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Danghe area (western Gansu, China) biostratigraphy and implications for depositional history and tectonics of northern Tibetan Plateau

Wang Xiaoming[a,b,*], Wang Banyue[b], Qiu Zhanxiang[b], Xie Guangpu[c], Xie Junyi[d], Will Downs[e], Qiu Zhuding[b], Deng Tao[b]

[a] *Department of Vertebrate Paleontology, Natural History Museum of Los Angeles County, 900 Exposition Boulevard, Los Angeles, CA 90007, USA*
[b] *Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences, P.O. Box 643 Beijing 100044, PR China*
[c] *Natural Science Department, Gansu Provincial Museum, No. 3 Xijingxi Road, Lanzhou 730050, Gansu, PR China*
[d] *Cultural Relic Archaeology Institute of Gansu, No. 3 Xijingxi Road, Lanzhou 730050, Gansu, PR China*
[e] *Department of Geology, Northern Arizona University, Flagstaff, AZ 86001-4099, USA*

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Abstract

The Danghe area in western Gansu Province is at the focal point of interaction of the northeastern end of the left-lateral Altyn Tagh Fault and growing ramp thrusts of the Danghe Nanshan Mountains along the northern rim of the Qinghai–Tibetan Plateau. With a thick sequence of Tertiary sediments and associated fossil records, the Danghe area is one of few places on the Tibetan Plateau that can offer integrated studies of its tectonic history, depositional environment, and biological records, including vertebrate and plant fossils. Past studies, however, have not been able to capitalize on the paleontological data or were often misguided by an outdated notion of regional chronology. Incorrect age estimates in these studies often have profound effects on tectonic interpretations. We present new stratigraphic and paleontologic evidence from the Danghe area and demonstrate a new chronologic scheme that indicates a much younger age for the majority of the sediments. We recognize three packages of sediments in the Danghe area: (1) Oligocene Paoniuquan (new name) Formation, basal, predominantly fine-grained, dark purple mudstones and siltstones that include the classic Yindirte Fauna, which forms the basis of the Tabenbulukian mammal age; (2) early Miocene to early late Miocene Tiejianggou (new name) Formation that contains a new platybelodont proboscidean in a coarsening-upward sequence terminating in a massive conglomerate; and (3) an unnamed late Neogene formation that contains another coarsening-upward sequence. In light of our new stratigraphic framework, we reinterpret a previously published magnetic column for the middle sequence in Xishuigou as representing chrons C6n through C4Ar corresponding to a span of about 20–9.3 Ma, much younger than has been realized so far. This new chronological framework suggests a depositional history of the Danghe Nanshan that spans at least the early Oligocene through late Miocene, to possibly Pliocene. Early depositions during the Oligocene through middle Miocene are dominated by fine-grained sediments indicating a distant source of sedimentation. Paleontological data suggest a relatively dry environment, as is typical of northern China today. By late Miocene

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* Corresponding author. Tel.: +1-213-763-3310; Fax: +1-213-746-7431. *E-mail address:* xwang@nhm.org (X. Wang).

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(around 9–12 Ma), the Danghe area began to receive coarse sediments and was much closer to the mountain front. The new stratigraphic framework indicates an earlier onset of sedimentation than has generally been assumed, but also suggests the presence of sediments much younger than many have realized.

Keywords: Tertiary mammals; stratigraphy; tectonics; Tibetan Plateau

1. Introduction

The Danghe area (formerly known as Taben-buluk area) of western Gansu Province is well known among vertebrate paleontologists since the 1930s for its rich mid-Tertiary mammalian fossil beds that were discovered and described by Swedish paleontologist Birger Bohlin (Fig. 1). Bohlin's most representative fauna of the area, the Taben-buluk fauna, was later chosen as the name-bearer of a late Oligocene Asian mammal age [1–6]. The Danghe area has recently gained worldwide attention among geologists interested in the tectonics of the northern Tibetan Plateau in general and the timing and magnitude of movement on the Altyn Tagh Fault (ATF) in particular [7]. Increasing significance has been placed on the sinistral faulting along the ATF and thrusting in the northern foothills of large mountain ranges (Danghe Nanshan, Daxue Shan, and Qilian Shan) as an important mechanism for accommodating the crustal shortening and thickening, northeastward extrusion, and uplifting of the northern rim of the Tibetan Plateau [8–10].

Although Tertiary deposits are scattered along much of the northern rim of the Tibetan Plateau, the Danghe area offers three advantages for studies of tectonics: (1) a thick sequence of more than 3000 m of mountain foreland deposits bears direct evidence of local uplifts of the Danghe Nanshan; (2) both the ATF and the frontal thrust faults truncate the Tertiary deposits; and (3) the Danghe area is the only Tertiary deposit that has a rich fossil vertebrate record that offers a tight constraint on the timing of these tectonic activities.

We present new paleontological data spanning much of the Tertiary sequence in the Danghe area, and these bear directly on the question of the ages of these deposits. We now possess fossils representing at least five stratigraphic levels (in contrast to Bohlin's single fauna) ranging from early Oligocene to middle Miocene and possibly later. A new stratigraphic framework can now be proposed based on the new fossil finds. In light of the new data, we suggest an alternative correlation of a paleomagnetic section in Xishuigou [11] with an age range of 20–9.3 Ma. On the basis of this new chronology, a different scenario of the uplift of the northern rim of the Tibetan Plateau can now be proposed.

2. Abbreviations

IVPP, Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences, Beijing; Dh, IVPP Danghe locality numbers; Tb, Taben-buluk specimen numbers in Birger Bohlin collection.

We adopt the abbreviations used by Van der Woerd et al. [12] for geological structures in the Danghe region. ATF, Altyn Tagh Fault; F0, thrust fault south of S0; F1, thrust fault south of S1; S0, syncline of massive conglomerates near the Danghe Nanshan range front; S1, syncline of massive conglomerates near the ATF.

3. Geologic setting

Located approximately 100 km southwest of Dunhuang and 20 km west of Subei Mongolian Autonomous County, the Danghe area lies west of the Danghe River on the northern foothills of the Danghe Nanshan at the western end of a series of NW–SE-trending mountain ranges such as the Qilian Shan and Daxue Shan (Fig. 1). At an elevation of 2500–3000 m, the Danghe area is currently at the northern forefront of the Danghe

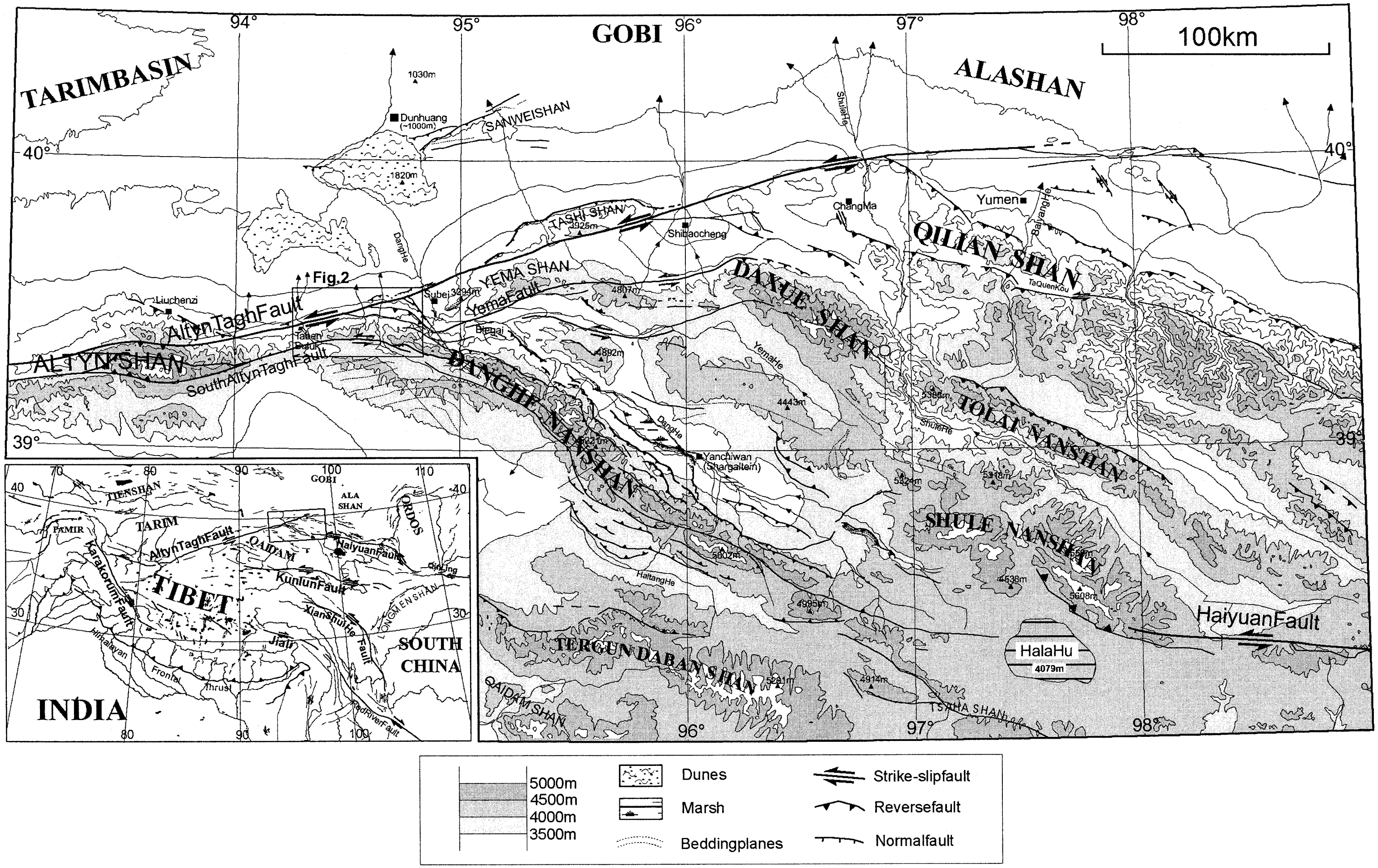


Fig. 1. Map of the northeastern Tibetan Plateau, modified from Van der Woerd et al. ([12], figure 1). The Danghe area is at the junction of the ATF and the western end of the frontal thrust fault of Danghe Nanshan. Tertiary deposits form along much of the Danghe Nanshan range: Yanchiwan to the east, Biegai in the middle, and Taben-buluk to the west, and were intimately related to the Danghe Nanshan orogeny. Some sediments in the Taben-buluk area may have been laterally displaced to Liuchengzi [18,23]. Inset is location of figure in relation to the entire Tibetan Plateau.

Nanshan, north of which are Holocene fans that form the Gobi plains gradually lowering to 1200 m in elevation.

Deposition of the Danghe area is intimately related to the uplift of the Danghe Nanshan. Massive Tertiary conglomerates are distributed along the piedmont of the Danghe Nanshan range, which supplies clastic material for later Tertiary and Quaternary sediments. Similar deposits are found in the Biegai area (Pieh-kai) ([13], map 3), 10 km southeast of Subei County, and Yanchiwan Basin (Shargaltein) [13–15], 100 km further southeast along the Danghe River [13,14] (Fig. 1). There are at least two major episodes of rapid deposition of the massive conglomerates, each preceded by a long sequence of finer-grained red beds.

One of the most prominent tectonic features in the region is the sinistral ATF, which, with a horizontal distance of ~2000 km, figures prominently in the interpretations of the convergence of the Indian and Eurasian plates and the northeastward extrusion of the northern Tibetan Plateau [7,12,16–24]. The Danghe area is located at the junction of the ATF and western end of the Danghe Nanshan. The ATF is particularly active along its northeastern tip, where it ends with a NNE-vergent thrust system that transforms the strike-slip movement into crustal thickening and mountain building [17,25,26]. Locally, the ATF cuts through the Tertiary sediments in the Danghe area and may have displaced a northern segment of the basin to the Liuchengzi area some 67–75 km to the west (Fig. 1) [18,23].

Recent geologic and geomorphic studies of the eastern half of the Danghe area by Van der Woerd et al. [12] and Yin et al. [24] laid the foundation for the basic tectonic framework for the region. A combination of sinistral strike-slip displacement along the ATF, a series of ramp thrusts splaying from the ATF and cutting the Tertiary sediments into a series of imbricate wedges, and folding within each segment of the wedge define the basic structural characteristics of the region (Figs. 2 and 3). The Danghe area is a slender east–west-oriented wedge bending southeastward near its eastern end. The northern bound of the Tertiary deposits is delineated by the ATF in the western half and by thrust faults in the eastern half starting at the southeastern bend of the wedge. This northern boundary of the basin is in fault contact with Quaternary conglomerates. The southern boundary of the basin is delineated by frontal thrusts (F0 and F′0, or southern branch of the ATF in Yin et al.) that brought the red beds in direct contact with basement rocks (Precambrian Danghe or Duoruo Nor groups). Extensive faulting obscures the original depositional contact with the basement rock. The strike-slip and thrust faults and folds are the main mechanisms of plate shortening and uplift of the Danghe Nanshan range at the northern edge of the Tibetan Plateau. Northward migrations of a series of shallower thrust faults (F″1, F1, F2, etc.) absorb the more recent shortening, as the older thrusts near the range front have mostly ceased to be active. The thrusts are postulated to root into a master ramp under the range [12], and may penetrate the upper crust in much of the northern Tibetan Plateau [10,19,21]. Van der Woerd et al. estimated an accumulated shortening of 10–20 km along the range front from a combination of the thrusting, strike-slip displacement, and folding. The deep thrust faults stack wedges of imbricate packages against each other, and bring into contact sediments of completely different ages. Such deep faulting, coupled with large-scale folds, makes stratigraphic interpretations extremely challenging without a sound stratigraphic framework. The recent paleomagnetic study by Gilder et al. [11] suggests a substantial counterclockwise rotation of 27° ± 5° in the Danghe area, in contrast to a much smaller rotation of 7.3° ± 7.6° postulated by Rumelhart et al. [20].

4. Stratigraphic framework

In an unofficially published geologic report, Sun [27] created the terms Baiyanghe and Shulehe formations for the widely distributed mid-Tertiary continental deposits of the Yumen district, some 200 km northeast of the Danghe area. This work served as the basis for later geologists to assign the fossil-bearing deposits of the Taben-buluk–

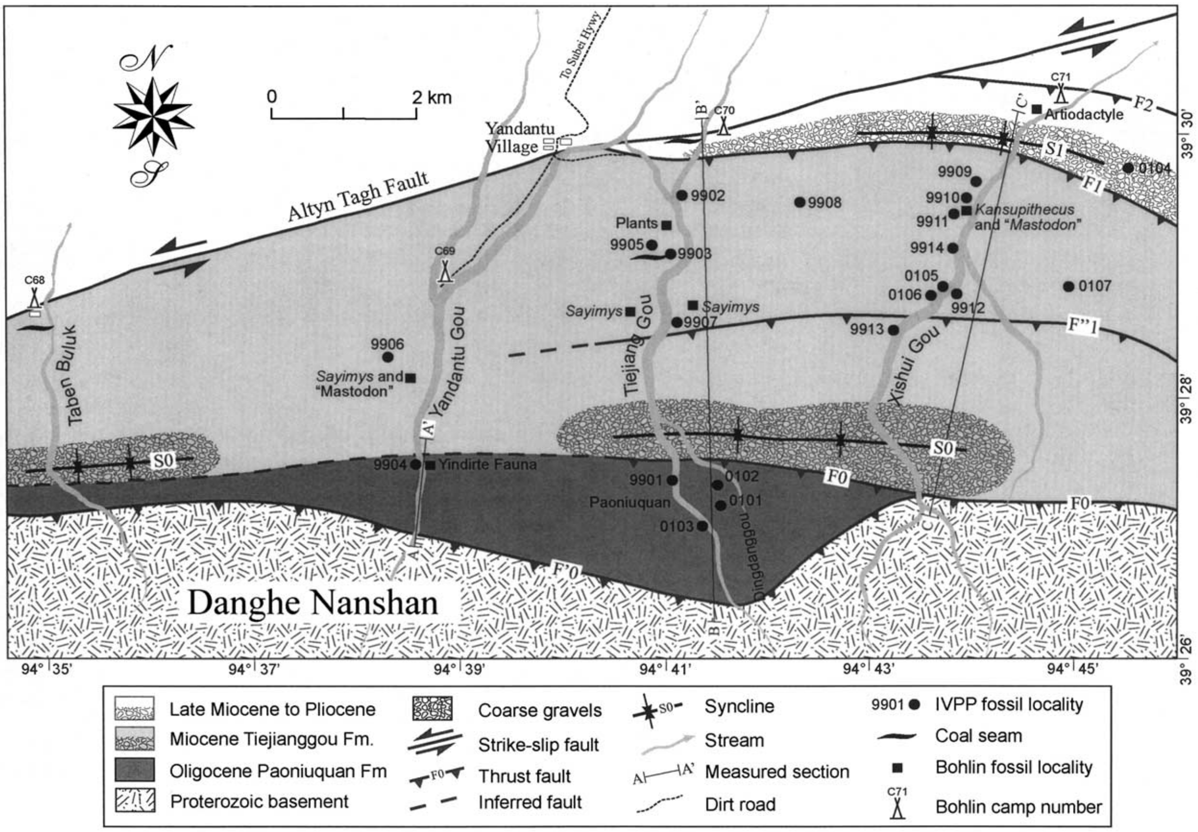


Fig. 2. Geologic map of the Danghe area and distribution of fossil localities. All geological boundaries are mapped on a 1:50 000 Chinese topographic map (Yandantu Quadrangle). We follow Bohlin [13] and Subei Geological Map [28] for geological boundaries in the western area (along Taben-buluk) in the map. Northern boundaries for the massive gravels along the syncline axes are approximate because grain size changes are gradual. IVPP fossil localities are plotted using GPS data, and selected Bohlin localities are plotted from unpublished maps from Birger Bohlin Archive in Folkens Museum Etnografiska (Stockholm). Terminology for major faults and folds follows that of Van der Woerd et al. [12], except the F′0 which is not in their system. See Figs. 3 and 4 for cross-sections and measured stratigraphic columns.

Xishuigou area to either the Baiyanghe or Shulehe Formation, or both [28–30]. Unfortunately, later authors mostly missed or ignored the nuances and warnings repeatedly mentioned by Bohlin, and were often content in citing Bohlin for a late Oligocene age for the entire sequence (e.g. [18,23]).

Although Bohlin did not formally name the Danghe beds, he [13,31,32] envisioned a system of three informal units within a single upward-coarsening sequence for the Danghe area: (1) the lower package of 'brick-red sediments, consisting of clayey and sandy silts, sandstone and scarce, fine conglomerate'; (2) the middle beds of 'purplish red clayey and sandy silt, sandstone, and moderately coarse conglomerate'; and (3) the upper package of 'coarse conglomerates and brown sandstone in very heavy beds' marking the final stage of the accumulation of the Tertiary sediments. These beds are generally laterally (east–west) extensive and often correlative across different streams.

Lacking a coherent fossil sequence and without the benefit of modern tectonic data, Bohlin's stratigraphic model strayed in several aspects. Firstly, Bohlin assumed the two major synclines formed by conglomerates in the northern and southern part of the basin represented the same strata, i.e. between these synclines is an assumed anticline. As demonstrated by Van der Woerd et al.'s [12] model of imbricated wedges, the two synclines represent entirely different sequences of sediments. Secondly, Bohlin's brick red-purplish red-coarse conglomerate sequence is also flawed. In Tiejianggou, Bohlin ([13], section 3) correlated the long sequence of red beds south of S0 with a small segment near the northern end of the section. Our paleontological data contradict this correlation (see below). Consequently, thirdly, Bohlin's division of 'brick red' and 'purplish red' beds is not satisfactory. Although within the Miocene part of the section Bohlin's division seems right (this can be confirmed visually from a distance standing at the village of Yandantu), he overextended this relationship to rocks north of F1, which actually belong to the Mio–Pliocene part of the section (S1).

Our own field observations indicate three major sequences of deposits in the Danghe area, all bounded by thrust or strike-slip faults, as described below.

4.1. Paoniuquan Formation (Figs. 3 and 4)

At the base, the first sequence is mostly composed of fine-grained red beds. Toward the bottom, the red beds are in fault (F′0) contact with the basement rocks of the Danghe Nanshan, and an unknown amount of this basal sequence is truncated by the fault. At the top, it is bounded by a major thrust fault (F0) and is in contact with the next sequence above (a massive conglomerate and red beds). Distributed as an east–west-oriented narrow strip, the eastern end of this sequence tapers off just west of the Xishuigou and thus was missed in the studies by Gilder et al. [11], Van der Woerd et al. [12], and Yin et al. [24]. This section is itself fractured by two or more faults along its length and the beds are strongly folded in between faults. This sequence was assigned to the Baiyanghe Formation by various geological survey teams [30,33]. However, according to Sun [27], who originally defined these terms, the Baiyanghe Formation in the type section just east of Yumen (see Fig. 1) is composed mainly of red clayey sandstone in the lower part and red and green claystone capped with white and yellow coarse sandstone, with gypsum and impregnated with oil, about 300–320 m thick. The different lithology of the two areas renders it difficult to assign them to the same formation. From a tectonic point of view, Burchfiel et al. [34] suggested that the Tibetan Plateau had been growing toward the northeast, which resulted in progressively younger, northeastward-migrating deformations and later onset of sedimentation of foreland basins. Métivier et al. [35] also proposed a northeastward growth of the northern Tibetan Plateau along the ATF and related depositional history of the Qaidam and Hexi Corridor basins. If this model is correct, foreland basins in the Danghe area and Yumen area are likely of different ages. Indeed, recent paleomagnetic and ESR investigations indicate a much younger age of 13–0 Ma for the Yumen sequence in Jiuxi Basin [36,37]. We designate this partial sequence the Paoniuquan Formation, after the name of a local spring near the southern end of the Tiejianggou. A type section is selected along the segment between the F0 and F′0 in the Tiejianggou.

4.2. Tiejianggou Formation (Figs. 3 and 4)

The second sequence is characterized by fine-grained red beds gradually coarsening to massive conglomerates. This middle sequence is fault-bounded both above and below by thrust faults (F0 and F1). High competence of the conglomerates permits this sequence to be relatively resistant to heavy deformation and its bedding sequence is relatively undisturbed. Besides minor faults in the lower and middle part of this sequence, structurally it forms an asymmetrical syncline with its southern limbs variously truncated at different streams. At Tiejianggou the southern limb is almost entirely truncated, whereas a small segment (650 m in thickness) of the southern limb is preserved at Xishuigou. The axis of the syncline is marked by a layer of conglomerate that can be used as a marker for correlation. Where lateral changes of lithology are drastic, as is the case between Tiejianggou and Yandantu (the latter

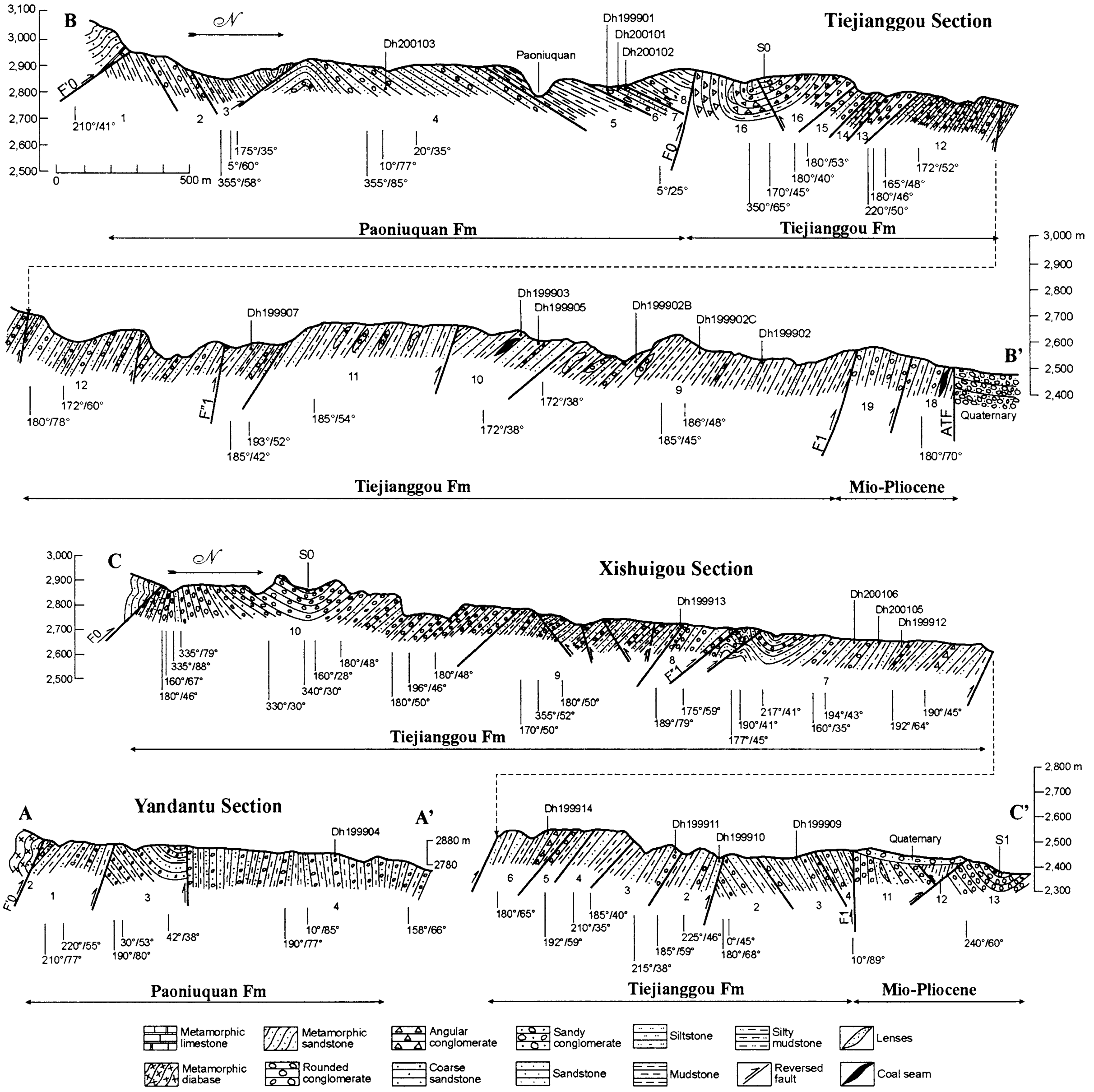


Fig. 3. Measured sections along Tiejianggou (B–B′), Xishuigou (C–C′), and lower section of Yandantu (A–A′) (see Fig. 2 for locations of the sections). Numbers in the sections represent bed numbers (from lower to higher) that correspond to those in Fig. 4. Major structural features are indicated by capital letters (e.g. F0, F1, S0, ATF). IVPP fossil localities (e.g. Dh200101) are indicated along the top of the section.

lacks the large conglomerate), the extensive coverage by terrace seriously hinders visual observation of stratigraphy. Such difficulties have led to erroneous tracing of the S0 that makes a northward detour west of Tiejianggou and loops back to S0 at Taben-buluk [28]. We are in agreement with Bohlin [13] that the absence of S0 conglomerates at Yandantu is better interpreted as a lateral facies change (Fig. 2).

This sequence has also been referred to as

Baiyanghe Formation [30,33]. As stated above, the 300–320 m thick Baiyanghe Formation is mainly fine-grained sediments with gypsum and is impregnated with oil. The upward coarsening of the deposits and the predominance of large-sized clasts (up to 2 m in diameter) in the breccias of this second sequence in the Tiejianggou section certainly represent a proximal fan facies of a rapidly uplifted mountain range. It strongly contrasts with the fluvial facies of the Baiyanghe Formation in the type section as described by Sun [27]. Furthermore, our fossil records for this sequence suggest a completely different age from that of the type area in Jiuxi Basin [36]. Therefore, a new name is given for these sediments, the Tiejianggou Formation, with type section designated along the Tiejianggou between the F1 and F0.

4.3. Unnamed formation in late Miocene to Pliocene (Figs. 3 and 4)

The third sequence is represented by another sequence of fine-grained red beds coarsening upward to a massive conglomerate. This upper sequence is mainly present at the entrance of the Xishuigou and tapers off toward the Tiejianggou (only a small remnant is present at its entrance). Its lower boundary is cut by the ATF and F2 and its upper boundary is in fault contact (F1) with the Tiejianggou Formation in the middle sequence. As in the middle sequence, the top conglomerates in the upper sequence indicate an asymmetrical syncline. So far this unit is poorly dated.

5. Paleontological data

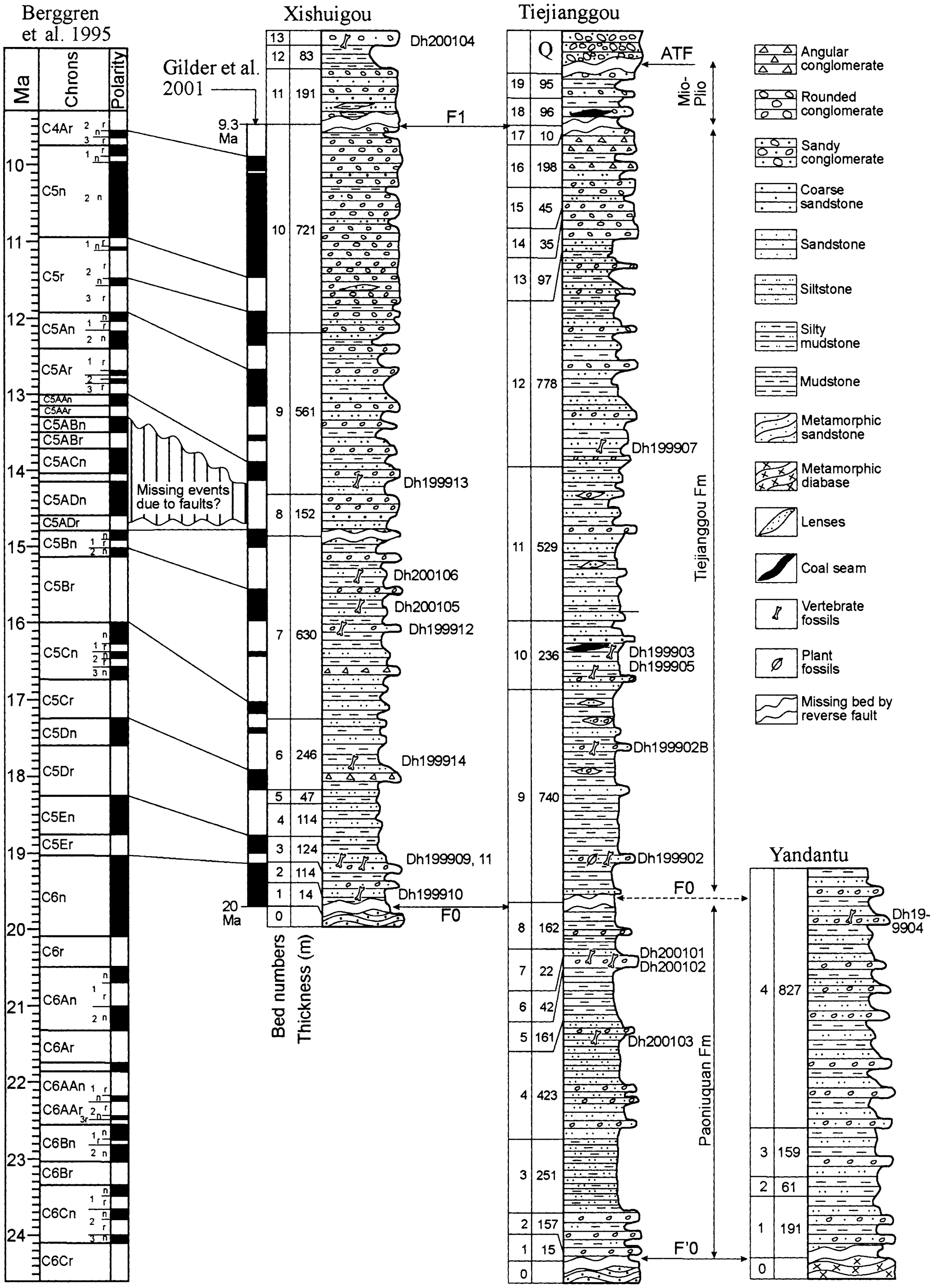
Paleontological data come mainly from two sources: (1) specimens collected by the Sino–Swedish Expeditions during the 1931 and 1932 field seasons and published by Bohlin [31,38,39] and Chaney [40]; (2) specimens collected in our 1999 and 2001 field seasons and now under study. Both collections are housed in the IVPP. Locality numbers are indicated in the measured sections (Figs. 3 and 4).

5.1. Dingdanggou Fauna, late early Oligocene

The earliest mammal assemblages occur in the southernmost section of Tiejianggou and Yandantu in the Paoniuquan Formation. Despite their still poorly known status, our newly discovered fossils from Dh200101–03 in Dingdanggou, a small tributary of the Tiejianggou, appear to be somewhat older than the Yindirte Fauna at Dh199904. The stratigraphically lowest locality in the Danghe area is Dh200103. Two taxa were found in 2001: *Desmatolagus gobiensis* and *Cyclomylus* sp. Both are restricted to the early Oligocene of Mongolia and China [6]. Dh200101–02 localities, about 260 m (thickness) above Dh200103, yielded four small mammals: *Desmatolagus gobiensis*, *Desmatolagus pusillus*, *Tataromys* cf. *T. sigmodon*, and *Amphechinus*? sp., and three large mammals: *Sivameryx* sp., *Phyllotillon* sp., and ?*Aprotodon* sp. Most of the small mammals range through much of the Oligocene. *D. gobiensis*, however, is restricted to early Oligocene only [41]. The stage of evolution of *Phyllotillon* may indicate an early late Oligocene age around 27 Ma.

5.2. Yindirte (Yandantu) Fauna, late Oligocene

Bohlin's Yindirte (now Yandantu) Fauna in Yandantu valley and the equivalent assemblage from Dh199904 across the canyon is still the single most completely known faunal assemblage from the Danghe area. The Yindirte Fauna lies on the right (eastern) bank of Yandantu in three vertical coarse sand to fine conglomerate beds (called 'wings' by Bohlin). After treatments with H_2O_2, materials from this locality proved far richer than Bohlin had originally realized during his first visit in 1931, and he was able to make a second trip there in 1932. Despite our careful efforts to search for fossils in Bohlin's original three vertical beds on the eastern side of the canyon, we were unable to duplicate his finds in the field and only a few bone fragments were recovered. We were, however, able to find enough material in three vertical fine gravel beds on the opposite side of the canyon (western bank) to suggest



Xishuigou bed	Thickness (m)
13	
12	83
11	191
10	721
9	561
8	152
7	630
6	246
5	47
4	114
3	124
2	114
1	14
0	

Tiejianggou bed	Thickness (m)
Q	
19	95
18	96
17	10
16	198
15	45
14	35
13	97
12	778
11	529
10	236
9	740
8	162
7	22
6	42
5	161
4	423
3	251
2	157
1	15
0	

Yandantu bed	Thickness (m)
4	827
3	159
2	61
1	191
0	

Fig. 4. Stratigraphic columns of the Danghe area and an alternative correlation of the paleomagnetic section from Xishuigou by Gilder et al. [11]. Fault contact relationships between adjacent beds may not reflect actual contacts (see Fig. 3) due to restoration of bed sequences. Bed numbers to the left of each column correspond to those in the measured sections in Fig. 3. Thickness of beds (numbers on left of column) often represents minimum estimates if the bed concerned is bounded by reverse fault(s). Important fossil locality numbers are indicated to the right of the columns (Tb, Bohlin fossil specimen numbers; Dh, IVPP vertebrate fossil localities of this study). Geomagnetic polarity timescale follows Berggren et al. [64].

that two of these (Dh199904A,C) seem correlative to those on the right bank.

The orientation of the three beds was a matter of some concern to Bohlin ([38], p. 242), who concluded that the top of the three beds dips toward the south. Bohlin acknowledged that it is difficult to ascertain the orientation in the field because the local sections are all fault-bound and extensively folded. His conclusion seems mainly based on his judgment of mammal composition from the three beds. If the sequence in our new Tiejianggou localities (Dh200101–03) is correctly established (younger rocks toward the north), a similar orientation might be present in Dh199904 in Yandantu, contrary to Bohlin's interpretation (see Figs. 3 and 4).

Bohlin's [31,38] earlier work remains the primary source of information for the Yindirte Fauna. The following faunal list is based on recent updates by Russell and Zhai [2], Wang [5], Wang and Qiu [42], and new forms discovered in our own field studies [43]: *Amphechinus* cf. *A. rectus*, *A. minimus*, *Desmatolagus* sp., *Sinolagomys kansuensis*, *S. major*, '*Sciurus*' sp., *Eucricetodon* sp., *Tachyoryctoides* sp., *T.* cf. *T. obrutschewi*, *Yindirtemys grangeri*, *Y. ambiguus*, *Y.* sp., *Parasminthus asiae-centralis*, *P. tangingoli*, *P. parvulus*, *Heterosminthus lanzhouensis*, *Litodontomys huangheensis*, *Eomyodon dangheensis*, *Didymoconus* sp., *Eumeryx* sp., *Schizotherium*? sp., Rhinocerotidae indet., and Primate indet.

On the basis of the Yindirte Fauna, Li and Ting [1] proposed the term Tabenbulukian mammal age, which is widely regarded as the last mammalian age in the late Oligocene of East Asia (e.g. [3,4,6,44]).

5.3. Xishuigou Fauna, early Miocene

The Miocene Tiejianggou Formation is bounded by two major thrust faults, F0 and F1, and is well exposed in all major stream sections. Representing the bulk of the Danghe sediments, this part of the section produced the largest number of fossil localities, including one plant locality, although most localities produced no more than a few specimens. Bracketing a thick conglomerate, this sequence is also the most resistant to deformation and best preserves the original stratigraphic context.

Chaney ([40], p. 94) initially argued for a Pliocene age for plants collected by Bohlin from Tiejianggou, partly because he thought that these plants were contemporaneous with the Tunggur Formation (then considered Pliocene in age) of Inner Mongolia. Bohlin's Tiejianggou plant locality is in the lower part of the Tiejianggou section within the predominantly fine-grained red beds (Fig. 2). Subsequent publications of fossil mammals clearly indicate an older age. Bohlin [31,38] was keenly aware of the mixed nature of his mammal collections. To him, the occurrence of *Sayimys* (Tb 261, 268 and 279 from Tiejianggou; Tb 254 from Yandantu) and '*Kansupithecus*' in the middle of Yandantu, Tiejianggou, and Xishuigou sections (see Fig. 2) represents a faunal assemblage totally different from the rest of his collection. He was quite convinced of the existence of Miocene deposits in this area, but lacking a reasonable structural and stratigraphic framework, he was unable to put these localities into a proper context. Independently, studies on early catarrhine primates in East Asia also suggest an early Miocene age for '*Kansupithecus*' [45–49].

Our own fieldwork not only confirms Bohlin's suspicion about a Miocene fauna but also substantiates the faunal composition and basic stratigraphic orientation of the Miocene section. Near the base of this sequence are the Dh199909–11 localities from Xishuigou. In particular, Dh199910 and 199911 yielded a small number of mammals based on well-preserved specimens and here designated the Xishuigou Fauna: *Platybelodon* sp., *Turcocerus* sp., *Amphimoschus* cf. *A. artenensis*, and a new form related to the primitive mustelid *Schultzogale*. Compared to elements from the middle Miocene Tunggur Formation of Nei Mongol, the horn-core of the Danghe *Turcocerus* is smaller and less twisted than that of either *T. grangeri* or *T. noverca*, indicating an earlier stage of evolution. The Danghe *Platybelodon* also differs from the Tunggur species (*P. grangeri*), although it is represented by a juvenile lower jaw with characteristics not completely comparable [50]. *Amphimoschus* is mostly known in the early Miocene of Europe. Li et al. [51] mentioned an occurrence in the early Miocene Xiacaowan Fauna (Shanwangian) of Jiangsu Province, but did not describe it in detail. The nearly complete lower jaw and upper cheek teeth from Danghe seem best comparable to *A. artenensis* from MN 3–4 of Europe. Finally, the new mustelid carnivoran appears closely related to a recently described genus and species *Schultzogale* from the early Hemingfordian of Nebraska, believed to be the most primitive member of the subfamily Leptarctinae [52]. The Chinese and American forms share double temporal crests and a narrow upper first molar typical of this genus. The Danghe form, however, is probably somewhat more derived in its larger size and parallel anterior and posterior borders of the M1. Dental morphology of *Schultzogale* is also close to that of the European early Miocene *Plesiogale* and *Paragale*, which share a similar primitive stage of evolution among basal mustelids. Overall, the Xishuigou assemblage indicates an early Miocene age around 17–18 Ma.

It is likely that Bohlin's '*Kansupithecus*' (Tb 309) was collected from near Dh199910 (map in Bohlin Archive). We were unable to find additional material of this intriguing primate. However, Bohlin [38] mentioned a partial radius of a large 'Mastodont', a cervid tarsal, and a partial metatarsus of a rhino, all from his locality Tb 308, which is very close to where '*Kansupithecus*' was discovered (Tb 309). Although it is not possible to ascertain if these forms are the same proboscidean or cervid as those in our new collection, it does suggest that the '*Kansupithecus*' locality is nearby or identical with Dh199910.

In Tiejianggou, the Dh199903 locality, located within a narrow coal seam, may be laterally equivalent to the Dh199910–11 and yielded an upper and lower jaw of *Heterosminthus* sp. This zapodid rodent is morphologically transitional between *H. orientalis* from the middle Miocene Tunggur Formation of Nei Mongol [53] and the uppermost Xianshuihe Formation of Lanzhou [54], and *H. lanzhouensis* from the late Oligocene lower red mudstone of the Xianshuihe Formation [41,42]. North of Dh199903, we were able to relocate Bohlin's fossil plant locality (Dh199902) described by Chaney [40].

Further along the Xishuigou section, Dh200105 yielded a pair of lower jaws of *Litodontomys* sp. The only Asian species of this genus, *L. huangheensis*, occurs in the Yandantu Fauna as well as the lower member of the Xianshuihe Formation in Lanzhou [41,42]. Simpler occlusal patterns in this specimen may indicate a more derived condition, but the character polarity and age estimate are difficult to determine when compared to a single known species.

The topmost locality along the Miocene section of the Xishuigou is Dh199913, which produced a right metacarpus III of a chalicothere. Preliminary identification indicates that this hand bone may belong to an unusually large *Phyllotillon*. Lacking better materials, it is difficult to estimate how much younger this locality is relative to Dh199910. However, based on Bohlin's archive data, three of the *Sayimys* localities in Tiejianggou and Yandantu are at approximately the same level as Dh199913 and are scattered on either side of the F″1 thrust fault (Fig. 2). *Sayimys obliquidens* was described by Bohlin [38] from the Yandantu and Tiejianggou valleys. The crowns of the cheek teeth are higher than those of the early Miocene *Sayimys minor* and *S. intermedius* from South Asia and *Sayimys* sp. from Sihong of Jiangsu Province and subequal to those of middle Miocene *S. sivalensis* from South Asia. On the other hand, *S. obliquidens* retains some features that seem more primitive than those of the above-mentioned species. This is in general accordance with the age assignment provided by the *Platybelodon* fauna.

5.4. North Xishuigou section (S1 and its underlying red beds), Mio-Pliocene

Van der Woerd et al. [12] postulated a Plio–Pleistocene age for the red beds and conglomerates in the vicinity of the S1 axis, based on their structural interpretations of the thrust faults. S1 is in fault contact with the northern limb of the S0 near and to the south of the S1 axis. Van der Woerd et al. interpreted it as a thrust fault, an interpretation that we agree with, and if so, the beds around the S1 must be younger than those at the northern base of S0.

Bohlin ([38], p. 248) reported 'a lower jaw fragment of a more modern-looking artiodactyle' (Tb 307) from approximately 1 km west of his Xishui camp number 71 (see Fig. 2). This is one of the most northern fossil localities in Bohlin's collection, and he ([38], pp. 213–214, plate VIII, figures N and O] compared this bovid with species of *Gazella* and *Tragoreas lagrelii*. Although far from convinced that this may be a late Miocene bovid, he commented that 'it might indicate that a limited amount of younger sediments enter the folded lower series of the Taben-buluk deposit'.

Our own search for fossil evidence yielded only one site (Dh200104) where a fragment of a proboscidean distal humerus and broken turtle shells are found. The poor state of preservation does not permit further identification beyond Proboscidea indet. As such, the age is constrained only to early Miocene or later. Given that F1 is a thrust, and assuming the conglomerates in S0 and S1 represent different ages, this second package of conglomerates should be at least younger than 9 Ma (the age of S0 as estimated from the paleomagnetic section below).

6. Reinterpretation of magnetostratigraphy

Gilder et al. [11] measured a partial paleomagnetic section in Xishuigou between the S0 axis and F1 of 2179 m thick. A magnetic section along the same segment was also published by Yin et al. [24]. Although there are broad similarities in reversal patterns between the above two published sections, Gilder et al.'s section reveals more magnetozones of short durations because of its greater density of sites and of its inclusion of segments interpreted as repetitive due to folds by Yin et al. Our reinterpretations of these published sections are mainly based on that by Gilder et al., not only because of its better sampling but also its overall consistency with our own field data.

We have re-measured the Xishuigou section in order to integrate Gilder et al.'s magnetic sample sites and our fossil localities. Thickness measurements by both parties are generally within 10% of each other in the upper part of the section, where structures are relatively simple. However, we arrive at a total thickness of 2723 m for the Xishuigou section, 25% longer than the 2179 m by Gilder et al. Much of the discrepancy presumably occurs in the lower part of the section, where individual interpretations of the complex structures must have influenced how thickness should be calculated (no detailed lithostratigraphic section was published by Gilder et al.; see Fig. 4 for our field interpretations). We therefore scaled Gilder's section proportionally to that of our own.

Lacking information about actual occurrence of vertebrate fossil localities, Gilder et al. assumed that the Xishuigou section includes both the late Oligocene Yandantu Fauna and Bohlin's Miocene fauna that contains '*Kansupithecus*' and *Sayimys*. In addition, Gilder et al. obtained a single charophyte specimen at the base of their section. They identified it as *Steftethamochara huangjianensis*, and citing Lu and Luo's [55] work in the Tarim Basin, inferred that their section could not be later than Oligocene. In order to cover both late Oligocene and early Miocene and assuming an essentially continuous section, they arrived at a magnetic correlation that spans the chrons C6n through part of C8n, or 26–19 Ma. Such a correlation is nearly identical to one of the two alternatives by Yin et al. [24], although they prefer the other alternative correlation of C8r through 13r, or about 33.5–27 Ma in the Oligocene.

Our stratigraphic framework indicates that the Yindirte Fauna is not present in the Xishuigou section. Instead, only the Miocene part of the section is present, i.e. Xishuigou Fauna and above. As discussed above, our new fossil evidence strongly suggests a late early Miocene age near the base of the Xishuigou section. We therefore propose a reinterpretation of Gilder et al.'s magnetic section (Fig. 4). As noted by Gilder et al., the Xishuigou section is characterized by a long interval of normal polarity at its base. Given our paleontological constraint of a late early Miocene age in the lower part of the section, we find a good match for the lower two-thirds of the section with the magnetic chrons C6n through C5Bn around 20–14.8 Ma. Correlation of the upper section is less clear. At the top of the section, a long interval of predominantly normal polarity seems best fitted with C5n plus the lower portion of C4Ar around 9.3–11 Ma, followed by an interval of mixed polarities in C5r through C5An. Such a correlation has the inevitable consequence of missing polarity zones (spanning 13.2–14.7 Ma) somewhere in the middle of the Xishuigou section, with the implication that one of the reverse faults (probably Gilder et al.'s F″1) has truncated a significant portion of the section up to a few hundred meters in thickness. Drag folds along the F″1 between beds 7 and 8 (Fig. 3) seem to indicate a significant interruption to the original bedding sequence.

Our correlation results in a total span of 9.05 million years (excluding parts truncated by faulting), somewhat longer than the 7.3 million years of Gilder et al. [11]. This translates into a lower overall sedimentation rate of 24 cm/kyr as compared to the 30 cm/kyr in Gilder et al.'s correlation. However, the top half of the section (C4Ar to C5AAn), which is dominated by massive boulder conglomerates, has a slightly higher rate at 26 cm/kyr than the lower half (C5Bn to C6n) at 23 cm/kyr, which almost entirely consists of fined-grained mudstones. These rates are comparable to those from the Siwaliks of Pakistan, which generally fall in a range of 20–30 cm/kyr except in channel deposits [56].

The implication that F″1 is a large reversed fault shortening the sedimentary column by several hundred meters is also worth further comment. Gilder et al. [11] entertained the question that F″1 may have been a ramp fault (as in F0, F1, F2) potentially placing older sequences over young ones, but concluded that F″1 represents a minor disturbance, i.e. the Xishuigou section essentially has a continuous record. Although our reinterpretation does not overturn Gilder et al.'s conclusion (i.e. the Xishuigou magnetic section is still younging northward), it is contrary to the notion of a continuous record. With respect to this we also note that a large F″1 has the effect of evening out the width of the sedimentary wedges in the Danghe area, i.e. the Tiejianggou Formation is now divided by F″1 into two halves of approximately equal intervals comparable in thickness to the Paoniuquan Formation and the Mio–Pliocene section in Xishuigou.

7. Depositional history and structural implications

The fault-bounded Tertiary rocks do not permit observation of the depositional contact between Tertiary and basement rocks. The nature of the pre-depositional terrain is thus not clear. However, lacking coarse clastic sediments in the preserved part of the basal sequence (Paoniuquan Formation), the pre-depositional surface was probably a low-relief terrain and some distance from the sediment sources.

Our fossil records indicate a minimum age of late early Oligocene for the onset of terrestrial sedimentation in the Danghe area. However, approximately 800 m of red beds below the lowest occurrence of fossils (Dh200103) suggests that sedimentation must have started at least in the earliest Oligocene and possibly ranges into the late Eocene. The Paoniuquan Formation mostly consists of fine-grained red mudstones and is free of large conglomerates. Ranging through the entire Oligocene to possibly early Miocene, this thick sequence of fine sediments indicates low-relief terrain with large areas receiving over-bank deposits. After a gap in the record in the beginning of the Miocene, and cut off by the ramp fault F0, the late early Miocene sediments remain fine-grained. By middle Miocene, sediments have gradually coarsened to boulder conglomerates, indicating proximity to high-relief sedimentary sources. Whether the massive conglomerates are the result of the newly thrusted Danghe Nanshan, as has traditionally been assumed, or shifting sedimentary facies along a Nanshan range that was already in place 30–40 Ma, as postulated by Yin at al. [24], remains to be tested in the future. Flow indicators in the conglomerates were predominantly northward, suggesting foreland streams proximal to the range front and transverse to the direction of the Danghe Nanshan.

A second interval of fine-grained red mudstones resumed following the above sequence of coarse conglomerates. This second sequence also includes a coarsening-upward cycle ending in a second massive conglomerate. Lacking adequate paleontological and paleomagnetic data, this sequence is harder to constrain, and is here regarded as latest Miocene to Pliocene. Elsewhere in the western Kunlun Mountains and in the Jiuxi Basin, a similar coarsening-upward conglomerate was also observed [36,57,58]. Whether this latest coarsening of sedimentation is the result of climatic disturbance, as suggested by Zhang et al. [59], or a reflection of tectonic activity cannot be resolved at the present time.

A recent proposal by Yin et al. [24] for an early uplift history of the Danghe Nanshan at around 33 Ma and syn-depositional folds since then is in sharp contrast to a scenario of much later uplift and largely post-depositional deformation dominated by thrust faults as proposed by Gilder et al. [11]. Our own paleontological evidence supports Yin et al. in an early initiation of Danghe deposits, but seems more consistent with a structural interpretation by Gilder et al. that emphasizes a series of younger wedges of sediments toward the north as the first-order structure. While syn-depositional activities were likely present in a tectonically active region like Danghe, it remains difficult to tease out the various components without a detailed understanding of the stratigraphic sequence.

There are some broad depositional similarities along much of the Qilian range front. A long coarsening-upward sequence that typically starts with fine-grained red beds and coarsens to massive conglomerates in the middle to upper parts can be seen from the Jiuxi Basin in the Hexi Corridor [36] to the northeastern corner of the Tibetan Plateau in Lanzhou [60] and Linxia [61] basins, and even in southwestern Ningxia [62,63]. While individual basin histories may vary in time and space, there is little doubt that these sediments are broadly related to the uplift of the plateau and therefore are sensitive to its tectonic histories.

8. Conclusion

We recognize three depositional sequences in the Danghe Tertiary. At the base is the Paoniuquan Formation, consisting of mostly red mudstones and containing the late Oligocene Yindirte Fauna. In the middle is the Tiejianggou Formation, characterized by a long sequence of coarsening-upward red mudstones and conglomerates, and terminating in a thick boulder conglomerate. A new mammal assemblage indicates an early Miocene age for this middle sequence. At the top is an unnamed formation of another coarsening-upward sequence, also terminating in a massive conglomerate. We propose a new magnetic correlation for the Tiejianggou Formation in the Xishuigou section. It spans the chrons C6n through C4Ar in 20–9.3 Ma, averaging 24 cm/kyr in depositional rate.

Our new chronological framework helps to constrain the tectonic history of the Danghe Nanshan. The fine-grained Paoniuquan Formation shows no sign of intense tectonic activities in the Oligocene. This thick red bed sequence is widespread in much of western China and indicates a flat terrain still not incorporated into the northern Tibetan Plateau. Such steady but relatively quiet deposition continues well into the early to middle Miocene, as indicated by the lower part of the Tiejianggou Formation. The upper massive conglomerate of the Tiejianggou Formation registers the first pulse of major uplift of the Danghe Nanshan during the late Miocene (around 9–12 Ma). The area regained a period of slow, fine-grained deposition in the late Miocene through early Pliocene. A second pulse of uplift or intense weathering is recorded in the late Pliocene.

Tectonic activities intensified after the Tertiary deposition. The Danghe Nanshan becomes an integral part of the northern Tibetan Plateau to accommodate crustal thickening, shortening, uplifting, and northeastward extrusion. Much of the crustal thickening and shortening is through ramp thrusts and left-lateral strike-slip faults. Thrust faults cut through Tertiary sediments and divided them into narrow wedges that are also extensively folded. The folding and faulting likely occurred in the Quaternary and are still active at the present time.

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