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Responses of landform development to tectonic movements and climate change during Quaternary in Fenhe drainage basin

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Tectonic movements and climate changes are two main controllers on the development of landform. In order to reconstruct the history of the evolution of the landform in the Fenhe drainage basin during middle-late Quaternary comprehensively, this paper has provided a variety of geomorphological and geologic evidences to discuss how tectonic movements and climate changes worked together to influence the landform processes. According to the features of the lacustrine and alluvial terraces in this drainage basin, it is deduced that it was the three tectonic uplifts that resulted in the three great lake-regressions with an extent of about 40-60 m and the formation of the three lacustrine terraces. The times when the tectonic uplifts took place are 0.76 MaBP, 0.55 MaBP and 0.13 MaBP respectively, synchronous with the formation of paleosol units S8, S5 and S1 respectively. During the intervals between two tectonic uplifts when tectonic movement was very weak, climate changes played a major role in the evolution of the paleolakes and caused frequent fluctuations of lake levels. The changes of the features of lacustrine sediment in the grabens show the extent of such fluctuations of lake level is about 2-3 m.

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HU Xiaomeng1, LI Youli2, FU Jianli2 (1. Department of Geography, Shanghai Normal University, Shanghai 200234, China; 2. Department of Geography, Peking University, Beijing 100871, China) 1 Introduction Because of abundant geomorphological phenomena and extensively exposed sections of Quaternary deposit in the Fenhe drainage basin, it has been one of the areas which interest many geomorphologists since the early 20th century (Baarbour, 1931; Licent, 1935; Guo, 1956; Yang, 1987). Previous investigations on this drainage basin mainly concerned with the relation between the development of the landform and tectonic movement (e.g. Yang, 1987); the episodes of the evolution of the landform were always attributed to the periodical tectonic movements. Served as two active forces influencing the development of the landform (Schumm, 1977; Yang, 2001), tectonic movements and climate changes actually combined with each other to act on landform processes simultaneously (Krzyszkowski and Przybylski, 2002). We have to take the two factors into account to analyze the development of the landform in this drainage basin in order to acquire a comprehensive knowledge about this discipline. Finished studies (Wang et al., 1996) show that the grabens in this drainage basin had been occupied by paleolakes during Quaternary, and experienced several lake regressions and aggressions, while depositing lacustrine and alluvial sediment about 1,000 m thick. The recent field work also find there developed several lacustrine and alluvial terraces around the edge of the grabens and along the Fenhe River. Because of the loess deposition from the air, the lacustrine and alluvial terraces with different ages were normally capped by different succession of loess/palosols stratigraphy with different thickness. The purpose of this study is to use lacustrine and alluvial terraces and sediment to reconstruct the history of the evolution of the landform in the Fenhe drainage basin during middle-late Quaternary and moreover, to reveal its response to the neotectonic movements and climate changes. 2 Methods The formation of lacustrine and alluvial terraces, along with the changes in the features of lacustrine sediment demonstrates that the landform in the Fenhe drainage basin evolved through several episodes during Quaternary. It is the key to date these terraces and sediment for making the sequence of the development of the landform clear. Because the ages of these terraces and sediment are usually beyond the range of conventional radiocarbon dating, loess/paleosols series is primarily adopted for dating, and TL and U-series datings are also in use in this research. The thick succession of loess/paleosols units that forms the Loess Plateau of central China constitutes a continuous terrestrial recor

d of changing climate conditions spanning more than two million years (Liu, 1985; Kukla and An, 1989). In addition to providing a history of fluctuations in monsoon circulation in eastern Asia (An et al., 1991), the sedimentary sequence can be employed as a dating tool in much the same way that marine oxygen-isotope record can be used to correlate and date Quaternary sediments in deep sea cores. The eolian section has been divided stratigraphically into successive loess units and paleosols (Figure 1), each of which has been assigned a stratigraphic designation (e.g., loess units: L1, L2 .; paleosols: S1, S2…). The loess/paleosols sequence has been dated using a combination of approaches (e.g. radiocarbon, thermoluminescence, paleomagnetism, magnetic susceptibility), and has been shown to compare closely with the standard marine ?啄18O times series. The Fenhe drainage basin has been receiving loess deposition, and once a terrace formed, the loess or paleosols would deposit or develop on its surface immediately, so the age of the lowest loess or paleosol superjacent to the terrace surface may represent the time when the terrace appeared above water level. The determination of the loess/paleosol units is based on their distinctive physical characteristics (e.g., texture, structure, thickness, color), their features of paleomagnetism and magnetic susceptibility and TL dating. 3 Effects of tectonics on the formation of lacustrine and alluvial terraces 3.1 Lacustrine terraces in Taiyuan Graben Taiyuan Graben extends from NE to SW, with a length of about 80 km and a width of about 30 km. In its southeastern part, there developed a loess platform named Zhangbi Tableland, and a steep valley has incised through it, providing a large natural exposure. Exposed sections show that there deposited three units of lacustrine sediment from the upvalley to the downvalley and the top surfaces of three lacustrine sediment units are decreasing step by step in elevation. These lacustrine sediments are capped by loess/palosol stratigraphy with different succession and thickness, which indicates there are differences in time when paleolake level dropped and each lacustrine sediment unit appeared above water. Zhangbi Tableland is actually composed of three lacustrine terraces (Figure 2a). According to field investigations on three lacustrine terrace sections, sedimentary changes from the underlying lacustrine deposit to the overlying loess/paleosol stratigraphy are gradual without erosion surfaces between them. This phenomenon shows that deposition was continuous, although there experienced several alternations in sedimentary environment from under water to under air. The first lacustrine sediment unit underlying the highest lacustrine terrace (T5) surface (120 m above Fenhe River level), cropping out on both cliffs of the upvalley, is made of gray-green silt and fine sand, and contains a lot of fragments of shell fossils. Over it, there deposited eolian loess/paleosol stratigraphy about 50 m thick and eight distinct paleosols can be realized; the lowest of them is the eighth paleosol. Beneath the lacustrine sediment also developed another older paleosol, so the lacustrine sediment depositing between the two paleosols is wedge-like with its thickness less toward the upvalley. This implies the studied section site was located near the edge of the paleolake at that time. In order to identify the stratigraphic designation of the 8th paleosol, paleomagnetism samples were taken from the older paleosol through the lacustrine sediment to the top of the section. The paleomagnetism result demonstrates the reversal of paleomagnetic field (B/M boundary) lies in a layer of loess between the 8th paleosol and the 7th one (Figure 2a). According to the research (Yue and Xue, 1996), B/M boundary in Chinese loess is located in L8, so the 8th paleosol nearest to the lacustrine sediment unit is S8. The study by Liu (1985) shows the beginning time of the formation of S8 is about 0.76 MaBP. The height of the top surface of the second lacustrine sediment unit (T4) is 40 m lower than that of the highest one, with loess/paleosol about 30 m thick covering it. The sediment is composed of gray compacted clay and silt, locally with bright interlayered fine sand. Above the sediment there developed five paleosols in the loess/paleosol section, among which the 5th paleosol formed directly on the top surface of the sediment. On the basis of the characteristics of this paleosol combined with the magnetic susceptibility of the loess section, we infer the 5th paleosol is S5 (S5 is characterized in its color, thickness, the value of magnetic susceptibility and the intense pedogentic process and is actually an easily identifiable stratigraphic marker in Loess Plateau). In the backward position of this lacustrine terrace, beneath the lacustrine deposition exists another paleosol. The paleomagnetism is used to identify it and finds it is S8 extending from the highest lacustrine terrace and disappearing in this sediment unit. In the forward position of this terrace, S5 dips toward the lowest lacustrine terrace, and capped by the 3rd lacustrine sediment unit. The beginning time of S5 is 0.55 MaBP (Liu, 1985). The youngest lacustrine sediment unit comprises the lowest lacustrine terrace (T3), 60 m lower than T4, on which there deposited loess/paleosol stratigraphy about 15 m in thickness. This sediment unit is primarily composed of light fine silt and sand, with many shell fossils in it. A shell sample taken from 6 m below the top surface of the sediment is dated to be of an age about 220±14.2 kaBP by U-series dating. Superjacent to the top surface of the sediment developed a layer of paleosol. According to the TL dating (discussed below), this paleosol is S1. The beginning time of S1 is about 0.13 MaBP (Nie, 1996). 3.2 Lacustrine terraces in Linfen Graben The shape of Linfen Graben is like a reversed letter "L", extending from NNE to SSW in its northern sector and from NEE to SWW in the southern sector. In the northern p art of the graben, there developed an extensive tableland about 20 km in width to the east of the Fenhe River, and field work finds it can be divided into one loess platform and two lacustrine terraces from the east to the west according to the topography and sediment features (Figure 2b). The easternmost is a loess platform named Fushan Platform. This platform is made of loess/paleosol of Quaternary and red clay of Neogene, without any alluvial or lacustrine sediment in it. In its forefront exists a normal fault dipping toward NNW that defines the eastern margin of the graben, and to its west there occurs lacustrine sediment. The higher lacustrine terrace, Dayang Terrace with 4 km wide, is about 100 m above Fenhe River level and composed of gray-green laminated silt and fine sand. The thickness of exposed lacustrine deposit is about 30 m and its lower contact is nowhere exposed. Loess/paleosol stratigraphy up to 30 m thick overlay the lacustrine sediment, among which the oldest is the easily identifiable paleosol unit S5. S5 extends horizontally until the forefront of the terrace where it dips toward the lower terrace and partially covered by the lower lacustrine sediment and finally dies out in it. The lower lacustrine terrace, Qiaoli Terrace with 13 km wide and 50 m above river level, fills fine sand and silt with interlayered clay. On its surface deposited eolian stratigraphy nearly 15 m thick, among which there are two layers of paleosols, one well developed and the other less developed. The samples for magnetic susceptibility and TL dating are taken to identify the sequence and the designation of the loess/paleosol stratigraphy. The result indicates the variation of the section in magnetic susceptibility and ages with depth is highly consistent with that of Potou profile (Stephen et al., 1995) and the well developed paleosol in the lowest of the section is inferred to be S1 (Figure 2b). In addition, in the southernmost of the graben there is another tableland named Emei Tableland extending from east to west, being the south boundary of the Fenhe drainage basin from Yuncheng Graben in the south. The features of the tableland profile in deposit stratigraphy are very similar with that discussed above but the oldest lacustrine terrace. The oldest lacustrine terrace there is capped by S8 and subsequent loess/paleosol stratigraphy. 3.3 Alluvial terraces in the highland within the grabens Chaizhuang Highland is within Linfen Graben, and was crossed and incised by the Fenhe River to form a narrow channel with steep bank slopes. This highland divides Linfen graben into two parts-north sector and south sector, and the channel has been a hydrological channel linking the two sectors of the grabens. Because of the drops and rises of the paleolake levels during middle -late Quaternary, the channel had experienced several floodings and intense vertical incisions since middle Quaternary and formed five terraces (Figure 2c). Among these terraces, the highest (T5, 49 m above river level) is a lacustrine terrace whose fill is composed of yellow-green laminated mud and silt. The oldest of the loess/paleosols units overlying the terrace is S8. T4 and T3 are bedrock seated terraces with a height of about 28 m and 18 m respectively and their fills consist of gravel and sand with a lot of shell fossils in it. The lowest of the loess/paleosol stratigraphy which are superjacent to the terrace surfaces are S5 and S1 respectively. This demonstrates the extensive regression of the paleolake and the intense vertical erosion of the channel which resulted in the formation of one lacustrine terrace and two alluvial terraces took place when S8, S5 and S1 began to develop respectively. Actually, the grabens have drained many streams originating from the mountainous area around them and two bedrock seated terraces with the same ages as that of S5 and S1 respectively were often well preserved, e.g., in Wenyu Creek (with its origin in the west mountain of Taiyuan Graben) and Longfeng Creek. 3.4 Analysis on the formation of lacustrine and alluvial terraces Based on the features of the lacustrine and alluvial terraces in this drainage basin, we can obtain some information about the sequence of the evolution of the paleolakes. Before S8 was formed, the grabens were occupied by a highstand lake which caused lacustrine deposition forming the highest lacustrine terrace. When S8 began to develop, a lake regression took place and paleolakes contracted to make some of lacustrine sediment appear above water; subsequently, there developed S8 on the top surface of the lacustrine sediment. This is the first lake regression in the grabens during middle-late Quaternary. At the end of the development of S8, a lake aggression occurred and paleolakes expanded; the high level water drowned the lake bank and part of S8 over the bank was capped by the young lacustrine deposit. The elevation of the top surface of this lacustrine sediment unit shows the level of this highstand lake was about 60 m lower in height than that of the former one. The period of this high lake level lasted until S5 began to develop. The second lake regression came at the beginning of the formation of S5 and the low lake level made some area drowned by lake water before exposed under the air, and allowed the pedogenetic process of S5 on its top surface, so some of the top surface of the lacustrine sediment deposited during last highstand period was covered by S5. At the end of the development of S5, the level of the paleolakes rose once again, and highstand lake sediment overlay the S5 locally. The distribution of the lacustrine deposit circumscribing the extent or level of paleolakes during this highstand period indicates that it is smaller or lower than that of the former two ones. This highstand remained till S1 began to develop. The occurrence of the third lake regression coincided with the formation of S1 in time and caused S1 developing directly on the top surface of the youngest lacustrine sediment unit. This lake regression was so intens ive that nearly all of the lake water drained away and the bottom of the grabens was exposed under the air and S1 extended to the centers of the grabens. After this lake regression, all of the grabens but some low-lying locals are lakeless; the Fenhe River came to flow in the grabens and has formed two alluvial terraces since then. What is the reason causing three lake regressions? Three lake regressions were nearly synchronous with the formation of S8, S5 and S1 respectively. The formation of the paleosols indicates the paleoclimate were warm and wet and the annual precipitation was great. Moist climate may bring more runoff to the grabens and caused the paleolake level to rise. According to such a belief, it must not be the climate changes that result in three lake regressions. Tectonic uplift is the main factor causing these lake contractions. Normally, the lake level is controlled by the lake threshold elevation or the erosion base level elevation in the low reach of the graben. Once the neotectonic movement uplifted the whole graben relative to the threshold or the erosion base level, much of the lake water would drain away and water level decreased extensively. Three lake regressions recorded three tectonic uplifts which occurred when S8, S5 and S1 began to develop respectively, with the age of 0.76 MaBP, 0.55 MaBP and 0.13 MaBP respectively. Meanwhile, these three tectonic uplifts also had left their trails in some alluvial terraces, e.g., in Chaizhuang Highland, Wenyu Creek and Longfeng Creek. In general, although the wet climate brought much more runoff to the grabens during the periods of the formation of S8, S5 and S1, the three tectonic uplifts were so significant that each drop of the lake level reached up to 40-60 m. 4 Effects of climate changes on paleolake level fluctuations 4.1 Features of the lacustrine sediment in chemical content Hongshan Tableland is a low lacustrine terrace adjacent to the north of Zhangbi Tableland in Taiyuan Graben. An incised gully exposes a section, which shows the features of the deposit of this terrace (Figure 3a). This section is about 16 m high with its low contact unexposed, and can be divided into three portions or into eleven layers. The upper portion consists of paleosol S1 and the later loess L1 (layers 2, 1) about 5 m thick; the lower portion is composed of a thin layer of gravels and paleosol S5 with a thickness of 1.1 m (layers 10, 11); between them is lacustrine deposit about 10 m thick. This lacustrine deposit is characterized by gray-green interbeded silt (layers 8, 6, 4) and silt containing efflorescent calcareous tufas (layers 9, 7, 5, 3) resulting from evaporation of ground water brine. The vertical interval of adjacent calcareous tufas is about 2-3 m. In the upvalley about 50 m from the section, incised gully reveals a loess/paleosol section which includes loess units L5, L4, L3, L2, L1 and paleosol units S5, S4, S3, S2, S1 (Figure 3b). Tracking these loess and paleosol stratigraphy horizontally toward the lacustrine section, we find that besides S5, S1 and L1 on both sections distributed continuously, L5, L4, L3, L2 are distributed continuously and gradually connect with the lacustrine layers 9, 7, 5, 3 respectively; S4, S3, S2, distributed continuously and gradually connect with lacustrine layers 8, 6, 4 respectively. This shows that the deposition of the lacustrine sediment occurred during the period from the end of the development of S5 to the beginning of the development of S1, and the deposition of lacustrine layers 8, 6, 4 is synchronous with the development of the paleosols S4, S3, S2 respectively, while the formation of calcareous tufas in layers 9, 7, 5, 3 is synchronous with the deposition of loess L5, L4, L3, L2 respectively. In order to obtain further evidence to prove such correspondence, we have taken four calcareous tufa samples from layers 9, 7, 5, 3 for U-series dating. Maybe contaminated by older loess and the limitation of this dating method, only three samples get their ages: layer 9, more than 500 kaBP; layer 5, 289.0±14.5 kaBP; layer 3, 160.0±8.0 kaBP. These dating results are nearly consistent with the ages of L5, L3 and L2 (Liu, 1985). 4.2 Analysis on the chemical changes of the lacustrine sediment The features of Hongshan sections indicate that the site of the sections was located near the strandline of the paleolake. According to the above discussion, there occurred tectonic uplifts when S5 and S1 began to develop. During the interval between the two tectonic uplifts, the highstand lake level made the lacustrine sediment in Hongshan section deposit and meanwhile loess/paleosol units L5, S4, L4, S3, L3, S2 and L2 also formed subsequently on the land. Owing to the weak tectonic movement, the climatic changes became the main factor to control the fluctuations of the paleolake level and caused the changes of the features of lacustrine sediments. During the period when paleosol formed, the paleoclimate was very warm and wet, and intensive precipitation caused abundant runoff to the paleolake resulting in a high lake level. Under such circumstance, the site of the section was submerged and deposited the layers of gray-green silt. During the time when loess deposited, the paleoclimate was cold and dry, and less runoff and intensive evaporation made the paleolake level drop to cause the site of the section appear above the water level, so the intensive evaporation might cause the crystallization of calcium carbonate dissolved in the ground water and formed the layers of silt containing calcareous tufas. 5 Conclusion The three paleolake regressions took place at ages of 0.76 MaBP, 0.55 MaBP and 0.13 MaBP respectively when paleosols S8, S5 and S1 began to develop respectively in the Fenhe drainage basin. The vertical extent of each regression reaches up to 40-60 m. The analysis on the factors controlling the evolution of the paleolake shows that it is the three intense tectonic uplifts that resulted in the three paleolake regressions. These tectonic uplifts may be the tectonic resp

onses to Kunlun-Huanghe Movement and Gonghe Movement occurring in the Tibetan Plateau (Cui et al., 1997), because the y took place almost at the same time. Between the interval of two tectonic uplifts, tectonic movement was very weak a nd the climate changes became the dominant control on the fluctuations of paleolake levels, resulting in the drop an d rise of the lake level about 2-3 m (Figure 4). Taking all mentioned above into consideration, we come to the conclu sion that the tectonic movement is the predominant factor controlling the evolution of the paleolakes and only when t he tectonic activity was quite stable did the climate changes show their effects on the fluctuations of paleolake lev els in the Fenhe drainage basin during middle-late Quaternary.

关键词： lake regression; loess/paleosol series; tectonic movement; climate change; Fenhe basin

