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泥河湾盆地上新世生物地层序列与环境[1)]

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摘要：总结了泥河湾盆地晚上新世生物地层，讨论了12个剖面含哺乳动物化石层位的相互关系，以稻地老窝沟剖面的地层顺序为基础排列出约3.7～2.6 Ma时段内的9个代表性的生物地层单位。哺乳动物以 *Paenelimnoecus chinensis*、*Lunanosorex* cf. *L. lii*、*Trischizolagus*、*Pliopentalagus nihewanicus*、*Ungaromys*、*Mimomys* sp.、*Chardina truncatus*、*Mesosiphneus praetingi*、*M. paratingi*、*Pliosiphneus lyratus*、*Pseudomeriones complicidens*、*Castor anderssoni*、*Huaxiamys downsi*、*Chardinomys yusheensis*、*C. nihowanicus*、*Hipparion houfenense* 和 *Gazella blacki* 组合为特征。动物群在时代上与榆社麻则沟动物组合、静乐红土动物群、灵台雷家河剖面V带及任家沟静乐红粘土动物组合、宁县水磨沟动物组合、游河动物群及沂南棋盘山洞穴动物组合相当。动物群所反映的是温带草原为主、间有树林和干草原的稀树草原环境。

关键词：泥河湾盆地，上新世，哺乳动物，生物地层序列，环境

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1 前 言

河北泥河湾盆地出露了150余米厚的河湖沼泽相堆积物（袁宝印等，1996；闵隆瑞等，2006）。该套沉积物之下、出露于桑干河峡谷（＝石匣）附近约30 m（～“90 ft”）的红粘土（不含任何化石和砾石）最初被认为是古老岩石的风化物（Barbour et al., 1926），其时代被推测为？蓬蒂期（Teilhard and Piveteau, 1930）或晚中新世的保德期（Black et al., 1933）。陈茅南（1988）将出露于石匣里大红沟剖面底部约30 m厚的红粘土（含砂砾石）命名为“大红沟组”，同时也将红崖南沟剖面下部厚约12 m、红崖扬水站剖面下部厚约7 m的红粘土归于该组，其时代为上新世。出露于红崖村乱石疙瘩沟约20～30 m厚的红色、黄红色砂质粘土和砾石交互层，因产三趾马和大唇犀而被称为三趾马红土，其时代为上新世（黄万波等，1974）。出露于西窑子头花豹沟约45 m厚的砂砾石和钙质结核透镜体的红粘土层因产有大型哺乳动物化石被分成上部“蔚县组”和底部“壶流河组”，其时代分别相当于上新统的静乐组和上中新统的灞河组（王安德，1982）；但张兆群等（2003）认为这两个组之间的地层界线并不清

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楚,而且所含化石没有如此大的区别,因此建议将两个组合并成蔚县组,其时代为晚上新世。出露于稻地老窝沟、红崖南沟、西窑子头将军沟、祁家庄后沟、芫子沟、钱家沙洼村小水沟、北马圈连接沟、铺路牛头山(=铺路)及大南沟等地点的一套河湖相和沼泽相堆积物被命名为"稻地组",其时代为晚上新世(杜恒俭等,1988);张兆群等(2003)认为这些剖面均很短,从宏观地层对比看仅仅是蔚县组的一部分,建议将稻地组归入蔚县组,但蔡保全等(2004)认为目前证据不够充分,仍建议同时使用蔚县组/稻地组。至于稻地老窝沟剖面底部第1层红粘土因粒度均一、无砾石成分、筛洗小哺乳动物过程中未发现任何水生动物化石等原因,而暂时未定组;由于所采到的哺乳动物化石较少,其时代估计为晚上新世初或中上新世(张兆群等,2003;蔡保全等,2004)。上新统/更新统的界限在老窝沟剖面(蔡保全等,2004)、洞沟剖面(郑绍华等,2006)、台儿沟剖面(闵隆瑞等,2006)和牛头山剖面(蔡保全等,2007)已被确定。

至此可以得出如下结论:泥河湾盆地下部出露层位属上上新统;地层分布于桑干河峡谷地带与壶流河下游两岸,岩性包括风成红粘土、含砂砾石河湖相红粘土与沼泽相砂质粘土。

目前已知12个地点的剖面含有一个或多个哺乳动物化石层位(图1)。本文将在重新鉴定标本的基础上,根据动物组合、地层位置及岩性特征将它们对应到老窝沟剖面的不同层位并建立起一套晚上新世生物地层序列,从而探讨它们的时代和环境演变。

2　上新世哺乳动物地点及层位

泥河湾盆地上新世哺乳动物除原先"稻地组"中的兔形类(lagomorphs)、啮齿类中的鼠亚科(Murinae)以及东窑子头剖面中的大型哺乳动物被描述(蔡保全,1989;Tomida and Jin,2005;Erbajeva and Zheng, 2005;蔡保全、邱铸鼎,1993;郑绍华、蔡保全,1991;汤英俊,1980;汤英俊、计宏祥,1983)外,其他门类或引用或由本文第二作者进行了初步鉴定。

1) 老窝沟剖面:位于泥河湾盆地壶流河西岸,阳原县辛堡乡(原南辛庄乡)稻地村西北约750 m的老窝沟左岸,距沟口约150 m。该剖面是杜恒俭等(1988)建立"稻地组"的典型剖面。地理位置是北纬40°08′59″,东经114°39′31″。按张兆群等(2003)和蔡保全等(2004)的地层划分(剖面厚度128.08 m,从下至上共29层)及1985-2006年间的化石积累,含化石层6个,主要含小哺乳动物29种,其在地层中的分布如表1所示。

2) 洞沟剖面:位于泥河湾盆地壶流河东岸,阳原县化稍营镇钱家沙洼村东北约500 m的896 m高地。地理位置北纬40°12′11.7″,东经114°38′45.2″,剖面底部海拔高度840 m。此剖面是杨子赓等(1996)建立泥河湾标准剖面的典型地点之一。作为探讨泥河湾盆地堆积物中下部上新统/更新统界限的典型剖面之一,其界限被确定在10和11层之间,即上新统地层出露于沟底以上18.9 m范围内(郑绍华等,2006)。所测剖面厚度56.25 m,从下至上被分成28层。其中从2、4、7、11、16和19这6层采集到一批小哺乳动物化石(共33种),其在地层中的分布参见郑绍华等(2006,表2)。

3) 牛头山剖面:位于壶流河东岸,蔚县铺路村南约500 m或东窑子头村北约700 m

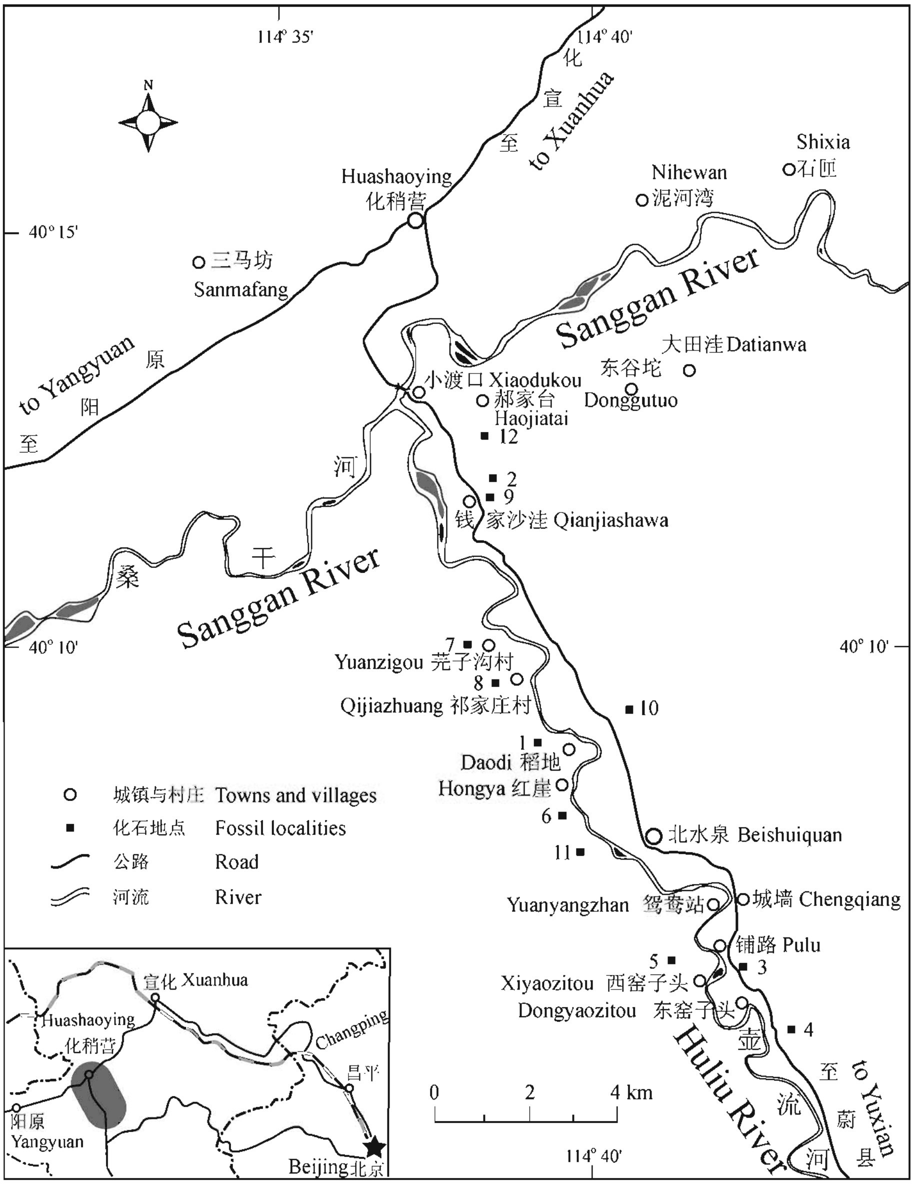

图1 泥河湾盆地上新世哺乳动物产地分布

Fig. 1 Sketch-map of the Pliocene mammalian localities in the Nihewan Basin

1. 老窝沟 Laowogou; 2. 洞沟 Donggou; 3. 牛头山 Niutoushan; 4. 大南沟 Danangou; 5. 花豹沟 Huabaogou; 6. 红崖南沟 Hongya Nangou; 7. 芫子沟 Yuanzigou; 8. 后沟 Hougou; 9. 小水沟 Xiaoshuigou; 10. 连接沟 Lianjiegou; 11. 将军沟 Jiangjungou; 12. 台儿沟 Taiergou

的宣 - 蔚公路左侧。北纬 40°06′13.4″,东经 114°42′36.6″。公路旁海拔高度 838 m。它是杜恒俭等(1988)建立“稻地组”的主要剖面之一(= 铺路剖面)。最初只有 2 个含化石层,即 L3 和 L9, 2005 年增加 L6、L15 和 L16,2006 年增加 L12。按蔡保全等(2007),L3-

L12 层的小哺乳动物组合代表晚上新世,L15－16 代表早更新世,因此上新统/更新统的界限被置于 L13 和 L12 之间。该剖面共发现小哺乳动物化石 29 种,其在地层中的分布见蔡保全等(2007,表 1)。

表 1　老窝沟剖面中的哺乳动物

Table 1　Mammals from the Laowogou section

种类 species	上新统 Pliocene					
	层位 layers					
	1	2	3	9	11	19
Sorex sp.			●			
Paenelimnoecus chinensis Jin & Kawamura, 1997				●		
Lunanosorex cf. *L. lii* Jin & Kawamura, 1996					●	
Quyania sp.					●	
Ochotona sp.			●			
Ochotona minor (Bohlin, 1942)					●	
Trischizolagus sp.	●					
Cricetinae indet.	●					
Kowalskia similis Wu, 1991		●				
Sinocricetus progressus Qiu & Storch, 2000		●	●	●	●	
Nannocricetus mongolicus Schaub, 1934		●	●	●	●	●
Ungaromys spp.		●	●		●	
Mimomys sp.			●	●	●	
Mimomys sp. 2				●		
Chardina truncatus (Teilhard, 1942)		●				
Mesosiphneus praetingi (Teilhard, 1942)				●	●	
Pliosiphneus sp. 2			●			
Pseudomeriones complicidens Zhang, 1999			●			
Dipus fraudator (Schlosser, 1924)				●	●	
Paralactaga anderssoni Young, 1927				●		
Castor anderssoni (Schlosser, 1924)					●	
Micromys tedfordi Wu & Flynn, 1992		●	●	●		
? *Huaxiamys* sp.		●				
Huaxiamys downsi Wu & Flynn, 1992		●				
Apodemus zhangwagouensis Wu & Flynn, 1992		●	●		●	
Chardinomys yusheensis Jacobs & Li, 1982	●	●	●			
Chardinomys nihowanicus (Zheng, 1981)			●	●	●	●
? *Karnimata* sp.				●		
Saidomys sp.				●		

4) 大南沟剖面:位于壶流河东岸,蔚县北水泉镇东窑子头村东南约 1000 m 的大南沟内,距沟口约 300 m。北纬 40°05′36″,东经 114°43′35″。为泥河湾地区典型的上新世/更新世生物地层剖面(蔡保全等,2004),也是杜恒俭等(1988)建立"稻地组"的重要剖面之一。其底部 1－2 层被归入上新统(郑绍华、蔡保全,1991),所含化石见表 2。

表 2 大南沟剖面中的哺乳动物

Table 2 Mammals from the Danangou section

种类 species	层位 layers	
	1	2
Soriculus sp.	•	
Blarinella sp.	•	
Erinaceus sp.	•	
Ochotona sp.	•	•
Phodopus sp.	•	
Sinocricetus progressus Qiu & Storch, 2000	•	•
Nannocricetus mongolicus Schaub, 1934	•	•
Mimomys sp.	•	
M. sp. 2	•	
Borsodia chinensis (Kormos, 1934)	•	
Ungaromys spp.	•	
Mesosiphneus paratingi (Teilhard, 1942)	•	
Paralactaga anderssoni Young, 1927	•	
Dipus fraudator (Schlosser, 1924)	•	
? *Dipoides* sp.		•
Micromys tedfordi Wu & Flynn, 1992	•	
Apodemus zhangwagouensis Wu & Flynn, 1992	•	
Chardinomys nihowanicus (Zheng, 1981)	•	
Lynx variabilis Tang, 1980		•
Paracamelus sp.		•
Antilospira yuxianensis Tang, 1980		•
Palaeotragus progressus Tang & Li, 1983		•

5) 花豹沟剖面:位于壶流河西岸,蔚县北水泉镇西窑子头村西北约 1000 m 的花豹沟内,距沟口约 500 m。它是王安德(1982)建立"蔚县组"和"壶流河组"的典型剖面。近来有人认为两组是同物异名,建议只保留蔚县组(张兆群等,2003)。所测剖面厚约 50 m,从沟底至上被分成 8 层。其中,第 1 层为原先的"壶流河组"、第 3 和 5 层为原先的"蔚县组"。表 3 中大哺乳动物为王安德(1982)所列,其中"*Sinoryx*"鉴定明显有误,暂不列出;小哺乳动物由蔡保全等于 2002 年所采集。

6) 红崖南沟剖面:位于泥河湾盆地壶流河西岸,阳原县辛堡乡(原南辛庄乡)红崖村南约 500 m 的南沟中。北纬 40°08′07.3″,东经 114°39′57.1″。剖面底部海拔高度 858 m。它是杜恒俭等(1988)建立"稻地组"的主要剖面之一。所测剖面厚 25.31 m,被分成 7 层,1、4 层为含化石层,主要为小哺乳动物(表 4)。

表 3 花豹沟剖面中的哺乳动物

Table 3 Mammals from the Huabaogou section (after Wang, 1982; Zhang et al., 2003)

种类 species	层位 layers		
	蔚县组 Yuxian Fm.		
	"壶流河组" "Huliuhe Fm."	"蔚县组" "Yuxian Fm."	
	1	3	5
? *Blarinella* sp.			•
Leporidae indet.	•		
Cricetinae indet.		•	
Sinocricetus progressus Qiu & Storch, 2000	•		
Pliosiphneus lyratus (Teilhard, 1942)	•		
Chardina truncatus (Teilhard, 1942)	•		
Pseudomeriones complicidens Zhang, 1999	•		
Huaxiamys downsi Wu & Flynn, 1992	•		
Apodemus zhangwagouensis Wu & Flynn, 1992	•		
Chardinomys nihowanicus (Zheng, 1981)	•	•	•
Canis sp.	•		
C. multicuspus[1)]	•		

续表

种类 species	层位 layers		
	蔚县组 Yuxian Fm.		
	“壶流河组” “Huliuhe Fm.”	“蔚县组” “Yuxian Fm.”	
	1	3	5
Nyctereutes sinensis (Schlosser, 1924)	•		
Viverra sp.		•	
Hipparion cf. *H. hippidiodus* Sefve, 1927	•		
H. houfenense Teilhard & Young, 1931		•	
Hipparion sp.	•		
Palaeotragus sp.	•		
Gazella blacki Teilhard & Young, 1931	•	•	
Gazella spp.	•	•	
Antispiroides hopeiensis Zong & Wei, 1993		•	

1) 王安德(1982)原文中记为“*Canis multicuspus* sp. nov.”,无任何描述和图示,应为裸记名称。为便于查阅,表 4 和表 8 仍引用之。

表 4　红崖南沟剖面中的小哺乳动物

Table 4　Small mammals from the Hongya Nangou section

种类 species	层位 layers	
	蔚县组/稻地组 Yuxian/Daodi Fm.	
	1	4
Lunanosorex cf. *L. lii* Jin & Kawamura, 1996	•	•
Beremendia sp.		•
Sorex sp.		•
Yanshuella sp.		•
Ochotona sp.	•	•
Hypolagus schreuderi Teilhard, 1940	•	•
Pliopentalagus nihewanensis Cai, 1989	•	
Nannocricetus mongolicus Schaub, 1934	•	•
Sinocricetus progressus Qiu & Storch, 2000	•	•
? *Kowalskia* sp.		•
Mimomys sp.	•	•
Ungaromys spp.	•	•
Mesosiphneus paratingi (Teilhard, 1942)	•	•
Dipus fraudator (Schlosser, 1924)	•	•
Mus sp.	•	
Micromys tedfordi Wu & Flynn, 1992	•	
Huaxiamys downsi Wu & Flynn, 1992	•	
Apodemus zhangwagouensis Wu & Flynn, 1992	•	
Chardinomys nihowanicus (Zheng, 1981)	•	•

7) 芫子沟剖面:位于泥河湾盆地壶流河西岸,阳原县辛堡乡(原南辛庄乡)芫子沟村西约 300 m。北纬 40°10′05.8″,东经 114°38′28.9″。剖面底部海拔高度 863 m。主要为沼泽相堆积,所测剖面厚 20.9 m,被分成 6 层。2、4 层含化石(见表 5)。

表 5 芫子沟剖面中的小哺乳动物

Table 5 Small mammals from the Yuanzigou section

种类 species	层位 layers	
	蔚县组/稻地组 Yuxian/Daodi Fm.	
	2	4
Ochotona cf. *O. lagrelii* Schlosser, 1924	•	
Pliopentalagus nihewanensis Cai, 1989	•	
Sinocricetus progressus Qiu & Storch, 2000	•	•
Mimomys sp.	•	•
Ungaromys spp.	•	•
Apodemus zhangwagouensis Wu & Flynn, 1992		•
Micromys tedfordi Wu & Flynn, 1992		•

8）祁家庄后沟剖面：位于泥河湾盆地壶流河西岸，阳原县辛堡乡（原南辛庄乡）祁家庄村西约 300 m 的后沟内。北纬 40°09′38.6″，东经 114°38′53.1″。剖面底部海拔高度 870 m。所测剖面厚 30.3 m，主要为沼泽相堆积，是杜恒俭等（1988）建立“稻地组”的主要剖面之一。被分成 6 层，4、5 层为含化石层位，共有 16 种动物（表 6）。

9）小水沟剖面：位于泥河湾盆地壶流河东岸，阳原县化稍营镇钱家沙洼村东约 300 m 的小水沟口左岸缓坡。北纬 40°11′43″，东经 114°38′40.6″。剖面底部海拔高度 848 m。主要为沼泽相堆积，是杜恒俭等（1988）建立“稻地组”的主要剖面之一。所测剖面厚 18.37 m，被分成 7 层，其中 1、2、4 层含化石，共发现小哺乳动物 14 种（表 7）。

表 6 后沟剖面中的小哺乳动物

Table 6 Small mammals from the Hougou section

种类 species	层位 layers	
	蔚县组/稻地组 Yuxian/Daodi Fm.	
	4	5
Lunanosorex cf. *L. lii* Jin & Kawamura, 1996	•	•
? *Beremendia* sp.	•	
Quyania sp.		•
Hypolagus schreuderi Teilhard, 1940	•	•
Pliopentalagus nihewanensis Cai, 1989		•
Nannocricetus mongolicus Schaub, 1934		•
Sinocricetus progressus Qiu & Storch, 2000	•	
Mimomys sp.	•	•
M. sp. 2	•	
Ungaromys spp.	•	•
Mesosiphneus praetingi (Teilhard, 1942)	•	•
Dipus fraudator (Schlosser, 1924)	•	
Micromys tedfordi Wu & Flynn, 1992		•
Apodemus zhangwagouensis Wu & Flynn, 1992		•
Chardinomys nihowanicus (Zheng, 1981)	•	•
Karnimata sp.		•

10）北马圈连接沟剖面：位于泥河湾盆地壶流河东岸，蔚县北水泉镇北马圈村东南约 1500 m 的连接沟抽水站旁。北纬 40°09′18.3″，东经 114°40′38″。剖面底部海拔高度 852 m。所测剖面厚 21.74 m，为沼泽相堆积，只第 7 层 1 个含化石层位。产出小哺乳动物 6 种：*Ochotona* cf. *O. lagrelii* Schlosser, 1924、*Pliopentalagus nihewanensis* Cai, 1989、*Sinocricetus progressus* Qiu & Storch, 2000、*Mimomys* sp.、*Mesosiphneus praetingi* (Teilhard de Chardin, 1942)、*Dipus fraudator* (Schlosser, 1924)。

11）将军沟剖面：位于壶流河西岸，蔚县北水泉镇西约 1500 m 的将军沟口。剖面厚 18.35 m，为红粘土之上的沼泽相堆积，被分成 7 层，只第 1 层含化石，产出有：*Ochotona minor*?（Bohlin, 1942）、*Nannocricetus mongolicus* Schaub, 1934、*Mimomys* sp.、*Ungaromys* spp.、*Mesosiphneus paratingi* (Teilhard de Chardin, 1942)、*Dipus fraudator* (Schlosser, 1924)、*Chardinomys nihowanicus* (Zheng, 1981)。

12) 台儿沟剖面:位于泥河湾盆地壶流河下游东岸,化稍营镇小渡口村郝家台的南坡、大道坡沟一支沟内。北纬 40°12′52″,东经 114°38′22″。剖面顶海拔高度 953 m。剖面厚 151.45 m,从下到上被分成 12 段、146 层;剖面深 33.55 m 处为古地磁年表的 B/M 界限,123 m 处为 M/G 界限。其中,第 9 段(97 层)和第 3 段(29 层)分别产出更新世和上新世小哺乳动物。含化石层位大致分别位于剖面 68 m 和 131 m 处(闵隆瑞等,2006)。经重新观察,第 3 段上新世的小哺乳动物有:*Sorex* sp.、*Erinaceus* sp.、*Ochotona* cf. *O. lingtaica* Erbajeva & Zheng, 2005、*Hypolagus* cf. *H. schreuderi* Teilhard de Chardin, 1940、*Nannocricetus mongolicus* Schaub, 1934、*Sinocricetus progressus* Qiu & Storch, 2000、*Mimomys* sp. 1、*Mesosiphneus paratingi* (Teilhard de Chardin, 1942)、*Dipus* sp.、*Sicista* sp.、*Mus* sp.、*Micromys tedfordi* Wu & Flynn, 1992、*Apodemus zhangwagouensis* Wu & Flynn, 1992、*Chardinomys nihowanicus* (Zheng, 1981)、? *Saidomys* sp.。

表 7　小水沟剖面中的小哺乳动物

Table 7　Small mammals from the Xiaoshuigou section

种类 species	层位 layers		
	蔚县组/稻地组 Yuxian/Daodi Fm.		
	1	2	4
Lunanosorex cf. *L. lii* Jin & Kawamura, 1996	•	•	
Ochotona minor? Bohlin, 1942			•
Hypolagus schreuderi Teilhard, 1940			•
Nannocricetus mongolicus Schaub, 1934	•		•
Sinocricetus progressus Qiu & Storch, 2000		•	•
Mimomys sp.	•	•	
M. sp. 2			•
M. sp. 1			•
Ungaromys spp.	•	•	
Mesosiphneus paratingi (Teilhard, 1942)		•	•
Dipus fraudator (Schlosser, 1924)			•
Micromys tedfordi Wu & Flynn, 1992			•
Apodemus zhangwagouensis Wu & Flynn, 1992	•		•
Chardinomys nihowanicus (Zheng, 1981)	•		•

3　上新统地层对比

近年来为追寻上新统/更新统界线,在台儿沟剖面(闵隆瑞等,2006)、洞沟剖面(郑绍华等,2006)和牛头山剖面(蔡保全等,2007)进行了系统地层工作。主要根据生物地层并

参考了部分磁性地层确立了各剖面上新世/更新世界线。但这些界线的确定都是孤立和分散的,未能反映出泥河湾盆地各上新统地点地层的相互关系及全貌。为了将不同地点、不同剖面统一起来,这里选用新近完善起来的稻地老窝沟剖面作为典型剖面。剖面总厚度为 128.08 m,被分成 29 层,其上新统/更新统界线被置于 19/20 层之间,上新统地层厚 76.45 m(蔡保全等,2004)。

事实上,泥河湾盆地不同剖面之间的地层对比是相当困难的,根据软体动物层、砂砾石层和沼泽相堆积层作为标志层进行不同剖面间的对比是不可信的,因为这些标志层在同一剖面上往往不是惟一的;根据湖侵 - 湖退旋回(杨子赓等,1996)进行对比是一个好的方法,但它似乎更适合于上部更新统地层之间的对比。本文主要根据岩石地层、磁性地层和生物地层相结合的方法对它们进行对比。

1) 壶流河西岸地层对比:从北向南上新统含化石地点已知有芫子沟、后沟、老窝沟、红崖南沟、将军沟和花豹沟等 6 个主要含化石剖面。如果以老窝沟作为典型剖面,那么其第 1 层为未定组名的风成红粘土(张兆群等,2003);第 2- 19 层为蔚县组/稻地组。第 2 层红粘土层可以作为标志层与邻近的花豹沟剖面第 1 层红粘土层对比;第 3 层可与红崖南沟剖面第 1-4 层、将军沟剖面的第 1-5 层相对比;第 5-15 层河湖沼泽相堆积应与祁家庄后沟剖面第 1-5 层沼泽相堆积、芫子沟剖面第 1-6 层沼泽相堆积相对比(图 2)。

2) 壶流河东岸地层对比:从北往南上新统含化石地点有台儿沟、洞沟、小水沟、连接沟、牛头山和大南沟等 6 个地点。台儿沟剖面的古地磁测年结果(闵隆瑞,2006)显示,在 151.45 m 厚的剖面上,上新统/更新统(或松山/高斯)界线位于剖面底部之上约 28 m 处,凯纳(Kaena)和马莫斯(Mammoth)负极性事件分别为剖面底部之上 9 m 和 2.5 m 处。这样,整个剖面代表了约 3.4 Ma 的沉积时间。根据小哺乳动物,洞沟剖面上新统/更新统界线位于 10 和 11 层之间,在剖面底部之上约 18.9 m 处(郑绍华等,2006)。由于两剖面相距较近,岩性变化不特别大,可进行直接对比。如果按沉积厚度计算,洞沟剖面和小水沟剖面底部应大致对应于台儿沟剖面的凯纳事件(3.04 Ma)。按生物地层划分,大南沟剖面上新统地层仅 7 m 厚,即蔡保全等(2004)的第 1-2 层,由于其上第 2 和第 3 层间为不整合接触,上新统上部层位可能有缺失。邻近的牛头山剖面可对大南沟剖面进行补充。该剖面上新统地层出露厚 45.6 m,它和更新统界线被置于第 12 和 13 层之间(蔡保全等,2007)。

如果将洞沟剖面与牛头山剖面相对比,前者 1- 10 层的厚度相当于后者的 8- 12 层;如果将牛头山剖面与台儿沟剖面相对比,那么前者 1- 12 层的厚度大致相当于后者的 1-3 段厚度。

此外,北马圈连接沟剖面单一的含化石层的层位靠下,可能相当于牛头山剖面的第 3 层。

3) 壶流河东、西两岸地层对比:从上分析可以看出,壶流河西岸上新统地层出露厚度显著比东岸的大;壶流河西岸地层对比主要以下部红粘土层作为标志从下至上进行;壶流河东岸上新统地层对比主要根据上新统/更新统地层界线确定以后从上往下进行。由于老窝沟剖面第 19 层产化石少且不能十分肯定其上新世属性,只能根据岩石地层来区分。如果置上新统/更新统界线于第 19 和第 20 层之间,那么壶流河两岸的上新统地层就能排

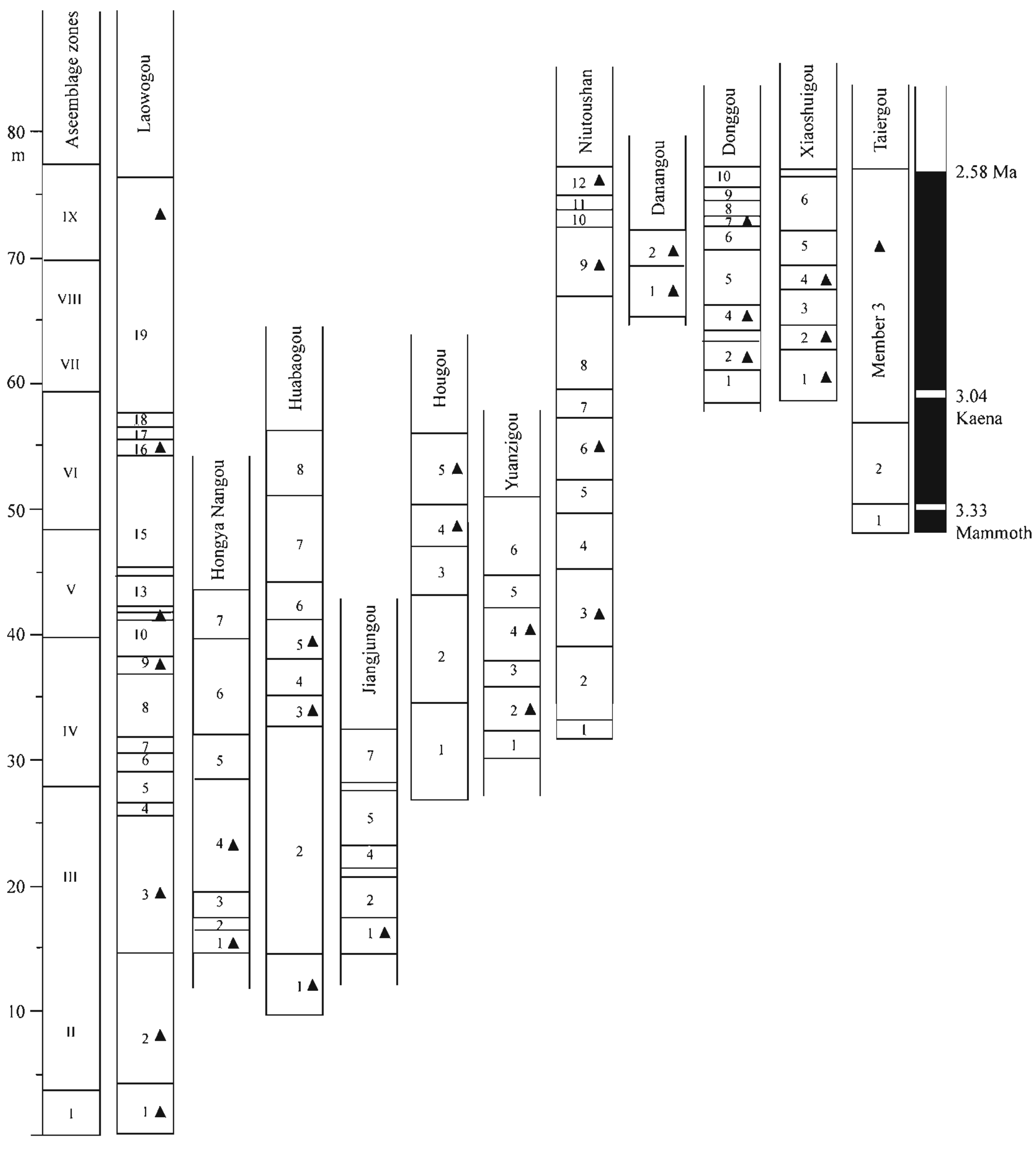

图 2　泥河湾盆地上新世生物地层的对应关系

Fig. 2　Biostratigraphic correlation among the Pliocene localities in the Nihewan Basin

Solid black triangles and roman numerals represent the fossil layers and assemblage zones, respectively

出一个以老窝沟剖面为基准的早晚顺序来。

与岩石地层相对应的生物地层大致可以归纳为 9 个组合带。从早到晚是:

I　老窝沟第 1 层;*Trischizolagus* sp. 和 *Chardinomys yusheensis* 组合;

II　老窝沟第 2 层、花豹沟第 1 层;*Chardina truncatus*、*Pliosiphneus lyratus*、?*Huaxiamys* sp.、*Huaxiamys downsi* 和 *Hipparion* cf. *H. hippidiodus* 组合;

III　老窝沟第 3 层、红崖南沟第 1 和 4 层、将军沟第 1 层;*Beremendia* sp. 和 *Yanshuella* sp. 出现,*Mimomys* sp.、*Ungaromys* spp.、*Mesosiphneus praetingi*、*M. paratingi* 和 *Chardinomys nihowanicus* 刚开始出现,*Huaxiamys downsi* 最后出现;

IV 老窝沟第 9 层、花豹沟第 3 层、芫子沟第 2 层;*Hipparion houfenense* 出现,*Paenelimnoecus chinensis*、*Mimomys* sp. 2、*Paralactaga anderssoni* 开始出现,*Gazella blacki* 最后出现;

V 老窝沟第 11 层、花豹沟第 5 层、芫子沟第 4 层、牛头山第 3 层;出现 *Quyania* sp. 和 *Castor anderssoni*;

VI 祁家庄后沟第 4–5 层、牛头山第 6 层;*Quyania* sp. 和 *Mesosiphneus praetingi* 最后出现。

VII 洞沟第 2 层、小水沟第 1–2 层;*Lunanosorex* cf. *L. lii* 和 *Pseudomeriones complicidens* 最后出现;

VIII 洞沟第 4 层、小水沟第 4 层、牛头山第 9 层、大南沟第 1 层;*Ungaromys* spp.、*Mimomys* sp.、M. sp. 2 和 *Mesosiphneus paratingi* 最后出现,出现进步的仓鼠 *Phodopus* sp. 和䶄类如 *Mimomys* sp. 1、*Borsodia chinensis* 和 *Cromeromys gansunicus*;

IX 台儿沟第 3 段、大南沟第 2 层、洞沟第 7 层、牛头山第 12 层、老窝沟第 19 层;出现进步的鼠兔类 *Ochotonoides complicidens*、鼢鼠 *Yangia omegodon* 和副骆驼 *Paracamelus* sp.。

从大尺度来讲,III–VII 组合带中常见 *Lunanosorex* cf. *L. lii*、*Hypolagus schreuderi*、*Pliopentalagus nihewanensis*、*Nannocricetus mongolicus*、*Sinocricetus progressus*、*Ungaromys*、*Mimomys* sp.、*Mimomys* sp. 2、*Mesosiphneus praetingi*、*M. paratingi*、*Pseudomeriones complicidens*、*Dipus fraudator*、*Micromys tedfordi*、*Apodemus zhangwagouensis* 和 *Chardinomys nihowanicus* 等 15 个种。从组成上来说,III–VII 组合带分别与有原始种类的 I–II 组合带和具进步种类的 VIII–IX 组合带是有所差异的。

4 泥河湾盆地上新世动物群的组成及其时代讨论

按照上述生物地层划分,将不同地点、不同层位的哺乳动物化石综合到一起,就能看出泥河湾盆地至今所知上新世哺乳动物群组成的基本面貌(表 8)。

从表中可以看出,泥河湾上新世哺乳动物群由 57 种哺乳动物组成,其中小哺乳动物 46 种,大哺乳动物 11 种;小哺乳动物有食虫类(11 种)、兔形类(5 种)和啮齿类(30 种),大哺乳动物有食肉类(4 种)、奇蹄类(2 种)和偶蹄类(5 种);小哺乳动物中有 14 个优势种:*Lunanosorex* cf. *L. lii*、*Hypolagus schreuderi*、*Pliopentalagus nihewanensis*、*Nannocricetus mongolicus*、*Sinocricetus progressus*、*Ungaromys*、*Mimomys* sp.、*Mesosiphneus praetingi*、*M. paratingi*、*Pseudomeriones complicidens*、*Dipus fraudator*、*Micromys tedfordi*、*Apodemus zhangwagouensis* 和 *Chardinomys nihowanicus*。其中 15 个现生属,占总数 48 个属的31.2%,没有现生种。

表 8　泥河湾盆地上新世哺乳动物及其层位分布

Table 8　Distribution of fossil mammals in the Pliocene biostratigraphic sequence of the Nihewan Basin

生物地层顺序 biostratigraphic sequence	I	II	III	IV	V	VI	VII	VIII	IX
Soridae Fischer von Waldheim, 1817									
1 *Sorex* sp. (large)								★	★
2 *Sorex* sp. (small)			★						
3 *Soriculus* sp.							★	★	
4 *Paenelimnoecus chinensis* Jin & Kawamura, 1997				★			★		
5 *Lunanosorex* cf. *L. lii* Jin & Kawamura, 1996			★		★	★	★		
6 *Beremendia* sp.			★		★?				
7 *Blarinella* sp.								★	
Erinaceidae Fischer von Waldheim, 1817									
8 *Erinaceus* sp.								★	★
Talpidae Fischer von Waldheim, 1817									
9 *Yanshuella* sp.			★						
10 *Quyania* sp.					★	★			
11 Talpidae indet.							★		
Ochotonidae Thomas, 1897									
12 *Ochotona* cf. *O. lingtaica* Erbajeva & Zheng, 2005							★		
13 *Ochotonoides complicidens* Zhang, 1999									★
Leporidae Fischer von Waldheim, 1817									
14 *Trischizolagus* sp.	★								
15 *Hypolagus schreuderi* Teilhard, 1940			★		★	★		★	
16 *Pliopentalagus nihewanensis* Cai, 1989			★	★	★	★			
Muridae Illiger, 1811									
Cricetinae Fischer von Waldheim, 1817									
17 *Phodopus* sp.								★	
18 *Nannocricetus mongolicus* Schaub, 1934		★	★	★	★	★	★	★	★
19 *Sinocricetus progressus* Qiu & Storch, 2000		★	★	★	★	★	★	★	★
Arvicolinae Gray, 1821									
20 *Ungaromys* spp.		★	★	★	★	★	★	★	
21 *Mimomys* sp.			★	★	★	★	★	★	
22 *M.* sp. 2				★		★		★	
23 *M.* sp. 1								★	★
24 *Borsodia chinensis* (Kormos, 1934)								★	
25 *Borsodia* sp.									★
26 *Cromeromys gansunicus* (Zheng, 1976)								★	
Myospalacinae Lilljeborg, 1866									
27 *Chardina truncatus* (Teilhard, 1942)		★							
28 *Mesosiphneus praetingi* (Teilhard, 1942)			★	★	★	★			
29 *M. paratingi* (Teilhard, 1942)			★				★	★	
30 *Yangia omegodon* (Teilhard & Young, 1931)									★
31 *Pliosiphneus lyratus* (Teilhard, 1942)		★							
32 *Pliosiphneus* sp. 2			★						
33 *Pliosiphneus* sp. 1								★	
Gerbillinae Gray, 1825									
34 *Pseudomeriones complicidens* Zhang, 1999		★	★			★	★		

续表

生物地层顺序 biostratigraphic sequence	I	II	III	IV	V	VI	VII	VIII	IX
Murinae Illiger, 1811									
35 *Micromys tedfordi* Wu & Flynn, 1992		★	★	★	★	★	★	★	★
36 ? *Huaxiamys* sp.		★							
37 *H. downsi* Wu & Flynn, 1992		★	★						
38 *Apodemus zhangwagouensis* Wu & Flynn, 1992		★	★		★	★	★	★	
39 *Chardinomys yusheensis* Jacobs & Li, 1982	★	★							
40 *C. nihowanicus* (Zheng, 1981)			★	★	★	★	★	★	★
41 ? *Karnimata* sp.				★	★	★			
42 *Saidomys* sp.				★					
Dipodidae Fischer von Waldheim, 1817									
43 *Dipus fraudator* (Schlosser, 1924)			★	★	★	★	★	★	★
44 *Paralactaga anderssoni* Young, 1927				★				★	
Castoridae Hemprich, 1820									
45 *Castor anderssoni* (Schlosser, 1924)					★				
46 ? *Depoides* sp.									★
Canidae Fischer von Waldheim, 1817									
47 *Canis multicuspus*		★							
48 *Nyctereutes sinensis* (Schlosser, 1924)		★							
Felidae Fischer von Waldheim, 1817									
49 *Lynx variabilis* Tang, 1980									★
Viverridae Gray, 1821									
50 *Viverra* sp.				★					
Equidae Gray, 1821									
51 *Hipparion* cf. *H. hippidiodus* Sefve, 1927		★							
52 *H. houfenense* Teilhard & Young, 1931				★					
Bovidae Gray, 1821									
53 *Antilospira yuxianensis* Tang, 1980									★
54 *Antilospiroides hopeiensis* Zong & Wei, 1993				★					
55 *Gazella blacki* Teilhard & Young, 1931		★		★					
Giraffidae Gray, 1821									
56 *Palaeotragus progessus* Tang & Li, 1983		★							★
Camelidae Gray, 1821									
57 *Paracamelus* sp.									★

动物群中因含有 *Ungaromys*、*Borsodia*、*Mesosiphneus paratingi*、*Chardinomys nihowanicus*、*Nyctereutes*、*Hipparion houfenense*、*Antilospira* 和 *Gazella blacki* 等，可与山西静乐贺风晚上新世(MN16)动物群(Teilhard and Young, 1931; 周晓元,1988)相对比。因含有 *Yanshuella*、*Hypolagus schreuderi*、*Ochotonoides complicidens*、*Ungaromys*、*Cromeromys*、*Mesosiphneus praetingi*、*M. paratingi*、*Castor anderssoni*、*Dipoides*、*Dipus fraudator*、*Micromys tedfordi*、*Apodemus zhangwagouensis* 和 *Chardinomys nihowanicus* 等可与榆社盆地麻则沟组动物群(吴文裕、Flynn,1992;Flynn et al., 1997)相对比。因含有 *Ochotona* cf. *O. lingtaica*、*Ochotonoides complicidens*、*Trischizolagus*、*Pliosiphneus lyratus*、*Chardina truncatus*、*Mesosiphneus praetingi*、*M. paratingi*(进化程度相当于 *M. intermedius*)、*Yangia omegodon*、*Cromeromys gansunicus*、*Borsodia*、*Pseudomeriones complicidens*、*Paralactaga anderssoni*、*Castor anderssoni*、*Micromys ted-*

fordi、*Huaxiamys downsi*、*Chardinomys yusheensis* 和 *C. nihowanicus* 等可与甘肃灵台雷家河 V 带动物群(郑绍华、张兆群,2001)相对比。因含有 *Chardina truncatus*、*Pseudomeriones complicidens* 和 *Paralactaga anderssoni* 可与甘肃宁县水磨沟的动物组合(张兆群,1999)相对比;因含有发育程度相当的 *Mimomys* 以及 *Chardinomys nihowanicus*、*Ochotonoides complicidens*、*Nyctereutes sinensis* 和 *Hipparion houfenense* 等可与渭南游河动物群(薛祥煦,1981)相对比;因含有 *Chardinomys*、*Nyctereutes sinensis*、*Hipparion houfenense*、*Paracamelus* 和 *Gazella blacki* 等可与甘肃灵台任家沟剖面中静乐红土的动物组合相对比,后一含化石层的古地磁年龄为 3.4 ~3.5 Ma(张云翔等,1999)。

根据 *Mimomys* 的齿冠高度和个体大小,泥河湾盆地的 *Mimomys* sp. 要比内蒙古比例克动物群(Qiu and Storch, 2000)中的 *M. bilikeensis* 的齿冠显著增高、个体显著增大,其时代应较晚;灵台雷家河动物群中的 *M. bilikeensis* 分布于第 IV 带(4.3 ~3.6 Ma),所在层位的古地磁年代约为 4.2 Ma(郑绍华、张兆群,2001)。因此泥河湾盆地第 III 组合带的时代较灵台雷家河的第 IV 带为晚,估计应晚于 3.5 Ma。

根据 *Pliosiphneus lyratus* 在雷家河及榆社盆地的最晚记录均在古地磁年龄 3.6 Ma 左右,泥河湾盆地含该种的第 II 组合带的时代也应与此相当;根据 *Mesosiphneus paratingi* 在雷家河(为与其进化程度相当的 *M. intermedius*)和榆社盆地的分布时限分别在 3.5 ~3.2 Ma 和 3.5 ~3.0 Ma,泥河湾盆地的第 III- VIII 组合带应与它们相当;根据 *Pseudomeriones complicidens* 在雷家河分布的时限在 3.5 ~3.2 Ma,泥河湾盆地含该种的第 II- VII 组合带也大致与其相当;根据 *Huaxiamys downsi* 在雷家河和榆社盆地分布的时限分别在 4.2 ~3.3 Ma 和 4.6 ~4.0 Ma、*Apodemus zhangwagouensis* 在榆社盆地的时限在 3.6 ~3.3 Ma、*Chardinomys yusheensis* 在雷家河和榆社分布的时限分别在 4.8 ~3.4 Ma 和 4.8 ~3.7 Ma 等综合判断,泥河湾盆地含这些种类的第 I- II 组合带的时代估计应在 3.7 ~3.6 Ma 范围。

根据 *Mimomys* 的进化程度及 *Mimomys-Ungaromys* 相组合的特点,泥河湾盆地上新世哺乳动物群可与欧洲早 Villanyian 期动物群(Kowalski, 2001)相对比。

总起来看,泥河湾盆地上新统地层的时代属晚上新世,绝对年龄大致在 3.7 ~2.6 Ma 范围内。

动物群中的 *Paenelimnoecus chinensis* 和 *Lunanosorex* cf. *L. lii* 进一步证实了山东沂南棋盘山洞穴堆积的时代属晚上新世或欧洲哺乳动物分期的 MN16(Jin and Kawamura, 1996, 1997;李亦征,1993)的可能性较大,而属 MN15(郑绍华,1984)的可能性较小。

5　哺乳动物群所反映的生态环境

尽管泥河湾盆地以河湖沼泽相为主的上新统地层反映出水体广布的自然环境,但化石哺乳动物反映出的却是另外一种景象。动物群的组成有如下特点:主要由食虫类(11 种)、兔形类(5 种)、啮齿类(30 种)、食肉类(4 种)、奇蹄类(2 种)和偶蹄类(5 种)等 6 类动物组成,缺失翼手类、长鼻类、大型肉食类、犀类和鹿类等森林栖居的类型;兔形类和啮齿类中的仓鼠亚科(3 种)、鼢亚科(7 种)、鼢鼠亚科(7 种)、奇蹄类马科(2 种)和牛科的转角羚亚科(3 种)反映出一种草原景观;犬科(2 种)、鼠亚科(8 种)、河狸科(2 种)反映

出森林或森林灌丛环境;跳鼠科(2 种)、沙鼠亚科(1 种)和骆驼科(1 种)反映出荒漠草原环境;长颈鹿科(1 种)反映出稀树草原环境;只有 *Soriculus*、*Blarinella* 和 *Viverra* 是我国南方亚热带森林分子。由此可以判断出泥河湾盆地上新世时期基本上是一个以温带草原为主、间有树林和干草原的稀树草原环境。至于不同组合带的环境变化可以作如下统计(表 9;图 3)。

表 9 不同生态环境哺乳动物种数统计

Table 9 Statistical analysis of the specific numbers adapted in the different environments

阶段 Stages	种数 Species number	草原型 Grassland	灌木-树林型 Shrub-woodland	干旱草原型 Arid grassland	广布型 Wide-spread
IX	16	8 (50%)	3 (18.7%)	2 (12.5%)	3 (18.7%)
VIII	22	14 (63.6%)	3 (13.6%)1)	2 (9.1%)	3 (13.6%)
VII	15	9 (60%)	3 (20%)2)	2 (13.3%)	1 (6.7%)
VI	17	11 (64.7%)	3 (17.6%)	2 (11.8%)	1 (5.9%)
V	15	9 (60%)	4 (26.7%)	1 (6.7%)	1 (6.7%)
IV	19	12 (63.2%)	3 (15.8%)3)	2 (10.5%)	2 (10.5%)
III	19	12 (66.7%)	3 (16.7%)	2 (11.1%)	2 (11.1%)
I-II	17	11 (64.7%)	4 (23.5%)	1 (5.9%)	1 (5.9%)

1)南方亚热带分子 *Soriculus* 和 *Blarinella* 进入 immigration of the subtropical *Soriculus* and *Blarinella*;2)南方亚热带分子 *Soriculus* 进入 immigration of the subtropical *Soriculus*;3)南方的 *Viverra* 进入 immigration of the subtropical *Viverra*.

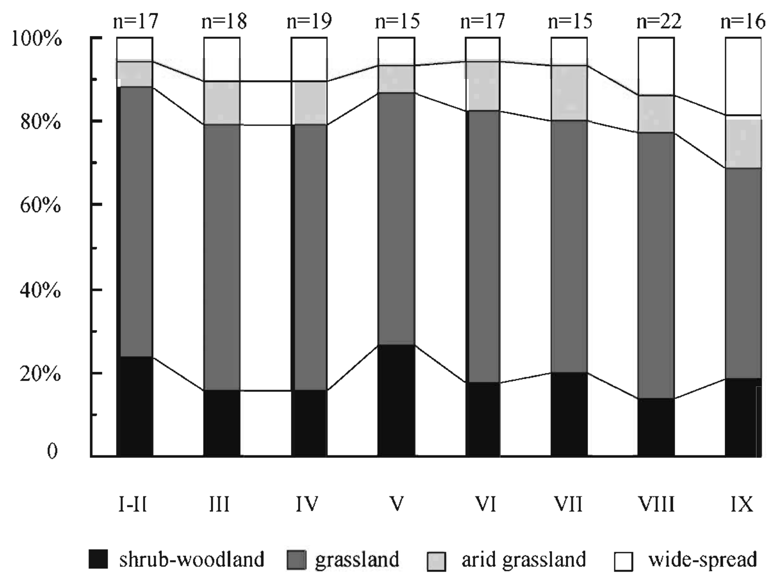

图 3 泥河湾盆地上新世不同生境哺乳动物种类百分比柱状图

Fig. 3 Columnar diagram showing the percentage of the different environmental species in each stage

从表中可以看出,除了第 IX 组合带外,草原类型均占各层总数的 60% 以上,因此各带均反映以草原为主的景观;森林灌丛类型在 20% 以上的层位是 I-II、V、VII 带,反映出当时的林地较其他层位发育;荒漠草原类型在 I-II、V 带的比例较小,因此当时的干旱化程度也较小,*Castor anderssoni* 的出现也暗示了 V 带冷湿的环境;第 IV、VII、VIII 带的少许亚

热带分子指示出当时的气候比较湿热,但这种湿热延续的时间是非常短暂的,因为它们只零星地出现在地层中。

从表 8 上还可以看出两次较明显的生物转换事件,一次是发生在第 III 阶段,原始的 *Trischizolagus* sp.、*Pliosiphneus lyratus* 和 *Chardinomys yusheensis* 随后分别被进步的 *Pliopentalagus nihewanensis*、*Pliosiphneus* sp. 2 和 *C. nihowanicus* 所替代。类似的情况在第 VIII 阶段也有发生,*Mimomys*、*Pliosiphneus/Mesosiphneus* 各自被进步的 *Borsodia/Cromeromys* 和 *Yangia* 所取代。这些转换事件中的属种牙齿形态演化上都有一个共同的趋势,即冠面形态趋于复杂和齿冠愈加增高,一般认为这是对于日渐干旱环境下粗糙和坚硬食物的一种适应。

6　初步结论和问题

泥河湾盆地上新统地层主要分布于桑干河峡谷地段和壶流河中下游两岸;发现哺乳动物化石的地层集中在壶流河下游两岸;产化石的地点 12 个,有的地点含化石层位较多,只有 3 个地点为单一含化石层;各化石层位以小哺乳动物(46 种)为主,占总数(57 种)的 80.7%。动物群的时代为晚上新世(相当于欧洲新近纪哺乳动物分期的 MN16),可与静乐贺风、榆社麻则沟、灵台雷家河 V 带、灵台任家沟静乐红粘土层、宁县水磨沟、渭南游河和沂南棋盘山动物群的时代相对比;将所有地点综合成 9 个生物组合带,其中 IV、VII、VIII 带有零星亚热带分子侵入,但整个时段的生态环境为温带稀树草原,尽管局部有荒漠化的现象。

除了台儿沟剖面外,其他剖面还没有近期的磁性年代学资料可以利用;作为标准的老窝沟剖面上新统/更新统界线的确定仅仅是根据岩石地层,缺少哺乳动物化石和磁性地层学依据;各个种的生态习性判断只是根据一般的原则,对一些绝灭种类的判定不可能十分准确。若要解决这些问题需要多学科交叉的长期细致工作。

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PLIOCENE BIOSTRATIGRAPHIC SEQUENCE IN THE NIHEWAN BASIN, HEBEI, CHINA

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Summary

A sequence of fluvio-lacustrine and paludine deposits with thickness over 150 meters occurs in the Nihewan Basin, Hebei, China (Yuan et al., 1996; Min et al., 2006). A series

of ~30 m (= "90 feet") thick red homogeneous clay exposured near the Sanggan River Gorge (= Shixia) was originally considered as the weathering matter of the base rocks (Barbour et al., 1926). Due to the absence of fossils, its age once was speculated to belong to the Pontian (Teilhard and Piveteau, 1930) or the Late Miocene Baodean (Black et al., 1933). However, a sequence of ~30 m thick red gravel-bearing clay at the bottom of the section of Dahonggou in Shixia was named as "Dahonggou Formation" by Chen (1988). At the same time, the ~12 m and ~7 m thick red clays in the lower part of the Hongya Nangou and Pump Station, respectively, were also included into this Pliocene formation. A series of 20 ~ 30 m thick redish or yellow-redish alternating sandy clay and gravel beds are exposed in the Luanshigedagou near Hongya village. Yielding *Hipparion* and *Chilotherium*, this deposit was considered to belong to the "*Hipparion* Red Clay" with a Pliocene age (Huang et al., 1974). The sequence of ~45 m thick red clay containing sandy gravel and lens of calcareous nodules in the Huabaogou near Xiyaozitou village was divided into the upper "Yuxian Formation" and the lower "Huliuhe Formation" by the composition of large fossil mammals. These two formations were respectively correlated to be equal in age to the Pliocene Jingle Formation and the Late Miocene Bahe Formation (Wang, 1982). In view of the illegibility of the boundary and the lack of significant differences in the fossil faunas between these two formations, Zhang et al. (2003) incorporated them both in the Late Pliocene Yuxian Formation. A series of fluvio-lacustrine and paludine deposits exposed on the both sides of the Huliu River were named "Daodi Formation" and considered of Late Pliocene age (Du et al., 1988). The original sections used for erecting the "Daodi Fm." are located in the Laowogou near Daodi, the Nangou near Hongya, the Jiangjungou near Xiyaozitou, the Hougou near Qijiazhuang, the Yuanzigou near Yuanzi, the Xiaoshuigou near Qianjiashawa, the Lianjiegou near Beimajuan, the Niutoushan (= "Pulu") near Pulu and the Danangou near Dongyaozitou. Zhang et al. (2003) figured that these short sections all belong to the "Yuxian Fm.", so they suggested that "Daodi Fm." should be abolished and attributed to the "Yuxian Fm.", whereas Cai et al. (2004) retained both "Daodi Fm." and "Yuxian Fm.". The red clay stratum from the first layer at the bottom of the Laowogou section is still unnamed due to the uniformity of the grain size, the absence of gravels and aquatic animal remains. Based on the limited fossil mammals, the age of this stratum was thought to be the late Middle or early Late Pliocene (Zhang et al., 2003; Cai et al., 2004). The Pliocene/Pleistocene boundaries, on the other hand, have already been established in the Laowogou, Donggou, Taiergou and Niutoushan sequences (Cai et al., 2004; Zheng et al., 2006; Min et al., 2006; Cai et al., 2007).

Judging from the known information, the lower part of the exposed strata in the Nihewan Basin should be attributed to the Late Pliocene Yuxian Formation or some unnamed red clays. These outcrops exist in the Sanggan River Gorge area and on the both sides of the lower reaches of the Huliu River with lithology of aeolian clay, fluvio-lacustrine red clay contained gravels and paludine sandy clay.

On the both sides of the lower reaches of the Huliu River, there are 12 localities and sections, in which one or more layers of fossil mammals have been found (Fig. 1). The purpose of this paper is to update a faunal list of these mammals based on the review of specimens and their localities, and also an attempt to correlate the other sections to the Laowogou section by comparing their mammalian compositions and lithological strata. Finally, a Late Pliocene biostratigraphic sequence and the environmental changes in the Nihewan Basin are discussed.

1 Pliocene mammal localities and strata

1) Laowogou section (N 40°08′59″, E 114°39′31″) lies on the west side of the Huliu River and ~750 m northwest of Daodi village, Yangyuan county. The section is 128.08 m in

thickness, within which 29 layers are recognized (Zhang et al., 2003; Cai et al., 2004). Initially, the layers from 3 to 13 were considered by Du et al. (1988) to be the type strata of the "Daodi Fm.". At the same time, the small fossil mammals were collected from layers 9 and 11. After additional field work during 2002 to 2006, the number of fossil-bearing layers increased to 6. The distribution of the small fossil mammals in this section is listed in Table 1.

2) Donggou section (N 40°12′11.7″, E 114°38′45.2″) is 56.25 m thick and divided into 28 layers. Small fossil mammals were found from the layers 2, 4, 7, 11, 16 and 19. This section was once selected to establish the standard-stratotype section in the Nihewan Basin (Yang et al., 1996). The Pliocene/Pleistocene boundary was placed between layers 10 and 11 by biostratigraphy (Zheng et al., 2006). The identification of fossils was listed in the Table 2 in page 322 of their paper.

3) Niutoushan section (N 40°06′13.4″, E 114°42′36.6″) is 82 m thick and divided into 23 layers, in which layers 1 to 11 were also chosen as one of the stratotype sections for the "Daodi Fm." (Du et al., 1988). Samll fossil mammals occur in layers 3, 6, 9, 12, 15 and 16, in which the Pliocene/Pleistocene boundary was placed between layers 12 and 13 (fossil list see Cai et al., 2007:235, Table 1).

4) Danangou section (N 40°05′36″, E 114°43′35″) is 97.85 m thick and includes 27 layers. This section was once selected as an important section of the "Daodi Fm." (Du et al., 1988) and used to establish the Pliocene/Pleistocene standard-stratotype section in the Nihewan Basin (Cai et al., 2004). Ages of the lower layers 1 and 2 were considered to be Pliocene (Zheng and Cai, 1991). Table 2 lists the fossil mammals.

5) Huabaogou section is the typical stratotype for the "Yuxian Fm." and the "Huliuhe Fm.". It is about 50 m thick and includes 8 layers. "*Sinoryx*" is misidentified by Wang (1982) and here provisionally eliminated from the faunal list (see Table 3).

6) Hongya Nangou section (N 40°08′07.3″, E 114°39′57.1″), as one of the stratoypes for the "Daodi Fm." (Du et al., 1988), is 25.31 m thick and contains 7 layers, in which layers 1 and 4 yield small mammal remains (see Table 4).

7) Yuanzigou section (N 40°10′05.8″, E 114°38′28.9″), a sequence of paludine deposit, is 20.9 m thick and includes 6 layers, in which the layers 2 and 4 are fossil-bearing beds (fossil list see Table 5).

8) Hougou section (N 40°09′38.6″, E 114°38′53.1″) near Qijiazhuang village is also mainly paludine deposited with 30.3 m thickness and 6 layers. Fossils are present in the layers 4 and 5 (Table 6).

9) Xiaoshuigou section (N 40°11′43″, E 114°38′40.6″), as one of stratoypes for the "Daodi Fm." (Du et al., 1988), is mainly paludine deposited with 18.37 m thickness and 7 layers. Fossils occur in the layers 1, 2 and 4 (Table 7).

10) Lianjiegou section (N 40°09′18.3″, E 114°40′38″) near Beimajuan village is 21.74 m thick with only one fossil-bearing layer, from which 6 species can be recognized.

11) Jiangjungou section belongs to paludine deposit on the top of the red clay and is divided into 7 layers, in which only layer 1 bears fossils (7 species).

12) Taiergou section (N 40°12′52″, E 114°38′22″) is 151.45 m thick with 12 members and 146 layers. The Brunhes/Matuyama and Matuyama/Gauss boundaries lie at 33.55 m depth and 123 m depth, respectively. The Pleistocene and Pliocene fossil-bearing beds lie at 68 m depth and 131 m depth, respectively (Min et al., 2006). Our revision suggests that the Pliocene small mammals should include 15 taxa.

2 Correlation between Pliocene lithology and biostratigraphic sequence

In recent, systematic magnetic and biostratigrahic works have been undertaken in the

Taiergou (Min et al., 2006), Donggou (Zheng et al., 2006) and Niutoushan sections (Cai et al., 2007). The Pliocene/Pleistocene boundary has been primarily established in these sections. For conveniently unifying and correlating the isolated and dispersed localities in the Nihewan Basin, the Laowogou section is here selected as the type section for its well developed Pliocene deposits (76.45 m). The Pliocene/Pleistocene boundary in this section was estimated to be between layers 19 and 20 (Cai et al., 2004).

Even in the same section, the sedimentary facies often change very quickly, which makes it very difficult to directly correlate among the different sections in the Nihewan Basin. It is also impossible to correlate transversely among the sections by using the index beds bearing mollusk or gravels due to their lack of uniqueness. It seems an analysis of the lake transgression and regression cycles is an effective way of correlation (Yang et al., 1996), but this way is only applicable for the Pleistocene strata. In this paper, the Pliocene strata correlation will be based on the synthetical analysis of lithologic-, bio-and magnetic stratigraphies.

1) West side of the Huliu River: In the known 6 sections, the Laowogou section is the most integrated and typical one, which layer 1 belongs to an unnamed aeolian red clay while 2–19 to the Yuxian Fm./Daodi Fm. The red clay of layer 1 from the nearby Huabaogou section can be correlated directly to that of layer 2 of Laowogou. The layers 1–4 from the Hongya Nangou and the layers 1–5 from the Jiangjungou can also be correlated to the layer 3 from Laowogou. Furthermore, the layers 5–15 from Laowogou can be correlated to those 1–5 from Hougou near Qijiazhuang village and 1–6 from Yuanzigou, resepectively (Fig. 2).

2) East side of the Huliu River: The biostratigraphical correlations among the 6 sections except the Taiergou one were primarily suggested by Cai et al. (2007). According to the magnetic results, the Pliocene/Pleistocene boundary lies, and the Kaena and Mammoth events begin, respectively about 28 m, 9 m and 2.5 m above the bottom of the Taiergou section. Age range of the whole section is about 3.4 Ma. Considering the similarly thick deposits, the bottoms of the Donggou and the Xiaoshuigou sections could be correlated to the Kaena layer of the Taiergou section. The Upper Pliocene strata in the Danangou section are possibly partically absent, whereas those in the Niutoushan section are well developed. Compared the Niutoushan section to the Donggou one, thickness between the layers 8–12 in the former could correspond with that between layers 1–10 in the latter. The deposits between the layers 1–12 in the Niutoushan section can be correlated to those between the layers 1–3 in the Taiergou one. Furthermore, the single fossil-bearing bed of the Lianjiegou could be correlated to layer 3 of the Niutoushan.

3) Correlation between both sides of the Huliu River: The correlation among the sections on the west side is mainly based on lithology, especially on the bottom red clay, whereas that of the east side is based on the Pliocene/Pleistocene boundaries. The Pliocene/Pleistocene boundary in the western deposits has only been estimated in the Laowogou section, which is selected as the typical section to correlate between eastern and western deposits.

In sum, the early and late biostratigraphical sequence in the Nihewan Basin should be divided into 9 stages (Fig. 2):

I Layer 1 in Laowogou; remains of *Trischizolagus* sp., *Chardinomys yusheensis*.

II Layer 2 in Laowogou, layer 1 in Huabaogou; assemblage of *Chardina truncatus*, *Pliosiphneus lyratus*, ?*Huaxiamys* sp., *Huaxiamys downsi* and *Hipparion* cf. *H. hippidiodus*.

III Layer 3 in Laowogou, layers 1 and 4 in Hongya Nangou, layer 1 in Jiangjungou; appearance of *Beremendia* sp. and *Yanshuella* sp., the first appearance of *Mimomys* sp., *Ungaromys* spp., *Mesosiphneus praetingi*, *M. paratingi* and *Chardinomys nihowanicus*, and the last appearance of *Huaxiamys downsi*.

IV Layer 9 in Laowogou, layer 3 in Huabaogou, layer 2 in Yuanzigou; appearance of *Hipparion houfenense*, the first appearance of *Paenelimnoecus chinensis*, *Mimomys* sp. 2 and

Paralactaga anderssoni, and the last appearance of *Gazella blacki*.

V　Layer 11 in Laowogou, layer 5 in Huabaogou, layer 4 in Yuanzigou, layer 3 in Niutoushan; appearance of *Quyania* sp. and *Castor anderssoni*.

VI　Layers 4–5 in Hougou (Qijiazhuang), layer 6 in Niutoushan; the last appearance of *Quyania* sp. and *Mesosiphneus praetingi*.

VII　Layer 2 in Donggou, layers 1–2 in Xiaoshuigou; the last appearance of *Lunanosorex* cf. *L. lii* and *Pseudomeriones complicidens*.

VIII　Layer 4 in Donggou, layer 4 in Xiaoshuigou, layer 9 in Niutoushan, layer 1 in Danangou; the last appearance of *Ungaromys* spp., *Mimomys* sp., *M.* sp. 2 and *Mesosiphneus paratingi*, and the first appearance of the progressive species, *Phodopus* sp., *Mimomys* sp. 1, *Borsodia chinensis* and *Cromeromys gansunicus*.

IX　Member 3 in Taiergou, layer 2 in Danangou, layer 7 in Donggou, layer 12 in Niutoushan, layer 19 in Laowogou; appearance of derived species, *Ochotonoides complicidens*, *Yangia omegodon* and *Paracamelus* sp..

III–VII assemblage zones share entirely or partly 15 species, including *Lunanosorex* cf. *L. lii*, *Hypolagus schreuderi*, *Pliopentalagus nihewanensis*, *Nannocricetus mongolicus*, *Sinocricetus progressus*, *Ungaromys*, *Mimomys* sp., *Mimomys* sp. 2, *Mesosiphneus praetingi*, *M. paratingi*, *Pseudomeriones complicidens*, *Dipus fraudator*, *Micromys tedfordi*, *Apodemus zhangwagouensis* and *Chardinomys nihowanicus*, which are different from those original and derived species from I–II and VIII–IX zones, respectively.

3　Composition and chronology of the Pliocene mammalian fauna in the Nihewan Basin

Following the above biostratigarphical framework, the fossil mammals from the different Pliocene localities and beds in the Nihewan Basin are listed in the Table 8.

The Pliocene mammalian fauna in the Nihewan Basin composes of 57 species, in which 11 species of large mammals and 46 species of small mammals are identified. Large mammals include 4 species of carnivores, 2 species of perissodactyls and 5 species of artiodactyls. There are 14 dominant species of small mammals. There are 15 extant genera in the entire fauna, making up 31.2% of all 48 genera. However, there is no extant species in this fauna.

Eight taxa in genera level and 4 taxa in species level are shared, between this fauna and the Late Pliocene (MN16) Hefeng fauna from Jingle, Shanxi (Teilhard and Young, 1931; Zhou, 1988). 13 genera and 10 species are shared between this fauna and the Mazegou fauna from Yushe Basin, Shanxi (Wu and Flynn, 1992; Flynn et al., 1997). Compared with the V biozone of Leijiahe section from Liangtai, Gansu (Zheng and Zhang, 2001), they share 17 genera and 15 species. This fauna also has some comparability with the Shuimogou fauna from Ningxian, Gansu (Zhang, 1999) for 3 species occur in both faunas. Based on the co-occurrence of 3 species of small mammals and 2 species of large mammals in both faunas, this fauna also can be compared to the Youhe fauna from Weinan, Shaanxi (Xue, 1981). 5 genera and 3 species are shared between this fauna and the red clay fauna of Renjiagou section from Lingtai, Gansu, the magnetic dating of the latter is about 3.4 ~ 3.5 Ma (Zhang et al., 1999).

Judged from the evolutionary stages of *Mimomys*, the Pliocene mammalian fauna in the Nihewan Basin can be roughly correlated to the early Villanyian European ones (Kowalski, 2001).

In conclusion, the Pliocene strata in the Nihewan Basin should belong to Late Pliocene with an age range from 3.7 to 2.6 Ma.

4 Paleoenvironmental reconstruction

The well developed fluvio-lacustrine and paludine deposits in the Nihewan Basin indicate a paleoenvironment with widespread water body in the Pliocene. The typical sylvatic elements, such as chiropteran, primates, proboscidean, large carnivore, rhinos and cervids etc., are absent in this Pliocene mammalian fauna. The appearances of ochotonids, cricetines, arvicolinaes, siphneinines, equids and bovids indicate a grassland environment. The occurrences of insectivores, murids, castorids, and carnivores such as *Nyctereutes*, *Lynx*, *Viverra* imply a shrub or woodland-forest environment. In addition, lagomorphs, murid *Micromys*, wolf *Canis* and giraffine *Palaeotragus* may live in a wood-grassland area. Jerboa *Paralactaga*, gerbil *Pseudomeriones* and camel *Paracamelus* are similar in morphology to their extant relatives found in desert or semidesert environments. Only the insectivores *Soriculus* and *Blarinella* and feliform *Viverra* belong to the familiar elements of the subtropical forest in South China. All in all, the Nihewan Basin in the Late Pliocene should be a temperate woodland-grassland mixed partial deserts area. The changes of the presumed environments in the different ages are shown in the Table 8 and Fig. 3.

Transition events on the level of genera or species can be observed in some stages of this biostratigraphical sequence. The most obvious one occurs in the age range of the stage III, because at the same time *Trischizolagus* sp., *Pliosiphneus lyratus* and *Chardinomys yusheensis* were followed by morphologically more derived *Pliopentalagus nihewanensis*, *Pliosiphneus* sp. 2 and *C. nihowanicus*, respectively. A similar event also occurred in age of the stage VIII with the morphospecies of *Mimomys* and *Pliosiphneus/Mesosiphneus*, respectively. These species share some common evolutionary tendencies in their dental morphology such as increasing complexity of the occlusal morpha and heightening of the crown. These tendencies might be considered adaptations for grinding the coarser and harder foods in the new arid environment.

5 Conclusions and problems

The Pliocene strata are distributed in the Sanggan River Gorge and on the both sides of lower reaches of the Huliu River area, with known fossils-yielding strata concentrated on the latter. Thirty beds from 12 different localities are arranged in a biostratigraphical sequence divided into 9 assemblage-zones. The entire Pliocene fauna in the Nihewan Basin is dominated by small mammals (46 species, 80.7% of the total) of Late Pliocene age. This fauna can be roughly correlated to those from Hefeng (Jingle) and Mazegou (Yushe), biozone V of Leijiahe (Lingtai), Jinglean red clay of Renjiagou (Lingtai), Shuimogou (Ningxian), Gansu, Youhe (Weinan), Shaanxi and Qipanshan (Yinan), Shandong. The percentage of steppe species is much higher than that of wood-grassland ones, especially in the stages I–III, IV and VIII. The species transition events that occurred in the stages III and VIII indicate aridification trends in the environment. On the whole, paleoenvironments represent mainly temperate woodland-grassland mixed with local deserts in the Late Pliocene Nihewan Basin.

To draw more precise conclusions, some problems seem to be ineluctable, such as the lack of updated magnetic results, the reliability of some Pliocene/Pleistocene boundaries, the validity of actualism in analyzing the paleoenvironment and the veracity of the identifications on fossil species. To resolve these problems, a deep and synthetical work of lithologic-, bio-and magnetic stratigraphies is necessary.

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