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中国晚第三纪哺乳动物生物地层：回顾、现状与展望

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摘要 中国新生代陆相沉积的研究是前中央地质调查所最早的研究项目之一。当时，晚第三纪化石的相对时序是通过地貌与古生物学研究相结合的独特方法建立起来的。至30年代末人们对华北晚第三纪的自然和生物事件的了解已初具轮廓，并依据化石与国际性地质年表作了对比。由于这种方法的局限性，本世纪中该项工作便中止了。过去20年中，在中国恢复了建立新生代动物群的排序工作，并与欧洲已建立的生物年代进行对比。由于距离遥远以及中国动物群的明显土著性使这种对比很受限制，因此有必要采用另外的编年手段。由于中国新生代陆相地层中可用于同位素测年的材料极少，因此磁性地层学用于地区性和区域性对比工作不失为一个有效的方法，借助于生物年代学，可与标准地磁极性年表(GPTS)比较予以年代标定。这种方法已应用于晋中榆社盆地晚中新世至上新世的生物地层工作。它能较精确地确定生物年代的界限并标定年龄，在中国晚第三纪早期（和早第三纪）地层中的应用是有广阔前景的。

关键词 中国，新第三纪，生物地层，磁性地层，化石哺乳动物

一、前　　言

中国晚第三纪生物地层是中央地质调查所——古脊椎动物与古人类研究所的前身——的最早期的研究课题之一。课题的目的是为阐明在相邻动物地理区域内动物群变化的性质和速率，最终应用这些资料将地方性事件编入全球动物群演变史。此外还有一个很实际的原因，即推动中国的脊椎动物生物地层学的研究。在中国新生代盆地中缺少广泛的新生代火山活动，只有很少的熔岩和火山碎屑岩夹层，因此同位素测年技术的应用很有限。唯有脊椎动物化石相当丰富并分布广泛，可作为断年和盆地间对比的手段。因此，加强对中国陆生哺乳动物群时序的研究，使其更加精确，并用国际地质年表对其年龄进行标定，这一工作具有理论和实践意义。

二、回　　顾

十九世纪后期，客居在中国的一些杰出的欧洲地质学家，以及本世纪初美国地貌学家

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B. 威利斯 (Bailey Willis) 和 E. 布莱克韦尔达 (Elliot Blackwelder) 发表了他们的地形发展史研究论文 (1907)。他们识别出一系列在华北分布相当广泛的地貌面。在20年代后期和30年代G. 巴尔布 (George Barbour)，E. 桑志华 (Emile Licent)，德日进 (Teilhard de Chardin) 和数量日益增多的中国同行 (卞美年、裴文中和杨钟健) 做了更为详细的工作。研究内容是根据由威利斯，布莱克韦尔达和W. M. 戴维斯 (William Morris Davis) 提出的地形发育原则，并与传统生物地层学紧密结合进行地文分析。地貌工作的目的是定义那些能在大范围内追溯到的剥蚀面，这些剥蚀面代表了地形削减的各个阶段并具有等时性。剥蚀面的形成过程与邻近盆地内的堆积过程是同时发生和进行的，在盆地堆积物中埋藏有记录物种演变过程的生物化石。在华北这套地方性的生物地层中包含有一些在欧洲也有的属或高级分类单元，因此可以认为与欧洲的相应地层的地质年龄大致相当，并可根据时间标尺推测统或世的界限。这些早期的观念曾经是很强的。李四光 (1939，资料仅到1936) 和德日进 (1941) 最后综合了这项工作。

早期的研究者们认识到，由地貌推导来的年代地层系统，会由于局部的构造和气候因素而扰乱，因此难以在整个华北地区普遍应用。在秦岭以南的长江盆地 (Barbour等，1935) 和黄河上游 (杨钟健和卞美年，1936—1937) 的研究工作就有这种情况。然而这个年代地层框架很重要，它综合了各个事件，这些事件可被用来作为与中国其它地区对比的依据。我们认为，华北的地层提供了最详尽的古生物学证据，因此在建立东亚哺乳动物生物年代表的工作中始终占首要地位。

地貌工作奠定了晚第三纪研究的早期基础，但在1949年以后，很少有人继续这项工作。工作重点从研究整个的地文区转移到测制20万分之一地质图，因而改变了地质工作的布局。1960年古脊椎动物与古人类研究所成立了，在它的创建者杨钟健的领导下，研究所的工作重点放在发现新的化石层位和描述日益增多的化石，而不是生物地层学。除了像蓝田那样的卓越的工作外，晚第三纪哺乳动物群的排序工作并没有得到应有的重视，倒是积累了许多新的资料，这些资料尚待综合研究和有针对性的野外工作。

三、现　　状

为加强对晚第三纪生物年代学的研究工作，周明镇所长在1978年组建了古脊椎动物与古人类研究所的晚第三纪地层与哺乳动物研究小组。1979年邱占祥、李传夔和邱铸鼎发表文章，回顾总结了中国晚第三纪哺乳动物群的研究工作，首次提出了这些动物群的年代排序方案。此后又有一系列有关晚第三纪哺乳动物群排序的文章面世：李传夔、吴文裕和邱铸鼎 (1984)，邱占祥 (1987)，邱占祥和邱铸鼎 (1990)。然而被排序的动物群中仅有不到一半是以地层实体为基础的，最重要和最多样化的动物群组合却经常是彼此孤立的，化石在年代表中的相对位置只能根据动物群中各分类单元的系统发育关系来确定。排序的原则大致与北美和欧洲一样：识别被称为“动物群”和“地方动物群”的生物实体，根据相互间的系统发育关系将动物群按时间排序，在可能的情况下，直接观察化石层位的层序以提高信息的可靠性。中国比欧洲更具备建立精确的生物地层层

序的条件。但是，由于缺乏同位素测年所需的材料以及由于东亚地区的动物地理隔离所造成的大量土著动物群，使对比和年代标定工作特别困难。

在晚第三纪晚期哺乳动物群的早期对比工作中，人们采用欧洲的年代地层名称来表示它们的年龄（如蓬蒂期、维拉方期）(Teilhard, 1941)。现代的学者们也一直在从西方寻求可以用来将地方性的排序与国际地质年表进行比较的媒介。虽是常规的做法，但由于是长距离的对比，加上动物地理区系因素的影响，也还存在问题。在中国的生物年代对比工作中，大量使用欧洲生物年代系统，具体为MN带（参阅Mein, 1989新近的文章)。在中、晚晚第三纪的某些时段的一些MN带的特有动物群中相似的属可达中国晚第三纪动物群中属的40—50%。在MN6—7 (Astaracian), MN11（早Turolian), MN13—14（晚Turolian和早Ruscinian）和MN16（早Villafranchian）就是这种情况。在晚第三纪早期则相似程度较低，MN1—2的动物群中与中国共有的属少于2%, MN3—5共有的分类单元低于30%。如果共有属的寿命短，或者它们共生的时间段较短，那么动物群相似性较大的时期，如邱占祥（Qiu, 1989）所讨论的那样，对中国的生物年代对比具有重要的参考价值。然而，欧洲的生物年代系统显然并不完全适用于东亚，因此最好的办法是建立一个完全反映地方性事件的中国的生物年代表。中国目前进行的研究工作与这种观点是吻合的。

生物年代学的理论基础是系统发育理论,在动物群对比的基础上，依据系统发育关系对生物组合进行时间排序。“排序”通常是“进化阶段”的比较，进化阶段的比较可能是，也可能不是在精确地重建系统发育的基础上进行的。由此建立的相对时间表可以借助同位素年龄或是其它生物门类的生物地层系统与国际地质年表对比，其它生物门类的生物地层系统也是用同样的方法标定年龄的。

在化石记录允许的情况下，建立在生物地层基础上的年代更为精确。中国的情况正是这样的。只要观察分类单元的地层分布，就可以避免纯理论性的系统发育关系探讨，可以通过同分类单元线系或是共生的分类单元来进行对比。建立在观察基础上的生物地层单位间的界限应该是可确定的，与之相反，生物年代单位间的界限无法观察到，各年代单位中的分类单元的时间跨度通常是未知的。

还有一个问题是如何把地方性生物地层系统与全球的地质年代表对应起来。这种年表与要对比的生物分类单元无关。由于缺乏同位素测年材料和无法确定它与国际地质年表的直接关系，有必要转向应用其它时间标尺。最广泛应用的时间标尺是磁性地层学，它将全球性的磁场极性变化编制成表。近一个世纪来，对地球磁场变化历史的研究表明，其极性漂移是不规则的。细粒沉积岩中的磁性矿物记录了沉积时的周围磁场。在文献中曾对实验程度有过广泛讨论（Lindsay等，1987在讨论中强调了磁性地层学的应用问题）。古地磁学家告诫使用者在技术中易犯的错误，特别强调在野外工作中仔细地采集标本的重要性，需要批判性地评估实验室程序以及野外工作中磁性地层与生物地层的关系。精确测定的磁性地层能反映全球性的同时性极性变化，因此在对比中具有最重要的价值。

在过去的20年中，这些技术已被应用到陆相沉积物。最初是在北美，现在则推广到凡是条件适合的所有大陆上（Lindsay等，1987）。在中国最引人注目的成就是华北

巨厚黄土层序的对比与标定，以及黄土小哺乳动物生物地层（Liu，T－S.，1985）。这一方法也被用于标定华北（图1）和华南（元谋）的一些地方性盆地沉积物的年龄。因此一个可用的资料网络正在不断得到充实。

从最近在晋中榆社盆地实施的中美合作项目（Tedford 等，1991），我们举一些实例来说明用生物地层和磁性地层相互标定年龄的方法。该盆地沉积物充填在深切入轻微褶皱的三叠纪沉积物中的树枝状水系中，大都来自于三叠纪地层，因此，尽管岩相不同，在岩性上却非常一致。由于大部分沉积物被老水系的河间地隔离，因此，水系各部分（次级盆地）的岩石单位之间不能互相直接追索。幸亏沉积物中哺乳动物化石丰富，可以进行次级盆地间的地层对比。每个次级盆地的磁性地层资料则被用来检验生物地层对比的同时性，即，不仅以岩层中所含化石组合（图2）进行地层对比，还以岩层的极性进行对比。榆社工作的有利条件是：新生代最晚期的极性期时段，与地层时段，尤其是小哺乳动物在地层中分布的时段相比非常长。因此只有当分类单元的分布时段很长时才可能出错。基于这些原因我们在图表中只表达持续时间短的分类单元共存区间，并且充分使用证据，用尽可能多的各分类单元共存区间来与磁性地层对比。用来在每个次级盆地建立剖面的岩石地层对比也同样能经住磁性地层的检验。榆社的各个次级盆地构造变动小，因此可以准确地确定地层在剖面中的位置。而在构造较复杂的地区则必须使用生物地层学方法。

这种方法可被推广于检验盆地间的生物地层对比（图3和图4）。尽管各盆地的沉积速率不同，在生物地层上互相覆盖的分类单元，如果确定是同时的，应该出现在相同的极性带上。这些地区性的对比是脱离地磁极性年表（GPTS）进行的。对比表明，在这个地区的各分类单元一起出现的时间是相对稳定的，除个别剖面反映出地方性分布带的差别外，其共同出现的区间带基本上是同时的。

榆社盆地晚第三纪剖面内部没有重大间断，仅在其顶部有一个被黄土覆盖的地区性不整合。黄土正好落入地磁极性年表（GPTS）的最后正向带布容期。因此其下伏海眼组应大部分落在负向带松山期，麻则沟组为正向带高斯期，高庄组则位于大部分是负向的吉尔伯特期，马会组位于混合极性的第5期。与各极性期（Chrons）相对应的地层的厚度与每个期的时间跨度成正比，因为沉积速率大体一致。

对比的正确与否还可以通过比较那些在榆社和欧洲都出现在假定的时段内的“迁入物种”的生物地层顺序来检验。这里说的“迁入物种”是指一个动物群中的外来的分类单元（即，它们在出现之前，并不是该地区的分支系统的成员）。图5比较了一些迁入种的大致生物年代，其中大部分被确认为起源于北美（兔、犬科、骆驼和马）或非洲（猛犸象），后来才在欧亚大陆广泛分布。MN带是时间跨度；每个时带的大部分特征性动物出现的精确时间并不清楚，因此它们的初始出现时间都被主观地放在每个时带的开端，除非还可以分出亚带。这使一些分类单元在欧洲出现的时段较东亚长。然而，除犬科外，它们在欧洲和亚洲的首次出现时间大致在同一个极性带内。马的出现基本上是同时的，在高斯－松山界限带上。对这个广泛分布于欧亚大陆不同地点的迁入物种的研究证明，这条界限是首次出现基准面（Lindsay 等，1980），是一个重要的年代标志，它也支持榆社盆地层序与地磁极性年表（GPTS）的对比结果。

从地磁极性带图谱及动物群某些成员的众所周知的年代关系来看，榆社盆地生物地层层序与地磁极性年表的比较和进一步与国际地质年表的比较是较可靠的。这方面曾有过失败，因为从晚第三纪往前倒退，磁极倒转的速率增加，因此其极性图谱较复杂，以致只有少数的地磁时带长于可以作为标志的平均的地磁时带。此外，较大的沉积速率差异，伴随不整合而产生的沉积间断都进一步增加了与地磁极性年表对比的复杂性。

由于缺乏同位素测年条件，地方性的磁性地层与地磁极性年表的对比必须借助于特殊的生物事件，这些事件在同一动物地理区或是邻近的动物地理区的某个地方在较有利的条件下可被识别和标定年龄。经过年龄标定的首次出现事件，例如榆社的马，或是在一个地层序列中出现一些地理分布广泛的分类单元，对于建立与地磁极性年表的关系是重要的。

四、展 望

上述地层研究项目的目的是利用中国丰富的晚第三纪哺乳动物化石证据来确定这些化石的地质年代顺序。根据与地磁极性年表对比过的磁性地层层序解析的同一剖面的生物地层层序提供了直接用国际地质年表来标定层序的时标。通过综合对比各分类单元在它们的地理分布范围内各剖面中的出现区间，可以组合成各分类单元的地区性年代带。图6是由图2—4中的各地方带通过核对综合而成，表现各分类单元的最长分布时限。根据这些资料可以编纂正式的生物地层单位，因为它们的时序在对比中肯定是有意义的。经过校准的盆地沉积物磁性地层的另一个优点是，一旦剖面中含化石部分与地磁极性年表接轨，不含化石的部分也可被断年。

将来的一个任务是，找到在时间上互相叠覆的含化石地质剖面，以便建立连续的剖面。在上面的例子中我们工作的起点是在上新世。进一步的工作可以在沿黄河的保德和邻近的府谷地区的较老的地层，以及在陕西蓝田地区的早至中中新世地层中进行。在内蒙古二连地区看来正在建立起一个类似的层序。在甘肃则特别有希望建立早－中中新世的序列。古脊椎动物与古人类研究所的同行们已在上述地区开展了初步工作。

（吴文裕 译）

NEOGENE MAMMALIAN BIOSTRATIGRAPHY IN CHINA: PAST, PRESENT, AND FUTURE

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Abstract Research in the biostratigraphy of Cenozoic terrestrial deposits was one of the first organized programs in paleontology of the Geological Survey of China. Neogene fossil occurrences were placed in relative temporal order through a unique union of geomorphological and paleontological research. By the end of the 1930's the broad outline of late Neogene physical and biological events in north China and their correlation through the fossil record with the International Geological Time Scale had been effected. Extension of these methodologies into other parts of China were confounded by local conditions, and by mid-century this research program was discontinued. The past two decades have seen a resurgence of efforts to establish the temporal sequence of Cenozoic faunas in China and their calibration by correlation with established biochronologies in Europe. Great distance and spans of marked endemism of the Chinese fauna have limited such comparisons, thereby necessitating consideration of other chronological strategies. The rarety of materials for radioisotopic dating in the continental Cenozoic strata of China has shifted attention to magnetostratigraphy as a practical tool in local and regional correlation and, aided by biochronology, as a means of calibration through reference to the Geomagnetic Polarity Time Scale (GPTS). Examples are provided of the methodology as applied to the biostratigraphy of latest Miocene through Pliocene sediments of the Yushe Basin, central Shanxi. The methodology shows considérable promise in future application to older Neogene (and Paleogene) strata yielding more precisely delimited biochronologies and age determinations for the containing strata.

Key words China, Neogene, biostratigraphy, magnetostratigraphy, fossil mammals

INTRODUCTION

The development of the Neogene biostratigraphy of China was one of the earliest goals of the Cenozoic Research Laboratory of the Geological Survey of China, predecessor of today's Institute of Vertebrate Paleontology and Paleoanthropology (IVPP). The rationale for such studies lies in the universal objective of establishing the nature and tempo of faunal change in a region and in adjacent regions that are linked zoogeographically. Eventually the data are used to incorporate local events into the global history of faunal change. Besides this goal, there is another, and very practical reason, for pursuing vertebrate biostratigraphy in China. At the moment there simply is no other universally applicable geochronological yardstick to measure the geologic history of China's continental Cenozoic deposits. Lacking widespread Cenozoic volcanism there are very few intercalated lavas or pyroclastic debris in China's Cenozoic basins so that the opportunities for isotopic dating are greatly restricted. Only vertebrate fossils occur widely and abundantly enough to offer a means of dating and interbasin correlation. Research to improve and refine our knowledge of the terrestrial faunal succession in China and its calibration with the International Geological Time Scale are thus objectives of considerable theoretical and practical importance.

THE PAST

In the late nineteenth century China hosted a number of prominent European geologists, and at the turn of the century the American geomorphologists Bailey Willis and Elliot Blackwelder (1907) published their studies of landform history that recognized a succession of geomorphic surfaces that could be traced across a considerable part of north China. More detailed work was carried out in the late 1920's and 1930's by George Barbour, Emile Licent, Teilhard de Chardin and a growing number of Chinese colleagues (Bian, Pei and Yang). These studies involved an interesting interplay between physiographic analysis following the principles of landform development articulated by Willis, Blackwelder and William Morris Davis coupled with conventional biostratigraphic reconstructions. The geomorphological work was directed toward definition of widely traceable erosion surfaces representing phases of landscape degradation. The surfaces were envisioned as broadly isochronous. Their formation initiated aggradational episodes in adjacent basins where entombed fossil remains recorded the historical succession of species. This local, north Chinese, biostratigraphy contained some generic or higher level taxa that were also known to the west in Europe, allowing approximate geochronologic ages to be assigned to the Chinese sequence and series-epoch boundaries to be postulated according to the criteria of the times. These early concepts have been remarkably robust. Lee (1939, but data only up to 1936), and later, Teilhard (1941) presented the final syntheses of this work.

The early investigators realized that the geomorphically derived chronostratigraphic scheme would be perturbed by local tectonic and climatic effects and that extension of the system beyond north China would be difficult. This proved to be the case as investigations were carried out south of the Qinling Mountains into the Yangtze basin (Barbour et al., 1935) and westward into the upper Huanghe drainage (Young and Bein, 1936—37). Nevertheless the scheme formed an important synthesis of events that could be used as a standard of correlation with other districts in China. From our present perspective the north China sequence still provides the most detailed paleontological record and hence will always be paramount in developing a mammalian biochronology for eastern Asia.

Since 1949 there have been few attempts to continue the geomorphic studies that formed this early basis for Neogene historical geology. The necessary narrowing of focus from whole physiographic provinces to the mapping of 1 : 200 000 quadrangles by the Geological Survey of China and provincial geological brigades changed the perspective in geological studies. Likewise the establishment of the IVPP in 1960, largely around the concepts of its founder Yang Zhongjian (C. C. Young), directed that institute's activities toward exploration of new fossil deposits and descriptive studies of the burgeoning collections rather than biostratigraphic investigations. With a few prominent exceptions (that of the Lantian area in Shaanxi being the best example), studies of Neogene faunal successions were not vigorously pursued. Nevertheless, important new data was accumulating awaiting synthesis and a directed field program.

THE PRESENT

To focus attention on the biochronologic reconstruction of the Neogene, Director Zhou Minzhen formed the Neogene Working Group within the IVPP in 1978. In a series of papers, first by Qiu Z-x., Li C-k. and Qiu Z-d. (1979) followed by Li C-k., Wu W-y., and Qiu Z-d. (1984), Qiu Z-x. (1989) and Qiu Z-x. and Qiu Z-d. (1990) the Neogene mammalian faunas of China were reviewed and their chronological sequence was proposed. However, less than half of the reconstructed sequence was based on observations of physical superposition, the most important and diverse assemblages were often isolated from one another. Only the phylogenetic relationships among component taxa could be used for relative placement of the fossils in a chronological scheme. The principles used were roughly those employed in North America and Europe to recognize biological entities, termed "faunas" and "local faunas", and to arrange them in temporal sequence by mutual phylogenetic relationships augmented by direct observation of superposition of fossiliferous strata where possible. There are greater opportunities in China, than in Europe, for establishment of a precise biostratigraphic basis for the historical record. However, the calibration and correlation of this record has particular difficulties due to the lack of materials for isotopic dating and the zoogeographic isolation of eastern Asia which at times resulted in the formation of largely endemic faunas.

Early correlation of the late Neogene mammal faunas led to the use of European chronostratigraphic terms for their ages (e.g. Pontian, Villafranchian, Teilhard, 1941). Modern workers have also looked westward for correlatives which can be used to relate the local sequence to the International Geological Time Scale. This is a common procedure, but not without the problems imposed by the great distances between correlation points and the influence of zoogeographic factors. It is also not sufficiently precise to discuss fruitfully many issues in paleobiology. Much use has been made of the European biochronological scheme embodied in the MN zonation (see Mein, 1989, for a recent statement) in correlation of the Chinese biochrons. There are times during the middle and late Neogene in which the generic resemblance of the characterizing fauna of certain MN chrons reaches 40 — 50÷ of the genera also present in the Chinese Neogene. This is particularly true of MN 6 — 7 (Astaracian), MN 11 (early Turolian) MN 13 — 14 (late Turolian and early Ruscinian) and MN 16 (early Villafranchian). Low resemblance characterizes the early Neogene, MN 1 — 2 faunas having fewer than 2÷ shared genera and MN 3 — 5 less than 30÷ of taxa shared with China. Given that the genera shared may have usefully short biochrons or coexist over shorter time intervals, the times of greater resemblance are important references in correlation of the Chinese biochronology as discussed by Qiu (1989). Nevertheless it is clear that the biochronological system derived from European evidence is not capable of useful extension to eastern Asia for the entire Neogene and therefore the efforts to establish a Chinese biochronology fully expressive of local events is still the preferred course. Ongoing research in China supports this view.

Biochronology based on faunal comparisons contains a theoretical element embodied in the hypotheses of phyletic relationships used to order the assemblages in time. These are often referred to as "stage-of-evolution" comparisons and they may or may not stem from precise phylogenetic reconstructions. The relative time scale based on these relationships may be correlated with the International Geologic Time Scale through isotopic dating of component assemblages or by correlation with biostratigraphic systems based on other organisms that can be so calibrated.

Greater precision in chronological reconstruction is found in biostratigraphy where the fossil record permits it, as is the case in China. Theoretical phylogenetic relationships can be avoided by referring simply to the observation of taxon stratigraphic ranges where only problems of taxon identity arise. Correlations can be effected by homotaxial taxon sequence or coexistence of taxa. Biostratigraphic units based on observed occurrence should have definable boundaries in contrast to biochronologic units where boundaries cannot be observed and the ranges of component taxa are often unknown.

There remains the problem of reference of local biostratigraphic systems to a universal geochronological indicator independent of the taxa that are being compared. Lacking materials for isotopic dating and its direct relationship to the International Geological Time Scale, it is necessary to turn to other temporal indicators. The most widely applicable is magnetostratigraphy which charts the changes in the polarity of the global magnetic field. Nearly a century of study of the history of the earth's magnetic field has shown that it shifts polarity in an irregular fashion. Magnetic minerals in finegrained sedimentary rocks record the ambient field at the time of deposition. This remanent magnetism can be recovered from field oriented samples with a set of laboratory procedures that have been widely discussed in the literature (a useful discussion, emphasizing the practical aspects of magneto-stratigraphy, is to be found in Lindsay et al., 1987). Paleomagnetists are eager to warn users about the pitfalls in the technique, especially the importance of careful field collecting, and the need for critical evaluation of laboratory procedures and field relationships of magneto- and biostratigraphies. Nevertheless, precisely determined magnetostratigraphies delineate isochronous polarity changes that are global in significance and hence of paramount value in correlation.

These techniques have been applied to continental sediments over the last 20 years, initially in North America, but now on all continents wherever suitable conditions occur (Lindsay et al., 1987). In China, the most spectacular accomplishments have been in correlation and calibration of the thick loess sequences of North China and their contained micromammal biostratigraphies (Liu, T-s., 1985). The methodology has also been used to calibrate a few local basins in north (Fig. 1) and south China (Yuanmou) so that a growing network of data is becoming available.

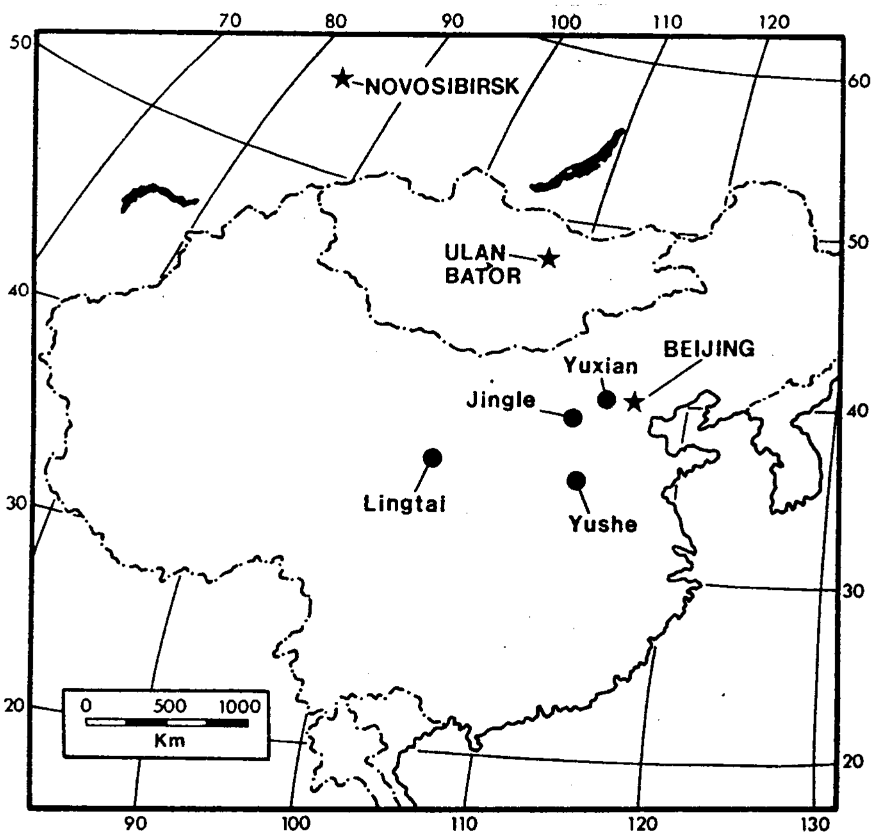

Fig.1　Map showing Pliocene mammal localities mentioned in the text and subsequent figures. As discussed by Tedford et al. (1991) the zoogeographic province to which the Chinese sites belong extends, northwestard across Mongolia into southwest Siberia.

图1　上新世哺乳动物地点图。示正文及插图中提及的地点。据Tedford等 (1991), 中国的化石点所属的动物地理区向西北延伸, 通过蒙古, 直至西伯利亚的西南部。

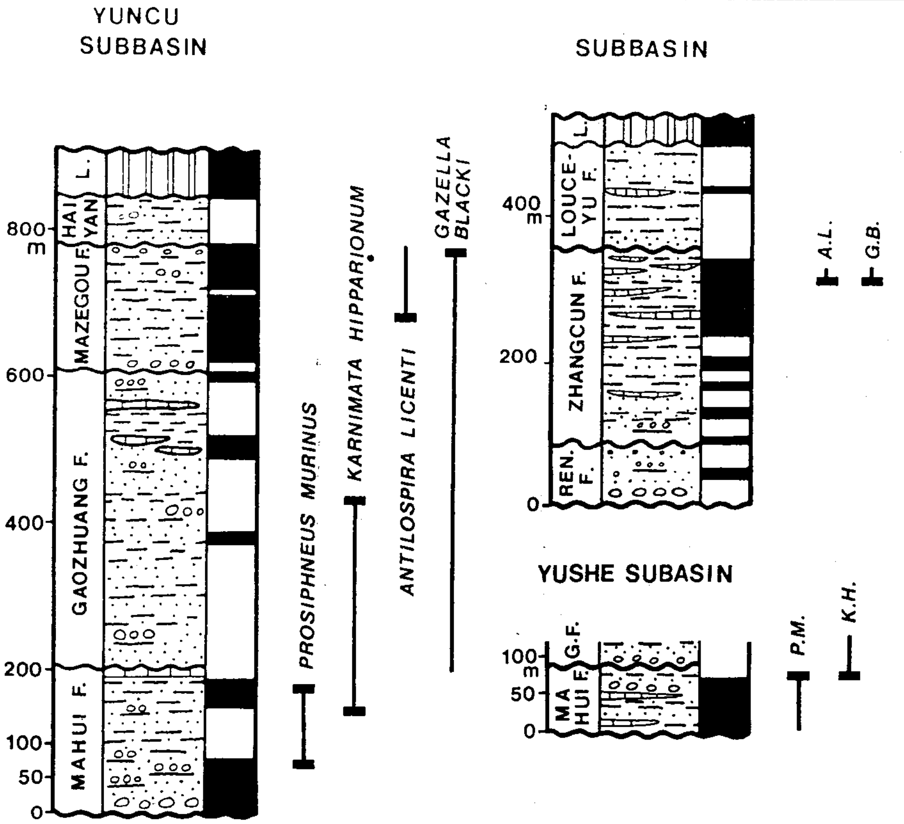

Fig.2 Litho-, bio- and magnetostratigraphies for three subbasins within the Yushe Basin, central Shanxi Province. The Yuncu and Yushe subbasins are part of the same basin but separated tectonically. The Zhangcun subbasin lies in an isolated region southwest of the Yuncu-Yushe subbasins hence its separate lithostratigraphic nomenclature. Its magnetostratigraphy has recently been revised by Shi et al. (1993) and we follow this. Shi et al. (1993) also restricted the Zhangcun Formation upward and the Wangning Formation was introduced for the lower part of this conformable sequence. We do not show this refinement. The stratigraphic ranges of selected pairs of taxa (abbreviated in the right hand columns) illustrate that such cooccurrences occupy magnetozones of the same polarity and sequence corroborating the hypothesis of synchroniety implied by their biological correlation. Roughly similar rates of sedimentation are also indicated by these data. "L." indicates the Lishi Loess equivalent that caps the fluvo-lacustrine sequence in these subbasins, "REN. F." is the Renjianao Formation in the Zhangcun subbasin.

图2 晋中榆社盆地内三个次级盆地的岩性、生物和磁性地层。云簇和榆社次级盆地都是在构造上被分开的同一个盆地的一部分。张村次级盆地是位于云簇－榆社次级盆地西南的孤立地区，因而有不同的岩石地层名称。此处采用的磁性地层是新近修正的Shi等（1993）。Shi等（1993）限定了张村组的上界，该组岩层的下部被命名为王宁组。本图省略了进一步的地层划分。图中选择的几对分类单元（在右侧柱状图中为略语）的地层分布说明它们的共存区间位于同一个地磁极性带和层位，证明了由生物地层对比指示的同时性是正确的。这些资料还表明沉积速率大致相同。"L."指覆盖在这些次级盆地的河湖相岩系之上的相当于离石黄土的沉积物，"REN. F."指张村次级盆地中的任家堖组。

A few examples of how biostratigraphy and magnetostratigraphy can mutually illuminate one another can be drawn from recent Chinese-American work in the Yushe Basin of central Shanxi Province (Tedford et al., 1991). The basin deposits fill a deeply dissected dendritic drainage system cut into gently folded Triassic sediments. The basin fill is largely derived from the Triassic and shows a great deal of lithologic uniformity in the array of facies represented. Most of these deposits are isolated by interfluves in the old drainage system so that rock units cannot be traced directly from one part of this drainage (each called a subbasin) to another. Fortunately the basin-fill is rich in fossil mammals so that correlations from one subbasin to the next can be effected. Parallel magnetostratigraphies for some of these subbasins have been used to test the synchroneity of the biostratigraphic correlations simply by reference to the polarity of the rocks containing the coexisting taxa (Fig. 2) on which the correlations are based. In the present case the technique benefits from the unusually long polarity intervals of the latest Cenozoic compared with the stratigraphic ranges, especially of small mammals, such that potential mismatches are possible only with the longest ranging taxa. For these reasons we illustrate the correlations based on concurrent ranges that define short intervals, and in more complete use of the evidence, employ as many coexistence intervals as possible to support correlation with the magnetostratigraphy. Lithostratigraphic correlations used to reconstruct the section in single subbasins are also amenable to the same testing from magnetostratigraphy. In the case of the Yushe subbasins homoclinal structure and minimal local tectonic effects allows confident placement in the stratigraphic column. In regions of more complex structure biostratigraphy would have to be employed as well.

This methodology can be extended to tests of interbasin correlation based on biostratigraphic data (Figs. 3 and 4). Biostratigraphically overlapping taxa should occur in zones of the same polarity if truly synchronous despite differences in depositional rates from basin to basin. These local comparisons have been made independent of correlation with the Geomagnetic Polarity Time Scale (GPTS). They do reveal that over the area sampled taxon cooccurrences are relatively stable chronologically, with some individual sections showing variation in the local range zones, but the concurrent range zones, are essentially synchronous.

The Yushe Basin Neogene section is truncated by a regional unconformity but lacks significant internal hiatuses. It is overlain by loess that lies within the final normal chron, the Brunhes, of the GPTS, therefore it is logical to suggest that the underlying largely reversed Haiyan Formation lies in the Matuyama Chron, the Mazegou in the normal Gauss, Gaozhuang in the mostly reversed Gilbert and the Mahui of mixed polarity in Chron 5. Moreover, the relative stratigraphic thicknesses of these chrons (given that the Matuyama is truncated) follows the temporal span for each magnetozone because sedimentation rate is roughly similar throughout.

This correlation can be tested by comparing the biostratigraphic sequence of taxa

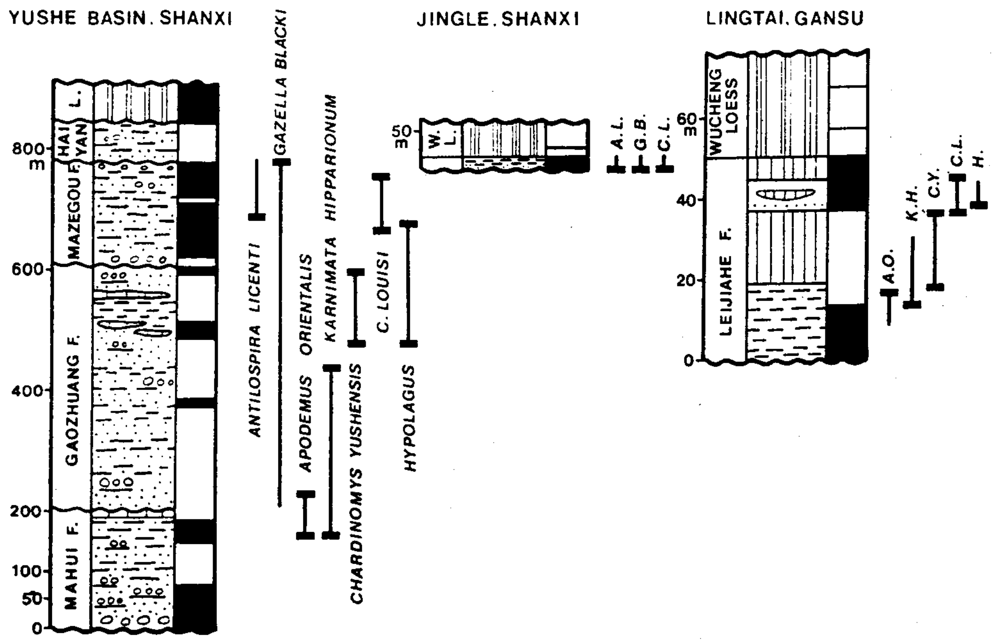

Fig.3 Correlation of the Yuncu subbasin sequence of the Yushe Basin with sections to the west for which comparable bio- and magnetostratigraphic data are available. Additional taxa are used to effect biological correlation. The Jingle data is from Chen (1994), that for Lingtai, eastern Gansu, from Zheng (1994). Range zones of comparable taxa are identified by abbreviations in the central and right-hand columns. The data indicate that the Yushe Haiyan Formation is a fluvo-lacustrine facies of the Wucheng Loess ("W. L.") in the weastern sections. Note the widely different sedimentation rates implied by the correlations.

图3 榆社的云簇次级盆地与静乐（据 Chen, 1994）及陇东灵台（据 Zheng, 1994）剖面的生物地层和磁性地层比较。图中所附分类单元示生物学对比；在中间和右侧的柱状图中分类单元的名称都以略语表示。资料表明榆社的河湖相海眼组与西部的午城黄土（"W. L."）相当。对比表明沉积速率的差异很大。

that appear as "immigrants" in both the Yushe Basin and Europe during the hypothesized interval. In the sense used here "immigrants" are taxa that are phylogenetically exotic in the fauna in which they appear (i. e. they are not members of clades present in the region prior to their appearance). Figure 5 compares the approximate biochrons of some immigrant taxa, most of which can be identified as of North American (rabbits, canids, camels, horses) or African (*Mammuthus*) origin. Their appearance across Eurasia is homotaxial to the extent that it can be determined. Note that the MN chrons are spans of time; the precise appearance of elements of their characterizing faunas are largely unknown so they are arbitrarily assigned to the beginning of each span unless subchron differentiation is available. This contributes

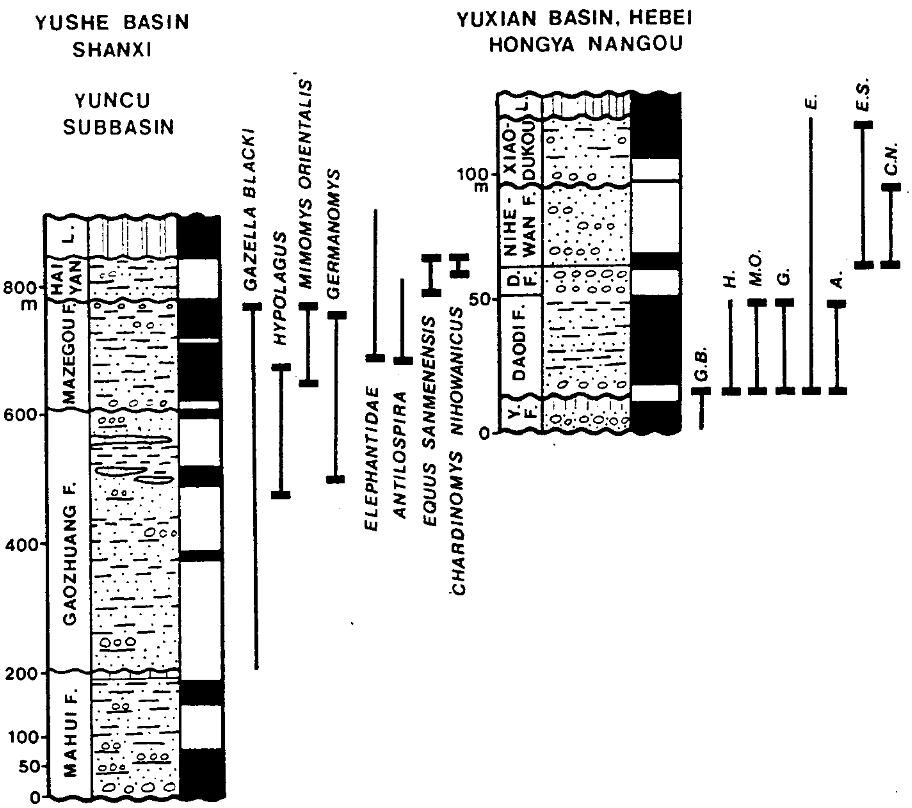

Fig.4 Correlation of the Yuncu Subbasin sequence of the Yushe Basin with that from the Hongya Nangou section of the Yuxian Basin. The latter forms part of the besin of deposition of the Nihewan Formation, a lithostratigraphic unit now restricted by subsequent proposal of other stratigraphic units. At the base of the stratigraphic column illustrated, the upper part of the former "Hipparion red-clay", is now the Yuxian Formation ("Y.F."). The Daodi Formation (Du et al., 1988; Zheng and Cai, 1991), the Dongyaozitou Formation ("D.F.") concept follows Zheng and Cai (1991), the Nihewan Formation restricted and Xiaodukou Formation (Cheng, 1988) formerly constituted the Nihewan Formation of previous workers. The fluviatile beds are disconformably overlain by equivalents of the Lishi and Malan Loess. The poorly fossiliferous Dongyaozitou Formation leaves a hiatus in the range zones of most of the taxa exemplified. Note the slower depositional rate in the Yuxian Basin. The names of the selected taxa are abbreviated in the Hongya Nangou column.

图4 榆社云簇次级盆地与蔚县盆地红崖南沟剖面的对比。蔚县盆地是泥河湾组沉积盆地的一部分，泥河湾组现在被限定为岩石地层单位。柱状地层图的底部，是过去被称为“三趾马红土”的上部，现称蔚县组（“Y.F.”）。稻地组（Du等，1988; Zheng and Cai，1991），东窑子头组（“D.F.”）的概念依据Zheng and Cai（1991），狭义的泥河湾组和小渡口组（Cheng，1988）从前组成前人称为的泥河湾组。河流沉积物之上不整合地覆盖着与离石和马兰黄土相当的沉积物。大部分分类单元的分布区间在化石贫乏的东窑子头组间断。很明显蔚县盆地的沉积速率较低。在红崖南沟柱状剖面中分类单元的名称以略语表示。

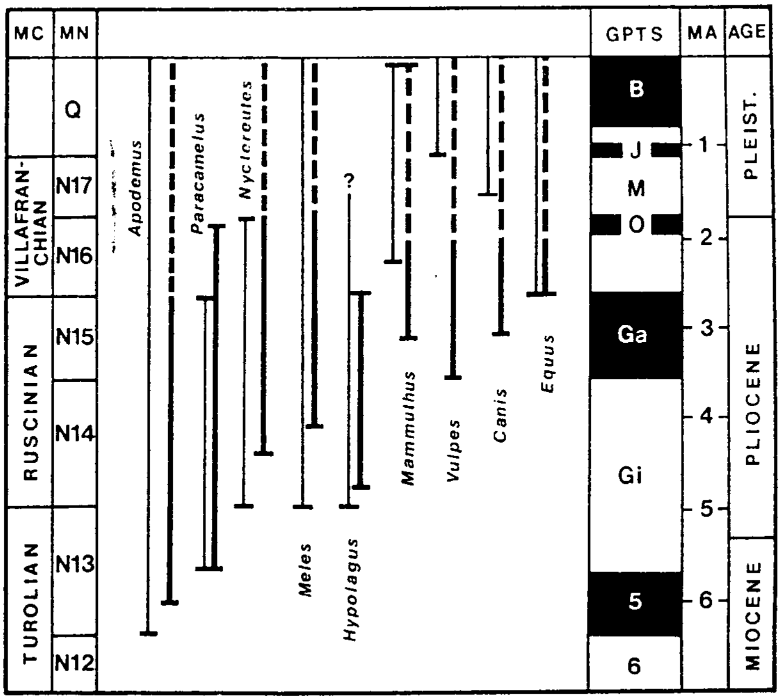

Fig.5 Comparison of biochrons of some "immigrant" taxa (see text for definition) in the Yushe Basin (bold lines) and Europe (fine lines). The European ranges are from their occurrence in the MN chrons of Mein (1989) plotted at the base of each chron unless the data permits placement within the span of each chron. Neogene Mammal (MN) chrons are correlated with the GPTS using the data of Steininger et al. (1989). Within the limitations of the European data the Yushe biostratigraphy closely approximates the sequence of first occurrences in Europe. MC: Mammal chrons ("ages"); MN Neogene mammal chrons ("zones"); GPTS Geomagnetic Polarity Time Scale; 6, Chron 6; 5, Chron 5; Gi, Gilbert; Ga, Gauss; M, Matuyama with O (Olduvai) and J (Jaramillo) subchrons; B, Brunhes; Ma age in millions of years; Age, units of the International Geologic Time Scale. Calibration of GPTS follows Cande and Kent (1992). Dashed ranges are those demonstrated in China but outside the Yushe Basin.

图5 榆社盆地(粗线)与欧洲(细线)的一些"迁入"分类单元(定义请见正文)的生物年代对比。各分类单元在欧洲的分布区间依照它们在MN带(Men, 1989)中的分布,一般都从MN带的底部算起,除非资料表明应从带内某处开始出现。晚第三纪哺乳动物MN带与地磁级性年表(GPTS)对比,采用Steiniger等(1989)的资料。榆社生物地层与欧洲的首次出现的顺序很接近,马的首次出现时间是完全一致的。MC: 哺乳动物时带 (Zones); GPTS 地磁极性年表; 6第6正向期; 5第5负向期; G吉尔伯特反向期; Ga高斯正向期; M松山反向期包括0奥杜威和J加拉米洛事件; B布容正向期; Ma年龄单位百万年; Age国际地质年表单位。地磁极性年表的年龄标定依据Cande和Kent (1992)。虚线表示在榆社盆地以外的中国地域内的分布区间。

to the longer apparent ranges for some taxa in Europe than in eastern Asia. Nevertheless, with the exception of the canids, first appearances of taxa lie approximately in the same magnetozones. The appearance of *Equus* is essentially synchronous at the Gauss-Matuyama boundary. Investigation of this immigrant's occurrence in widely separated sites in Eurasia confirms this as a first appearance datum (Lindsay *et al.*, 1980). This is an important chronological marker that also supports the correlation of the Yushe Basin sequence with the GPTS deduced from the magnetostratigraphic pattern.

Correlation of the Yushe Basin biostratigraphic sequence with the GPTS, and consequently the International Geologic Timescale, is relatively secure from the pattern of the magnetozones and the well known chronological relationships of some members of its fauna. The methodology has been belabored because as one moves back into the Neogene the rate of polarity reversal increases, the pattern is consequently more complex and there are few longer than average magnetozones that can be used as markers. Additional complications lie in significant differences in depositional rates and hiatuses accompanying unconformities which further complicate correlation with the GPTS.

Lacking the opportunity for isotopic dating, correlation of local magnetostratigraphies with the GPTS must depend on the occurrence of unique biological events that can be recognized and calibrated under more favorable conditions elsewhere in the same or adjacent zoogeographic regions. Well calibrated first appearances, such as *Equus* in our Yushe example, or homotaxal appearances of several taxa giving more than one point of correlation in a sequence will be important in establishing relationships with the GPTS.

THE FUTURE

The goal of the stratigraphic research program described above is to utilize the superb Chinese record of Neogene mammals to provide a detailed and well-tested knowledge of their geochronological succession. Understanding of biostratigraphic sequence in terms of a parallel magnetostratigraphic sequence correlated with GPTS, provides time-lines that directly calibrate the succession in terms of the International Geological Time Scale. These data also permit the assembly of regionally applicable chronozones for taxa by correlating the occurrences throughout their zoogeographic range as exemplified in Figure 6 where the local zones shown in Figures 2—4 are collated into a composite depicting the maximum known temporal limits of the ranges. Formal biostratigraphic units could be compiled from these data with fair confidence that their sequence in time would be meaningful in correlation. A further advantage of a calibrated magnetostratigraphy of basin deposits, especially for geologists, is that non-fossiliferous intervals can also be dated once the fossiliferous parts of the section have been tied to the GPTS.

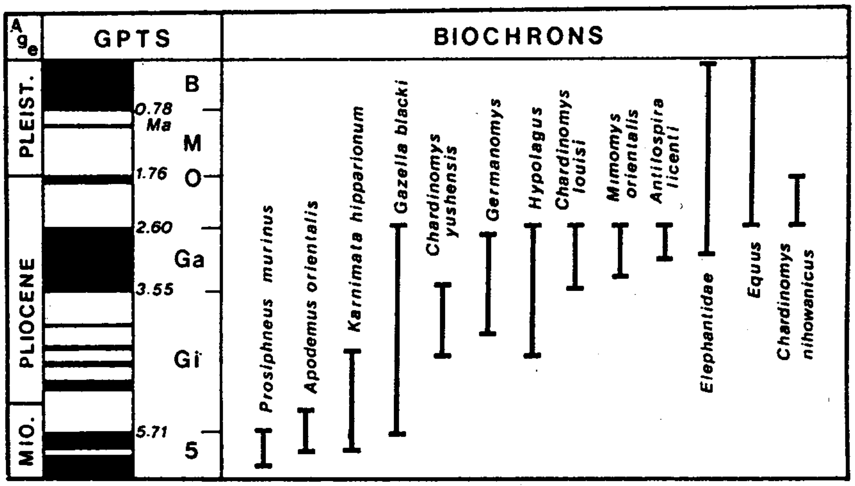

Fig.6 Biochrons of taxa used in Figures 2—4 after correlation of local range zones with the GPTS. The plot indicates the limits of the ranges in time as demonstrated with the data from five localities in north China. Extension of ranges may be necessary as greater geographic coverage is achieved in future studies. Units of the GPTS as in Fig.5; calibration follows Cande and Kent (1992).

图6 图2—4中的各分类单元的生物年代分布，依据华北5个地点的地方性分布带与地磁极性年表对比综合而成。线条表示时间分布范围，时间分布范围有可能随着今后研究工作地理覆盖面的增大而扩展。GPTS的单位如图5；年龄标定依Cande and Kent (1992)。

A task for the future will be to find fossiliferous geological sections that overlap one another in time so that a continuous record can be developed. A starting point has been made in the Pliocene as in the above examples. Extending this backward in time can probably be effected in sequences in the Baode and adjacent Fugu area along the Huanghe and the Lantian area of Shaanxi where the sequence extends downward into the middle Miocene. Evidence of a similar succession seems to be developing in the Erlian Basin of Nei Mongol. Gansu holds particular promise for mid to early Miocene successions, and preliminary work there, along the lines suggested above, has already been undertaken there by the IVPP and their colleagues.

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