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Loess Landform Inheritance: Modeling and Discovery

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Li-Yang Xiong
School of Geography
Nanjing Normal University
Nanjing, China

Guo-An Tang
School of Geography
Nanjing Normal University
Nanjing, China

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Foreword

The loess landforms in the Loess Plateau of China are famous for their thick loess deposits, various landscape types, serious soil erosion, and unique geomorphology formed by human–nature interaction under the background of globe change during the Cenozoic period. Therefore, the Loess Plateau is hailed as one of the most valuable geographical areas for earth science research of the world, and it is also regarded as the important stage for Chinese earth science researchers to make world-leading research achievements.

The modern loess landforms, with complex and diverse landscape as well as specific spatial distribution pattern, were formed after more than two million years of loess deposition and sculptured by forces of water and wind erosion. However, these loess landforms were also formed and developed on the basis of inheritance of the underlying paleotopography. The morphology and distribution of such paleotopography profoundly affect the combination and spatial distribution of the modern loess landforms. Hence, the study of loess landform inheritance is critical toward understanding the formation mechanisms and development stages of the Loess Plateau and loess landforms. However, studies on loess landform inheritance have introduced controversial viewpoints on several issues, such as the formation mechanism, influence degree, and spatial difference. Given the limitations in data sources and research methods, current studies on loess landform inheritance are stuck in the stage of qualitative description or semiquantitative analysis. We still cannot reconstruct a model of loess underlying paleotopography in the regional scale, reveal the depositional characteristics of loess dusts on the original terrain surface, investigate the controlling effects of loess underlying paleotopography on the modern erosion process, and explain the regional difference and scale variation of loess landform inheritance. Solving these issues is of great significance in improving the present understanding of the formation mechanism of loess landform.

From a new perspective of modern geographical information science and based on GIS digital terrain analysis method, the authors re-examine and interpret the basic theoretical problem of loess landform inheritance in this research and make a breakthrough in this field. In this monograph, the conceptual model of loess landform inheritance is systematically elaborated first. Then, on a basis of multiple data sources, this research reconstructs the loess underlying paleotopography in three different scales. In addition, a dual-layer terrain model of the modern and underlying terrains is built. This model reveals the loess landform inheritance characteristics from the perspectives of elevation statistical distribution, terrain profile morphology, and terrain derivative variation. This research also explores the spatial variations and scale effects of loess landform inheritance to further understand the loess landform formation process and its spatial variation patterns. This research presents an interesting exploration and discussion of a popular and important geoproblem by using DEM data and by applying the GIS spatial analysis method.

In recent years, the research team of digital terrain analysis, leading by Prof. Dr. Guo-An Tang in Nanjing Normal University, has made many achievements of landform formation mechanism in the Loess Plateau by using GIS spatial analysis method. This monograph has clear academic thinking and novel research methods. In addition, this monograph is full of systematicness and logicality, sufficient argumentation, simple narration, fluent writing, and exquisite illustrations. I believe that readers will certainly get new useful theories and methods of analyzing problems. Here, I would like to congratulate the publication of this monograph and solemnly recommend it to a wide range of readers, and I believe that it will be welcomed and beneficial to their work.

Xi’an, China
January 2019

Guo-Wei Zhang
Academician of Chinese Academy of Sciences

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Contents

About the Authors

Dr. Li-Yang Xiong is Associate Professor at the School of Geography, Nanjing Normal University (NNU), China. He is currently responsible for managing NNU's research in digital terrain model and digital terrain analysis. His main research interests include loess terrain feature characterization, landform evolution modeling, paleotopography reconstruction, and geomorphological process mining. He obtained his Ph.D. degree in cartography and geographical information system at the School of Geography Science, Nanjing Normal University (NNU), China, and has previously worked at University of Wisconsin–Madison (UWM) as Postdoctoral Research Fellow.

Dr. Guo-An Tang is Professor at the School of Geography, Nanjing Normal University (NNU), China. He is Director of the key laboratory of geographical information science of Jiangsu Province. He is currently responsible for managing NNU's research in geographical information science (GIS). His main research interests include loess landform classification, GIS spatial analysis, geomorphometry, and GIS education. He obtained his Ph.D. degree in geographical information science at University of Salzburg, Austria.

Abstract

Loess landform inheritance refers to the controlling effects of pre-Quaternary paleotopography on the deposition, erosion, and accumulation of loess dusts. The key point of loess landform inheritance research is to investigate the scientific issue of how the modern loess landform morphology was inherited from the pre-Quaternary paleotopography in the Loess Plateau of China. The research of modeling and discovering loess landform inheritance can also help understand the geological environment and formation history of the loess dust deposition process, which can be used to predict the tendency and pattern of the loess landform evolutionary process in the foreseeable future. In this monograph, from a new perspective of geographical information science and based on GIS digital terrain analysis method, we re-examine the basic theoretical problem of loess landform inheritance. In Chap. 1, we discuss the significance of modeling and discovering loess landform inheritance. In Chap. 2, we introduce the basic geographical background and research materials of the severe soil erosion area in the Loess Plateau. In Chap. 3, we systematically elaborate the conceptual model of loess landform inheritance. In Chap. 4, on a basis of multiple data sources, we reconstruct the loess underlying paleotopography in three different scales. In addition, a dual-layer terrain model of the modern and underlying terrains is built. In Chap. 5, with the dual-layer terrain model, we reveal the loess landform inheritance characteristics from the perspectives of elevation statistical distribution, terrain profile morphology, and terrain derivative variation. In Chap. 6, we also explore the spatial variations and scale effects of loess landform inheritance to further understand the loess landform formation process and its spatial variation patterns. And in Chap. 7, we analyze and summarize the proposed method and the experimental results of this monograph. The limitations of this monograph will also be examined to help identify the next steps for loess landform inheritance or loess landform research. Accordingly, this study should be an exploration and practice of geoscientific problem solving by using national basic geographical data, other related measured data, and the GIS spatial analysis method.

Chapter 1
Significance of Loess Landform Inheritance

Abstract This chapter discusses the significance of modeling and examining loess landform inheritance. The feasibility of considering inheritance as the entry point of loess landform research will also be investigated. The major research contents, objectives, and significance of this monograph will be discussed and proposed.

Keywords Loess deposition · Loess landform inheritance · Loess underlying paleo topography

1.1 Introduction of the Scientific Problem

The Loess Plateau of China is regarded as one of the most valuable geographical areas for geoscience research in the world. The loess landforms in this plateau were formed after more than two million years of loess deposition and were sculpted by forces of water and wind erosion. These landforms have a complex and diverse landscape and a unique spatial distribution pattern. However, the loess landforms were also developed based on the underlying paleotopography; the morphology and distribution of such paleotopography profoundly influence the combination and spatial distribution of modern loess landforms. Therefore, the characteristics of the paleotopography underlying these landforms, especially the controlling effect of paleotopography on the modern loess landform evolutionary process (i.e., loess landform inheritance), should be examined to understand the formation mechanisms and developmental stages of the Loess Plateau and loess landforms. As academician, Liu Dongsheng once pointed out, "the morphological sequences of loess landforms should have a time-period sequences as the existing depositional sequences of loess landform have" (Liu et al. 2001a). Investigating loess landform inheritance is also necessary to understand the morphological sequences corresponding to the time-period sequences of loess landforms.

From the philosophical perspective, inheritance refers to the connected or inherited relationships among things before and after their development. The early status of a thing should serve as the foundation of its later development, while its later development is preconditioned by its early status (from the positive or negative aspects).

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In geomorphology research, inheritance refers to landform inheritance, which in turn refers to the inherited relationship of different landform morphologies in a certain area during the evolutionary process (Liu 1965). This inherited relationship is expressed by the reliant or dependent effect of the early stage of surface morphology on the later stage of surface morphology. **Loess landform inheritance** represents the controlling effects of pre-Quaternary paleotopography on the deposition, erosion, and accumulation of loess dusts. The key point of loess landform inheritance research is to investigate the scientific issue of how the modern loess landform morphology was inherited from the pre-Quaternary paleotopography in the Loess Plateau of China.

Geoscience research has confirmed the profound environmental effects of the Loess Plateau and loess landform formations (Liu et al. 2001a). During the Quaternary period, under the environmental influence of the Tibetan Plateau uplift and the East Asian monsoon climate, the loess dusts from the arid desert region of Central Asia have been gradually deposited in three typical Cenozoic tectonic regions in the Loess Plateau, namely the tectonic stable Ordos platform in the center, the LongXi Basin in the west divided by the Liupan Mountains, and the Fenwei Cenozoic rift valley in the southeast. The most typical loess landforms (i.e., loess tableland, loess ridge, and loess hill) are located in the Ordos platform, which is considered the main body of the Loess Plateau (Yuan et al. 2012). The Ordos platform is also selected as the study area for examining loess landform inheritance in this monograph. However, many geomorphological questions need to be clarified due to the complexity of the loess landform inheritance in this area, such as

- What are the scientific meanings of loess underlying paleotopography and loess landform inheritance?
- How many types of loess underlying paleotopography exist and what are their surface morphologies?
- What are the basic geomorphological characteristics of loess landform inheritance?
- What are the controlling and restricting effects of loess underlying paleotopography on the development of the modern loess landform?
- How are loess dusts deposited on the original surface and how does the loess landform evolve under the controlling effect of loess underlying paleotopography, which serves as the basis for erosion?

To address these questions, scholars have conducted several in-depth research and exploration works and achieved much progress. As early as 1907, Willis et al. adopted Davis's theory of geomorphic cycle (Davis 1899) in loess research to understand the loess landform formation mechanism. They believed that the loess landforms are formed along with the erosional cycle of the loess tableland to the loess ridge and then to the loess hill. However, several other scholars have also gradually understood the controlling effect of the loess underlying paleotopography on the development of the modern loess landform in China and have descriptively investigated the characteristics of loess underlying paleotopography and loess landform inheritance (Liu 1966, 1985; Gan 1989). In addition, limited sampling points of several outcrops and few geological drillings were used to reconstruct the corresponding loess underlying paleotopography or paleotopographic profiles, which were subsequently used to investigate the characteristics of loess landform inheritance (Bureau of Shaanxi Geology and Mining 1986; Guo 2002; Sang et al. 2007; Cheng et al. 2010). Other scholars have adopted qualitative and semiquantitative methods to describe the erosional and developmental stages of loess landforms (Li et al. 1990; Li and Lu 2010; Lu 1991; Jin et al. 1992; Jing et al. 1997; Cheng et al. 2010; He et al. 1988, 1999; Luo et al. 1956; Chen et al. 1956, 1983; Yan et al. 2004; Liu et al. 1990). With the advancement of geomorphological theories and methodologies, the present understanding of the landform formation process has improved. The controlling effects of the original terrain surface on the landform evolutionary process have attracted increasing attention from geomorphological researchers, and different methods have been used to simulate the landform evolutionary process by considering the effects of the original terrain surface (Willgoose et al. 1991; Tucker and Slingerland 1994; Braun and Sambridge 1997; Coulthard et al. 2000; Tucker et al. 2000; Maniatis et al. 2009; Perron et al. 2009; Willett et al. 2014; Braun et al. 2014). These studies have inspired us to comprehensively examine landform inheritance based on the original paleotopographic surface.

However, given the limitations in data sources and research methods, current studies on loess landform inheritance (especially the inheritance of the typical loess landforms of tablelands, loess ridges, and loess hills in the Ordos platform) are stuck in the qualitative description or semiquantitative analysis stage by using several field-investigated terrain profiles. In addition, studies on loess landform inheritance have introduced controversial viewpoints on several issues, such as the formation mechanism, influence degree, and spatial difference (Liu 1985; Gan 1989; Deng et al. 2001; Guo 2002; Qiao et al. 2006; Sang et al. 2007; Yuan et al. 2007; Cheng et al. 2010). These issues can be summarized as follows: (1) from the perspective of **theory**, we still lack a systematic understanding of the scientific problems related to loess landform inheritance; (2) from the perspective of **methodology**, we still cannot reconstruct a model of loess underlying paleotopography with different scales, especially in the regional scale; and (3) from the perspective of **analysis**, we still cannot effectively reveal the depositional characteristics of loess dusts on the original terrain surface, the controlling effects of loess underlying paleotopography on the modern erosional process, and the regional difference and scale variation in loess landform inheritance. Solving these issues is of great significance in improving the present understanding of the formation mechanism, the degree of influence, and the spatial differences in loess landform inheritance. To understand these issues, we must

- **clarify** the basic characteristics, influential factors, analysis preconditions, and geographical meanings of loess underlying paleotopography and loess landform inheritance;
- **know** the structural features, hierarchical features, and regional differences in loess landform inheritance under the dual-layer terrain model of the modern terrain and underlying terrain;
- **propose** the reconstruction idea of the loess underlying paleotopography and the method for expressing loess landform inheritance under the dual-layer terrain model;

- **clarify** the controlling effect of loess underlying paleotopography on modern loess landform evolution; that is, how does the geological environment and formation history of loess deposition shape the morphology of modern loess landforms; and
- **solve** the restricting effect of bedrocks on modern erosional gully evolution, depositional thickness and erosion volume of loess sediments, and evolution tendency of loess landform and loess gully.

With the development of the digital elevation model (DEM) and DEM-based digital terrain analysis (DTA), new ideas and methods have been proposed to quantitatively express the surface morphology and analyze geomorphological features in the geographical information science (GIS) platform. In recent years, our research team has demonstrated fruitful achievements in their study of loess landforms by using DEMs. Many theories and methodologies have also been proposed, and significant progress has been achieved (Tang et al. 2015), especially in topographic information TUPU, a geomorphological pattern recognition method based on topographic features, and multi-scale terrain analysis. These studies have profoundly improved our understanding of the spatial variations in loess landforms. However, DEMs are always or exclusively used to express surface morphology, and the current DEM-based studies on loess landforms have mainly concentrated on revealing the geomorphological mechanism and process based on surface morphology. These studies have obtained significant findings regarding the spatial variation in loess landforms. However, despite originating from the geomorphological mechanism, surface morphology does not determine such mechanism. Given that surface morphology should be representative of the geomorphological mechanism, the previous DEM-based studies on loess landforms have failed to explore the formation of loess landforms from the perspective of their inner original mechanisms, thereby limiting the present understanding of the features and inner mechanisms of loess landforms. If loess strata materials with time sequences can be acquired and if the DEM of pre-Quaternary loess underlying paleotopography can be reconstructed, then a dual-layer terrain model that contains the terrain models of the underlying surface and modern surface can be built. With this dual-layer terrain model, many GIS spatial analysis methods, such as spatial overlay analysis, can be used to explore the scientific issues related to loess landform inheritance during the loess landform evolutionary process. Theoretical breakthroughs and methodological innovations in loess landform research can then be expected from this study.

GIS not only effectively organizes spatial geometry information but also reveals the corresponding spatial attribute information, such as geological, geomorphological, geophysical, and geochemistry attributes, as well as all types of geographical information TUPU. The loess landform formation processes dominated by erosion or deposition have been largely represented by geological, geophysical, and geochemistry attributes in this area. Therefore, studies on loess landform inheritance must organize these attributes scientifically, utilize them effectively, and express them precisely. The 3D modeling of underground in DTA research can provide an opportunity to explore the loess underlying paleotopography and the loess landform inheritance from the perspective of the time sequence and process mechanism. In this way, loess landform research can be a true space-time integration research that passes the era of "space-for-time substitution" research on loess landforms.

With the help of the National Natural Science Foundation of China, the authors have achieved some initial progress in landform inheritance research by reorganizing multiple data sources and extending DTA methods (Xiong et al. 2014a, b), such as reconstructing the loess underlying paleotopography in the macroscale and dual-layer terrain analysis. Based on such advancements, this monograph systematically analyzes the basic concepts, characteristics, geographical meaning, and influential factors of loess landform inheritance. Afterward, based on multiple data sources such as DEMs, geological maps, drillings, and geophysical detecting profiles, three different scales of DEMs of pre-Quaternary paleotopography before the loess depositional process will be reconstructed via GIS digital terrain analysis and mathematical statistics. By using the paleotopographic terrain model, the dual-layer terrain model can be built together with the modern terrain model. The loess landform inheritance is eventually investigated by using the dual-layer terrain model and quantitative indexes. The spatial coupling relationship between the modern terrain and the underlying paleotopography can be further analyzed, and the controlling effect of the underlying terrain on the modern terrain can be revealed. With all these results, a novel understanding of the loess landform evolution process can be achieved under both the controlling effect of paleotopography and the deposition process of loess dusts.

1.2 Research Significance

The research significance of modeling and discovering loess landform inheritance is outlined as follows. First, the scientific implications, intrinsic properties, and methods for expressing loess underlying paleotopography and loess landform inheritance are important in examining the loess landform formation mechanism. From this perspective, research on loess landform inheritance should not only focus on the syntagmatic relations among different loess strata but also reveal the inherited relationship of modern landforms based on the underlying paleotopography. This study can also help understand the geological environment and formation history of the loess dust deposition process, which can be used to predict the tendency and pattern of the loess landform evolutionary process in the foreseeable future.

Second, this study proposes a new theory and method for exploring DTA from the entry point of loess underlying paleotopography and landform inheritance. The loess underlying paleotopography is a loess-covered stratum that cannot be easily recognized and reconstructed by using the currently available DTA methods. Meanwhile, loess landform inheritance is a loess landform formation process under the controlling effect of original paleotopography, which in turn proposes a geoscientific problem solution with a dual-layer terrain model. Therefore, investigating these two aspects requires a more practical DTA method. Accordingly, this study should be an exploration and practice of geoscientific problem solving by using national basic geographic data, other related measured data, and the GIS spatial analysis method.

1.3 Literature Review

This section summarizes the previous studies from three main aspects, namely landform inheritance and landform evolution, loess landform inheritance and loess landform-related studies, and DEM-based digital elevation analysis. The problems that can be further advanced in the current research are then discussed.

1.3.1 Studies on Landform Inheritance

Previous studies on landform inheritance have focused on seven topics, including the inheritance of sedimentary landform under the controlling influence of the underlying terrain, the reconstruction of the underlying terrain and its controlling effect on the subsequent landform evolution, the inheritance of the deposition process of submarine landforms, the landform inheritance of river formation, the landform inheritance under neotectonic activity, the inheritance of the karst landform formation process, and the geological hazards caused by landform inheritance (i.e., earthquakes and landslides).

Specifically, the majority of the studies on landform inheritance have focused on the landform inheritance driven by the deposition process. According to Zhou et al. (2012), climbing dunes show a significant inherited relationship to floodplains and terrace dunes near the Yarlung Zangbo River in the aspects of provenance and formation. Cui et al. (2009) proposed that in the proluvial area and depressed multistage terrace of the western Sichuan Province, the Pleistocene gravel layers not only show a close relationship with spatial location but also inherit sedimentary characteristics and formation ages. Xie (2009) suggested that the Quaternary Sebei group in the southern area of the Qaidam Basin is a typical lacustrine deposit under a landform inheritance environment formed on a concave basin. Li et al. (2004) found that the underlying synsedimentary fault in the Yuzhou coalfield profoundly controls the formation of coal (i.e., thickness, lithofacies, and coal-bearing property). Li et al. (2008a) revealed that the distribution of the deposited sandstone, which belongs to the Triassic series Xujiahe Formation in the southwestern Sichuan Province, has both the characteristics of landform inheritance and spatial difference. This sandstone transfers as the main provenance changes, while its development is mainly controlled by geological structure, provenance supply, and paleo-landform. Tan et al. (2009) argued that in the sedimentary period, the combined factors of underlying paleo-landform, water depth, seawater turbulence degree, and relative sea-level change control the development and distribution of carbonate platform beaches in the epicontinental sea.

With the advancements in surface simulation techniques, some scholars have attempted to reconstruct the underlying paleo-landform or erosion basis to examine the inheritance characteristics of the landform formation process. Wu et al. (2013) established the lower Cretaceous stratigraphic sequences of the Songliao Basin by referring to multiple geological data on outcrop samplings, drillings, logging while drilling, earthquake prospecting, and ancient extinct life. They found that the geomorphological process of the study area was in the stage of basin rapid rifting. The underlying paleo-landforms appear gentle, and the significant inheritance characteristics of sequence evolution in the longitudinal direction show the same depositional pattern. Xian et al. (2007) found that the glutenite body in the steep slope of the faulted basin is characterized by belts in the plane, stages in the vertical direction, continual retrocede, and strong inheritance. Xu et al. (2005) found that the evolution of sedimentary paleotopography in the west depression of Liaoning Province is influenced by the conversion of the structural plane, strike-slip structure, underlying paleo-landform, and paleo-climate. In addition, the restriction effect on the sedimentation of the lake basin is not isolated yet comprehensive. Jia et al. (2013a) found that the temporal and spatial differences in the underlying paleo-landform control the sedimentation of red layers in the western Dongying depression.

By studying the inheritance of the submarine landform deposition process, Song (2005) summarized the geomorphic genesis and evolution of the continental shelf in the East China Sea since the Miocene period and found that the evolution of the submarine landform and the formation of continental landform have a transitional and inherited relationship. Liu et al. (2006) pointed out that the deepwater sediment deposition process in the northern continental slope of the South China Sea has an obvious inheritance characteristic. The overall sedimentary background is basically reflected in the development characteristics of modern submarine canyons. The deepwater sediments since the 13.8 Ma in the Baiyun depression are slightly affected by the relative changes in sea level and are controlled by the underlying paleo-landforms. A significant inheritance relationship can also be observed in the underlying topography, which appears to be very similar to the modern sedimentary landform.

Recent studies on landform evolution modeling have mostly taken into account the original paleotopography. Specifically, Braun et al. (2014) published a paper in Nature Geoscience about the controlling effects of rock density on topographic relief, which quantitatively expresses the controlling effect of the underlying paleotopography on the formation of the sedimentary landform, and their findings reveal the landform inheritance. Some other scholars have also examined the geomorphological evolution process under the controlling effects of the original basement terrain by using different methods (Willgoose et al. 1991; Braun and Sambridge 1997; Tucker et al. 2000; Coulthard et al. 2000; Maniatis et al. 2009; Perron et al. 2009; Willett et al. 2014).

Among studies on river formation inheritance, Wu et al. (2006a) found that the evolution of the Pearl River Delta largely originates from its inherited geological and geomorphological structures. Many bedrock islands scattered across the ancient Pearl River Bay are among the significant factors that influence the long-term evolution of the Pearl River Delta. Zhang and Wang (1997) found that the developed main channel in the northwestern Pearl River Delta shows high lateral stability and vertical inheritance and has formed a thick sand body. Lu et al. (2000) found that the developmental process of the lower reaches of the Yellow River mainly shows an inherited relationship in its bedrock concave part because other human factors can hardly change the long-term evolution tendency of the river. Luo et al. (2003) revealed that the formation process of Da'an ancient river channel is dominated by a large-scale inherited and slow deposition process during the Quaternary crustal movement. Liu (2011) pointed out that the geographical attributes, such as sedimentation, river bottom, erosion force, and storm flood, of the lower reaches of the Yellow River have an inherited evolution process since the Holocene period.

Among studies on landform inheritance under neotectonic activity, Wu (2006) found that the evolution of tectonization in the western China plate is characterized by landform inheritance. Guo et al. (2009a) revealed an inherited paleo-uplift process in the southern part of the East Qinling–Dabie Mountains. This process controls the paleo-geomorphological features of high in north and low in south of the Middle Yangtze region during this period, respectively. Jia et al. (2013b) revealed that the formation of the ancient plate margin in the basin–mountain structure of the Qinghai–Tibet Plateau was inherited from the foreland basin group. On a basis of the discussion of the terrain and geology of Beita Mountain, Qiao (1988) concluded that the new tectonic movement in this region has an obvious inheritance characteristic that plays a decisive role in landform formation and development. Dang (1997) found that the surface morphology of the underlying basement in the eastern China oilfield builds a strong internal relationship between the underground structure and landforms.

Among studies on the inheritance of the karst landform, Williams et al. (1990) revealed that the surface morphology of the karst landform is a dynamic factor that not only reflects the previous landform processes but also influences the modern erosion process and the future landform formation. Erosion stage and climatic background are two factors related to landform inheritance. Other studies show that the neotectonic movement determines the stage and inheritance of karst landform formation and is the primary driver of the formation and development of some special karst landforms in the southern part of Xishan, Beijing (Zhang et al. 1995; Weng et al. 1995).

Among studies on geological disasters caused by landform inheritance, Zhou et al. (1992) argued that the inheritance of the fault zone in the northern margin of the Laohu Mountain is directly caused by the 1888 Jingtai earthquake. Xiao et al. (2012) found that the law of landslide activity is mainly manifested as inheritance, concealment, suddenness, and difference. Based on the historical records of landslides, geomorphological conditions, and residual traces of ancient landslide activities, Luo (1987) found that the Xintan landslide is a resurrection-inherited push-type stacked landslide with the characteristics of collapse loading, impact instability, and ancient multi-periods. Ma et al. (1995) focused on the vertical zoning, regional, seasonal, periodic, inherited, and symbiotic characteristics of the gravitational geological action of the slope in the Longnan Mountain and revealed the activity law of the gravitational geological action of the slope.

1.3.2 Studies on Landform Evolution

Among the previous studies on the development and evolution of landforms, Davis (1899) divided the landform evolution process into three main stages, namely the young, metaphase, and old stages. He found a circulation pattern in these three stages, and his understanding of the landform evolution process greatly influenced the current research on the loess formation mechanism. Based on Davis's theory, Willis (1903) proposed the application of physiographic stages to divide the landform evolution stages into different regions. Strahler (1952) proposed a geomorphological index (i.e., hypsometric integral curve) to quantify the landform development pattern of Davis's theory. The hypsometric integral value calculated from the hypsometric integral curve was used to measure three landform evolution stages, that is, the young (hypsometric integral value greater than 0.6), metaphase (hypsometric integral value greater than 0.35 and less than 0.6), and old stages (hypsometric integral value less than 0.35). This quantification method has also been widely accepted and used in subsequent studies (Lu 1991; Guan and Gao 2002; Zhang and Ma 1998; Zhu et al. 2013).

With the development of geochemical dating methods, several scholars have attempted to reveal the landform formation processes and mechanisms based on the age of the exposed rock (Chen et al. 1988; Chen et al. 2011) and the indication of minerals (Liu et al. 2007; Deng and Li 2012). Some other geochemical dating methods, such as the thermal age method (Hu and Pan 2008), EOF analysis method (Xia et al. 2009), and cosmogenic nuclides (Zhao et al. 2013), are used to trace the landform and environment development process. However, most scholars still start from the perspective of landform formation and check for the inner relationship between the geomorphological features and landform evolution by fully recognizing and excavating the connotation of geomorphological features (Hu et al. 2008; Li 2003; Liu et al. 1996; Sun et al. 2006; Qiu and Lu 2013; Wu 2008; Wu et al. 2002; Zhao et al. 2011; Zhang et al. 2011a; Chen et al. 2008). Based on the relationship between the geomorphological features and landform evolution, some scholars have examined the natural geological disasters caused by the development and evolution of landforms, such as landslides and debris flow (Feng et al. 2004; Su et al. 2011), earthquakes (Liu et al. 2013; Zhang 2008), and soil erosion (Ma 1996; Sun et al. 2005; Zhu et al. 1999; Liang et al. 2004; Cui et al. 2008). Other scholars have also examined the impact of human activities on the evolution of landforms (Du et al. 2012; Gao et al. 2008; Shi and Peng 2005; Wang et al. 2006a; Xu and Ai 1989).

Among the typical landforms in China, the Qinghai–Tibet Plateau is known worldwide for its unique geographical location and is even regarded as "the roof of the world." The landform evolution studies on this specific area have focused on the formed planation surface (Feng et al. 2005; Zhang et al. 2007; Pan et al. 2002; Xiong et al. 2017a), the relationship between the Plateau and the Asian monsoon (Li 1999), the formation mechanism of the upper reaches of the Yellow River (Li et al. 1996; Zhang et al. 2003), the thermochronology method used in landform evolution (Wu et al. 2001), and the development history of the Qinghai–Tibet Plateau (Zhao et al.