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Terrestrial mollusk records from Chinese loess sequences and changes in the East Asian monsoonal environment

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ABSTRACT

The terrestrial mollusk fossils found in Chinese loess strata have been studied for over one hundred years. However, the greatest progress in these studies has been made only in the last two decades. In this paper, we review the advancements, advantages and limitations of terrestrial mollusk studies in Chinese loess deposits. Improvements in research methods and approaches have allowed the extraction of more detailed paleoenvironmental and paleoclimatic information from mollusk assemblages. The broadened research scope and content have yielded many new findings and results. The mollusk record has thus become one of the most important proxies in the paleoenvironmental and paleoclimatic reconstruction of loess-paleosol sequences in China. The greatest progress in the studies of terrestrial mollusks in Chinese loess sequences can be summarized as follows: (1) modern mollusk assemblages can be classified into four ecotypes, based on their temperature and humidity requirements, including eurytopic, semi-aridiphilous and sub-humidiphilous, cold-aridiphilous, and thermo-humidiphilous types; (2) Quaternary mollusk assemblages can be modified into the following three ecological types: glacial loess, interglacial paleosol, and interstadial weakly-developed paleosol assemblages; (3) mollusk records successfully reveal long-term climatic and environmental changes reflective of the history of East Asian monsoonal variations since the Late Cenozoic, and the succession of mollusk species also indicate short-term environmental changes such as millennial climate variability during Last Glacial Maximum and unstable climatic fluctuations during glacial and interglacial periods; and (4) more recently, new analytical approaches have offered increased research potential in areas such as paleotemperature reconstruction using the isotopic compositions of modern and fossil mollusk shells, combined with higher accuracy ^{14}C dating of Quaternary loess deposits, which will greatly improve future loess paleoenvironmental research.

1. Introduction

The widespread fossil remains preserved in Quaternary loess-paleosol sequences represent an important record for the study of geological evolution and climate change. Terrestrial mollusks, taxonomically classified into the *Gastropoda* of *Mollusca*, are the most common biological remains identified in Quaternary loess deposits. They are highly sensitive to environmental, and therefore climatic changes, and can thus be considered typical 'index animals' for loess-based paleoenvironmental research (Liu, 1985). During the early years of loess research, Richthofen proposed in his initial research that the Chinese loess deposits contained fossil gastropods which were all terrestrial species sparsely distributed throughout the stratigraphic sequence, demonstrating that these loess deposits had not been reworked by water flow. This provided the most direct biological evidence for his hypothesis that the loess deposits in China had been transported there by the wind (Richthofen, 1877, 1882). Recently, international Quaternary studies have developed rapidly, using new methods and techniques, leading to an increasing importance being placed on the paleoenvironmental studies of terrestrial mollusk fossils found in Quaternary loess and Late Cenozoic wind-blown dust deposits. Especially in recent decades, the study of the loess snail in the world has made great progresses, including snail's ecological distribution, high resolution fossil record and stable isotopes analysis of terrestrial snail shell *etc*. (e.g. Metref et al., 2003; Balakrishnan et al., 2005; Zanchetta et al., 2005; Antoine et al., 2009; Yanes et al., 2009; Kehrwald et al., 2010; Zaarur et al.,

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2011; Huang et al., 2012; Colonese et al., 2013; Eagle et al., 2013; Yanes and Romanek, 2013; Horsák et al., 2015).

Important research activity was conducted in China between the 1920s and 1980s into the terrestrial mollusk fossils found in loess. Liu (1985), in 'Loess and the Environment', put forward a detailed compilation of the research conducted into terrestrial mollusk fossils during this period. It can be concluded that this period's body of work could be subdivided into: (1) the period prior to the 1950s, when the focus was placed on descriptions of the genus and species of terrestrial mollusks (Yen, 1939, 1943); (2) the period from the 1950s to the 1980s, when the emphasis was still on the collection of terrestrial mollusk data, apart from some detailed work on the taxonomic identification and classification of terrestrial mollusks. A focus was placed on stratigraphic records and the ages of the strata in which the fossils were found (Yu et al., 1963; Li, 1966). Some research was also begun into the relation between the composition of terrestrial mollusks and their living environment during the period from the 1950s to the 1980s (Lu and An, 1979; Chen et al., 1982). All of this previous work lay the biological foundations for the subsequent subdivision and differentiation of loess strata, and therefore of past paleoenvironments and paleoclimates. Liu (1985), in 'Loess and the Environment', explicitly suggested that the terrestrial mollusk fossils preserved in the loess strata could be used as 'indicator animals' of the paleoenvironment and paleoclimate recorded in loess-paleosol sequences, pointing toward their potential for future studies of the paleoclimate and paleoenvironment of China's loess regions. However, due to the lack of much basic work on the relation between the composition of modern terrestrial gastropods and climatological parameters, research into this field of science in China came more or less to a full stop between the mid-1980s and the early 1990s. Internationally, this period saw a rapid development of research into terrestrial mollusk fossils, allowing paleoenvironmental and paleoclimatic research to progress from a state of qualitative analysis state toward a semi-quantitative or quantitative stage (Rousseau, 1991).

From the beginning of the 1990s, research on the terrestrial mollusk fossils found in Chinese loess entered a new phase. Research methods and fields of terrestrial mollusk fossils made remarkable headway, gradually being used as new and vital indices in loess paleoenvironmental research. Major advances in research approaches were reached in terms of: (1) the employment of an internationally-used washing and sieving of snail samples using water became the preferred method for collecting fossil terrestrial mollusks from Chinese Quaternary loess. For example, in our study, mollusk samples were taken from loess sections at 3, 5 and 10 cm intervals (Wu et al., 1995, 1996, 1997, 1999, 2000, 2001, 2002, 2007; Rousseau and Wu, 1997, 1999; Chen and Wu, 2008). Each sample was approximately $60 \times 45 \times 20\ cm^3$ in size, or weighed ~15 kg to 20 kg. All samples were washed and sieved in the field using a mesh of diameter 0.5 mm. The mollusk shells were sorted and identified under a binocular microscope. All identifiable mollusk fragments were considered in the total count of individuals following the method developed by Puisségur (1976). This new method of sampling and collecting mollusks has since been used in sampling of the Quaternary loess sequence in China, yielding a great abundance of terrestrial mollusk fossils. This meets the requirements of quantitative statistics and improves the reliability of any environmental analysis and interpretation, and also greatly reduces the transportation difficulties caused by the vast quantities of sediments in all the samples; (2) a wide variety of multivariate statistical methods have been used to handle and process the terrestrial mollusk fossil data and to establish the statistical relation between terrestrial mollusk species and/or its assemblages, and climatic factors. Of these methods, the use of transfer functions based on terrestrial mollusks can quantitatively or semi-quantitatively reconstruct paleoclimatic parameters (Rousseau, 1991; Wu et al., 1997); and (3) the introduction of geochemical methods, especially stable isotope analysis, into the research of the relation between terrestrial mollusk shell stable isotopes and climatic or environmental factors, has been able to produce remarkable results, and can therefore be considered a vital research tool for investigating the evolution of the East Asian monsoonal environment.

Apart from the use of the new methods reviewed above, the studies of loess terrestrial mollusks has focused especially on paleoclimatic and paleoenvironmental studies related to the evolution of the monsoonal environment, and on investigations into the ecological requirements of modern terrestrial mollusk assemblages, thus: (1) paleoclimatic and paleoenvironmental studies have focused on different timescales, including climatic conditions during typical time intervals such as marine isotope stages (MIS) 24–22, 15–13, and 11 (Wu and Wu, 2008, 2011; Wu et al., 2007), climate instability and asynchronous changes in temperature and precipitation (Wu et al., 1999, 2002), and climatic periodicities and the response to orbital forcing as recorded by terrestrial mollusk fossils (Wu et al., 2000, 2001; Pei and Wu, 2005; Chen and Wu, 2008; Li et al., 2008; Rousseau et al., 2009; Li and Wu, 2010); and (2) investigations into the ecological requirements of modern terrestrial mollusk assemblages. This has included a survey of the habitats of modern terrestrial mollusks, and in particular their appearance, distribution and abundance within these habitats, the optimum conditions for survival, reproduction, and growth rates *etc.*, and the relation between terrestrial mollusk assemblages and their relevant environmental factors. These basic investigations are the key to using terrestrial mollusks to quantitatively reconstruct paleoclimatic and paleoenvironmental evolution. Recently, several studies have provided promising results. For example, experiment and observation of the survival, activity and feeding habits of *Bradybaena similaris* in environments with different relative humidities has provided reliable information for the interpretation of paleoenvironments (Xu et al., 2002).

Looking back on the progress of research in terrestrial mollusks found in loess since the publication of the seminal monograph 'Loess and the Environment' in 1985, such research can be seen to have entered a new phase. There have been comprehensive and systematic studies of terrestrial mollusk assemblages in loess. Additionally, considerable progress has been made in establishing the origins of loess and paleoclimatic evolution at different timescales, based on the analysis of terrestrial mollusk fossils preserved in Quaternary loess strata (e.g., Keen, 1995; Wu et al., 1995, 1996, 1997, 1999, 2000, 2001, 2002, 2007; Rousseau and Wu, 1997,1999; Chen and Zhang, 1998; Chen and Wu, 2008; Wu and Wu, 2008, 2011; Rousseau et al., 2000, 2009) and Late Miocene–Pliocene red clay strata (e.g., Pei et al., 2004; Wu et al., 2006), as well as Miocene–Pliocene loess strata (e.g., Li et al., 2006a, 2006b, 2008; Li and Wu, 2010).

2. The geographical distribution and ecological environments of extant terrestrial mollusks on the Chinese Loess Plateau

Information on the ecological requirements of modern terrestrial mollusk species, whose fossil species are found in loess, can provide a base for interpreting the paleoenvironment. The growth and reproductive rates of modern terrestrial mollusks are intimately related to the environments within which they live and develop. The type of vegetation, air temperature and relative humidity (RH), the degree to which the soil has been enriched with organic matter, soil moisture content, sunlight and habitat substrate, all greatly influence the diversity of terrestrial mollusk communities, the composition, distribution and abundance of mollusk species. Of these numerous environmental factors, temperature and RH appear to be the key factors controlling the growth and development of terrestrial mollusks. Nonetheless, there are marked differences in the sensitivities to changes in temperature and RH displayed by different terrestrial mollusk species (Li et al., 2016).

Yen (1939) conducted an outstanding piece of mollusk research, producing a systematic survey and classification of modern Chinese terrestrial mollusks. This remains a seminal point of reference when identifying terrestrial mollusk species. During the 1980s, Chen and Gao (1987) conducted a systematic identification and classification of the