KL, Kunlun Pass Basin locality.

3. History of studies

Chinese geologists occasionally reported in the 1960–70s glacial geology in the Kunlun Pass Basin (Du, 1964; Nanjing University Department of Geography Geomorphology Laboratory, 1974), which led to an early study of the pollen (Tang and Wang, 1976). Since 1975, geologists at the Institute of Geomechanics, Chinese Academy of Geological Sciences, made the first systematic investigation on the Quaternary glacial geology of the Kunlun Pass area (Qian et al., 1982; Wu et al., 1982). Kidd and Molnar (1988) and Kidd et al. (1988) followed with a brief investigation of the Kunlun Pass Basin with the aim of using pyroxenite outcrops and cobbles in the moraine to estimate the lateral offset of the Kunlun Pass Fault (see more discussion under Tectonic implications section). In the 1990s, scholars from the Geography Department, Peking University, initiated a series of studies on the geochronology, sedimentology, freshwater mollusks and ostracods, and paleoecology (Ge et al., 1994; Yin et al., 1996; Cui et al., 1998b, 1999). More recently, high resolution magnetostratigraphy and sedimentology were attempted by researchers from Lanzhou University (Song et al., 2005; Zhang, 2007). Much of the early efforts were concentrated on the geochronology of the basin sediments, and so far, dating of the Kunlun Pass Basin sediments has been attempted by electron spin resonance (ESR) (Cui et al., 1998b, 1999; Hu et al., 2004), thermoluminescence (TL) (Cui et al., 1998b, 1999), and magnetostratigraphy (Qian et al., 1982; Qian and Zhang, 1997; Cui et al., 1999; Qian, 1999; Song et al., 2005). Adding additional interest to the region was the discovery of Neolithic artifacts and pottery from terrace deposits in the nearby Yeniugou area (Cui et al., 1996) and Paleolithic sites in Xidatan (Brantingham et al., 2013).

Tectonically, studies have focused on the reconstruction of seismic activities related to the Kunlun Pass strike-slip fault, especially after the November 14, 2001 Ms 8.1 Central Kunlun earthquake (Lin et al., 2002, 2004; Fu et al., 2005; Lin et al., 2006). Chinese geologists are also in pursuit of what was termed the “Kunlun-Yellow River Movement” (or Kunhuang Movement) that attempts to integrate the Kunlun Range uplift with climatic and environmental change and the development of upper reaches of the Yellow River during the Pleistocene (Cui et al., 1998a; Jiang et al., 2005; Han et al., 2014).

In August 1993, while collecting paleomagnetic samples in the Kunlun Pass Basin, Qian and Zhang (1997) recovered a partial metapodial of a *Hipparion* horse (now identified as *Proboscidipparion pater*; see Faunal assemblage and biochronology section), although *Ochotona* cheek teeth and rodent incisors had been found earlier (Ge et al., 1994). Systematic explorations of vertebrate fossils by us began in 2003, and since then several mammal-producing sites have been discovered (most of low productivity) and one rich fossil fish site was also discovered (Wang and Chang, 2010, 2012) (Fig. 2D). Members of our field team have also published on mammalian enamel isotopes and paleoaltimetry that suggests an uplift of $\sim 2700 \pm 1600$ m of the Kunlun Pass Basin since $\sim 3–2$ Ma (Wang et al., 2008), in contrast to less than 1000 m estimated by fossil fish studies (Wang and Chang, 2012).

4. Stratigraphic nomenclature

Wu et al. (1982) first established the stratigraphic framework in the Kunlun Pass Basin. From the bottom upward, they recognized the Kunlun Gravel Beds ($\sim 60$ m) resting unconformably on Triassic basement followed by the Jingxian Till/Moraine ($\sim 60$ m) above, the Qiangtang Formation ($536$ m) conformably overlying the Jingxian Moraine, and topped by the Wangkun Till/Moraine ($14–20$ m), which rests unconformably above the Qiangtang Formation. Subsequent workers generally follow this scheme with variations (Yin et al., 1996). Cui et al. (1998b, 1999), however, further divided the Qiangtang Formation into deltaic-gravely Jingxiangu Formation, deltaic–lacustrine Qiangtang Formation, and fluvial–deltaic Pingtai Formation. More recently, Song et al. (2005: table 1) formally named the Kunlun Gravel of Wu et al. (1982) as the Kunlun Formation and measured a total of $\sim 680$ m for the combined thickness of the Wangkun Till, Qiangtang and Kunlun formations. In this study, we...
follow the usage of Song et al. (2005) due to its greater sample density and more detailed documentation.

5. Faunal assemblage and biochronology

Explorations by us during the past eight field seasons have yielded a small collection of fossil mammals in a fluviolacustrine deposit in the lower member of the Qiangtang Formation west of the Kunlun Pass Monument (Wang et al., 2006). We name the new mammal assemblage the Yuzhu Fauna, after Mount Yuzhu (also known as Burhan Budai), the highest peak in the Kunlun Range east of the Kunlun Pass Basin (Wang et al., 2013a). The following is a brief description of the most diagnostic taxa of the Yuzhu Fauna.

5.1. Insectivora

*Petenyia* sp. (IVPP V 19106, locality KL0402, Fig. 3A): A broken right lower incisor indicates the presence of this shrew. The incisor has a dagger-like outline with only two shallow and smooth incisements. In morphology, it is very similar to those of the latest Miocene *Paenepetenyia zhudingi* from Ertemte (Storch, 1995) or the early Pliocene *Petenyia katrinae* (Qiu and Storch, 2000) from Bilike, Nei Mongol (Inner Mongolia). However, it is much smaller in size than the incisor of *Pa. zhudingi* and closer in size to that of *Pe. katrinae*. Due to the lack of adequate material, the Kunlun Pass Basin shrew is here treated as an indeterminate species of the genus *Petenyia*.

5.2. Rodentia

*Aepyosciurus* sp. (IVPP V 19107, locality KL0402, Fig. 3L): A single broken and heavily worn lower molar (m1 or m2) confirms the presence of this unique squirrel high on the plateau. The molar has unilateral hypsodonty, and a flat, trapezoid occlusal surface, and indistinct cusps but well-developed lophids. The buccal valley (Bv) is narrow, deep into the crown, and opposite to the deepest part of the talonid basin (Tabd), closed due to heavy wear. It has four roots, the front buccal rootlet being remarkably stronger than the others. So far, the genus *Aepyosciurus* includes only the type species *A. orientalis*, which was erected by Wang and Qiu (2003) based on material from the Pleistocene loess in Linxia Basin, Gansu Province. Based on the features of the skull and cheek teeth, the genus *Aepyosciurus* was considered a kind of ground squirrel (Qiu et al., 2004). Scarce material of *Aepyosciurus* has been recorded from the Pliocene of Zanda Basin and the early Pleistocene in Linxia and Nihewan basins (Qiu et al., 2004; Cai et al., 2013; Wang et al., 2013a). The size of the molar from Kunlun Pass Basin is ca. 2.15 × 2.25 mm (length × width), which falls in the size range of *A. orientalis* from Linxia Basin (Qiu et al., 2004: table 2). However, due to inadequate material, it is here treated as an indeterminate species of the genus *Aepyosciurus*.

*Nanocricetus mongolicus* Schaub, 1934 (IVPP V 19108.1–2, locality KL0402; V 19109.1–12, locality KL0605; Fig. 3F–H): Fourteen specimens were recovered, including one M1 (1.76 × 1.22 mm, length × width), one M2, one M3, three m1s, six m2s and two m3s. This material is referred to the Neogene hamster genus *Nanocricetus* (Schaub, 1934) by having the following characters: lacking mesoloph(id)s on molars, distinctly anteriorly bilobed anterocone on M1 and quite elongated and narrow outline of m1. The Kunlun Pass Basin form is basically identical, both in size and morphology, to *N. mongolicus* from the latest Miocene of Ertemte and early Pliocene of Harr Obo (Wu, 1991), Bilike (Qiu and Storch, 2000), and Gaotege (Li, 2010) of Nei Mongol.

cf. *Orientalomys sinensis* (Qiu and Storch, 2000) (IVPP V 19110.1–2, locality KL0402; V 19111.1–5, locality KL0605; Fig. 3I–K): Seven specimens are available, including two M1s (one broken), one M3 and four m1s. The sample presents the characteristic dental morphology of the Neogene murid *Orientalomys*, such as cusp t1 being seated far behind cusp t2, cusps t4 and t5 on M1 being well separated by a wide...
valley, and accessory cusplets being well-developed on m1. The Kunlun Pass taxon seems most closely related to O. sinensis from the early Pliocene of Bilike (Qiu and Storch, 2000), from which it differs in having strongly alternating main cusps on m1 and more roots on M1 (i.e., 5 roots).

Mimomys n. sp. (Qiu and Li, 2014) (IVPP V 19112.1–7, locality KLO402; V 19113.1–4, locality KLO605; Fig. 3D–E): Eleven specimens were recovered, including four M1s (three broken), one broken M2, one M3, three m1s (two broken), and two damaged m2s. The taxon is a small-sized species of Mimomys with primitive dental morphology. It has rooted molars, without cement in the valleys. The Mimomys kante (MK in Repenning, 2003) on m1 is weak but distinctly developed, and the dentine tract (DT in Repenning, 2003) is rather smooth and weakly curved (Fig. 4). PA-index of M1 and HH-index of m1 (Carls and Rabeder, 1988) are 0.85 and 0.44, respectively, which are slightly higher than those of Ochotona (Carls and Rabeder, 1988) are 0.85 and 0.44, respectively, which are slightly higher than those of Mimomys (Aratomyx) bilkeensis (PA, 0.34/0.50/0.65; HH, 0.09/0.22/0.38, minimum/mean/maximum) from Bilike (Qiu and Storch, 2000), and fall well within variation observed in a sample of Mimomys n. sp. (PA, 0.40/0.76/1.19; HH, 0.21/0.47/0.87) from the early Pliocene of Gaotege, Nei Mongol (data from Qiu and Li, 2014). The sample includes three-rooted M1s and two-rooted M3, which also support the attribution of the Kunlun Pass Basin arvicolid to the relatively derived Mimomys n. sp. from Gaotege.

Prosiphneus cf. P. eriksoni (Schlosser, 1924) (IVPP V 19119.1–12, locality KLO605; Fig. 3M–N): Twelve specimens have been collected, including one M1, two M2s, two M3s, three m1s, two m2s, and two m3s. All molars are rooted. The outline of M1 is ω-shaped. The first couple of anterior reentrant angles, BRA2 and LRA3 (Zheng et al., 2004), on m1 are opposite in position. The anterior cap (AC) is rather round and seated near the longitudinal axis of the m1. The specimens are considered close to a sample of Prosiphneus cf. P. eriksoni from Bilike (Qiu and Storch, 2000), Nei Mongol in their large size, strongly curved dentine tract (DT), and rather high DT parameters.

5.3. Lagomorpha

Ochotona minor (Bohlin, 1942) (IVPP V 19114.1–4, locality KLO402; V 19115.1–8, locality KLO605; V 19116, locality KLO607; Fig. 3B): Thirteen specimens were recovered, including four P2s, one P3, three upper middle cheek teeth, three p3s, and two lower middle cheek teeth. The taxon has small-sized cheek teeth with simple occlusal pattern. It is nearly identical to the cheek teeth of O. minor from the latest Miocene of Ertemte, and early Pliocene of Harr Obo and Bilike, Nei Mongol in both size and morphology (Qiu, 1987; Qiu and Storch, 2000).

Ochotona cf. O. lagreli (Schlosser, 1924) (IVPP V 19117, locality KLO605; V 19118, locality KLO607; Fig. 3C): Seven specimens are available, including one P2, four P3s, one upper middle cheek tooth and one p3. The size of the p3 is 2.60 × 2.65 mm (length × width), which is substantially larger than that observed in Ochotona minor from Kunlun Pass Basin, O. nihewanica, O. picodenta, O. gracilis, O. linguisca, O. youngi, O. magna and O. zhangi from late Miocene to Pleistocene of northern China, slightly larger than O. lagreli from the late Miocene of Ertemte, Nei Mongol, and fall in the range of Ochotonaoides complicidens from the early Pleistocene of Shanxi, Shaanxi, Gansu and Hebei provinces (Teilhard de Chardin and Young, 1931; Qiu, 1985, 1987; Erbajeva and Zheng, 2005). In morphology, the p3 from the Kunlun Pass Basin has a very simple occlusal pattern with relatively small rhomboid-shaped anteroconid, opposite anteroexternal and anterointernal flexids of comparable depth, and absence of plications on the anterointernal flexid and anteroexternal fold on the trigonid. These features distinctly differ from those of the Pleistocene Ochotonaoides complicidens but fall within the morphological variation of p3 observed in Ochotona lagreli from latest Miocene Ertemte (Qiu, 1987). Considering its slightly larger size and inadequate material, we tentatively refer the Kunlun Pass Basin specimens to O. lagreli.

5.4. Carnivora

Vulpes qiu zhudingi (Wang et al., 2014): a left m2 (IVPP V 19060, locality KLO605, Fig. 5A) and a left metacarpal III (IVPP V 19061, locality KL1101) are consistent in size and morphology with this species described from Zanda Basin in southern Tibet (Wang et al., 2014). Highly hypercarnivorous dentition characterizes this species and strongly suggests relationship with the arctic fox Vulpes lagopus.

Panthera blytheae (Tseng et al., 2013): a partial right m1 (IVPP V 19064, locality KLO605, Fig. 5D) is identical in size and morphology with this ancestral pantherine. Better material is needed to allow a more confident identification.

P. arctomelas sp.: a left ramal fragment with m2 (IVPP V 19063, Fig. 5B), a right fragment of m1 paracoind (IVPP V19063, locality KLO401; possibly associated with the ramal fragment), and an isolated right p3 (IVPP V 19062, Fig. 5C) show similarities with specimens of an undescribed new species of basal meline badger from the Zanda Basin and the specimens from the Kunlun Pass Basin notably share an anterior position of the m1 paracoind tip and a general wrinkled enamel surface.

Hyaenidae indet.: a partial premolar (IVPP V 19065, locality KLO401) with robust main cusp clearly indicates the presence of a hyaenine hyaenid. While the size and robustness are comparable to those of...
Pliocrocuta or Pliohyaena, its true identity will have to wait till better material becomes available.

5.5. Perissodactyla

*Hipparion* (*Proboscidipparion*) *pater*: several limb bone and dental fragments (localities KL0401, 0502, 0601, 0602, 0603, 0605, 0607; Fig. 5E, F) indicate the presence of this three-toed horse in the Yuzhu Fauna. On the lower premolars, the metaconid is a regular triangle with a handle; its lingual angle is the sharpest and its posterior angle joins the handle; the metastylid has a handle and a sharp posterolingual angle; the lingualflexid is very broad; the entoconid is a rectangle with a handle; the hypoconulid is relatively wide. On the lower molars, the double knots are small and the lingual angle of the metaconid is not very sharp; in contrast, the posterolingual angle of the metastylid is very sharp; the entoconid is smaller with a longer handle than in the lower premolars; the ectoflexid is deep, reaching but not penetrating into the isthmus. This horse is largely confined to early Pliocene Gaozhuangian Chinese land mammal age (Qiu et al., 2013).

*Rhinocerotidae* indet.: an articulated right calcaneum, astragalus, and unciform (locality KL0601) indicate the presence of a rhino-sized mammal. Its identity is not clear at the moment.

5.6. Artiodactyla

*Qurliqnoria* sp. (Bohlin, 1937): several skull, horncore, and dental fragments (IVPP V 19070–19073, localities KL0401, 0607, 1101) unambiguously suggest the presence of this endemic Tibetan lineage, which possibly gave rise to the modern Tibetan antelope *Pantholops* (Gentry, 1968). A separate study is under way to fully describe the available material.

Bovidae indet.: horncore fragments from locality KL0401 that are not referable to *Qurliqnoria* are here tentatively treated as an indeterminate taxon pending further analysis.

5.7. Biochronology

The Yuzhu Fauna consists of the following eight small mammals: *Petenyia* sp., *Aepyceros* sp., *Namocricetus mongolicus*, cf. *Orientalomys sinensis*, *Mimomys* n. sp., *Prosiphneus* cf. *P. eriksoni*, *Ochotona minor*, and *Ochotona* cf. *O. lagreli*. Eight large mammals are represented by Rhinocerotidae indet., *Hipparion* (*Proboscidipparion*) *pater*, *Qurliqnoria* sp., Bovidae indet., cf. *Panthera blytheae*, *Hyaeininae* indet., *Vulpes qizhudingi*, and aff. *Arctomeles* sp. Two cyprinid fishes were previously described: *Gymnocypris* sp. and *Triplophysa* sp. (Wang and Chang, 2010, 2012). Overall, the Yuzhu Fauna is northern Chinese or central Asian in character. Of the above taxa, the most age-diagnostic are *Prosiphneus*, *Mimomys*, *Orientalomys*, *V. qizhudingi*, aff. *Arctomeles* sp., *Hipparion* (*Proboscidipparion*) *pater*, and *Qurliqnoria* sp., all occurring mostly in the early Pliocene of eastern Asia. *Orientalomys* and *Mimomys* are known from the Pliocene of northern China. Morphologically, the cheek teeth of the Kunlun Pass Basin *Prosiphneus* and *Mimomys* still have roots and have relatively low dentine tracts, comparable to those of the early Pliocene Gaotege Fauna in Nei Mongol. The Kunlun Pass Basin *Prosiphneus* is similar to *Prosiphneus* cf. *P. eriksoni* from Bilike, Nei Mongol, but more primitive than those from Gaotege, in size and

![Fig. 5. Selected large mammals from Kunlun Pass Basin indicative of age relationships. Vulpes qizhudingi: A1, occlusal, and A2, lingual views of left m2, IVPP V 19060 (locality KL0605); aff. *Arctomeles* sp.: B1, occlusal, and B2 lateral view of left ramal fragment with m2, IVPP V 19063 (locality KL0401), C, occlusal view of left P3, IVPP V 19062 (locality KL0605); cf. *Panthera blytheae*: D, lateral view of partial right m1, IVPP V 19064 (locality KL0605); *Hipparion* (*Proboscidipparion*) *pater*: E, occlusal view of left p3, IVPP V 19082 (locality KL0601); and F, occlusal view of partial upper cheek tooth, IVPP V 19103 (locality KL0607). All scale bars are 5 mm.](image-url)
6. Magnetic chronology

Four magnetostratigraphic columns have been published, three representing independent studies. Qian et al. (1982) first proposed a magnetic correlation of the Qiangtang Formation based on a composite of three sections with 6 normal and 5 reversed chron and an estimated age of 2.7–1.4 Ma (see also Wu et al., 1982). This early effort was followed by Qian and Zhang (1997) with a restudy of their sections with increased sampling density and the top section (sections V–VI) added to the original column. They recovered an additional normal chron toward the top and extended their correlation to Brunhes through Gauss chron, arriving at an age range of 2.90–1.65 Ma (see also Qian, 1999) (Fig. 5D). Cui et al. (1998b, 1999) published a magnetic section with no documentation of sampling density and magnetic properties. Their correlation is similar to that of Qian and Zhang (1997), i.e., 2.5–0.7 Ma (Fig. 5E). More recently, Song et al. (2005) attempted the most densely sampled section yet and were able to recover 10 normal and 9 reversed chron in a composite of a Shizishan section and a Jingxiangu section (Fig. 1). They correlated these, with the help of ESR dates, to Brunhes through Gauss chron with an age range of 3.8–0.5 Ma for the entire sedimentary package (Fig. 5B), partly because their much denser sampling yielded more reversals than did in previous studies. Although it is not possible to precisely align the above three magnetic sections, it nonetheless lends a certain measure of confidence that some of these studies came up with a roughly consistent polarity pattern, except for the top long normal chron in Qian and Zhang (1997) not found in other studies, because more densely sampled sections reveal chron of shorter durations.

Fig. 6 summarizes the previously published magnetic sections, plus our reinterpretation. The correlation of our measured section containing fossils to Song et al.’s (2005) magnetic section was based on their section description as well as the following GPS constraints (Chunhui Song pers. comm. 2012): top of section at top of the Wangkun Till N35°38′23″ E94°03′29″, bottom of the Wangkun Till N35°38′22″ E94°03′32″, 407 m mark of magnetic section E35°38′40″ E94°03′53″, boundary of Qiangtang Formation and Kunlun Formation N35°39′31″ E94°04′35″, and the beginning of their section at the bottom is at the bottom of the Kunlun Formation near Highway G109 at road mark 2893 km (no corresponding GPS coordinate) Song et al.’s sections where they initially took the magnetic samples have no GPS coordinates associated with them; they made estimates of the above GPS coordinates during subsequent resampling of the sections (Song pers. comm., 2012).

Our measured partial section with vertebrate fossils is about 1 km northwest of Song et al.’s (2005) Shizishan section (Fig. 1B), beginning at N35°39′16.2″ E94°03′36.8″ (elevation 4737 m) and ending at N35°38′35.8″ E94°03′12.4″ (elevation 4880 m). One marker bed that can be used for correlation is the fine-grained, light-colored lacustrine beds in the mid-section of the Qiangtang Formation (white dash line in Fig. 1B), which tapers off laterally toward the southeastern and northwestern ends of the exposures. The lacustrine beds are well exposed in our fossil section, with thickness of 10–20 m, and are visible in satellite images, although they tend to be isolated patches. In the magnetic section, Song et al. described nearly 100 m of lacustrine facies rich in snails, plant debris (Fig. 2C), and ostracods.

Below the fine-grained lacustrine beds is a sequence of dark gray mudstone/siltstone with high organic content, or beds 13–15 of Song et al. (2005), where most of our fossil mammals occur. However, extensive vegetation coverage and permafrost weathering make it difficult to trace the beds laterally. Locally these beds are close to exposures of basement rock just across the highway to the north (Fig. 1B). The large patch of flat-lying exposures to the east of the highway, where the fossil fishes were collected (locality KL0607), is also difficult to correlate to our main section; they are tentatively placed in the mammal-producing horizons.

Fig. 6 is a correlation of our measured section to Song et al.’s (2005) magnetic section and our re-interpretation of their magnetochrons to the Geomagnetic Polarity Time Scale ATN TS2012 (Hilgen et al., 2012). Kunlun Pass Basin vertebrate fossil localities are mostly restricted to a dark-gray to black, organic-rich siltstone in a reversed magnetic zone, previously correlated to the Chron C2r.2′ (2.6–2.1 Ma) in the Pleistocene (Song et al., 2005: fig. 7). As discussed above, however, large and small mammals from the Kunlun Pass Basin clearly suggest an age more comparable to early to middle Pliocene in Nei Mongol and the Zanda Basin. This leads us to an alternative interpretation of the magnetostratigraphy by placing our Yuzhu Fauna in the lower part of Chron 2Ar (Gilbert Chron 4.2–3.6 Ma), and the entire basin sequence spans parts of chron 1n through 3n, i.e., −4.9–0.5 Ma, substantially older than correlations from previous studies. Interestingly, our downward re-interpretation of the basin strata coincides with Cui et al.’s (1998a) speculation that the Kunlun Pass Basin began extensional subsidence around 5 Ma with an influx of basal gravels. In addition, our reinterpretation of Song et al.’s (2005) magnetic section also resulted in a substantially faster depositional rate for the lower glacial moraines (Kunlun Formation) below the fine-grained Qiangtang Formation than that shown in Song et al.’s (2005: fig. 7) correlation for the Kunlun Formation.

7. Tectonic implications

The geology of the Kunlun Pass area has played an important role in our understanding of the history of offset of the Kunlun Pass Fault (= Southern Kunlun Fault of Song et al., 2005; Central Kunlun Fault of Lin et al., 2002), which is part of a larger Kunlun left-lateral strike-slip fault system. Molnar and Tapponnier (1975) were often credited for recognizing the Kunlun fault system as playing a major role in the accommodation of shortening and eastward extrusion of the high plateau. However, little is known about the structure of the Kunlun Pass Basin, and how and if the basin was controlled by the strike-slip fault system. Wu et al. (1982) proposed a widespread Qiangtang Formation through much of what they called the Qiangtang plateau and envisioned a tectonic regime of subsidence equivalent to the total thickness of the strata. Ge et al. (1994), however, thought that the early stage of the basin formation was by extension, followed by compression, and that no glacial deposit exists at the base. Song et al. (2005:1918) also thought the basin to be “a compressional and disymmetrical pull-apart basin driven [by] the Southern Kunlun Fault” based on their observations of faulting and folding in the older sediments of the basin and an unconformable contact of the top Wangkun Till.

Given that the Kunlun Pass Basin is presently bisected by the Kunlun Pass Fault, the basin sediments offer an opportunity to constrain rates of fault propagation. Wu et al. (1982) first recognized large pyroxenite clasts within the lower moraine (their “jingxian moraine/till”) of Kunlun Pass Basin sequence that are apparently sourced from an exposure of pyroxenite 30 km to the west of the Kunlun Pass area on the north side of the Xidatan–Tuosuohu–Maqu Fault. Using this 30 km offset, Kidd and Molnar (1968: fig. 6) estimated a slip rate for the Kunlun Pass Fault of 13 mm/yr, assuming an age of 2.4 Ma for the
lower moraine. Qian and Zhang (1997), based on their magnetic age of 3.0 Ma for the lower glacial moraines, came up with a somewhat lower slip rate of fault offset of 10 mm/yr. Our revised age estimates (Fig. 5) place the lower moraine (Kunlun Formation) roughly within chron 3n.1n–3n.3n, 4.896–4.187 Ma (Hilgen et al., 2012), which translate to a slip rate of 7.2–6.1 mm/yr. This is in contrast to higher slip rates in more recent time periods, such as a Holocene slip rate of 10–15 mm/yr in the Xidatan–Tuosuohu–Maqu Fault segment (Ren et al., 1993), a 11.5 mm/yr slip rate for 40 Ka along much of the length of the Kunlun Fault (Van der Woerd et al., 2000, 2002), a 16.4 mm/yr slip rate for the Kunlun Pass Fault during the past 7000 years (Lin et al., 2006), and a 12–14 mm/yr slip rate for the Kunlun Fault system at present as measured by the Global Position System (Wang et al., 2001; Lin et al., 2002). Our lower slip rate seems to suggest a slower fault movement during the early history of basin development. If this is the case, a counter clockwise rotation of 11° during the deposition of the Wangkun Till (0.7–0.5 Ma) may indicate a signiﬁcant change in structural deformation (Song et al., 2005).

Fig. 6. Biostratigraphic and magnetic correlations for Kunlun Pass Basin. Our partial biostratigraphic section (C) shows horizons of vertebrate fossil localities (locality KL0401, etc.) and leaves, as well as measured segments (0702 through 0714). Fossiliferous horizons are roughly comparable to levels 13–15 of Song et al. (2005: fig. 7) (E). Our re-interpretation of the magnetic correlation of Song et al.’s section to the ATNTS2012 (Hilgen et al., 2012) is to the left (A). Two previously published magnetic sections by Qian and Zhang (1997) (D) and Cui et al. (1998b) (E) are included for comparison. Solid circle at base of section III in Qian and Zhang (1997) indicates the horizon of the Hipparion metapodial, which also falls in a reversed interval as does our fossil sites. Note each of the authors have differing stratigraphic concepts, as well as scale.
constraint in basin chronology, and by extension, the offset history of the Kunlun Pass Fault.

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