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步林在甘肃党河流域塔奔布鲁克地区的早期工作记录——经典脊椎动物化石地点与现代地层框架的解译[1)]

王晓鸣[1,2]　王伴月[2]　邱占祥[2]

（1 美国洛杉矶自然历史博物馆　洛杉矶　90007）

（2 中国科学院古脊椎动物与古人类研究所　北京　100044）

摘要:1931－1932年博格·步林在甘肃省西部塔奔布鲁克地区(又名党河地区,位于肃北县城西南)首次发现丰富的新生代哺乳动物化石。步林在塔奔布鲁克盆地中部燕丹图沟中找到三个小哺乳动物化石异常丰富的层位。三个层位紧靠在一起,其中产出的哺乳动物群被命名为燕丹图动物群。步林明确指出燕丹图动物群为晚渐新世。该动物群以后成为晚渐新世塔奔布鲁克哺乳动物期的典型动物群并沿用至今。

除燕丹图化石点以外,步林还在塔奔布鲁克地区描述了一些中新世、甚至可能是上新世的化石。而塔奔布鲁克地区极度复杂的地质构造和地层使他无法短期内得出一个完全合理的地层顺序框架。遗憾的是步林此后就再没有机会重访塔奔布鲁克化石点。因此他在以后文章中屡屡提醒读者注意这些复杂性,并一再小心地把燕丹图动物群局限在燕丹图化石点本身,以防后人误解或混淆各地点的动物群。

可惜步林的警告未引起后人足够的重视,他所担心的误解屡屡发生。塔奔布鲁克地区是近20年来研究阿尔金山走滑断层的关键地点之一。原因之一是该盆地在青藏高原北缘多个山前盆地中惟一具有明确的哺乳动物年代控制的层序。因此塔奔布鲁克地层既可以帮助推算阿尔金山走滑断层的断距,又可以提供探索青藏高原北部祁连山－党河南山－阿尔金山隆起时代的重要依据。然而,诸多地质学者常常仅知道该地区存在晚渐新世动物群,却对其古生物地层层序及剖面位置了解不多,导致对该地区古地磁剖面的错误对比及年代学研究的混乱。

步林一定程度预感到塔奔布鲁克地区极其复杂的地层将来很可能会导致后人对化石分布的疑惑。因此他格外仔细地记录了化石地点的出露并编制了地形图。然而可惜的是,步林发表的地质记录被多数人忽略,他发表的个人游记鲜为世人所知,其个人档案记录则更是深埋在历史文献中。本文作者之一(王晓鸣)在1999年有机会在瑞典斯德哥尔摩民族博物馆收藏的Sven Hedin中瑞考察档案中找到一些步林未发表的化石分布图及照片。

这些珍贵资料对恢复步林在塔奔布鲁克地区建立的化石地点很有帮助。因此有必要将各种资料加以总结整理,以便推动该地区年代地层学的进展。本文试图整理这些未发表的资

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料,结合作者在 1999 及 2001 年两次野外考察的结果,并综合考证其他已发表的信息,以期理顺塔奔布鲁克地区经典化石点与现代地层框架的关系。

塔奔布鲁克地区至少有三套沉积序列。它们是晚始新世—渐新世狍牛泉组、早—晚中新世铁匠沟组及晚中新世—上新世(?)未定名组(步林本人未建立任何组名)。各组底部为一系列逆冲断层切断。逆断层导致部分层位缺失。铁匠沟组与未定名组都在顶部巨厚砾岩以后结束沉积。虽然步林根据哺乳动物辨认出两到三个时代,但他只正式建立了一个动物群,即燕丹图动物群。结合我们自己的地层古生物工作,从早渐新世到上新世我们至少可以辨认出 5 个动物群:早渐新世到晚渐新世早期叮当沟动物群、晚渐新世燕丹图动物群、早中新世西水沟动物群、中中新世铁匠沟组未定名动物群及晚中新世到上新世未定名动物群。

1)叮当沟动物群。步林未在此层位找到化石,本动物群是我们 2001 年发现的一个新组合。其成员包括如下大、小哺乳动物:*Palaeoscaptor* cf. *P. acridens*, *Palaeoscaptor* sp., *Oligosciurus dangheensis*, *Tataromys* cf. *T. sigmodon*, *Karakoromys decessus*, *Coelodontomys asiaticus*, *Parasminthus* spp., Cricetidae gen. et sp. indet., *Desmatolagus gobiensis*, *Desmatolagus pusillus*, *Allacerops* sp., *Schizotherium ordosium*, 及 *Parabrachyodus* sp. 。结合方小敏等尚未发表的古地磁结果,叮当沟动物群的时代在 31.5 ~26.5 Ma 左右。

2)燕丹图动物群。步林在燕丹图沟接近南端的一段地层内找到三层垂直竖起来的砂岩及细砾岩。燕丹图化石点是步林在中瑞考察过程中找到的最重要的一个哺乳动物化石地点,也是种类最多、化石最丰富的一个动物群。步林 1931、1932 两年收集到相当数量的标本,而有些标本后来又在室内经双氧水处理得到更多的牙齿。由于步林对该地点一开始就较重视,再加上对地层复杂性的担心,他逐层记录了所有燕丹图化石点的野外号码。它们包括 T. b. 199, 201-215,224-233,235-249,255-258,及 557-593。综合步林最初发表的动物群分子及我们近年来的修正与补充,燕丹图动物群包括如下大、小哺乳动物:*Amphechinus* cf. *A. rectus*, *A. minimus*, *A. kansuensis*, *Desmatolagus* sp., *Sinolagomys kansuensis*, *S. major*, "*Sciurus*" sp., *Eucricetodon* sp., *Tachyoryctoides* sp., *T.* cf. *T. obrutschewi*, *Yindirtemys grangeri*, *Y. ambiguus*, *Yindirtemys* sp., *Parasminthus asiae-centralis*, *P. tangingoli*, *P. parvulus*, *Heterosminthus lanzhouensis*, *Litodonomys huangheensis*, *L.* cf. *L. huangheensis*, *Eomyodon dangheensis*, *Didymoconus* sp., *Eumeryx* sp., *Schizotherium*? sp., Rhinocerotidae indet., 及 Primate indet. 。

燕丹图沟地层多处强烈折皱、切断甚至倒转,目前还没人做古地磁工作,其年龄只能通过与邻近的铁匠沟古地磁剖面的对比来估计。方小敏等未发表的古地磁资料显示狍牛泉组顶部最晚年龄在 23 Ma 左右。燕丹图地点三个化石层总共厚度 40 m 左右,其时代跨度应不超过 1 Ma。因此我们估计燕丹图动物群的时代在 23 ~25 Ma 之间。

为了将塔奔布鲁克地区哺乳动物群名称规范化,我们在 2003 年建议用燕丹图动物群作为塔奔布鲁克哺乳动物期的典型动物群,以区别于其他塔奔布鲁克地区的动物群。2006 年孟津等对燕丹图动物群的名称又有疑问,建议重新启用塔奔布鲁克动物群一名。塔奔布鲁克沟几乎不产化石,因此步林应用其名时一般泛指整个地区。而他在具体定义他的晚渐新世动物群时,则应用燕丹图动物群一名,以避免出现疑问。步林这样定义的燕丹图动物群完全局限在燕丹图沟南端 40 m 的三层化石层中。如此定义的燕丹图动物群地点位置确定无疑、跨时代短、动物群组成明确、与塔奔布鲁克地区其他动物群截然分开。孟津等认为燕丹图动物群"缺乏确切的层位",其实是忽略了步林已做的大量地质工作。

3)西水沟动物群。步林在西水沟中段偏北处找到一段破碎的灵长类下颌骨(T. b. 309),且非正式命名为"甘肃猿"("*Kansupithecus*")。虽然他又把燕丹图的一颗单独的灵长类牙齿(T. b. 557)归入同一类群,但他清楚地意识到西水沟地点的化石与燕丹图动物群截然不同。

由于与 T. b. 309 共生的其他化石特征不明显,步林没有正式建立动物群。我们 1999 及 2001 年在该点附近又补充找到一些早中新世分子。到目前为止,西水沟动物群包括 *Platybelodon dangheensis*, *Turcocerus* sp., *Amphimoschus* cf. *A. artenensis*, *Kinometaxia guangpui*, "*Kansupithecus*", 及 *Heterosminthus intermedius*。Gilder et al. 及 Yin et al. 在西水沟做了两个独立的古地磁剖面,但都因不熟悉步林的化石地点位置而错误地解释了古地磁年代(把燕丹图动物群算入西水沟剖面中,从而导致整个剖面向下延伸)。经我们重新解释古地磁年代后,西水沟动物群的年龄应在 20 ~ 17 Ma 左右。

4)铁匠沟组未定名动物群。步林在铁匠沟及燕丹图沟多处找到 *Sayimys*,因此对该地段的年代产生疑惑。应用步林的化石地点分布图我们大致可以把出产 *Sayimys* 的地层归入铁匠沟组的中段,在西水沟动物群之上。我们近期找到的化石对步林原先的动物群组合又略有增加。这个未定名动物群目前包括 *Sayimys obliquidens*, *Litodonomys xishuiensis*, *Phyllotillon* sp., Cervidae indet., 及 Proboscidea indet. 。2005 年 Sun et al. 发表了铁匠沟组的古地磁剖面。将步林及我们的化石地点估算进这个剖面中后,本动物群应在 15.5 ~ 12 Ma 左右的年龄段。然而步林在距他的铁匠沟 *Sayimys* 化石点不远处报道有 *Schizotherium* 的出现。*Schizotherium* 的出现时代一般不晚于晚渐新世,因此本动物群的时代及其真正面目还有待进一步探讨。

5)西水沟未定名动物群。步林在西水沟口附近找到个别破碎的牛羊类及象类化石(? *Gazella*, ? *Tragoreas*, 及 Proboscidea indet.)。他怀疑该点的时代应相当年轻。但由于缺乏更确切的证据,故只好对此问题悬而未决。我们两次野外工作都未能在此有所突破,未找到更有时代价值的化石。但步林的化石点无疑是在西水沟剖面上部(北口)未命名组的巨厚砾石层以下。该序列目前还没有做过古地磁测年,年龄不明,但可能是在晚中新世至上新世之间。

关键词:甘肃,青海,古近纪,新近纪,哺乳动物,生物地层

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EARLY EXPLORATIONS OF TABENBULUK REGION (WESTERN GANSU PROVINCE) BY BIRGER BOHLIN—RECONCILING CLASSIC VERTEBRATE FOSSIL LOCALITIES WITH MODERN STRATIGRAPHY

WANG Xiao-Ming[1,2] WANG Ban-Yue[2] QIU Zhan-Xiang[2]

(1 *Natural History Museum of Los Angeles County* Los Angeles, California 90007 xwang@ nhm. org)

(2 *Institute of Vertebrate Paleontology and Paleoanthropology*, *Chinese Academy of Sciences* Beijing 100044)

Abstract The classic Tabenbuluk localities first discovered by Birger Bohlin in 1931 have produced rich fossil mammals that become the basis of the Late Oligocene Tabenbulukian Land Mammal Age. Faunas from the Tabenbuluk areas are often confused, partly due to the tectonic complexities that resulted in the uplift of Danghe Nanshan and the large strike-slip Altyn Tagh Fault. However, part of the confusion is derived from a lack of appreciation of Bohlin's historic records. We attempt to integrate Bohlin's archive records, his journals, and his published (but often ignored) geologic descriptions. When the entire available records are brought together, it is clear that Bohlin was an exceptional paleontologist who has kept remarkably detailed locality records and was able to make clear distinctions about his Yandantu Fauna, which typify the Tabenbulukian Land Mammal Age. By placing Bohlin's fossil localities in modern stratigraphic frameworks and integrating with fossil mammals collected recently, we can recognize at least five faunas: Early to Late Oligocene Dingdanggou Fauna, latest Oligocene Yandantu Fauna, Early Miocene Xishuigou Fauna, Middle Miocene Tiejianggou Formation unnamed fauna, and a Late Miocene or Pliocene unnamed fauna. Of these, three faunas are tied to paleomagnetic sections that yield age ranges of ~31.5-26.5 Ma for the Dingdanggou Fauna, ~20-17 Ma for the Xishuigou Fauna, and ~15.5-12 Ma for the unnamed fauna of the Tiejianggou Formation. Although still not directly tied to a paleomagnetic section, the Yandantu

Fauna is confined to a narrow range of strata (~40 m) and probably spans less than 1 million years.
Key words Gansu, Qinghai, Paleogene, Neogene, mammal, biostratigraphy

1 Introduction

Birger Bohlin (1898–1990) is a pioneer Swedish vertebrate paleontologist and explorer. Although he is popularly known for his early involvement in the discoveries of the Peking Man fossils, Bohlin made equally important (if not more so) contributions as chief vertebrate paleontologist in the Sino-Swedish Expedition (1927–1935) led by the charismatic expedition leader Sven Hedin. In this latter capacity, Bohlin made wide ranging discoveries in much of northern China, particularly in Gansu and Qinghai provinces. His pioneering collections of vertebrate fossils provide the first glimpse into the Cenozoic evolution of mammals in and around the Tibetan Plateau. His fossil mammal collections from the Tabenbuluk area led to the establishment of the latest Paleogene land mammal age, the Tabenbulukian (Li and Ting, 1983; Luterbacher et al., 2004; Russell and Zhai, 1987). In light of the central importance of the geologic history of the plateau, Bohlin's collections have become a cornerstone in the study of vertebrate evolution and biostratigraphy of the Tibetan Plateau and geochronology of Asia.

However, uncertainties regarding the precise location and stratigraphic context have become a major hindrance or point of contention in the proper interpretation of his paleontologic data. Such uncertainties are particularly glaring in light of the fact that extraordinarily thick (~4 000 m) sedimentary records in Tabenbuluk area span much of the Cenozoic (from Late Eocene to possibly Pliocene), rendering such generic terms as "Tabenbuluk fauna" a difficult concept to grasp unless they are placed in proper stratigraphic context. Yet, Bohlin is a superb field geologist and paleontologist keenly aware of the importance of stratigraphic documentation. Given the reconnaissance nature of his field works and the technological limitation of his time, the level of details in his field records is actually ahead of those of his contemporary colleagues.

Despite this attention to details, Bohlin's work in Tabenbuluk area remains poorly understood. Such a lack of understanding has a lasting, adverse effect that misleads studies even in the 21st century. The "Tabenbuluk fauna" is either used as a chronological constraint completely out of its stratigraphic context (Gilder et al., 2001; Yin et al., 2002), or dismissed as "lacking concrete stratigraphic characterization" (Meng et al., 2006). Unraveling Bohlin's field record in light of modern stratigraphy has thus become a matter of primary importance and is the purpose of this paper.

This is the first of two papers to treat two of the most important Cenozoic localities discovered by Bohlin, Tabenbuluk and Tuosu Nor, and the latter locality in the Qaidam Basin will be the subject of a separate treatment. We intend to: 1) present unpublished archive records from Bohlin expeditions that are germane to the documentation of his fossil localities; 2) call to attention Bohlin's published geologic studies and travel accounts that are widely ignored but are of key importance in reconstructing his expedition history; 3) integrate, to the extent possible, historical locality information with current stratigraphic frameworks. Through this effort, we hope to clarify some historical misunderstandings regarding Bohlin's Tabenbuluk faunas. By doing so, we hope to provide a cohesive biostratigraphic framework linking historical records with more recent collections. We hope to demonstrate that, despite popular opinions to the contrary, Bohlin's Yandantu (Yindirte) Fauna is confined within a very narrow range of strata. As a result, mammals in the Tabenbulukian land mammal age (s. s.) represent a cohesive fossil assemblage that continues to serve well for the characterization of the latest land mammal age in the Paleogene.

2 Archive materials and methods for this study

The main sources of historical documents are housed in the Sven Hedin Archive in the Etnografiska Museet (Folkens Museum Etnografiska, Stockholm). One of us (XW) visited the Hedin Archive in 1999 and obtained copies of archival materials and maps (Norin and Montell, 1966) used in this paper. Another very important source of historical information is Bohlin's published account of his travels (Bohlin, 1945) and his accounts on his geologic reconnaissance in Gansu and Qinghai provinces (Bohlin, 1960).

As one of the first western scientists in the vast unexplored region in western Gansu and Qinghai, Bohlin did not have topographic maps or prior geologic information in all of the places he went. He thus had to spend a considerable amount of time drawing topographic maps and making geologic sketches, often at the expense of his time to collect fossils. Ironically, his attention to topographic and geologic documentations has led to an over-reliance on his field assistants to collect fossils for him, resulting in less detailed documentations of individual fossil localities, an unfortunate situation more noticeable in his Qaidam collection.

Despite these limitations, a wealth of rather detailed information is available in the above published accounts and in the archives, but, unfortunately, the valuable information has not gained wide recognition it deserves. We attempt to integrate the above sources of historic records, and verify these records whenever possible by our own field observations.

We follow Bohlin's scheme for specimen numbering. Bohlin used a prefix "T. b." for Tabenbuluk specimens. He appears to have devised a continuous numbering system throughout the expeditions. For example, Bohlin assigned the numbers T. b. 169-315 to collections obtained during his first visit to Tabenbuluk area in the summer of 1931. He then used numbers Nr 316-357 for specimens from Qaidam Basin collected in October 1931 (Bohlin did not encounter other fossil localities between these two basins, thus the continuous numbering). He next assigned Nr 358-556 to the second collection from Qaidam during his May 1932 visit (a "566" for a rhino humerus is probably a typo for "556" in Bohlin, 1937a: fig. 124). Finally he used T. b. 557-593 for collections from Yandantu during his October 1932 revisit. Thus the numbering also contains clues to stratigraphic locations as well as date of collections (see below). Bohlin's numbering system is thus a curious combination of locality number and catalogue number. Certain numbers represent more than one specimen, as in the common usage of a locality number, but many different numbers are from exactly the same locality, as in normal catalogue numbers.

Locality numbers for our 1999 and 2001 field seasons are composed of the four digit year plus two digit locality number, e. g., Dh 199904. We generally follow the official Pinyin system for geographic names, except where a name has been well entrenched in the literature (such as Tabenbuluk). We list the following Pinyin names and their corresponding usage by Bohlin: Xishui (or Xishuigou), Hsi-shui; Tiejianggou, Tieh-chiang-ku; Yandantu, Yindirte (Yindirte-ku). Abbreviations: IVPP, Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences, Beijing.

3 A brief history of the Sino-Swedish Expedition by Birger Bohlin

Early Chinese vertebrate paleontology was intimately related to Swedish colleagues in the early 1900s. The best known and most influential among them is the Swedish mining geologist J. Gunnar Andersson, advisor to Chinese government (initially in Department of Agriculture) (Andersson, 1934). Andersson's interests in vertebrate paleontology led him to several landmark discoveries in Chinese vertebrate paleontology (often with the helps from Swedish missionaries): Late Miocene *Hipparion* fauna in north China in 1918, Late Miocene Ertemte fauna in

Nei Mongol (Inner Mongolia) in 1919, Eocene Yuanqü (Yuan Chü) fauna in Shanxi in 1921, and most famous of all, the Pleistocene Zhoukoudian cave fauna in 1921. Although the first two teeth of the Peking Man were discovered by Otto Zdansky in 1921, Zdansky did not announce his discovery until 22 October 1926 during the visit of the Crown Prince of Sweden (Gustav V) (Zdansky, 1927). By then, Zdansky was no longer available for continued excavations in Zhoukoudian, and upon Andersson's recommendation, Birger Bohlin, then freshly graduated from Uppsala University with a Ph. D. degree, was hired to supervise the excavation (Mateer and Lucas, 1983).

In 1927, Sven Hedin launched his Sino-Swedish Expedition in northwestern China, commissioned by the Chinese Railroad Authority. However, despite a broad scope of the Sino-Swedish Expedition that supposedly resembled a "traveling university" (Weinberg and Green,

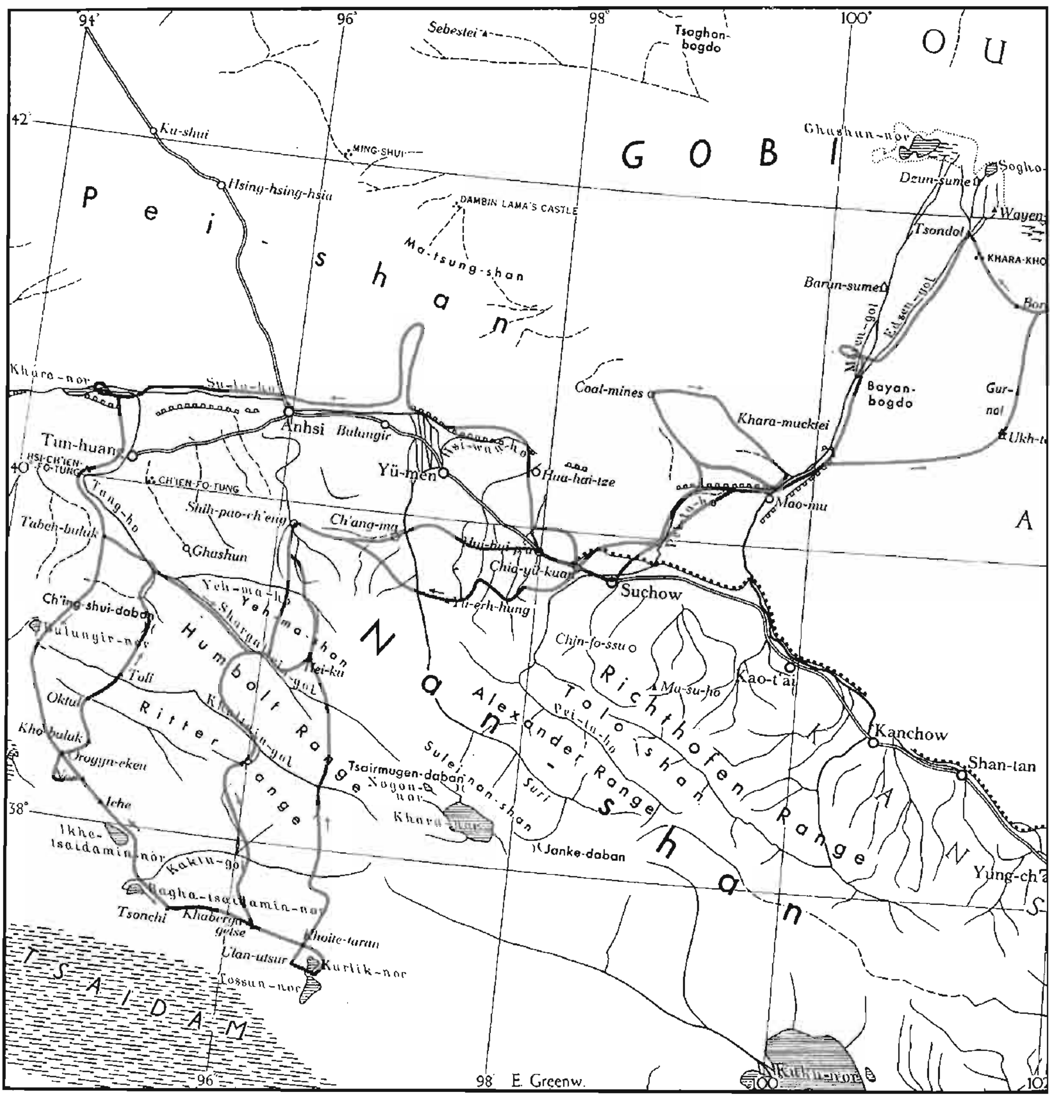

Fig. 1 Map of expedition route by Birger Bohlin from 1929 to 1932
Modified from Bohlin (1945: map insert)

2002), Hedin did not have a vertebrate paleontologist in his staff during the first two years of the expedition. In January 1929, Hedin sought out Bohlin in Beijing and solicited his service in the expedition (Bohlin, 1945). Bohlin readily agreed, thus began the most productive, and certainly most adventurous trip during his years in China.

Bohlin began his journey from Bailingmiao (Beli Miao) in central Nei Mongol on 11 November 1929, traversing much of western Nei Mongol in the spring and early summer of 1930, and arriving in Gansu (Suzhou) in the summer 1930 (Fig. 1). He spent the next 10 months exploring the southern foot hills of Beishan, reaching as far west as Khara Nor (Xihu), a dry lake at the end of the Suluohe, and were able to collect dinosaurs and Cenozoic mammals along the Jiayüguan-Huihuipu-Shi'ermacheng region. In June 1931, Bohlin encountered bandits from Ma Zhongying's army north of Dunhuang, and the danger posed by the warring warlords forced him to alter his field plans and started to head south immediately. This change of plan had turned out to be fortuitous as it led to the discovery of the Tabenbuluk mammal assemblage, a fauna Bohlin considered to be his single most important contribution in the Sino-Swedish Expedition (see below), which in turn has led his search for fossil mammals in Qaidam Basin.

4 Bohlin's Tabenbuluk fossil localities

Bohlin discovered four major fossil-producing basins in the Cenozoic of northern Tibetan Plateau: Tabenbuluk (Bohlin, 1942, 1946, 1953), Qaidam (Bohlin, 1935, 1937a), Shi'ermacheng (Bohlin, 1951), and Shargaltein (Bohlin, 1937b). Here we treat the Tabenbuluk basin first. We shall treat the Qaidam basin in a separate treatment.

On June 22, 1931, Bohlin arrived at Tabenbuluk (Mongolian, five springs), a small desert oasis fed by a few natural springs. Cenozoic exposures in an area of approximately 5 × 15 km are mostly fine-grained red siltstones, sandstones, and massive conglomerates along the northern foot hills of Danghe Nanshan, and the sediments were well exposed by a series of four major north-south oriented, steeply cut canyons. The Tabenbuluk is the western-most canyon, followed by Yandantu, Tiejianggou, and Xishuigou further to the east. Although Bohlin chose to use the term Tabenbuluk for the entire region, this canyon is actually the least fossiliferous and the name is nearly universally ignored by recent geologists, who refer this area as either Subei Basin or Danghe Basin, alluding to the nearby town and river to the east.

Upon arrival at the Tabenbuluk canyon (Fig. 2), Bohlin was immediately impressed by the vast exposures in the region and decided that a closer investigation was warranted. He made only two small fossil finds near the Tabenbuluk canyon (T. b. 169), but was hopeful that more would come. Although this canyon has played no significant role in the studies of geology and paleontology of the area, the name for the natural springs, Tabenbuluk, has come to represent the entire area and later to be adopted for the Tabenbulukian Land Mammal Age. Bohlin began to make a 1 : 50 000 scale topographic map as he systematically surveyed the entire badland to the east and the map ultimately covers all of his fossil localities (Bohlin, 1942: map insert).

A few days later, Bohlin moved his camp to Yandantu (Yindirte), the next big canyon about 5 km east of Tabenbuluk canyon. About 3 km south of his Yandantu camp, he made his best fossil finds along the steep canyon walls. Fossil assemblage collected from this locality has become the name bearer of the Yandantu Fauna (Wang et al., 2003a; Wang et al., 2003c), which defines the Tabenbulukian Land Mammal Age first proposed by Li and Ting (1983). Bohlin (1942: 8) described the Yindirte locality this way: "a locality which has proved to be of great interest lies on the Yindirte river a couple of kilometers from the foot of the mountains. We collected here on the right side of the ravine in three beds (vertical!) which stand out like wings." Bohlin personally collected in the Yandantu locality for only two days and spent the rest of his time surveying the region and making his topographic map. Most of the collecting was

Fig. 2 Photomosaic of Tabenbuluk canyon
To the right is the natural springs where Bohlin set up his first camp (BB 68) in this area, and to the left are exposures red beds where he found the first fossils (T. b. 169)

therefore done by his field assistants. The richness of this locality impressed him enough that he made a second trip for about a week specifically for this locality in early August 1932. Materials collected during these two trips permitted Bohlin to experiment the technique of dissolving matrices in H_2O_2 solutions, which yielded additional small mammal teeth.

The regional geology of the Tabenbuluk area is mainly controlled by the Altyn Tagh Fault, a large scale left-lateral strike-slip fault system that spans up to 2 000 km. Movements of this fault system play a critical role in the shortening and eastward extrusion of the northern Tibetan Plateau, and are the focus of many structural studies (e. g., Molnar et al., 1987; e. g., Ritts et al., 2004; Yin et al., 2002; Yue et al., 2003). Tectonic forces related to strike-slip and frontal thrust faults cause extreme deformation of the Cenozoic sediments, particularly in the less-resistant, fine-grained red beds. As a pioneer in the geologic study of the Tabenbuluk region, Bohlin (1942: 8) was immediately struck by the structural complexity: "…the structure is so intricate that it would have been meaningless only to go there and pick up the fossils without making a detailed survey of the region." Indeed, the stratigraphy is so convoluted and tightly folded that it is difficult to tell the ups and downs in the nearly vertical beds at Yandantu locality (Bohlin concluded that the upper surface faces south). In a broader scale, the entire Tabenbuluk exposure is dissected by a series of thrust and strike slip faults, and are tightly folded especially along the southern part, where compressive stress is the highest.

In the long sequence of Tabenbuluk sediments, >3 000 m in thickness and compounded by the structural complexity, it is imperative to document detailed locality information. Bohlin did just that, and, given the limitation of his time and available equipments, his topographic map (Bohlin, 1942: inset map) with 20-meter contour lines is remarkably accurate and marks 13 major vertebrate fossil localities with an "F." Bohlin later published a modified version of this topomap that marked prominent topographic features (small peaks) corresponding to those in his panoramic photos (Bohlin, 1960: map 1 and plate I). Unfortunately, however, individual specimens are not associated with the "F" marks in the published map. This has become a source of the biggest confusion for later investigations.

We are fortunate to be able to locate in Hedin Archive a copy of Bohlin's topomap that is marked with a large series of hand-written specimen numbers, some of which next to the "F" marks. This is the only document to indicate the location of the select localities. Although this locality map is obviously not made in the field, there is reason to believe that Bohlin's specimen numbers on this map were meant to be a realistic depiction of their actual positions.

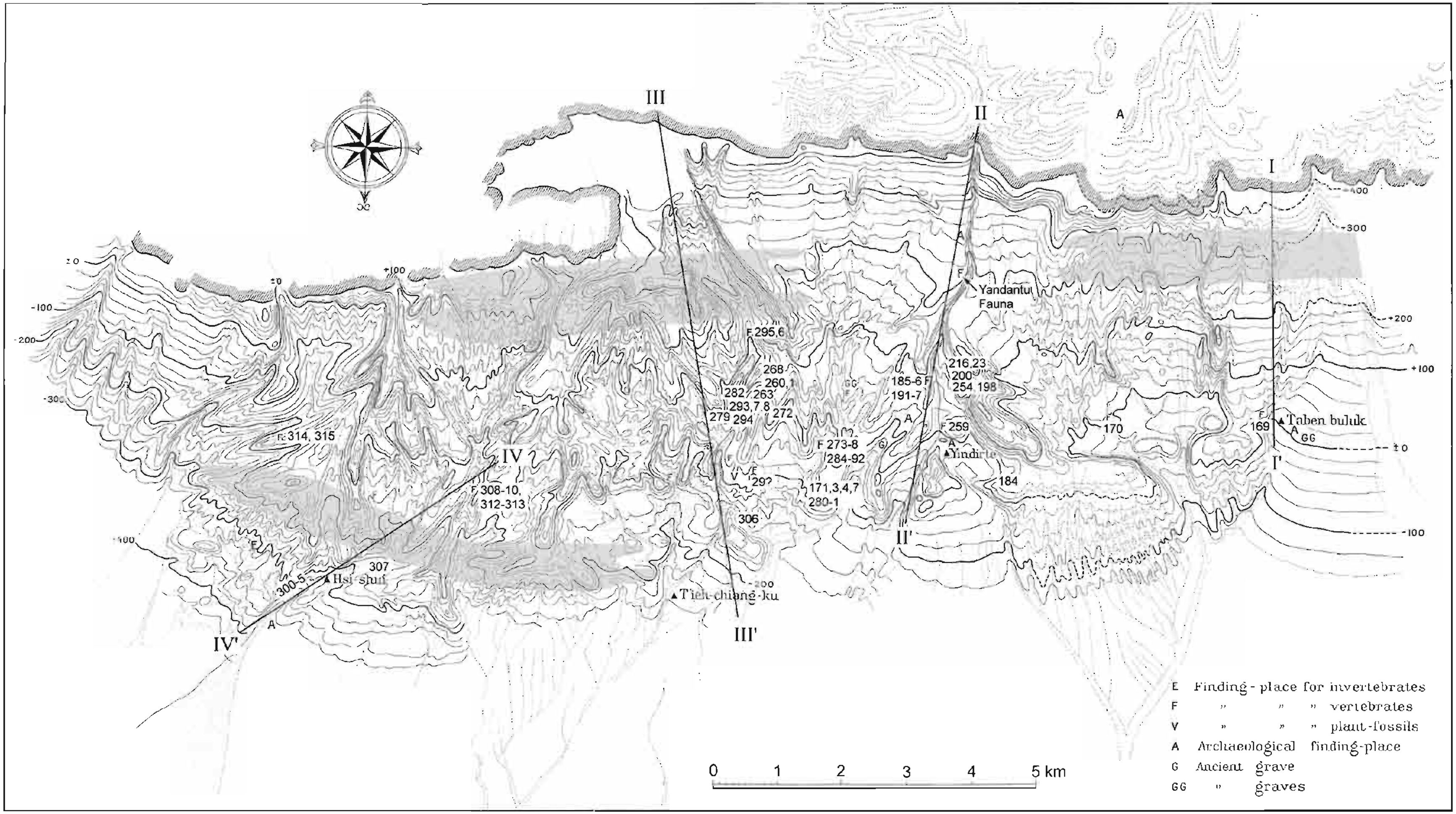

Fig. 3 Topographic map of the Tabenbuluk region from Hedin Archive, shown in upside-down (south side up) position as in Bohlin's original orientation
See text for further explanations; reproduction of archival map by permission from Sven Hedin Foundation, Stockholm

For example, he stated that T. b. 279 and 261 are about 1 km apart (Bohlin, 1946: 248), a distance roughly consistent with that shown in the map, as are depictions of other locality numbers. Even assuming that the location of the specimens to be somewhat imprecise, particularly for those numbers that are not associated with the "F" marks (because the numbers were obviously penned in after the map had been finalized and may contain an element of conjecture), Bohlin's archive map is obviously of prime importance and is reproduced here (Fig. 3). This is the same map as published by Bohlin (1942: map inset) but with specimen numbers added in. The original numbers are hand-written, some of which are difficult to recognize, and we replace them by typed numbers (307 was mislabeled as 207 by Bohlin). The Yandantu Fauna consists of the following specimen numbers: T. b. 199, 201–215, 224–233, 235–249, 255–258, and 557–593. Shaded areas are two major bands of conglomerates (modified from that in Bohlin, 1960: map 1) that are useful as distinct stratigraphic markers to correlate some localities. Numbers in sections (I–IV) correspond to those in Fig. 4.

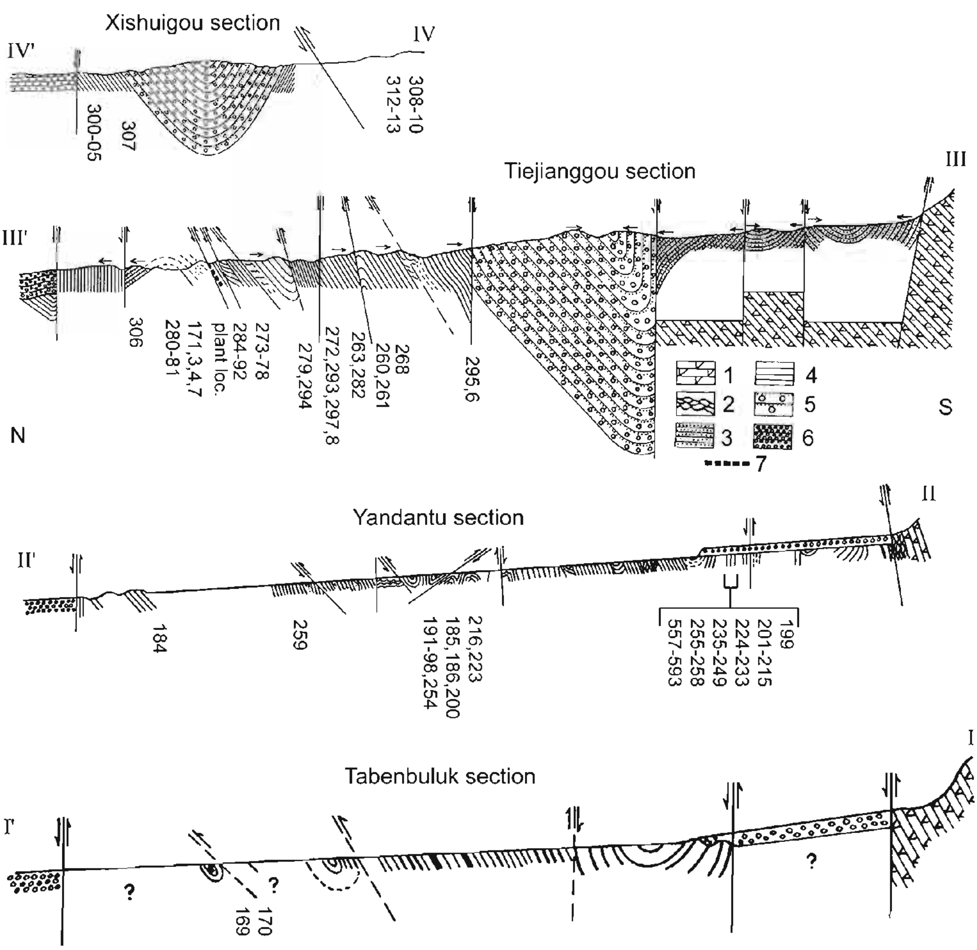

Fig. 4 Cross sections by Bohlin along four major canyons, with specimen numbers plotted along the sections (modified from Bohlin, 1960: sections 1–4)

See text for further explanations; lithological symbols are (modified from those in Bohlin, 1960): 1 and 2. pre-Cenozoic basement rocks; 3. sandstones; 4. mudstones; 5. conglomerates; 6. terrace deposits; and 7. fossil plant layers

With the availability of this map, we can plot the position of almost all major localities on Bohlin's published cross sections in the four major canyons (Fig. 4). Numbers in sections (I–IV) correspond to those in Fig. 3. Bohlin's section IV (Xishui section) is extended here to the right (toward the south) in order to plot the location of the "*Kansupithecus*" locality (T. b. 308). The approximate positions for specimen are calibrated by integrating Bohlin's archive topographic map (Fig. 3), his published geologic map (Bohlin, 1960: map 1), and a few tie-points, such as the Yandantu locality and *Sayimys* locality in the Yandantu canyon (Bohlin, 1946: fig. 89) and the plant localities in the Tiejianggou canyon. Rock symbols are modified from captions for sections 1–4 in Bohlin (1960): 1, basement rocks; 2, brecciated rocks at contact; 3, fine brick red sediments; 4, purple fine conglomerate, sandstone, and silt; 5, coarse conglomerate; 6, young conglomerate; and 7, plant locality.

Although some of Bohlin's structural interpretations are no longer viable in modern understanding of the geology of the Tabenbuluk region, his geologic sketches are rich in stratigraphic details. With these historical data, placed in light of the modern understanding of the magnetostratigraphy and chronology (Sun et al., 2005; Wang et al., 2003a; Wang et al., 2003c; Yin et al., 2002), we can recognize at least five major vertebrate faunas in the Tabenbuluk strata.

4.1 Remarks on Late Oligocene Yandantu Fauna

Bohlin recognized the importance of the Yandantu localities almost from the very beginning. Given the complexity of the local geology, he was careful to make sure the stratigraphy of the Yandantu collection is as clearly recorded as possible (Fig. 5). Bohlin's archive photo (circa 1931–1932) is the same as in Plate IV figure 11 in Bohlin (1960), except a hand-written arrow in the distance which indicates the unconformable contact between steeply tilted Tertiary red beds and flat-lying terraces on the top. The main Yandantu locality where the entire Yandantu Fauna came from is in the general vicinity of the arrow along the right (east) wall of the canyon. Bohlin took pains to separate fossils from the adjacent three vertical layers (corresponding to Dh 199904A, Dh 199904B, and Dh 199904C in Fig. 6), spanning a total thickness of ~40 m, where the fossil assemblage comes from. Bohlin's party collected small mammals within numerous small nodules and about 100 field numbers were recorded (T. b. 199, 201–215, 224–233, 235–249, 255–258, and 557–593, including materials from all three layers).

We were able to relocate the Yandantu locality (IVPP Dh 199904) and collect fossils on both walls of the canyon (those on the western wall are more fossiliferous) (Fig. 6). Bohlin wrote about "three wings" on the right (east) side of the canyon, which refer to the vertically tilted, resistant layers of sandstones and fine conglomerates containing calcareous nodules. The three layers on the east canyon wall are not as prominent as those on the western wall (only one is clearly visible in Fig. 6), nor are they as fossiliferous as the latter. Bohlin tried to make a distinction for the three layers, as did we in naming sites A, B, C (labels in lower part of Fig. 6; A is toward the north and C toward the south), although the layers on one side of the canyon may not correspond exactly to the counterparts in the opposite side due to the short lateral extents of these beds. Our own screen washing in 1999 and 2001 field seasons has resampled a large number of Bohlin's assemblage and also produced previously undescribed forms (Wang, 2002, 2003). Due to taphonomic biases in the local setting, small mammals are the dominant forms in the fauna, an imbalance we were unable to remedy.

The Paoniuquan Formation in the Yandantu locality, from which the Yandantu Fauna comes, is currently not calibrated by paleomagnetic studies. At an average depositional rate of 240 mm/thousand years in the overlying Tiejianggou Formation (Wang et al., 2003c), the 40-meter span for the three fossiliferous layers where the Yandantu Fauna was produced represents only ~0.1 million years in duration (possibly a somewhat longer duration given the fine-grained beds). Such a short duration makes the Yandantu Fauna a uniform assemblage with

Fig. 5 Comparison of historical photo (left) of Yandantu canyon from Hedin Archive and recent photo (right) from approximately the same position

Photos are looking north along the main canyon; reproduction of historical photo by permission from Sven Hedin Foundation, Stockholm; recent photo (right) taken by X. Wang on 22 July 1999

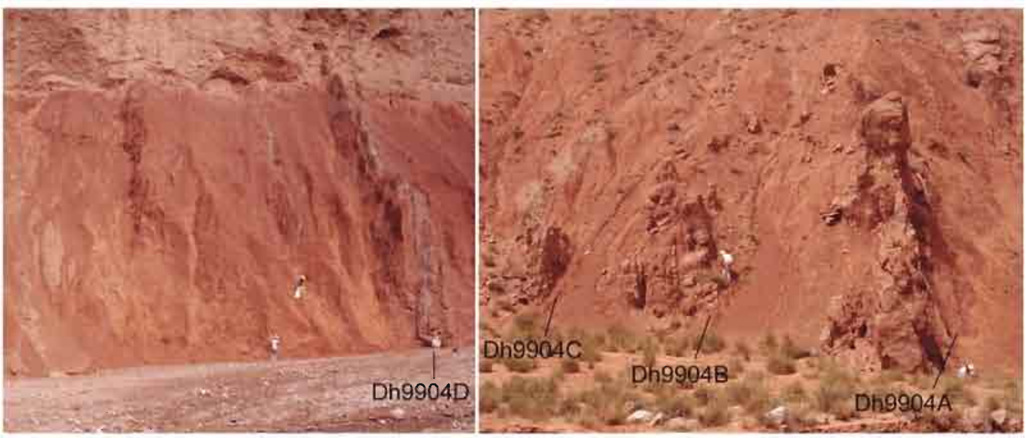

Fig. 6 Photo of Bohlin's Yandantu (Yindirte) locality along eastern wall of the Yandantu canyon (left) and IVPP Dh 199904 locality along the western wall (right)

Persons in background serve as scales; photos taken by X. Wang on 23 July 1999

Fig. 7 IVPP Dh 199910 locality, where "*Kansupithecus*" was presumed to come from

Photo looking toward the west wall of the Xishuigou canyon; photo by B. Y. Wang, 1999

little or no change through time. The type section for the Tabenbulukian Land Mammal Age is defined by this short span represented by IVPP Dh 199904 (A–C) on the western bank of the canyon, which is approximately equivalent to Bohlin's three vertical layers on the eastern bank.

Precise stratigraphic relationship of the Yandantu Fauna with the Dingdanggou Fauna in the Paoniuquan Formation in the lower Tiejianggou section is not clear due to the vegetational coverage between the Yandantu and Tiejianggou canyons. Additionally, a prominent conglomerate that forms a massive syncline (Bohlin, 1960: section 3) (labeled as section 4, contradicting that in text), cut through by a thrust fault (F0 of Wang et al., 2003c) at its southern limb, is missing in the Yandantu section either because the Tiejianggou conglomerates taper off laterally or are eroded away. Lacking (or in conspicuous presence of) this conglomerate/thrust fault relationship in Yandantu, precise visual correlation between the Yandantu and Tiejianggou sections is not easy. Nonetheless, Bohlin (1960: map 1; section 2a) appears to equate a conglomerate in the southern Tabenbuluk canyon with that in Tiejianggou and maps a narrow strip of what he called "brecciated rocks at the contact" (shaded with forward slash) immediately south of the conglomerates (see also Bohlin, 1946: fig. 89). By tracing the contact between the brecciated rocks and the conglomerates and by bridging the gap across Yandantu, F0 may be projected to pass just north of Bohlin's Yandantu locality (IVPP Dh 199904) (dash line projected from F0 in Wang et al., 2003c). Such a correlation implies that Dh 199904 is not far (perhaps slightly more than 100 m) above Dh 200102, the highest locality for the Dingdanggou Fauna (Wang and Qiu, 2004).

4.2 Remarks on Early Miocene Xishuigou Fauna and "*Kansupithecus*" locality

Bohlin's party set their fourth (last) camp in Xishuigou (His-shui), the eastern most major canyon that he visited. About 2.5 km up stream (southwest) of the camp, Bohlin found the jaw fragment of "*Kansupithecus*" (T. b. 309), along with remains of cervid, rhinocerotid, and proboscidean (T. b. 308, 310, 312, 313). Along the western wall of Xishui canyon, we found a horizon (Dh 199910 and Dh 199911) that produced a small fossil assemblage, the Xishuigou Fauna (Wang et al., 2003a; Wang et al., 2003c), including a primitive species of *Platybelodon* (Wang and Qiu, 2002), a primitive mustelid *Kinometaxia* (Wang et al., 2004), and other forms (Fig. 7). Bohlin's (1942: 9) primates jaw was from "fine, brick red sediments east of Hsi-shui" (he probably meant "west" as evidenced by his archive map in Fig. 3, an error probably stemming from his upside-down orientation of his topomap). The general position of T. b. 309 is consistent with localities Dh 199910-11, which is the only layer rich in carbonate nodules in that vicinity that tend to preserve fossil bones.

Another primate tooth, T. b. 557, found by Bohlin was from the Yandantu locality (in northern layer of his three-layer scheme) during his second visit to the locality in 1932 (Bohlin, 1946: 243). Although he placed it under the same "*Kansupithecus*" name, he strongly suspected that the single tooth was stratigraphically wide apart from the Xishui lower jaw. He suggested that the two specimens could well represent different genera of primates when better materials become available. Bohlin's suspension is now confirmed by current understanding of geologic and paleontologic relationships, and the Late Oligocene Yandantu Fauna and Early Miocene Xishuigou Fauna (19 ~ 20 Ma) are probably more than 5 million years apart.

Bohlin (1946: 249) also remarked the similarity of a rhino (which he tentatively called "Rhinocerotidae (? *Aceratherium*) sp.") from his Xishuigou primate locality to those from a locality between the canyons of Tiejianggou and Yandantu (T. b. 275, 284, 286, 288, 289, 290). Although he compared the latter with *Chilotherium* and *Dicerorhinus*, rhinos typical in the *Hipparion* faunas in the Late Miocene, he was fairly certain that these rhinos do not belong to Late Miocene forms. Stratigraphically, T. b. 275 can be projected along strike to the same general level as the primate jaw locality (physical correlation between the two localities are not possible, which are several km apart).

Furthermore, a fossil plant locality (V in Fig. 3) is also along strike of T. b. 275. We were able to locate some of the carbon-rich shales (IVPP Dh 199902-03) in the lower part of the Tiejianggou Formation, where Bohlin's plant fossils were presumed collected (see Wang et al., 2003c: fig. 4). An upper and lower jaw of *Heterosminthus intermedius* (Dh 199903) is found in the dark shales and displays an intermediate morphology between Late Oligocene and

Middle Miocene forms (Wang, 2003). Bohlin handed his fossil plant collection to Ralph Chaney for studying, who named it the Kucha Flora (Chaney, 1935).

In a recent paleomagnetic study, Sun et al. (2005: fig. 4) placed our Tiejianggou fossil locality within 2 400 ~ 2 600 m of their Tiejianggou section, and correlated to C5En (18.056 ~ 18.524 Ma) in the Early Miocene. This largely normal polarity interval for the lower fossil horizons in Tiejianggou is consistent with its corresponding interval in Xishuigou (Gilder et al., 2001), further lending confidence to our correlations between these two canyons.

4.3 Remarks on an unnamed fauna in the Tiejianggou Formation and related *Sayimys* localities

The discoveries of a nearly complete skull (T. b. 279a) and jaw (T. b. 268b), plus other materials, of a new species of *Sayimys*, *S. obliquidens*, in Tiejianggou is another stratigraphically interesting puzzle to Bohlin. At the time of the initial discovery, *Sayimys* was only known in the early Late Miocene "Nagri zone" of the Siwalik Group of India and Pakistan (Wood, 1937). It is now known to extend to Middle Miocene or even to late Early Miocene of Pakistan (Baskin, 1996). Its presence in Gansu is thus both biogeographically and geologically interesting. In fact, *Sayimys* is perhaps the most jarring taxon in Bohlin's collections from the Tabenbuluk area that convinced him rocks of Miocene age must have existed (Bohlin, 1946: 250).

From Bohlin's archive map (Fig. 3), the closest *Sayimys* locality (T. b. 279) to his plant locality in Tiejianggou is about 1 km south of the latter. In our own measurements (Wang et al., 2003c: fig. 4), this translates to more than 600 m in thickness between the lowest occurrence of *Sayimys* (close to our Dh 199907 locality) and the Tiejianggou plant locality. Elsewhere Bohlin (1946: 248) suggested that two of the *Sayimys* localities, T. b. 279 and 261, are about 1 km apart (corresponding to >600 m in thickness in this part of the section) along the Tiejianggou, implying an extended presence of this genus in Tabenbuluk strata. Given this extended range for *Sayimys* in Tabenbuluk region, it is not surprising that Bohlin (1946: 110) suspected that there are more than one species present, although he had restrained from naming a second species.

Evolutionarily, *Sayimys obliquidens* is considered to be more primitive than its Siwalik relative (Bohlin, 1946: 117), suggesting an older age for the Gansu species. Sun et al. (2005: fig. 4) bracketed our Dh 199907 locality, which is probably close to Bohlin's *Sayimys* localities, within 1 600 ~ 1 800 m range of their Tiejianggou magnetic section, which corresponds to a predominantly normal interval that was correlated to C5ACn–C5ADn (13.734 ~ 14.581 Ma) in the late Middle Miocene (Ogg and Smith, 2004). Furthermore, *Sayimys* appears to be phylogenetically derived from ancestral ctenodactylids from the Oligocene of central Asia (Wang, 1997), suggesting that the Siwalik forms may have been derived from Gansu.

The fauna associated with Bohlin's *Sayimys* localities is still poorly known. Bohlin (1946) described cervid antler fragment (T. b. 296) that may be related to Middle Miocene *Lagomeryx* or *Stephanocemas*, proboscidean dental and postcranial fragments (T. b. 200, 223, 283), and partial lower jaws and isolated tooth of ? *Schizotherium* sp. (T. b. 297). The latter, morphologically intermediate between *S. ordosium* and *S. avitum*, is not known to be pre-sent in Miocene, and thus represents an incongruent element in a presumed Miocene assemblage (Wang et al., 2003a; Wang, 2003). We caution, however, that we cannot be confident about our own interpretation of Bohlin's handwriting for locality T. b. 297 in his topomap (Fig. 3) because of poor legibility, and there is an alternative interpretation for T. b. 297 to be where our "29?" is, in which case T. b. 297 would have been in a stratigraphically much lower position than indicated in Fig. 3.

In the upper part of the Xishuigou section that is stratigraphically equivalent to *Sayimys* localities in Tiejianggou and Yandantu, we also found jaws of *Litodonomys xishuiensis* (Dh 200105) (Wang, 2003) and a *Phyllotillon* metacarpal (Dh 199913). With the chronologic constraints from Xishuigou and Tiejianggou paleomagnetic studies (Gilder et al., 2001; Sun et al., 2005), the fossil localities generally fall in the Middle Miocene part of the section (see Fig. 8). We refrain from formally establishing a fauna based on so few taxa and caution a possible mixing of faunal elements in this assemblage (Wang et al., 2003a,c).

4.4 Remarks on Late Miocene-Pliocene "*Gazella*" localities

Near Bohlin's Xishui camp at the mouth of the Xishuigou, Bohlin's party has found a medium-sized artiodactyle jaw with m1-2. He compared this specimen with species of *Gazella* and *Tragoreas*. Bohlin strongly suspected that he was dealing with a bovid of much later age: "T. b. 307 is considered by me as a comparatively late type that cannot possibly belong to an Oligocene fauna" (Bohlin, 1946: 214).

The strip of the unnamed orange-red beds and conglomerates along the northeastern edge of the Tabenbuluk exposures belong to the topmost sequence of the Cenozoic Tabenbuluk sediments. This package is bounded to the south by a low-angle thrust fault, F1, which is clearly visible near the conglomerate syncline axis close to a major bend in the Xishuigou (Fig. 8). Further north, this younger package is dissected by the Altyn Tagh Fault at a diagonal angle. Our own collecting in this region did not yield any age-diagnostic fossils. However, based on paleomagnetic studies (Gilder et al., 2001; Yin et al., 2002), which are reinterpreted by us (Wang et al., 2003a; Wang et al., 2003c), the top conglomerate in the Tiejianggou Formation is about 9 Ma, as also shown in a Tiejianggou paleomagnetic section (Sun et al., 2005). The Xishui top package (unnamed formation) must therefore be younger than 9 Ma, possibly much younger as postulated by Van der Woerd et al. (2001) and Gilder et al. (2001).

4.5 Comments on faunal and geographic names from Tabenbuluk area

Recently the use of the terms Tabenbuluk and Yandantu faunas has become controversial. We proposed to use the term Yandantu Fauna for the main Tabenbuluk mammal assemblage (Wang et al., 2003a; Wang et al., 2003c), whereas Meng et al. (2006) maintains that Tabenbuluk Fauna was Bohlin's original intention and should be used instead. It is thus useful to review the usage of these names for future clarity.

Throughout Bohlin's writings (Bohlin, 1942, 1945, 1946, 1953, 1960), the name Tabenbuluk (spelled Taben-buluk by Bohlin) is first and foremost used to designate an area of badlands that produced fossil mammals, plants, and archaeological relics, such as "Taben-buluk area," "Taben-buluk badland," etc. As a name for a series of small natural springs, Tabenbuluk (Mongolian for "five springs") is also used to represent the western-most major canyon of the area, with the springs situated at the entrance of the Tabenbuluk canyon (Fig. 2). The inviting oasis at the canyon mouth lies along a caravan road from Dunhuang to the northern Tibetan Plateau, and naturally is the first campsite (BB 68) for Bohlin when he arrived at the area in 1931. It is therefore not surprising that he adopted this name for the whole area, even though as a fossil locality the Tabenbuluk canyon is the least fossiliferous with only one locality near its entrance (T. b. 169 in Fig. 3; as far as we know, Bohlin did not mention specific fossils from this locality). Despite his later discoveries of far more fossiliferous canyons to the east in Yandantu, Tiejianggou, and Xishuigou, the name Tabenbuluk was stuck as the most common geographic term in his later writings.

As remarked above, Bohlin typically used the name Yandantu (Yindirte) to refer to the richly fossiliferous locality in the Late Oligocene near the southern end of the Yandantu canyon, despite the fact that mammals of later (Miocene) age are also found in the same canyon. However, Bohlin was keenly aware of this age difference and his references of the Yandantu locality always unambiguously stand for the restricted Oligocene locality. When in doubt, he (Bohlin, 1946: 110, 248) would use enough qualifiers to make this clear.

Bohlin's usage of "Tabenbuluk fauna" tends to be a mixed concept of either indicating a restricted fauna from the Yandantu locality or more broadly the entire vertebrate assemblage from the Tabenbuluk area (which includes mammals of at least four different ages; see Fig. 8). This blending of concepts, however, seems not because of his lack of understanding of the stratigraphy but simply due to the prevailing practices of his day, such as his similar usage of Qaidam fauna to represent fossils from a wide range of strata.

When Bohlin did use the term "Yindirte fauna," however, it was always in situations where he needs to be the most specific in expressing precise faunal relationships in their most restricted sense, as for example, "*Sayimys* is another fossil that seems to be younger than the Yindirte fauna" (Bohlin, 1946: 248). It seems reasonable to assume that Bohlin preferred Yindirte fauna to Tabenbuluk fauna in reference to fossils from the Yindirte locality whenever clear distinctions were necessary, although he did not expressly say so.

Meng et al. (2006: 224–225) argued that Bohlin used the Tabenbuluk fauna first and in a more formal context. While it is true that Tabenbuluk fauna was used first (but in a mixed context, see above), it is far from clear that it was more formally used. In fact, we think Bohlin's usage of Yandantu fauna was more formal because the latter's more specificity. As for the question of priority, we would submit that Bohlin's earlier usage of Tabenbuluk fauna was mostly intended as a generic term for the overall vertebrate assemblage from the entire region, and his later reference of Yandantu Fauna was his attempt at defining the faunal content, which can be construed as his first proposal to formalize these terms. Therefore, we propose to use the term Yandantu Fauna as its principal characteristic fauna and abandon Tabenbuluk fauna as an imprecise term, and to use Tabenbulukian Land Mammal Age as a well-established name.

5 Discussions

Bohlin did much to document the localities to his best abilities with limited resources. To his credit, he succeeded in distinguishing a number of faunas of different ages, particularly the Late Oligocene Yandantu Fauna and the Miocene *Sayimys* fauna, as well as his strong suspicion that "*Kansupithecus*" is of a different age as well. These distinctions were based as much on stratigraphic differences as on faunal comparisons with his meticulous attentions to details and astute observations. As the first geologist to explore such vast and complex a package of strata, he may be excused to make an occasional error of interpretations about the stratigraphic relationships. For an overall understanding of the regional geology, he alluded to a generally symmetrical stratigraphy surrounding a giant "anticline" (Bohlin, 1946: 249), with the consequently repetitive sequences on either sides of the "anticline." As a result, Bohlin seems to regard the red beds at the foot of the Danghe Nanshan as the same as those north of the anticline (beds containing *Sayimys*), a notion that is now known to be false.

Although Bohlin has embedded his nuanced discussions and caveats in various places, his characteristic tentativeness in his discourse about younger (Miocene) faunas has important consequences. This lack of a clear order of faunal sequences is possibly the single most critical omission that caused endless confusions right into the 21st century, such as recent paleomagnetic works that used Bohlin's faunas as chronologic constraints (Gilder et al., 2001; Yin et al., 2002).

We present a biostratigraphic framework (Fig. 8) and geologic events that summarize Bohlin's geologic and paleontologic records (Bohlin, 1942, 1945, 1946, 1953, 1960) as well as those of our own (Wang, 2002, 2003; Wang and Qiu, 2002, 2004; Wang et al., 2003a,b, c, 2004). Given the long geologic record in the Tabenbuluk area, future paleontologic investigations undoubtedly can further divide various faunal components.

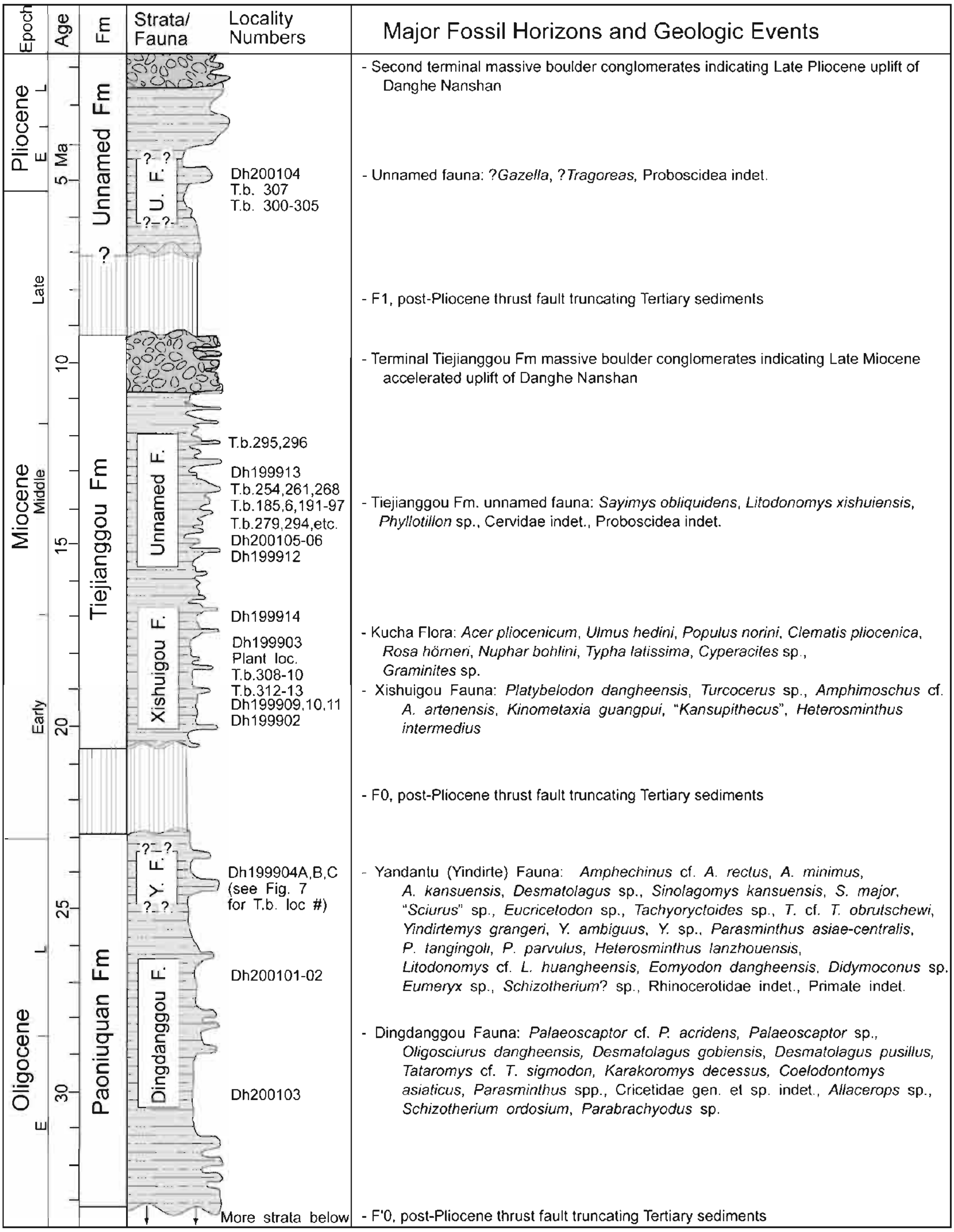

Fig. 8　Faunas in the Tabenbuluk area and important stratotectonic events

Stratigraphic positions of Bohlin's fossil localities are estimated based on a few tie points explained in Figs. 3, 4; the age for the Dingdanggou Fauna (Wang and Qiu, 2004) is based on unpublished paleomagnetic data by Fang Xiaomin; faunas whose boundaries are marked by question marks still lack magnetic calibration

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