J. Geogr. Sci. 2017, 27(11): 1283-1310
DOI: 10.1007/s11442-017-1436-y

Research and perspectives on geomorphology in China:
Four decades in retrospect

CHENG Weiming[1,2], LIU Qiangyi[1,3], ZHAO Shangmin[4], GAO Xiaoyu[1,3], WANG Nan[1,3]

1. State Key Laboratory of Resources and Environmental Information System, Institute of Geographic Sciences and Natural Resources Research, CAS, Beijing 100101, China;
2. Jiangsu Center for Collaborative Innovation in Geographical Information Resource Development and Application, Nanjing 210023, China;
3. University of Chinese Academy of Sciences, Beijing 100049, China;
4. Department of Surveying and Mapping, College of Mining Engineering, Taiyuan University of Technology, Taiyuan 030024, China

Abstract: Geomorphology is one of the main subdisciplines of geography. The research achievements and prospects in geomorphology have received considerable attention for a long time. In this paper, a general retrospect of geomorphologic research in China over the past 60 years was firstly addressed, especially the research progress during the last 40 years. Based on a summary of experience and a tendency of development, perspectives of geomorphologic research direction in the future were provided. It is concluded that the discipline of geomorphology has made great progress in the aspects of geomorphologic types, regionalization, as well as their subdisciplines such as dynamic geomorphology, tectonic geomorphology, climatic geomorphology, lithological geomorphology, palaeogeomorphology. We believe that persisting in the unity principle between morphological and genetic types would be conductive for the development of traditional landforms and integrated landforms. In addition, five perspectives aim to enhance China's geomorphologicl research capacity were proposed. They are: (1) strengthening the research of basic geomorphologic theory and the research of integrated geomorphology to expand the research space; (2) focusing more on the research of geomorphologic structure and geomorphologic function to improve the application ability of geomorphology; (3) constructing a comprehensive resource, environmental, and geomorphologic information system and building a sharing platform to upgrade the intelligent information industry of geomorphology; (4) putting more efforts on the research of coastal geomorphology and marine geomorphology to assist the transformation of China from a maritime country to an ocean power; and (5) cultivating talents and constructing research teams to maintain a sustainable development of China's geomorphologic research.

Keywords: retrospect; perspective; geomorphology; China

Received: 2017-04-06 **Accepted:** 2017-05-16
Foundation: Surveying and Mapping Geoinformation Nonprofit Specific Project, No.201512033; National Natural Science Foundation of China, No.41571388; Major State Basic Research Development Program of China, No.2015CB954101; Innovation Project of LREIS, No.O88RAA04YA
Author: Cheng Weiming (1973–), Professor, specialized in digital geomorphology and GIS. E-mail: chengwm@lreis.ac.cn

The discipline of geomorphology, also described as the study of landforms, focuses on the examination of morphological, genesis, distribution and evolution characteristics of the earth's surface (Zhou, 2006). Geomorphologic studies have attracted considerable attention in recent years, because the earth's surface not only supports human life, production, and survival, but also is the research subject in studies conducted on ecological environments, urban and rural land, transportation development, as well as in assessments of the quality of resources and their rational use in contemporary society. Geomorphologic research in China has evidently advanced in recent decades, demonstrating significant progress and contributing substantially to the development of construction activities, nationwide, along with urban and rural development, rational resource utilization, and ecological construction. For this study, Chinese papers relating to geomorphology that have been published from 1978 onward were compiled and analyzed to assess systematic progress within the discipline and its sub-disciplines over the last four decades. The study further aimed to assess the future development trend of geomorphologic research.

1 A retrospective look at published Chinese papers in the field of geomorphology over the last four decades

1.1 The number of published papers and the stages of development of the discipline

In the 1950s, based on key studies conducted in the field of geomorphologic science, the Natural Regionalization Work Committee of the Chinese Academy of Sciences published *Chinese Geomorphologic Regionalization* (Zhou *et al*., 1956; RZCCAS, 1959). Shen and Li have produced a comprehensive summary of the status of research in this field commencing from this time up to the 1970s (Shen, 1980; Li *et al*., 1994).

Published papers are an important measure of the development stage of a discipline and its achievements. They are also an important indicator for evaluating its dynamic development. The statistics reveal that more than 4700 Chinese papers in the field of geomorphology were published during the period 1978–2015 (Figure 1). This period can be subdivided into three development stages according to the publication dates of the papers. The first phase from 1978 to 1990 was a rapid development stage. During this phase, 1042 papers were published with an annual rate of increase of 6.5 papers. The next phase from 1991 to 2005 was a steady development stage, indicating a precipitative and ready state of the discipline. During this stage, 1497 papers were published, at an approximate annual rate of 110 papers. The final phase from 2006 up to the present has demonstrated a fast pace of development. During this stage, a total of 2161 papers were published with an annual rate of increase of 8.9 papers. Thus, by 2015, the number of published papers had reached 245.

1.2 The changing content of published papers

Academic achievements provide an important indicator of the development stage of a discipline, in addition to being a measure of its practical applicability. Geomorphology is a foundation for the development of land and national defense infrastructure, and has consequently made important contributions toward meeting China's construction requirements over the past four decades.

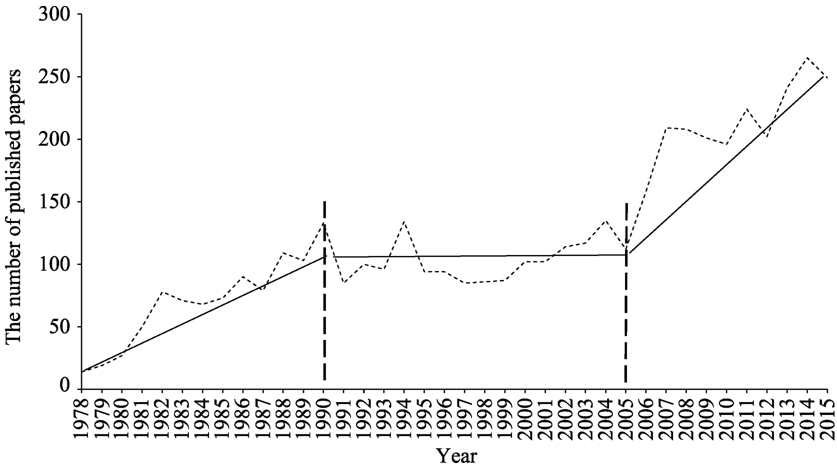

Figure 1 The number of papers published in Chinese journals about geomorphology over the past 40 years

Figure 2 shows the discipline system, research content and innovation model on geomorphology in China. Systematic geomorphology, branch geomorphology and applied geomorphology constitute the subject system of geomorphology. Moreover, other theory and new technology has been gradually introduced into geomorphology, which has gradually deepening and broadening the research fields of the geomorphology. Indicators of advances within this discipline are discussed below in detail.

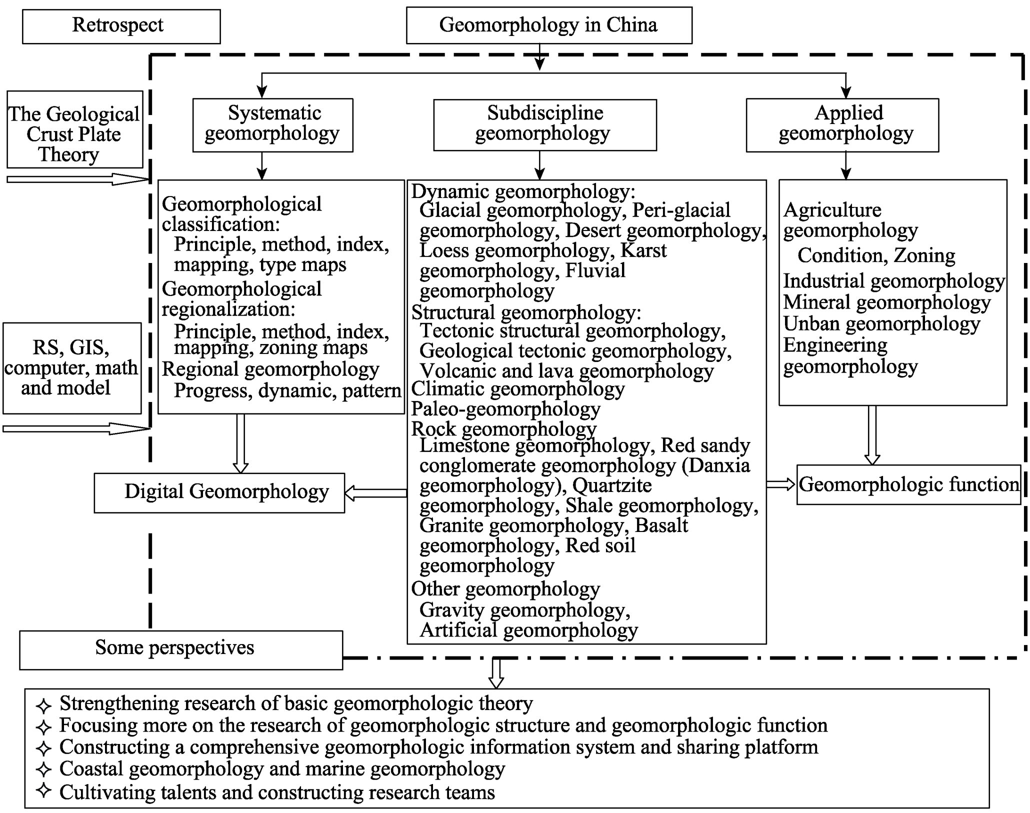

Figure 2 Retrospect on discipline system, research content and innovation model on geomorphology and some perspectives

1.2.1 Continual innovation in geomorphologic research theory and a significant elevation in its academic status

Over the past four decades, and especially from the onset of the 21st century, geomorphologic research in China has evidenced timely absorption of scientific research innovations, which have led to the advancement of theory, resulting in a significant elevation in this discipline's academic status. Four decades ago, plate and geosyncline theory, derived from geodynamics, was the main interpretive theory applied within this research field to determine geomorphologic morphogenesis mechanisms and to explain the formation and succession of plains, plateaus, and mountains. However, identifying the causal mechanism that brings these phenomena into being has proved challenging (ECCPG, 1980).

A significant breakthrough was achieved at the end of the 20th century with the development of the geological crust plate theory. Plate theory was applied in geomorphologic studies to explore the differentiation of morphogenesis aimed at deepening understanding of the functions of internal agents within this process and developing a theoretical explanation of the deep tectonic characteristics of the earth and the linkage mechanism underlying plate tectonics. This development marked a revolution in the history of geomorphologic research that was of great significance (ESDSRG, 2002).

1.2.2 Ongoing expansion of the research field and its content derived from traditional geomorphology through comprehensive research encompassing geomorphology and physical geography, thereby deepening the breadth and depth of geomorphologic theory

A number of synthetic and cross-sectional research initiatives have contributed to the advancement of geomorphology. Such studies have examined geomorphology in relation to land use, vegetation cover, hydrology, and soil classification. The significant and ongoing expansion of research content and depth is reflected in several areas. These include: studies on changes in vegetation cover in different types of geomorphologic regions (Liu *et al*., 2011), the impact of terrain on precipitation (Qian and Li, 1992), debris flow prediction based on different ecological contexts (Zhang, 2004), the distribution characteristics of organic micro-pollutants in tidal flat sediments of the Yangtze River estuary (Liu *et al*., 2002), the relationship between rocky desertification and geomorphology, and lithology, precipitation, and population density in the southwest karst area (Zhang *et al*., 2013).

Geomorphologic research has been conducted not just on the earth's surface; it has also been conducted on the moon, covering areas such as the morphology of its surface, the classification of lunar craters and their spatial distribution, and lunar evolution (Cheng *et al*., 2014). This research has even been extended to an examination of Mars to determine whether conditions for the formation of aeolian sand geomorphology are present on this planet (Li and Dong, 2016).

1.2.3 Evolution of the discipline into a full-fledged academic subject

Whether or not a disciple has evolved into a full-fledged system of knowledge is an important indicator of its maturity. Having been established as a research field for nearly half a century, geomorphology has demonstrated progress in a number of areas that indicate its evolution into an independent and mature discipline. These areas include mechanisms relating to surface morphogenesis, as well as geomorphologic classification, regionalization, application functions, and geomorphic research methods and techniques.

1) Maturity of geomorphologic classification system

There has been a long-standing dispute relating to the application of the principles of genetic and morphological classification within the discipline of geomorphology. In the 1950s, an outcome of key scientific research conducted within this field in China was published as *Chinese Geomorphologic Regionalization* (RZCCAS, 1959). Studies within this publication conducted by the Natural Zoning Work Committee of the Chinese Academy of Sciences posited the view that the genesis principle should be applied for classification and emphatically stated that the principle of morphological classification should not be used.

Based on the geological structure and new tectonic movement of China's mountainous areas, the following categories of mountains were identified: extremely high mountains, high mountains, middle mountains, low mountains, and hills and other landform types. Within smaller geomorphic units, the following land types were categorized: alluvial plains, lake plains, karst Fenglin and other land types. The division principle applied for this system of land types entailed flaws such as the lack of connection between the form and the causes and a significant lack of coordination between high-level types divided by geological structure and low-level types divided by external surface agents.

A further issue concerned the indicators used for categorization. Whereas mountains were categorized according to differences in elevation, this criterion was not used for plain regions, resulting in an imbalance of indicators. Moreover, the geomorphologic classification system was still at an exploratory and therefore evolving stage at the time. Chinese geomorphologists applied both the morphologic and genetic principles of division in their research (Zhou *et al*., 1956; RZCCAS, 1959; Shen, 1980). The article by Li *et al*. (2013) entitled "Research on geomorphologic regionalization of China" that was published is the most representative study that applied morphologic division. Using land surface morphological features, these authors categorized the land surface into seven types: plains, platforms, hills, low relief mountains, medium relief mountains, high relief mountains, and extremely high relief mountains. They then subdivided the 28 basic geomorphologic types into five levels based on the indicator of elevation. This classification system entailed the advantages associated with the innovative introduction of the indicator of relief for mountain categorization to the traditionally inherited geomorphic features.

However, it also evidenced defects relating to principles and indicators as follows. First, the influence and effect of genetic factors on morphology were not taken into account. The second issue related to the introduction of five elevation types, namely, low elevation (< 1000 m), medium elevation (1000–2000 m), high-medium elevation (2000–4000 m), high elevation (4000–6000 m) and extremely high elevation (≥6000 m) as a classificatory indicator. The addition of these five elevation types to each of the morphologic types (plains, terraces, hills, low mountains, medium mountains, and high mountains) created a complication.

In recent years, geomorphologic division applying the unity principle of morphology and genesis has gained acceptance within the academic community, and has significantly advanced geomorphologic theory and enhanced its application. Topographic and geomorphologic characteristics feature as basic research objects within several projects under China's 13th Five-Year Plan (2016–2020). These projects include a survey of China's geographical conditions, an investigation and assessment of torrential disasters in China, the study of urban mountain torrents in China and a trans-provincial investigation of the physical geographical entities relating to China's terrestrial terrain. These projects all apply the unity principle of morphology and genesis to determine geomorphologic types and to develop geomorphologic regionalization, which reflects significant progress within geomorphologic research.

2) Refinement of geomorphologic regionalization and the ongoing emergence of sub-disciplines

China's geomorphologic types are complex and diverse, exhibiting varying regional distribution patterns. Consequently, the national geomorphologic regionalization program is very different. After years of effort, the results of regionalization have gradually begun to follow the same direction. The draft document on geomorphologic regionalization developed in the 1950s was the first attempt to initiate regionalization covering all types of land areas in China (RZCCAS, 1959). Accordingly, the genesis principle was applied to divide the country's land area into 18 primary areas (large regions), 44 secondary areas (regions), and 114 tertiary zones (geomorphologic provinces). The fourth level division into districts was not completed. Complete and accurate data were compiled for the regionalization initiative, which resulted in the first broad-based monograph that synthesized the knowledge of China's geomorphologic researchers. Matched with a national geomorphologic map at a scale of 1:4,000,000, the data presented in the monograph demonstrated area attributes and relatively accurate boundary lines.

Because of the weak research foundation and the brevity of the research period, this monograph evidenced some flaws. First, regionalization units were constructed according to the tectonic genesis principle, which does not fully reflect the law of geomorphologic formation, occurrence and development in China. Second, despite that the geotectonic principle was mentioned in the description, first-level regional division did not consider China's three-level terrain pattern, which can not answer what constraints and impacts of tectonic system on China's geomorphology were, and why the redundant situation of the first-level regions that up to 18 units appeared. Third, division indicators were not specific. They generally proposed tectonic, surface morphology, and external force, but lacked specific indicators and grading of indicators. Fourth, the regionalization system was incomplete, with many third-level regionalization units remaining vacant.

This initial regionalization effort was followed by several others. One of the most representative initiatives in regionalization, entitled "Research on geomorphologic regionalization of China", was developed based on morphology (Li *et al*., 2013a). This initiative demonstrated several improvements. Using a regional combination transformation principle for geomorphologic types, it developed innovative practical research leading to geomorphologic regionalization within China. Second, it considered obvious differences between three geomorphologic ladders relating to China's land mass, which helps divide China's main land into 6 large geomorphologic regions at the first level. Subsequently 37 regions were categorized at the second level with attached maps and area values according to a combination of geomorphologic types.

In recent years, an in depth engagement with geomorphologic regionalization theory has been evident within discussions on improving and refining the discipline's practical applications. There are many projects that include geomorphologic regionalization tasks within China's 12th and 13th Five-Year Plans (2011–2020). The implementation of a combination of morphological, genesis, and service-related approaches within projects requires the adoption of a broad perspective within geomorphology. Such projects include ecological regionalization and planning, ecological evaluation and construction, geomorphologic disaster prediction and prevention, traffic line location selection, and culvert foundation stability, urban and rural flood geomorphologic analyses of urban and rural flooding, and geomorphologic functional regionalization in nature reserve areas.

Based on the needs of the special collaborative national project of the Geographic Conditions Census involving several academic institutions, the Institute of Geographic Sciences and Natural Resources Research of the Chinese Academy of Sciences created five levels of geomorphologic division at a scale of 1:250,000. This project will provide the most detailed regional categorization of China's geomorphology. The latest advances in China's geomorphologic regionalization strictly define the geomorphologic grading and index systems, grading characteristics, and applications of new technology, revealing continual improvements in the country's geomorphologic regionalization and the evolution of regionalization within branch disciplines. These advances are evident in, for example, the regionalization of China's ecological geography (Zheng, 2008), and specifically that pertaining to the comprehensive natural regionalization of the Gobi Desert (Shen and Wang, 2013; Shen *et al*., 2016).

1.2.4 Continued expansion of research teams with the capacity to conduct scientific research on a large scale

The earliest geomorphologic studies by Chinese scholars appear to be "Shandong coastal topography," conducted by Huang between 1934 and 1935 under the guidance of Weng and Ding (EGCHB, 1993), and a follow-up study by Li (1939) on "Chinese Geology" divided the country into 19 regions (GSC, 2006). Geomorphologic research began to enter the research tracking system after the establishment of a geomorphologic research laboratory by the Institute of Geography of the Chinese Academy of Sciences in 1954. Subsequently, a geomorphology major was offered by the Department of Geology and Geography at Peking University in 1956 and by the geography departments at Nanjing and Northwest Universities, and at East China Normal University, in 1958. Consequently the number of professionals trained in geomorphology began to rise substantially. Geomorphologic research laboratories were also developed by the Guangzhou Institute of Geography, the Changchun Institute of Geography, and the North China Institute of Geography of the Chinese Academy of Sciences, which conducted studies of geomorphologic issues on a large scale within China.

According to the statistics, there are dozens of geographical research institutes where geomorphologic professionals are engaged in research and teaching. There are close to 100 universities or colleges offering geography as a major, and more than 100 companies associated with geography, constituting a basic system of enterprises and production sections within the country (GSC, 2006).

Recent advances in research show that geomorphology in China has evolved into a complete disciplinary system, with a relative alignment of professional teams, an accelerated pace in the training of young talented researchers, and wider promotion of research and development reservation ability, fostering capacities to conduct big scientific research projects (Cheng *et al*., 2016a). For example, a recently completed research project on "Southwest Karst Mountain Rocky Desertification and Adaptation Ecosystem Regulation" addressed significant research problems through a comprehensive geomorphologic study. This project covered spatial and temporal patterns, changes and their driving forces, biogeochemical processes and rates of soil formation, dynamic processes relating to the water cycle and hydrological effects, and plant communities and their ecological adaptability to rocky desertification in China's southwest karst area. Incorporating a range of scientific and practical approaches, the project engaged systematically and comprehensively with scientific problems such as mechanisms, processes, the rate and ecological construction, disaster prevention, and control of rocky desertification in appropriate ways.

The countermeasures that were developed will provide important guidelines in the rehabilitation of the ecological environment in China's southwestern region. Another example of a recent project is the newly launched "China Mountain Torrent Disaster Investigation and Evaluation" Project, which is an important indicator of Chinese geomorphologic research on disaster prevention.

1.2.5 Advances in research methods and the establishment of a research system entailing new technologies

In recent years, with the rapid development of geographic information systems, remote sensing, global positioning, and other technologies, a new research methodology entailing extraction on geomorphologic characteristics has been launched using aerial photographs, satellite imagery, a digital elevation model (DEM), and other data sources. Moreover, there has been significant progress in areas such as determining the boundaries of geomorphologic types and in the acquisition and presentation of information on gradual geomorphologic changes (Chen and Zhao, 1990; Zhou *et al*., 2009a).

In particular, the development of a DEM at a scale of 1:50,000 by the national surveying and mapping departments, as well as the high-level accuracy of DEM data for the region between 60ºN and 56ºS obtained from the US Shuttle Radar Topography Mission (SRTM, http://srtm.csi.cgiar.org/) in 2000, and from ASTER GDEM data, have been notable. These developments have not only greatly facilitated the accurate extraction of geomorphologic feature data, but have also provided a sound basis for obtaining DEM data to extract typical geomorphologic features demonstrating a high-level accuracy on a large scale. In recent years, Interferometric Synthetic Aperture Radar (InSAR), Light Detection and Ranging (LiDAR), and other advanced technologies have been widely applied in the area of geological disasters. Examples of these applications include large-scale topographic surveying, fault movement monitoring, earthquake area deformation, uplift before volcanic eruptions, and deformation before landslides (Shan *et al*., 2001).

There are numerous examples of research entailing the extraction of quantitative digital geomorphologic data using DEM and remote sensing images. Geomorphologic feature segmentation, diluvial fan feature extraction, and geomorphologic mapping were conducted based on high resolution remote sensing images and highly accurate DEM data (Miliaresis and Argialas, 2000; Jordan *et al*., 2005). An overall review of DEM data modelling, uncertainty, methods of analysis, scaling effects, and high performance computing methods were addressed, moreover, the application of this methodology in digital terrain analysis (DTA), extending DTA research concepts and methods to other field models in the geosciences were discussed (Tang, 2014).

Evidently, geomorphologic remote sensing mapping has advanced as a result of the replacement of the traditional manual method of data compilation and mechanical mapping by remote sensing and GIS technology. A new technological system of remote sensing mapping has thus emerged. The *Geomorphologic Atlas of People's Republic of China* (*1:1,000,000*) is an important example of a comprehensive analysis of geomorphologic types using multi-source data such as remote sensing images (Zhou *et al.*, 2009a). This project began in 2004, with 15 existing geomorphologic maps at its disposal. These maps, including those developed for Beijing, Xi'an, and Taiyuan, created at a scale of 1:1,000,000, with a legend system and the "Mapping Criterion for Chinese 1:1,000,000 Geomorphologic Maps", were compiled and published (IG, CAS, 1987).

The Institute of Geographic Sciences and Natural Resources Research of the Chinese Academy of Sciences collaborated with other relevant national universities developed an interpretation of geomorphologic types based on remote sensing for 74 maps using standard sheets at a scale of 1:1,000,000, and designed China's first million scale digital geomorphologic classification database system based on a layered and hierarchical merging and expansion of the previous classification system to a scale of one million (ECGAPRC, 2009; Zhou *et al.*, 2009b; Zhou *et al.*, 2010). A layered and hierarchical combination classification method was adopted, combining morphology and genesis and incorporating morphology-structure data organization mode of point, lines and polygons, data support of geologic maps, old geomorphologic maps, and DEM at multi-scales. Moreover, a methodology to synthesize the interpretation to digital geomorphology based on data derived from multiple sources such as remote sensing images was applied using an appropriate technology. Thus, the compilation and publication of the *Geomorphologic Atlas of People's Republic of China* (*1:1,000,000*) and the "Remote Sensing Interpretation and Mapping for Digital Geomorphology" filled a knowledge gap, both domestically and internationally, in this field. The "Research and its Application of Digital Geomorphologic Maps for China (1:1,000,000)" Project was awarded a second prize for National Science and Technology Progress in 2009.

2 A retrospective and future projected analysis of the status of research within geomorphologic sub-disciplines

Given sustained in depth research and the requirement to expand application in the field of Chinese geomorphology, its sub-disciplines, primarily comprising dynamic geomorphology, climate geomorphology, structure geomorphology, and applied geomorphology have developed at a fast pace. Moreover, learning exchanges have occurred between geomorphology and related disciplines regarding their respective research methods. Geomorphologic sub-disciplines have evolved through the introduction of relevant principles and methods from other disciplines. Examples include river power, coastal hydrodynamics, glacial dynamics, and wind power. The specific research fields of paleoclimate and tectonic geomorphology were extended as a result of developments that occurred within other disciplines such as paleogeography and palaeoclimatology relating to sedimentary facies, sea surface changes, and neotectonic movement. Consequently, new research fields have evolved within all of these geomorphologic sub-disciplines. In addition, the development of rock geomorphology (e.g., studies on Danxia and granite) has made significant progress (You and Yang, 2013).

2.1 Dynamic geomorphologic research

Dynamic geomorphology, which focuses on the operations of external agents and the formation of geomorphologic features, encompasses glacial geomorphology, periglacial and permafrost geomorphology, aeolian geomorphology, loess geomorphology, karst geomorphology, fluvial geomorphology, and coastal and submarine geomorphology.

2.1.1 Glacial geomorphologic research

China's glacial geomorphology has mainly focused on the alpine region of the Tibetan Plateau and the high altitude belts of the Tianshan and Altai Mountains. The study of glaciers was almost non-existent prior to 1949. From the 1950s, beginning with investigations of the Yulong and Gongga mountains, the areas covered by glacial research were gradually extended to encompass the entire Tibetan Plateau and the Tianshan and Altai Mountains. The difference between glaciers in China and those at the north and south poles is mainly related to the glacial short history and the stage of glacier development (Zheng, 2000; Zhou *et al*., 2001; Cui *et al*., 2011). Chinese scholars in the field of glacial geomorphology have focused on the space, genesis, and stage of China's glacial development. A complete inventory of glaciers is currently being maintained in China, where glacial science has also attracted academic attention (Zhou *et al*., 2003; Yang *et al*., 2006; Zhao *et al*., 2011a; Liu *et al*., 2011). In recent years, glacial geomorphologic research has gradually been extended to cover the Tianshan Mountains and the Western Qinling and Pamir Mountains (Wang *et al*., 2011; Zhao *et al*., 2011b; Zhao *et al*., 2013). Several scholars have also addressed the long-standing question of whether any traces of the Quaternary glacier remain in eastern China's mountainous areas (such as Mount Lushan and the Siming Mountain in east Zhejiang). These scholars have confirmed that the associated morphology of the so-called "Quaternary glacial relics" is not in fact glacial ruins, but were mainly formed as a result of weathering, gravity, and fluvial processes (Xie and Cui, 1983; Sang *et al*., 2011).

2.1.2 Periglacial (permafrost) geomorphologic research

The distribution of periglacial (permafrost) geomorphology is extensive in areas characterized by a severely cold climate. Despite this geomorphology bears a certain relationship to glacial processes, it is also extensive in regions with no glacial process but frost action, whose ground surface is subject to a process of alternate freezing and thawing. Though Chinese researchers in the field of geomorphology have long been engaged in the study of periglacial geomorphology, preliminary research has mostly focused on information extraction on the characteristics and distribution of periglacial geomorphology (Xia, 1960; Zhu and Cui, 1992; Zhao *et al*., 2007), but rarely or no research focuses on vegetation, soil, hydrology, and micro-geomorphology in periglacial geomorphologic regions. In recent years, periglacial geomorphologic studies have focused on the Tibetan Plateau, the Qinling, Wutai, and Lesser Khingan Mountains, and the Liaodong mountainous region (Lv *et al*., 2010; Liu *et al*., 2014; Wu *et al*., 2015; Zhang *et al*., 2016; Zhu *et al*., 2016). These studies have shown that periglacial geomorphology can be further subdivided into various morphological types such as stone rivers, rock slopes, fields with boulders, stone forts, nivation hollows, *shitangs*, and jump stone ponds.

All of the abovementioned types can potentially exhibit mobility as a result of surface runoff action. The conditions for the growth of cold-tolerant plants are present in regions evidencing periglacial geomorphology, with community distribution demonstrating characteristics of differentiation. More shrubs can be found on glacial rock slopes than in fields of boulders, whereas the reverse is the case for herb species. Plant species extending from the upper part of the periglacial geomorphology to the lower part show a tendency toward transition from simple to complex communities. Moreover, soil development is also evident in periglacial geomorphologic regions, with soil formation and soil organic matter showing a tendency to increase moving from uphill to downhill areas. A further examination of these types reveals that the slopes of jump stone ponds are steeper, resulting in low stability. Consequently, stones are prone to tumble down, causing disasters. Projecting into the future, the integration of periglacial geomorphology and botany, soil science, hydrology, and other related disciplines within a comprehensive periglacial geomorphologic research system has emerged as an important future research direction for this sub-discipline.

2.1.3 Aeolian geomorphologic research

Aeolian geomorphology is formed by the effects of wind and is prevalent in arid, semi-arid, and even semi-humid areas of northwestern China. Thus, wind effects have influenced the formations, shapes, spatial combinations, and evolution of these areas (Greeley and Versen, 1985; Lancaster, 1994; Zhang and Dong, 2014). In the 1950s, the Chinese Academy of Sciences organized a comprehensive team of researchers to investigate desert areas. Subsequently, in the 1960s, the Chinese Academy of Sciences set up the Desert Research Institute. From this time onward, the depth of research as well as research institutions engaged in this field have demonstrated continuous expansion. Currently, a well-developed system is in place, covering all of the relevant research fields. In the 1950s and 1960s, the focus was mainly on desert exploration and classification, and summarizing the results of numerous experiences of sand control. From the 1960s to the 1990s, the focus shifted to sand movement law and the development dynamics and scientific control aspects of desertification.

From the 1990s, the concept of sustainable development has increasingly been integrated into desert research. Experimental stations have been widely established within every sandy stretch of desert from where in depth studies are conducted in areas such as regional climates and desert genesis and development, plants and ecological communities in sandy areas, water-saving agriculture in sandy areas, system construction of ecological shelter forests in sandy areas, characteristic resources and the sand industry, and ecological resources and desert GIS construction in sandy areas (Zhu and Zhu, 1999; Lu, 2000; Zhu and Shen, 2004). Consequently, China's desert-related research is cutting edge at the global scale. Aeolian geomorphologic research that is specific in its content and coverage of areas is also expanding, resulting in notable achievements. Examples include studies conducted on the wind system of feathery dunes in Kumtag Desert, sandy mountain formation, sandy micro-geomorphology, the hydrological dynamics of dune lakes in the Badain Jaran Desert, and wind energy research in the Gurbantunggut Desert (Yang, 2000; Guo *et al*., 2011; Shao *et al*., 2013; Cui *et al*., 2014). The development and publication of geomorphologic maps of deserts such as Tengger reveal specific spatial distribution patterns and patterns of change of China's desert geomorphology (Wen *et al*., 2014).

2.1.4 Loess geomorphologic research

China has a long history of research on loess geomorphology (mainly relating to the Loess Plateau). The definition of loess areas and the trajectory of scientific achievements in this area began in the 1950s with the institution of a comprehensive team for soil and water conservation established by the Chinese Academy of Sciences in the middle reaches of the Yellow River. The "Comprehensive management and development in the Loess Plateau" Project was subsequently initiated in the 1980s, followed by the development of a number of experimental bases for ecological construction (Liu and Zhang, 1962; SSTLPCAS, 1991). The study of loess geomorphology entails a detailed description of loess geomorphology and includes research topics such as the genesis of loess and loess and soil erosion.

Studies have shown that the formation of the Loess Plateau can be mainly attributed to sustained winds (Liu *et al*., 1985). At the end of the New Tertiary era (2.4 million years ago), China's monsoon climate began to develop, and the northwest began to experience drought and dry wind effects, with a gradual strengthening of winds emanating from a northwestern direction. Because of the Qinling Mountain barrier to the south, dust began to accumulate in the area. Extending back to the early Quaternary and middle Pleistocene eras (1.1 to 0.6 million years ago), dust accumulation reached a substantial level, with the average stacking thickness reaching 100–200 m. This led to the formation of the Loess Plateau (Xiong *et al*., 2014). Subsequently, there was a gradual increase in hydraulic erosion, with this erosion exceeding the dust accumulation, leading to the formation of loess gully landforms (Jing *et al*., 1997).

Studies of loess and soil erosion have shown that the area of soil erosion currently extends to 45.4 million km^2 in the Yellow River Basin, with an average annual erosion rate of 1.6 billion t/a, and 976 million t/a of natural erosion (Jing *et al*., 1993). Commencing from the 1990s, there have been significant advances in ecological construction, leading to a decrease in soil erosion, which has stabilized at 1.1–1.2 billion t/a (Zhang *et al*., 1994; Wang *et al*., 1992). The onset of the 21st century has witnessed a significant reduction in soil erosion as a result of the implementation of ecological construction measures such as conversion of farmland to forest and grassland. Thus, the annual level of sediment transportation has more or less been maintained at 6–7 billion t/a in the Yellow River, with the total amount of erosion being roughly 1 billion t/a in this area. Years of effort aimed at halting soil erosion have entailed experimenting with runoff control and gentle slope land and terraces that have resulted in a significant reduction of soil and water loss in China's loess geomorphologic areas (Shen and Hong, 2003; Guo and Duan, 2004; Shen *et al*., 2004).

Over the past decade, research on loess topography has advanced and been refined. For example, the use of fractal parameters to calculate the fractal dimension and stability coefficient of river networks has been found to be a feasible method for studying quantitative geomorphologic features (Cai *et al*., 2014). DEM data have been applied in studies to explore the spatial variability of vegetation cover, land use, and landslide frequency across different morphologic conditions (Yang and Bi, 2011; Yang *et al*., 2012a; Qiu *et al*., 2016). Experiments relating to geomorphologic extraction have also been conducted on the Loess Plateau (Zhang *et al*., 2012; Jiang *et al*., 2013; Xu *et al*., 2014; Zhao *et al*., 2016). A comparative study using the edge detection operator method has been conducted on the final generation of shoulder line of the valley (Yan *et al*., 2011). The regional growth method has been used to solve the problem of a large number of debris polygons in the partition of positive and negative terrains and to alleviate the slope distortion problem (Liu *et al*., 2016). Principal component analysis, based on multi-directional DEM terrain shading, slope, and other indicators, has been applied to eliminate multicollinearity and reduce dimension. Further the logistic regression model has proved effective in extracting positive and negative terrains on the Loess Plateau (Chen *et al*., 2012).

2.1.5 Karst geomorphologic research

Karst geomorphology is widely distributed in China, especially in the southwestern provinces. In the 1950s and 1960s, the study of karst geomorphology focused on the aspect of type (Zeng, 1994). In the 1970s and 1980s, further studies were conducted on the karst caves, pots, and developmental laws. From the 1990s onward, research gradually progressed to the areas of the karst water environment and regional ecological geomorphologic classification (Li *et al*., 1994; Yuan, 2015). In the last decade, in depth research on ecological restoration and construction and other issues relating to rocky desertification has been conducted, for example, to identify soil erosion characteristics and for the ecological restoration of small watersheds. Other areas covered by this research include SAR image registration and rocky desertification lithology, and land use relationships (Zhang *et al*., 2005; Zhang, 2013; Gao and Xiong, 2014; Wang *et al*., 2015; Yang *et al*., 2015). To further explore the correlation between the erosion modulus and erosion factors in karst areas, a study applying a regression model used for multi-factor equation selection of the soil erosion modulus under different slope conditions was carried out. This resulted in an improvement of the prediction accuracy of the erosion sediment yield of gentle and steep slopes (Gao *et al*., 2013b; Li *et al*., 2015a; Peng *et al*., 2016).

2.1.6 Fluvial geomorphologic research

Though China has a long research tradition relating to fluvial geomorphology, systematic studies within this field only commenced in the 1950s. During the 1950s and 1960s, studies were conducted on the valley geomorphology of several rivers, including the Yangtze, Yellow, Amur, Han, Xiang, Qin, and Brahmaputra rivers. As a result, data were obtained on river beds and types, and on the evolution law, and fluvial geomorphology was explored in more depth (Shen, 1980; Shen and Cai, 1985). Up to the 1970s, fluvial geomorphologic research extended to river source landform. A practical investigation was conducted to address an information gap relating to the sources of the Yangtze and Yellow rivers. This study definitively established that the Yangtze River originated in the Geladandong Snowberg, the main peak of the Tanggula Mountains, and that the Kariqu River was the source of the Yellow River. In the 1980s and 1990s, the study of fluvial geomorphology was broadened to include the evolution of river beds and a new classification scheme for river types and their formation was proposed (Qian, 1985).

At the beginning of the 21st century, this area of study was further broadened to cover the relationship between river bed structures and mechanisms of fluvial geomorphologic evolution, river systems, as well as river basin erosion and the mechanisms of sedimentation and river balance (Wang *et al*., 2013; Xu, 2015). To accumulate the necessary information for exploring the evolution of estuaries, a study of estuarine hydrological dynamics and sediment accumulation was also carried out in the estuary of the Yangtze River (Wang *et al*., 2011; Guo *et al*., 2013b). In commemoration of the 100th anniversary of Shen Yuchang's birth, the pioneer and founder of modern Chinese fluvial geomorphology, a review of the progress of research in this field was produced (Xu *et al*., 2016), which covered in this review included the development of water systems and the evolution of valley geomorphology, processes of erosion and sediment accumulation, as well as processes relating to river beds and river types, and research on fluvial geomorphologic systems. These studies represented cutting-edge developments in the study of fluvial geomorphology in China.

2.1.7 Coastal and submarine geomorphologic research

Coastal geomorphology research was carried out earlier in China than elsewhere in the world. In the 1950s and 1960s, a comprehensive coastline survey covering the entire length of China's coastline was carried out. Submarine geomorphology types and their genesis within important water bodies, namely the Yellow and East China Seas, were also studied, as were the seabed sediments of the East China and South China Seas, thus providing a solid foundation for coastal geomorphologic research in China (Chen, 1985). In the context of global warming, China's coastal geomorphologists predicted rises in sea levels for the period from the 1980s to 2030 based on trends of ground subsidence and sea level fluctuations in relation to the Yellow and Yangtze rivers and the Pearl River Delta, this was the first study to elucidate China's coastal estuary dynamic (Ren, 1993). During the same period, studies were conducted on the pattern of delta sediment movement and the process of its formation, evolution, coastal tidal flat types, and dynamic changes, which provided a scientific basis for activities such as port construction, estuary management, and channel improvement (CLQGSC, 1989).

In the 21st century, the relationship between the coast and the oceans has emerged as an issue of growing concern, and coastal geomorphologic research has consequently advanced considerably in China. This research has been comprehensive in its coverage, addressing areas such as coastal types, genesis and evolution, specific studies on the Bohai, Yellow, and East China Seas, and the continental shelf of South China Sea, as well as reef distribution and scale of island, hydrology and shallow sea tides, marine life and ecosystems, marine meteorology and climate, the coastline division, and coast and harbor construction. The breadth and depth of this research and the application of new methods and technologies is set to enter a rapid and comprehensive phase of development (Shen, 1980; Zhang and Wang, 2006; Wang and Ji, 2011; Li *et al*., 2013b). The latest seabed geomorphologic research and the course of its development were summarized in China (Zheng *et al*., 2012). Moreover, they projected the future direction of research on China's offshore geomorphology based on their analysis of the status of research on seabed geomorphology in China and abroad. With the continuous refinement of measurement technologies, China's submarine geomorphologic research will shift from a macro focus to a micro focus, from large geomorphology to specific geomorphologies, and from morphological characteristics to geomorphologic processes. Moreover, this research will also further examine the effects of human activities on geomorphologic processes (Zheng *et al*., 2012).

2.2 Structural geomorphologic research

Structural geomorphology, which focuses on internal regulating structural forces that are dynamic, refers to a geomorphologic form entailing certain structural characteristics shaped through the interaction of internal and external geological dynamic forces. Structural geomorphologic research encompasses the relationship between geomorphology and structure, the occurrence of structural geomorphology and the process of its development, and the internal dynamic process of the earth's structure, revealed by structural geomorphologic processes. In recent decades, research has advanced considerably in a number of related fields such as tectonic structural geomorphology, geological tectonic geomorphology, and volcanic and lava geomorphology.

2.2.1 Tectonic structural geomorphologic research

By the end of the 20th century, the geological plate theory had gained wide acceptance among geomorphologists, who hypothesized that the geosphere had a structure comprising three main layers: a core, mantle, and crust, with a warm current flowing through the mantle layer and producing a thermal convection cycle (ESDSRG, 2002). According to the theory of plate tectonics, continental plates of varying sizes are found in the rigid lithosphere of the earth's outer crust, and the contact zones between the plates are affected by the convection of the warm current within the upper mantle that can result in movements of the landmass. The rocky component of the landmass in the contact zone may fold inward through a strike effect to form a mountain. Where the ground surface is plain or comprises a plateau, the plate block is relatively stable. Relative movements of the plates can lead to their collisions with each other, or to rifts, thereby forming the earth's basic surface. In areas where plates become cracked, rifts or oceans are often formed; in areas where plates collide and extrude, trenches, islands arcs, sea rocks, and huge mountains are often formed. The formation and distribution of the earth's landmasses and oceans, the geomorphologic patterns the high mountains, and of plains and plateaus on the land, are all outcomes of movements of the crustal plates (Cui *et al*., 2001; ESDSRG, 2002).

Many Chinese scholars have done extensive research in the area of tectonic structural geomorphology to elucidate the spatial patterns of the four geomorphologic steps in China, which is located in the eastern part of the Eurasian plate (Zhou *et al*., 1956; RZCCAS, 1959; ECCPG, 1980). The southeastern part of China is adjacent to the Pacific plate, and southwestern part connects with the Indian plate. The evolution and relative movements of these three plates have led to the formation as well as the restriction of the distributional characteristics of China's geomorphology, commencing in the Mesozoic era, which also profoundly affected its formation, evolution, distribution, and regional combinations. The most representative outcome of tectonic structural geomorphic mapping is the "Geomorphologic Map for Land and Ocean of Asian and Adjacent Regions (1:8,000,000)". The mapped area covers about 35% of the earth's land surface and ocean geomorphology. The contemporary elements of the plate's geomorphologic structure are represented in a thematic map using a smaller scale, which is a reflection of the advancement of tectonic structural geomorphology mapping in recent years (Chen, 2011).

2.2.2 Geological tectonic geomorphologic research in the field of geology

In recent decades, scholars in the field of geology have produced a number of significant findings based on their tectonic geomorphologic research conducted in national tectonically active regions. Taking typical regions as examples, they have studied the relationship between stratified geomorphologic patterns and plateau uplift in the Qinghai-Tibet Plateau and surrounding regions (Pan *et al*., 2004), as well as the geomorphologic features and oxidation history in the surrounding graben regions of Ordos. These researchers have analyzed the mode, rate, historical changes, stress fields, and dynamic mechanisms of neotectonic activities and their regulatory influence on the formation and evolution of various geomorphologic types (Mo *et al*., 2016).

The key methods used in geological tectonic geomorphology are the pattern analysis method, morphological analysis, correlative sedimentation analysis, and age analysis (Wang and Wang, 2005; Shi and Du, 2006). Based on the spatial distribution and deformation of plateaus, evidenced in river terraces and piedmont alluvial fans and gullies, the history and characteristics of regional tectonic activity can be determined (Pan *et al*., 2004; Ma *et al*., 2016). In recent years, with continuous improvements in GIS and RS technologies, multi-source SRTM-DEM and ASTER-DEM data have been extensively applied in structural geomorphology. Based on drainage, topographic indexes such as terrain fluctuation, area-elevation integral, channel slope, fractal dimension, the basin shape index, basin asymmetry, and the ratio between valley width and height can be computed. These can be used to comprehensively analyze the relative stability of the regional geological structure (Gao *et al*., 2013a). Thus, structural geomorphology is expected to play an important role in the study of circle action, which also develops toward the information and quantified directions.

2.2.3 Volcanic and lava geomorphology research

China's volcanic and lava geomorphology distribution varies regionally according to geological structures, within two broad regions. The first region comprises land areas toward China's eastern border, in which hundreds of volcanic groups and cones are present, forming part of the Pacific Rim volcanic chain. The second region comprises the volcanic groups of the Qinghai-Tibet Plateau and surrounding areas. Liu (1999) conducted a systematic study of the distribution of China's volcanic geomorphology, including the history and geological characteristics of volcanic activity in China (Liu, 1999). In recent years, GIS technology has been applied to the studies of volcanic and lava geomorphology, thereby providing a supportive method for developing a detailed quantitative description of volcanic geomorphology.

2.3 Climate geomorphologic research

All geomorphologic types are continuously regulated and constrained by climatic conditions. Therefore, climatic geomorphology mainly focuses on the study of the combined characteristics of internal and external forces under different climatic conditions and the geomorphology formed as a result of this combination. The zoning and zonality of climatic geomorphology have always been key research topics within this discipline. For example, research combining mountain glacial geomorphology and climate change in relation to the Qinghai-Tibet Plateau and the alpine glacier that surrounds it has demonstrated the formation of glacial geomorphology and regional differentiation entailed in its development. The western mountain glacier of the Qinghai-Tibet Plateau formed early and glacial geomorphology was completely developed. However, the scale of the glaciers has gradually been reduced with rising temperatures commencing from the Oligocene era. The duration of the formation of the eastern mountain glacier has been shorter and at a smaller scale, and is confined to the local ridge which developed during the last Ice Age. Studies have also shown that not only has the regional climate affected glacial development; structural factors have also played a critical role (Shi *et al*., 1990; Shi *et al*., 1995; Shi *et al*., 1999; Zhang *et al*., 2013). In addition, studies have been conducted in associated fields such as frozen geomorphology and arid geomorphology.

2.4 Paleogeomorphologic research

In recent years, China has demonstrated significant research progress in several areas within the field of paleogeomorphology. The first area is geomorphologic evolution. Dynamic factors leading to geomorphologic changes have been identified, and studies have been conducted simulating the inversion of paleogeomorphology through geomorphologic evolution (Meng *et al.*, 2012; Yang *et al.*, 2012b; Lv *et al.*, 2014; Lin *et al.*, 2015). The second area in which significant progress is evident is the paleogeographic environment. For example, a study on paleogeographic restoration was conducted on the stratigraphic section for the Guangyi Building Project in Guang'anmen in Beijing. The findings of the study suggested that there was a significant correlation between morphological change that occurred 20,000 years ago with vegetative change and that evolution of the environment resulted in cooler and more arid grassland vegetation during the late Pleistocene epoch and warmer grassland and cooler meadow vegetation in this area during the Holocene epoch (Yue *et al.*, 2011). This research relating to paleomorphology and the paleoenvironment has important implications for the future.

Another example is the study of lacustrine geomorphology and sedimentary characteristics in the Fenwei graben series that confirms the existence of lakes and the occurrence of rapid subsidence and river cutting events on a large scale during the middle and late Quaternary periods. This phenomenon occurred in the Weihe Basin and extended to the Linfen-Taiyuan Basin, even reaching the Datong-Yangyuan Basin, but there were no differences in the times when these events occurred in the different basins (Hu *et al.*, 2012). The findings of paleogeomorphologic research have also been applied in exploratory oil reservoir research. The moulage and integrated geological methods, along with other methods have been applied to restore Jurassic paleomorphology in the Wangwazi and Longdong regions. The findings of an analysis of conditions under which reservoirs occurred indicated that the reservoirs were mainly distributed in a relatively high terrain near highlands, slopes, and ancient brae (Yuan *et al.*, 2013; Pang *et al.*, 2014; Wang *et al.*, 2014). The study of comprehensive model for paleogeomorphology restoration has also been carried out gradually. A recently established comprehensive geological model is being used to further explore the restoration of integrated features of paleotopography and paleogeomorphology, as well as paleoclimatic change (Lu and Guo, 2013).

2.5 Research on rock geomorphology

Studies in rock geomorphology mainly focus on the evolution and geomorphologic features of the same rock types under different natural and geographical conditions, or on all kinds of rocks under the same natural and geographical conditions. The evolution and morphological characteristics of the same rock types vary significantly under different natural and geographical conditions. For example, granite in southern China mostly presents towering shapes like mountains, whereas it appears as low hills in northern and northeastern China, and in other places. This is because different lithofacies and lithologies produce different weathering characteristics of granite in varying natural conditions entailing physical weathering in some conditions and chemical weathering in others. Common geomorphologic rock types in China are: limestone, red sandy conglomerate (Danxia), quartzite, shale, granite, basalt, loess, and red soil. Karst and loess geomorphologies have been discussed in a previous section of this paper on dynamic geomorphology. Here, the analysis of research progress will therefore focus on the geomorphologies of Danxia, granite, and rhyolite rock.

2.5.1 Geomorphologic research on Danxia

In 2010, "China Danxia" was successfully nominated as a UNESCO world natural heritage.

Given that the name Danxia has achieved worldwide recognition as a geomorphologic type, research on Danxia geomorphology conducted by Chinese scholars has correspondingly increased. In recent years, the scope and depth of basic survey data on Danxia geomorphology, supported by China's Ministry of Science and Technology, has been continuously strengthened, which has led to the successive discovery of Danxia geomorphology in Tibet and other regions. Consequently, basic data gaps relating to Danxia geomorphology in some provinces have been filled, promoting studies on topics such as Danxia geomorphology distribution, classification, zoning and natural landscapes, and dependence on cultural landscapes (Peng, 2000; Guo *et al*., 2013a; Huang *et al*., 2015). Applying a formula from Huang Jin for quantifying Danxia geomorphology, background, development, and landscape characteristics in the Kongtong Mountains were analyzed (Li *et al*., 2013c; Zhao *et al*., 2014; Qi *et al*., 2015; Zhang *et al*., 2015).

2.5.2 Geomorphologic research on granite and rhyolite

Many unique geomorphologic granite types formed under southern China's subtropical monsoon climate conditions. Their formation occurred through a tectonic process entailing different degrees of uplifting and undercutting during the late stage of the planation surface. A deep granite weathering crust was consequently created during the Pliocene and Miocene epochs. Examples of this granite geomorphology include peak and stone forests and modeling and wind stones found in the Huangshan and Sanqingshan Mountains (Cui *et al*., 2007; Chen *et al*., 2009). Studies have shown that China's granite geomorphology demonstrates the impacts of evident zonal laws within different climate zones, especially latitudinal zonality. Researchers have therefore posited that the age of granite geomorphology is closely related to the prevalence of the plane created during the Pliocene and Miocene epochs. The uplift amplitudes of different mountains can be calculated as follows: about 200 m of uplift occurred in coastal areas, gradually increasing as it moved in the direction of the hinterland, reaching approximately 1,600–2,000 m in the areas of the Nanling, Dabieshan, and Funiushan Mountains (Cui *et al*., 2007; Chen *et al*., 2009).

The most typical type of rhyolite geomorphology is mainly distributed in the area of the Yandang Mountains in the eastern part of Zhejiang Province. Studies have shown that the regional rhyolite landscape can be divided into two categories entailing six subclasses and 16 unit types. The first category is an erosion and collapse type and the second is a river valley water type. The development of valleys and rock peaks along a plane is controlled by the regional fault structure, extending mainly in three directions: northeast, northwest, and east-west. The distribution of summits, peaks, and waterfalls exhibits zonality, extending in a vertical direction, as determined by neotectonic movements and lithological differences (Hu *et al*., 2008). Such studies are of particularly importance in revealing regional geomorphologic evolution in eastern China.

2.6 Other kinds of geomorphologic research

1) Gravity geomorphology

This type of research focuses on issues related to collapse and landslides. In recent years, as a result of ecological and environmental changes in China, mountain gravity geomorphologic research has been attracting increasing attention. Examples of work in this area include mapped zones of landslide disasters and the degree of hazard of landslides. In recent years, mathematical models have been introduced within risk assessments of debris flow, which have enhanced the division method relating to debris flow risk, making it more rational and objective. Studies have evaluated the risk of landslides in regional and drainage basins using evaluation indexes of topography, stratigraphic lithology, atmospheric rainfall, and human factors, along with gray relational analysis, principal component analysis, and the fuzzy mean clustering method. These studies could provide a basis for developing comprehensive systems of governance in regional and drainage basins (Qiu *et al*., 2016; Cheng *et al*., 2016b).

2) Artificial geomorphology

Given the increasing capacity of humans to transform nature, anthropogenic activities have emerged as the third leading factor in the genesis of contemporary geomorphologic processes. Artificial geomorphology relates to geomorphologic bodies with human characteristics shaped by artificial effects and natural genesis in a natural geographical context. Li *et al*. (2015b), who proposed the concept of artificial geomorphology, classified artificial genesis and geomorphology. They analyzed artificial geomorphologic aspects such as transition, the influence mechanisms of evolution, representations through mapping, and environmental impacts, and projected future developmental directions of artificial geomorphology. The study of future artificial geomorphology requires the consolidation of the construction of the disciplinary system, material composition, and morphological characteristics. It also requires a process of spatial expansion, including deciphering its developmental law, regional differences, and the cumulative environmental effects of geomorphology, environmental management, international comparative analyses, and other relevant research (Li *et al*., 2015b).

3 Future prospects

During the last 40 years, geomorphologic research in China has made a significant contribution to the development of the discipline, as well as to social and economic development (Xu *et al*., 2009; Shi *et al*., 2010). However, China is a country with diverse landforms, and there are still many major geomorphologic issues that require further exploration, including geomorphologic formation and differentiation, ecological environmental construction, sustainable development and allocation of resources, disaster prevention and mitigation, and the construction of a geomorphologic system that safeguards sustainable social and economic development. The 21st century marks the onset of an age of significant human progress in the earth's management. Geomorphology, which focuses on the study of ground morphology, should further explore the topics described below to achieve future breakthroughs (Figure 2).

3.1 Strengthening of basic geomorphologic research and realizing the prejudgment of topographical variation by simulating the formation, cause, and evolution pattern of geomorphology

Contemporary geomorphology entails extending the ancient landform, with successive forms representing the future landform pattern. The basic research will reveal and analyze the succession rule. Currently, there are still a number of important practical problems to be resolved, globally, requiring basic research and analysis. This entails an examination of the abovementioned problems relating to the formation and differentiation of geomorphology, morphological features and the geographical landscape, the geomorphic process and the geologic structure, the structural type and the regional combination, and the systematic development of the discipline of geomorphology. Important future directions in geomorphologic research include developing a geomorphologic recognition system, simulating the process of geomorphologic formation and succession, realizing the prejudgment of topographical variation, and developing a basis for decision making and improved management in relation to geomorphology by applying modern scientific thought and existing practical information in conjunction with advanced GIS technology.

3.2 Strengthening crossover studies between geomorphology and other disciplines of geography, to expand the scope of geomorphologic research and develop an integrated geomorphologic approach

Geomorphology constitutes the basic space of human activities on the earth's surface, supporting surface fauna and flora, hydrology, soil, local climates, and land use. As long as there are morphologic changes, corresponding basic changes will also continue to occur in relation to the surface environment, resources, and human activities. Therefore, the essential direction of future geomorphologic research will be to implement multiple geomorphologic function-oriented studies, for example, on the relationship between landforms and environments, resources, disasters, human beings, tourism, and land utilization. Consequently, the scope of geomorphologic research will be extended and an integrated system of geomorphologic development will be established.

3.3 Implementation of in-depth studies on geomorphologic structures and functions, and enhancement of geomorphology's application potential

Geomorphologic types, regional combinations, and the corresponding quantity constitution and spatial permutation and combination characteristics collectively constitute geomorphologic structure. There are numerous functional aspects of morphology that interact with human activities such as land use, ecosystems, local climates, land surface hydrology, soil, tourism, transportation, urban construction, port construction, and geological disasters such as floods that are restricted and influenced by geomorphologic structures. Because all functions are restricted by the structure, structural development has emerged as an important future direction for this discipline. This entails establishing various aspects of geomorphology relating to the ecology, resources, disasters, engineering, tourism, urban development, architecture, transportation, and management. Evidently, the establishment of a theoretical system of geomorphologic structures and functions is necessary to deepen geomorphologic research and improve its practical contributions to sustainable ecological, economic, and social development at a national scale, which is certain to become a vital future development trend in geomorphology.

3.4 Consolidation of an information system relating to resources, the environment, and geomorphology and establishing an information sharing platform on resources and the environment to facilitate industrial information upgrading relating to geomorphology

It is inevitable that a powerful country like China that prioritizes geomorphology would apply advanced methods and technology such as those related to holographic research to study geomorphologic systems. As a first step for conducting this type of research, it is necessary to establish technologies for obtaining holographic information on geomorphologic bodies, including the positions of geographic coordinates, the holographic characteristics of the terrain and coated objects, and the characteristics of land use by applying remote sensing technology and geographical methods. Second, the resource environment space and quantitative databases of the geomorphologic system need to be developed to provide a multi-scale geographic database that meets different functional requirements. Next, the use of a computer recognition and analysis system enables the automatic extraction of various types of geomorphologic data for the performance of target analysis so as to achieve all-round analysis, processing, and output functions. Last, the creation of an intelligent geomorphic system with pre-research requisition capacities and comprehensive improvement of automation research capacities leads to the enhancement of the landform intelligent information industry.

3.5 Strengthening coastal and marine geomorphologic research and acquiring holographic information on coastal and marine resources and their environment to transform China from being a large country with an extensive marine environment into a marine power

China's marine environment comprises the Yellow, East China, and South China seas, as well as the continental Bohai Sea, the Beibu Gulf between China and Vietnam, and the country's coastline that covers a distance of 18,000 km. The Taiwan and Qiongzhou Straits are further components of this environment. China can therefore be considered as a country that has an extensive marine environment, with vast maritime territories and a very long coastline. Consequently, basic state policies are required to enable it to establish itself as a marine power that maintains a balance between development of its marine environment and resource utilization.

There is promising potential in the 21st century for the achievement of a major breakthrough within marine science. Geomorphologists should consider advancing marine studies, which are currently lagging behind, as their mission and undertake the following actions. They should conduct studies on offshore geomorphic types and their sedimentation characteristics to develop the essential structure and sedimentation environment of China's continental shelf. The resulting knowledge base would provide a scientific basis for protecting ocean rights and interests while enabling the development of ports. Site-specific stations should be constructed for observing geomorphology and the offshore environment. Such observations would focus on marine meteorology and hydrology, sea creatures, ocean pollution, and other relevant aspects to provide a basis for decision making relating to the protection and sustainable management of the marine environment and oceanic ecosystem.

A geomorphologic investigation and analysis of marine resources (including geomorphologic and geological environment of gas resources, types and quantities of hydrocarbon resources, gas layers, the types and distributions of mineral resources, the underwater sedimentation environment and the distribution of sedimentary mines, and differentiation and exploitation research related to ocean tidal power) should be conducted. There is also a need to conduct a preliminary assessment of geomorphologic resources and the deep sea and pelagic ocean environments. By the second half of the 21st century, marine holographic geomorphologic research should be in progress. This would cover marine geomorphology comprising mountains, plains, and trenches within the ocean and the oceanic tectonics of typical sea areas, the geomorphologic regional structure and the differentiation of ocean areas (ocean geomorphologic regionalization), and the geomorphology of oceanic environments, including the geomorphology of loop currents and differentiation of oceanic temperatures and sea creatures (animals, plants, microorganisms, and natural regionalization of the seas).

In addition, such research would cover the geomorphology of marine resources, including the geomorphologic characteristics and distribution of oil and gas fields, the types and distribution of oceanic minerals, as well as the differentiation and biomass of marine resources such as fishes, cetaceans, and shellfishes. The enormous energy potential of tidal currents is a vital resource for future utilization. This will be an important long-term research direction for marine geomorphology during the 21st century. It is conceivable that pilot tests on the energy produced by tidal currents will be conducted during this century.

3.6 Strengthening talent training and academic team building, establishing a sustainable system for developing talent training, and ensuring the gradual ascendance of geomorphologic research in China

Given that topography and geomorphology are fundamental land and carrier for the survival and development of a country, they require management by professionals deploying scientific thinking and methodologies. Based on China's development requirements, the need for professional geomorphologists, and correlatively of talent teams, will continue to increase. Thus, talent training and training to develop the research and development capacities of professional teams will constitute an important future trend in geomorphology in China.

Focusing on the cultivation of high-quality professionals is a recommendation of this study. This requires, as a first step, perfecting the recruitment system of geography departments within universities and cultivating geoscience professionals who are adept at geomorphology. Moreover, relevant courses that examine the relationships between geomorphology and environmental factors and between geomorphology and resources and the social economy should be developed and expanded. Consequently, universities would become the foundation for cultivating the talents of budding geomorphologists and developing professionals with a comprehensive geomorphology background. The cultivation of middle level and advanced expertise in geomorphology within research institutions and universities is critical to develop a sufficient cadre of graduates and postgraduates. It is important to emphasize the cultivation of practical abilities and to strengthen capacities for application when training geomorphologists. As morphology and geomorphologic features relate to the earth's surface, without investigation and practice in the field work, it would be impossible to acquire skills in classifying topographies and their formation mechanisms that would reveal the process and outcomes of the interactions between geomorphology and geographical factors. Thus, sustained and long-term professional training in the field of geomorphology should be pursued to develop and apply the practice of comprehensive geomorphology.

References

Cai Lingyan, Tang Guoan, Xiong Liyang *et al.*, 2014. An analysis on fractal characteristics of typical landform patterns in northern Shaanxi Loess Plateau on DEM. *Bulletin of Soil and Water Conservation*, 34(3): 141–144. (in Chinese)

Chen Shupeng, Zhao Shiying, 1990. Geo-Analysis of Remote Sensing. Beijing: Surveying and Mapping Press. (in Chinese)

Chen Yixin, Cui Zhijiu, Yang Jianqiang, 2009. Influence of climate and tectonic movements on granite landforms in China. *Journal of Geographical Sciences*, 19(4): 587–599.

Chen Yonggang, Tang Guoan, Zhou Yi *et al.*, 2012. The positive and negative terrain of Loess Plateau extraction based on the multi-azimuth DEM shaded relief. *Scientia Geographica Sinica*, 32(1): 105–109. (in Chinese)

Chen Zhiming, 1985. Latest advances of branch geomorphological survey and mapping in China. *Scientia Geographica Sinica*, 5(3): 259–266. (in Chinese)

Chen Zhiming, 2011. Land, Sea and Geomorphological Map to Adjacent Areas in Asia. Beijing: Surveying and Mapping Publishing House. (in Chinese)

Cheng Weiming, Liu Qiangyi, Shen Yuancun, 2016a. Research progress and effect of geomorphology based on projects supported by the National Natural Science Foundation of China. *Acta Geographica Sinica*, 71(7): 1255–1261. (in Chinese)

Cheng Weiming, Wang Jiao, Zhou Chenghu, 2014. Analysis on research progress and tendency of lunar morphological characteristics. *Geographical Research*, 33(6): 1003–1014. (in Chinese)

Cheng Weiming, Wang Nan, Zhao Min *et al.*, 2016b. Relative tectonics and debris flow hazards in the Beijing mountain area from DEM-derived geomorphic indices and drainage analysis. *Geomorphology*, 257: 134–142.

Committee of Landform and Quaternary of the Geographical Society of China (CLQGSC), 1989. Development and Evolution of China's Coast. Shanghai: Scientific & Technical Press. (in Chinese)

Cui Junwen, Li Pengwu, Li Li, 2001. Uplift of the Qinghai-Tibet Plateau: Tectonic geomorphology and lithospheric structure of the Qinghai-Tibet Plateau. *Geological Review*, 47(2): 157–163. (in Chinese)

Cui Xujia, Dong Zhibao, Lu Junfeng *et al.*, 2014. Relationship between vegetation feature and physiognomy morphology of mega-dunes in Badain Jaran Desert. *Bulletin of Soil and Water Conservation*, 34(5): 278–283. (in Chinese)

Cui Zhijiu, Chen Yixin, Zhang Wei *et al.*, 2011. Research history, glacial chronology and origins of quaternary glaciations in China. *Quaternary Sciences*, 31(5): 749–764. (in Chinese)

Cui Zhijiu, Yang Jianqiang, Chen Yixin, 2007. The type and evolution of the granite landforms in China. *Acta Geographica Sinica*, 62(7): 675–690. (in Chinese)

Earth Science Development Strategy Research Group, Earth Science Division of Chinese Academy of Sciences (ESDSRG), 2002. Earth Science: A Review and Prospect at the Turn of the Century. Jinan: Shandong Education Press. (in Chinese)

Editing Group of Collections of Huang Bingwei (EGCHB), 1993. Sixty Years of Studies on Integrated Physical Geography: Collections of Huang Bingwei. Beijing: Science Press, 491–492. (in Chinese)

Editorial Committee of Chinese Physical Geography of the Chinese Academy of Sciences (ECCPG), 1980. Physical Geography of China: Geomorphology. Beijing: Science Press. (in Chinese)

Editorial Committee of Geomorphologic Atlas of People's Republic of China (ECGAPRC), 2009. The Geomorphologic Atlas of People's Republic of China (1:1000000). Beijing: Science Press. (in Chinese)

Gao Jianfei, Xiong Kangning, 2014. Correlation of karst rock desertification and land use patterns in different geomorphologic environment. *Bulletin of Soil Water Conservation*, 34(3): 97–101. (in Chinese)

Gao M X, Zeilinger G, Xu X W *et al.*, 2013a. DEM and GIS analysis of geomorphic indices for evaluating recent uplift of the northeastern margin of the Tibetan Plateau, China. *Geomorphology*, 190: 61–72. (in Chinese)

Gao Xiang, Wang Ji, Cai Xiongfei *et al.*, 2013b. Study on soil erosion model under different slope in Southwest Karst Mountain Area. *Agricultural Science & Technology*, 41(12): 1847–1851. (in Chinese)

Geographical Society of China (GSC), 2006. Chinese Geographers and Geographical Units Directory. Beijing: Xueyuan Publishing Company: 364–516. (in Chinese)

Greeley R, Versen J, 1985. Wind as a Geological Process. Cambridge: Cambridge University Press.

Guo Fusheng, Jiang Fuwei, Jiang Yongbiao *et al.*, 2013a. The development directions of Danxia landform research. *Journal of East China Institute of Technology*, (3): 207–212. (in Chinese)

Guo Hongxu, Wang Xueqin, Jiang Jin *et al.*, 2011. Wind regime and its geomorphologic significance in the hinterland of Gurbantonggut Desert. *Arid Zone Research*, 28(4): 580–585. (in Chinese)

Guo Leicheng, He Qing, Roelvink D *et al.*, 2013b. Medium- to long-term morphodynamic modeling in estuaries and coasts: Principles and applications. *Acta Geographica Sinica*, 68(9): 1182–1196. (in Chinese)

Guo Tingfu, Duan Qiaofu, 2004. Conservation of Water and Soil Runoff Regulation Theory and Practice. Beijing: China Water & Power Press. (in Chinese)

Hu Xiaomeng, Chen Meijun, Wang Dutao *et al.*, 2012. The sequence difference in the times in the geomorphic-sedimentary evolution in the Fenwei graben basins during the middle-late Quaternary and its tectonic significance. *Quaternary Sciences*, 32(5): 849–858. (in Chinese)

Hu Xiaomeng, Xu Honggeng, Chen Meijun *et al*., 2008. The rhoyolite landforms and development law in Yangdang Mt. *Acta Geographica Sinica*, 62(3): 270–279. (in Chinese)

Huang Jin, Chen Zhijun, Qi Deli, 2015. Distribution of Danxia landform in China (Last). *Journal of Mountain Science*, 33(6): 649–673. (in Chinese)

Institute of Geography, Chinese Academy of Sciences (IG, CAS), 1987. 1:1000000 Geomorphological Mapping Specification. Beijing: Science Press. (in Chinese)

Jiang Ling, Tang Guoan, Zhao Mingwei *et al*., 2013. Extraction and analysis of loess gully heads considering geomorphological structures. *Geographical Research*, 32(11): 2153–2162. (in Chinese)

Jing Ke, Chen Yongzong, Li Fengxin, 1993. Sediment and Environment in the Huanghe River. Beijing: Science Press. (in Chinese)

Jing Ke, Lu Jinfa, Liang Jiyang *et al*., 1997. Erosion Environment Character and Change Direction in the Middle Reach of Huanghe River. Zhengzhou: Huanghe Water Conservancy Press. (in Chinese)

Jordan G, Meijninger B M L, Hinsbergrn D J J V *et al*., 2005. Extraction of morphotectonic features from DEMs: Development and applications for study areas in Hungary and NW Greece. *International Journal of Applied Earth Observation and Geoinformation*, 7(3): 163–182.

Lancaster N, 1994. Dune morphology and dynamics. In: Abrahams A D, Parsons A J. Geomorphology of Desert Environments. London: Chapman and Hall.

Li Bingyuan, Pan Baotian, Cheng Weiming *et al*., 2013a. Research on geomorphological regionalization of China. *Acta Geographica Sinica*, 68(3): 291–306. (in Chinese)

Li Fei, Yang Xiaoping, Hao Hongke, 2015a. Based on the DEM of Karst landform mountain and water system of information extraction: With Yangshuo County as an example. *Geomatics & Spatial Information Technology*, (8): 73–76. (in Chinese)

Li Jijun, Zhang Qingsong, Li Bingyuan, 1994. Main progress of geomorphology in China in the past fifteen years. *Acta Geographica Sinica*, 49(Suppl.): 641–649. (in Chinese)

Li Jialin, Yang Lei, Yang Xiaoping, 2015b. Progress in anthropogenic geomorphology. *Acta Geographica Sinica*, 70(3): 447–460. (in Chinese)

Li Jiyan, Dong Zhibao, 2016. Research progress of aeolian landforms on Mars. *Journal of Desert Research*, 36(4): 951–961. (in Chinese)

Li Mengmeng, Wang Qing, Zhang Anding *et al*., 2013b. Study on the geomorphic evolution of the muddy coast along the southern-western Laizhou Bay over the past 50 years. *Marine Science Bulletin*, 32(2): 141–151. (in Chinese)

Li Xia, He Qiongcheng, Dong Yin *et al*., 2013c. An analysis of characteristics and evolution of Danxia landform in the south of Chishui County, Guizhou. *Acta Geoscientica Sinica*, (4): 501–508. (in Chinese)

Lin Changsong, Xia Qinglong, Shi Hesheng *et al*., 2015. Geomorphological evolution, source to sink system and basin analysis. *Earth Science Frontiers*, 22(1): 9–20. (in Chinese)

Liu Dongsheng *et al*., 1985. Leoss and the Environment. Beijing: Science Press, 106–111. (in Chinese)

Liu Dongsheng, Zhang Zonghu, 1962. The loess in China. *Acta Geologica Sinica*, 41(1): 1–14. (in Chinese)

Liu Gengnian, Cheng Yixin, Zhang Mei *et al*., 2011. Glacial landform chronology and environment reconstruction of Peiku Gangri, Himalayas. *Journal of Glaciology and Geocryology*, 33(5): 959–970. (in Chinese)

Liu Jiaqi, 1999. Volcano in China. Beijing: Science Press. (in Chinese)

Liu Jiangang, Zhang Hua, Fu Jie *et al*., 2014. Periglacial landforms in the Mt. Laotudingzi of eastern Liaoning Province: Characteristics and environmental significance. *Journal of Glaciology and Geocryology*, 36(6): 1420–1429. (in Chinese)

Liu Min, Yang Yi, Xu Shiyuan *et al*., 2002. Distribution and ecological risk assessment of organic micro-pollutants in the tidal flat surface sediments of the Yangtze Estuary. In: Land Cover Change and Its Environment Effects. Beijing: Planet Map Publishing House, 251–258. (in Chinese)

Liu Wei, Li Fayuan, Xiong Liyang *et al*., 2016. Shoulder line extraction in the Loess Plateau based on region growing algorithm. *Journal of Geo-Information Science*, 18(2): 220–226. (in Chinese)

Liu Zhihong, Guo Weiling, Yang Qinke *et al*., 2011. Vegetation cover changes and their relationship with rainfall in different physiognomy type areas of Loess Plateau. *Science of Soil and Water Conservation*, 9(1): 16–23. (in Chinese)

Lu Huayu, Guo Zhengtang, 2013. Evolution of the monsoon and climate in East Asia during Late Cenozoic: A review. *Science China*: *Earth Sciences*, 43(12): 1907–1918. (in Chinese)

Lu Qi, 2000. Desertification: Urgent Challenge China Faces. Beijing: Kaiming Press, 12–20. (in Chinese)

Lv Honghua, Zhang Tianqi, Chang Yanchun *et al.*, 2014. Timing of paleotopographic and geomorphologic evolution and paleotopographic reconstruction by low-temperature thermochronologic approaches. *Marine Geology & Quaternary Geology*, 34(3): 175–183. (in Chinese)

Lv Xiuzhi, Guo Donggang, Shangguan Tieliang, 2010. Analysis of the plant community diversity in the periglacial landforms in Wutai Mountain, Shanxi Province. *Journal of Glaciology and Geocryology*, 32(3): 626–633. (in Chinese)

Ma Zhenhua, Li Xiaomiao, Guo Benhong *et al.*, 2016. Extraction and analysis of Maxianshan planation surfaces in northeastern margin of the Tibetan Plateau. *Acta Geographica Sinica*, 71(3): 400–411. (in Chinese)

Meng Kai, Shi Xuhua, Wang Erqi *et al.*, 2012. Geomorphic characteristics, spatial distribution of paleoshorelines around the Siling Co area, Central Tibetan Plateau, and the lake evolution within the plateau. *Chinese Journal of Geology*, 47(3): 730–745. (in Chinese)

Miliaresis G Ch, Argialas D, 2000. Extraction and delineation of alluvial fans from digital elevation models and landsat thematic mapper images. *Photogrammetric Engineering and Remote Sensing*, 66(9): 1093–1101.

Mo Duowen, Xia Zhengkai, Zhu Cheng, 2016. Prof. Wang Nailiang's contributions to the geomorphological research in China. *Acta Geographica Sinica*, 71(13): 2037–2048. (in Chinese)

Pan Baotian, Gao Hongshan, Li Bingyuan *et al.*, 2004. Step-like landforms and uplift of the Qinghai-Xizang Plateau. *Quaternary Sceinces*, 24(1): 50–57. (in Chinese)

Pang Jungang, Yang Youyun, Wang Guicheng *et al.*, 2014. Reconstruction of the sedimentary microfacies and paleogeomorphology in early Jurassic of Wangwazi area of Wuqi County, Ordos Basin. *Journal of Lanzhou University* (*Natural Sciences*), 50(4): 465–471. (in Chinese)

Peng Hua, 2000. A survey of the Danxia landform research in China. *Scientia Geographica Sinica*, 20(3): 203–211. (in Chinese)

Peng Xudong, Dai Quanhou, Yang Zhi *et al.*, 2016. Sediment yield of surface and underground erosion in the progress of rocky desertification of karst area. *Acta Pedologica Sinica*, 53(5): 1237–1248. (in Chinese)

Qi Deli, Chen Zhijun, Wang Suiji *et al.*, 2015. Stratigraphic classification, evolution stage and geomorphologic age of Kongtongshan Danxia landform in Pingliang, Gansu, China. *Mountain Research*, 33(4): 408–415 (in Chinese)

Qian Huaisui, Li Mingxia, 1992. Orographic influence on precipitation in transitional zone between Qinling Mountain Range and Huang-Huai Plain. *Geographical Research*, 11(3): 84–88. (in Chinese)

Qian Ning, 1985. On the classification and causes of formation of different channel patterns. *Acta Geographica Sinica*, 40(1): 1–10. (in Chinese)

Qiu Haijun, Cui Peng, Hu Sheng *et al.*, 2016. Size-frequency distribution of landslides in different landforms on the Loess Plateau of northern Shaanxi. *Earth Science*, 42(2): 343–350. (in Chinese)

Ren Mei'e, 1993. Relative sea level rise in Huanghe Changjiang and Zhujiang (Yellow, Yangtze and Pearl River) Delta over the last 30 years and predication for the next 40 years (2030). *Acta Geographica Sinica*, 48(5): 385–393. (in Chinese)

Resource Zoning Committee of Chinese Academy of Sciences (RZCCAS), 1959. Geomorphological Compartmentalization of China (The First Draft). Beijing: Science Press. (in Chinese)

Sang Guangshu, Ye Wei, Lv Huijin *et al.*, 2011. Study on landforms in the areas of the eastern part of Zhejiang Province: Discussion on Quaternary glacial remains in Zhejiang Province. *Journal of Zhejiang Normal University* (*Natural Sciences*), 34(2): 217–222. (in Chinese)

Scientific Survey Team for Loess Plateau, Chinese Academy of Sciences (SSTLPCAS), 1991. A Series of Study on the Comprehensive Development of the Loess Plateau: Natural Environment in the Loess Plateau and Its Evolution. Beijing: Science Press. (in Chinese)

Shan Xinjian, Song Xiaoyu, Liu Jiahang *et al.*, 2001. Obtaining digital elevation data in different terrain and physiognomy regions with spaceborne InSAR and its application analysis. *Chinese Science Bulletin*, 46(24): 2074–2079. (in Chinese)

Shao Tianjie, Zhao Jingbo, Dong Zhibao, 2013. Particle size composition and geomorphology zoning of the megadune in the Badain Jaran Desert. *Journal of Mountain Science*, 31(4): 434–441. (in Chinese)

Shen Yuchang, 1980. Thirty years in geomorphology in the People's Republic of China. *Acta Geographica Sinica*, 35(1): 1–13. (in Chinese)

Shen Yuchang, Cai Qiangguo, 1985. On attempt to study the progress of river geomorphology in the foreign countries. *Geographical Research*, 4(2): 79–88. (in Chinese)

Shen Yuancun, Hong Qinghua, 2003. Strategy to control soil erosion effectively in the Loess Plateau. *Science of Soil and Water Conservation*, 1(2): 22–27. (in Chinese)

Shen Yuancun, Wang Xiuhong, 2013. Eco-geographical zoning of desert and gobi in China. *Journal of Arid Land Resources and Environment*, 27(1): 1–13. (in Chinese)

Shen Yuancun, Wang Xiuhong, Cheng Weiming *et al*., 2016. Integrated physical regionalization of stony deserts in China. *Progress in Geography*, 35(1): 57–66. (in Chinese)

Shen Yuancun, Yang Qinye, Jing Ke *et al*., 2004. Strategic thinking on speeding up ecological building of soil water conservation in the Loess Plateau. *Soil and Water Conservation in China*, 21(6): 6–7. (in Chinese)

Shi Changxing, Xu Jiongxin, Cai Qiangguo *et al*., 2010. Retrospect and prospect of geomorphology in IGSNRR, CAS. *Geographical Research*, 29(9): 1546–1560. (in Chinese)

Shi Xingmin, Du Zhongchao, 2006. Review and prospect of tectonic geomorphology in China. *Northwestern Seismological Journal*, 28(3): 280–284. (in Chinese)

Shi Yafeng *et al*., 1990–1992. Advance of Climate and Sea Level Changes Research in China (1/2). Beijing: China Ocean Press. (in Chinese)

Shi Yafeng, Li Jijun, Li Bingyuan *et al*., 1999. Uplift of the Qinghai-Xizang (Tibetan) Plateau and East Asia environmental change during Late Cenozoic. *Acta Geographica Sinica*, 54(1): 10–20. (in Chinese)

Shi Yafeng, Zheng Benxing, Li Shijie *et al*., 1995. Studies on altitude and climatic environment in the middle and east parts of Tibetan Plateau during Quaternary Maximum Glaciation. *Journal of Glaciology and Geocryology*, 17(2): 97–112. (in Chinese)

Tang Guoan, 2014. Progress of DEM and digital terrain analysis in China. *Acta Geographica Sinica*, 69(9): 1305–1325. (in Chinese)

Wang An, Wang Guocan, 2005. Review on morphotectonic and its analytical methods. *Geological Science and Technology Information*, 24(4): 7–12. (in Chinese)

Wang Jiping, Huang Zhilin, Liu Yang *et al*., 2013. Quantitative analysis of the relationship between watershed topography and erosion-sediment processes: A case study of Hekou-Longmen section in Middle Yellow River. *Geographical Research*, 32(2): 275–284. (in Chinese)

Wang Jianmin, Wang Jiayuan, Sha Jianhuai *et al*., 2014. Karst paleogeomorphology and comprehensive geological model of the Ordovician weathering crust in the eastern Ordos Basin. *Journal of Jilin University* (*Earth Science Edition*), 44(2): 409–418. (in Chinese)

Wang Jie, Zhou Shangzhe, Zhao Jingdong *et al*., 2011. Quaternary glacial geomorphology and glaciations of Kongur Mountain, Eastern Pamir, China. *Science China*: *Earth Science*, 41(3): 350–361. (in Chinese)

Wang Shijie, Zhang Xinbao, Bai Xiaoyong, 2015. An outline of karst geomorphology zoning in the karst areas of southern China. *Journal of Mountain Science*, 33(6): 641–648. (in Chinese)

Wang Ying, Ji Xiaomei, 2011. Environmental characteristics and changes of coastal ocean as land-ocean transitional zone of China. *Scientia Geographica Sinica*, 31(2): 129–135. (in Chinese)

Wang Yonghong, Shen Huanting, Li Jiufa *et al*., 2011. Geomorphologic features and transport of sandwaves in the flood and EBB channels of the Changjiang Estuary. *Oceanologia et Limnologia Sinica*, 42(2): 330–336. (in Chinese)

Wang Yunzhang, Peng Meixiang, Wei Liye, 1992. Characteristics of precipitation in the Middle Yellow River and its effects on sediment entering into the Yellow River in 1980’s. *Yellow River*, 5(5): 10–14. (in Chinese)

Wen Qing, Dong Zhibao, Lu Jinhua *et al*., 2014. Compilation of geomorphologic map of the Tengger Desert. *Journal of Desert Research*, 34(1): 35–41. (in Chinese)

Wu Jichun, Sheng Yu, Cao Yuanbing *et al*., 2015. Discovery of large forst mound clusters in the source regions of the Yellow River on the Tibetan Plateau. *Journal of Glaciology and Geocryology*, 37(5): 1217–1228. (in Chinese)

Xia Kairu, 1960. Preliminary observation on paleoglaciation geomorphic character of marginal glacier in northern part of Qilian Mountains. *Acta Geographica Sinica*, 26(3): 165–180. (in Chinese)

Xie Youyu, Cui Zhijiu, 1983. On nonglacial genesis of “Glaciated Relics” of Lushan. *Acta Geographica Sinica*, 38(3): 298–308. (in Chinese)

Xiong Liyang, Tang Guoan, Yuan Baoyin *et al*., 2014. Geomorphological inheritance for loess landform evolution in a severe soil erosion region of Loess Plateau of China based on digital models. *Science China*: *Earth Sciences*, (2): 313–321. (in Chinese)

Xu Jiongxin, 2015. Increasing trend of green water coefficient in the middle Yellow River Basin and eco-environment implications. *Acta Ecologica Sinica*, 35(22): 7298–7307. (in Chinese)

Xu Jiongxin, Cai Qiangguo, Li Bingyuan *et al.*, 2016. Research progress in river geomorphology in China: In memory of 100-year anniversary of Shen Yuchang's birth. *Acta Geographica Sinica*, 71(11): 2020–2036. (in Chinese)

Xu Jiongxin, Li Bingyuan, Yang Xiaoping *et al.*, 2009. Recent progress in geomorphology and Quaternary geology in China and some perspectives. *Acta Geographica Sinica*, 64(11): 1375–1393. (in Chinese)

Xu Shuang, Li Feixue, Liu Aili *et al.*, 2014. Research on spatial variability of elevation in typical loess landform. *Bulletin of Soil and Water Conservation*, 21(5): 1–6. (in Chinese)

Yan Shijiang, Tang Guoan, Li Fayuan *et al.*, 2011. An edge detection based method for extraction of loess shoulder-line from grid DEM. *Geomatics and Information Science of Wuhan University*, 36(3): 363–367. (in Chinese)

Yang Hailan, Zhang Liheng, Wei Chuntao, 2015. Study on karst SAR image registration methods. *Science of Surveying and Mapping*, 40(1): 72–76. (in Chinese)

Yang J Q, Zhang W, Cui Z J *et al.*, 2006. Late Pleistocene glaciation of the Diancang and Gongwang Mountains, southeast margin of the Tibetan Plateau. *Quaternary International*, 154/155: 52–62.

Yang Qinke, Guo Lanqin, Wang Chunmei, 2012a. Extracting and analyzing slope and length based on ASTER GDEM and SRTM elevation datasets. *Bulletin of Soil and Water Conservation*, 32(6): 142–146. (in Chinese)

Yang Shunhu, Fu Bihong, Shi Pilong, 2012b. Late Quaternary structural deformation and tectono-geomorphic features along the Xiugou Basin Segment, Eastern Kunlun fault zone. *Quaternary Sciences*, 32(5): 921–930. (in Chinese)

Yang Xiaoping, 2000. Landscape types and its formation mechanism in the Badain Jaran Desert and its surrounding areas. *Journal of Desert Research*, 20(2): 65–69. (in Chinese)

Yang Yang, Bi Rutian, 2011. Fractal characteristics of land-use for typical geomorphic types in Loess Plateau. *Geography and Geo-Information Science*, 27(1): 101–104. (in Chinese)

You Lianyuan, Yang Jingchun, 2013. Geomorphology in China. Beijing: Science Press. (in Chinese)

Yuan Daoxian, 2015. Scientific innovation in karst resources and environment research field of China. *Carsologica Sinica*, 34(2): 98–100. (in Chinese)

Yuan Zhen, Li Wenhou, Zhu Jing *et al.*, 2013. The restoration of pre-Jurassic paleogeomorphology and its influence on oil accumulation in Longdong area. *Geological Bulletin of China*, 32(11): 1806–1814. (in Chinese)

Yue Shengyang, Miao Shui, Xu Haipeng, 2011. Ancient geomorphological environmental evolution of the ancient Jicheng area in Beijing: A case of the geotechnical profile in the construction field of Guangyi Building. *Acta Scientiarum Naturalium Universitatis Pekinensis*, 47(5): 845–852. (in Chinese)

Zeng Zhaoxuan, 1994. Some questions of limestone landform types in South China. *Acta Geologica Sinica*, 44(1): 119–128. (in Chinese)

Zhang Guangsheng, Hao Lixia, Tan Lugui *et al.*, 2015. Geological background and landscape characteristics of Danxia landform at the northern slope of the Dabie Mountain. *Journal of West Anhui University*, (5): 1–6. (in Chinese)

Zhang Guoping, 2004. A preliminary study on prediction method of rainstorm debris flow in China based on eco-environment background evaluation and meteorological forecast. In: Land Change Science and Ecological Construction. Beijing: The Commercial Press, 612–626. (in Chinese)

Zhang Lei, Tang Guoan, Li Fayuan *et al.*, 2012. A review on research of loess shoulder-line. *Geography and Geo-Information Science*, 28(6): 44–48. (in Chinese)

Zhang Liheng, 2013. Study on SAR image registration methods of karst geography [D]. Guilin: Guilin University of Technology. (in Chinese)

Zhang Shengli, Yu Yiming, Yao Wenyi, 1994. Method of Water and Sand Reduction Benefits for Soil and Water Conservation. Beijing: China Environmental Science Press. (in Chinese)

Zhang Wei, Dong Yingwei, Yu Zhilong *et al.*, 2013. Discussion of the difference of the timing and extent of glaciers in the Late Quaternary controlled by the westerly and East Asia monsoon as well as the tectonic movement. *Acta Geographica Sinica*, 68(7): 909–920. (in Chinese)

Zhang Wei, Liu Rui, Wei Yagang *et al.*, 2016. Periglacial geomorphologic characteristics and environment in Taibai, the Qinling Mountain. *Journal of Arid Land Resources and Environment*, 30(10): 171–178. (in Chinese)

Zhang Xinbao, Wang Shijie, Bai Xiaoyong *et al.*, 2013. Relationships between the spatial distribution of karst land desertification and geomorphology, lithology, precipitation, and population density in Guizhou Province. *Earth and Environment*, 41(1): 1–6. (in Chinese)

Zhang Yongrong, Zhou Zhongfa, Yan Lihui, 2005. An analysis of the evolutionary characteristics of rocky desertification in the karst plateau of Guizhou. *China Rural Water and Hydropower*, (3): 59–63. (in Chinese)

Zhang Yongzhan, Wang Yin, 2006. New progress in coastal ocean sciences research. *Acta Geographica Sinica*, 61(4): 446–446. (in Chinese)

Zhang Zhengcai, Dong Zhibao, 2014. Research progress on aeolian geomorphology and morphodynamics. *Advances in Earth Science*, 29(6): 734–747. (in Chinese)

Zhao Ding, Zhao Xun, Peng Hua *et al*., 2014. A tentative discussion on the definition and classification of Danxia landform. *Acta Geoscientica Sinica*, 69(3): 375–382. (in Chinese)

Zhao Jingdong, Shi Yafeng, Li Zhongqin, 2011a. Glacial geomorphology and glaciations at the headwaters of the Ürümqi River, Tianshan Mountain, China: Review and prospect. *Journal of Glaciology and Geocryology*, 33(1): 118–125. (in Chinese)

Zhao Jingdong, Shi Yafeng, Wang Jie, 2011b. Comparison between Quaternary glaciations in China and the Marine Oxygen Isotope Stage (MIS): An improved schema. *Acta Geographica Sinica*, 66(7): 867–884. (in Chinese)

Zhao Jingdong, Wang Jie, Shen Yongping *et al*., 2013. Distribution and features of glacial landforms in the northwest of the Die Shan, West Qinling Mountains. *Journal of Glaciology and Geocryology*, 35(4): 841–847. (in Chinese)

Zhao Shangmin, Cheng Weiming, Chai Huixia *et al*., 2007. Research on the information extraction method of periglacial geomorphology on the Qinghai-Tibet Plateau based on remote sensing and SRTM: A case study of 1:1000000 Lhasa Map Sheet (H46). *Geographical Research*, 26(6): 1175–1185. (in Chinese)

Zhao Shangmin, He Weican, Wang Li, 2016. Error distribution analysis of SRTM3 DEM V4 data in the typical geomorphologic area of Loess Plateau. *Science of Surveying and Mapping*, 41(2): 67–70. (in Chinese)

Zheng Benxing, 2000. Quaternary glaciation and glacier evolution in the Yulong Mount, Yunnan. *Journal of Glaciology and Geocryology*, 22(1): 53–61. (in Chinese)

Zheng Du, 2008. A Study on the Eco-Geographic Regional System of China. Beijing: The Commercial Press. (in Chinese)

Zheng Yongling, Wu Chengqiang, Cai Feng *et al*., 2012. The resent research trend of China's submarine geomorphology and new discoveries of the East China Sea offshore. *Advances in Earth Science*, 27(9): 1026–1034. (in Chinese)

Zhou Chenghu, 2006. A Dictionary of Geomorphology. Beijing: China Water & Power Press. (in Chinese)

Zhou Chenghu, Cheng Weiming, Qian Jinkai *et al*., 2009a. Research on the classification system of digital land geomorphology of 1:1000000 in China. *Journal of Geo-Information Science*, 11(6): 707–724. (in Chinese)

Zhou Chenghu, Cheng Weiming, Qian Jinkai, 2009b. Digital Geomorphological Interpretation and Mapping from Remote Sensing. Beijing: Science Press. (in Chinese)

Zhou Chenghu, Cheng Weiming, 2010. Research and Compilation of the Geomorphological Atlas of the People's Republic of China. *Geographical Research*, 29(6): 970–979. (in Chinese)

Zhou Shangzhe, Li Jijun, 2003. New dating results of Quaternary glaciations in China. *Journal of Glaciology and Geocryology*, 25(6): 660–666. (in Chinese)

Zhou Shangzhe, Yi Chaolu, Shi Yafeng *et al*., 2001. Study on the Ice Age MIS12 in western China. *Journal of Geomechanics*, 7(4): 321–327. (in Chinese)

Zhou Tingru *et al*., 1956. A Draft for Topographic Regionalization of China. Beijing: Science Press. (in Chinese)

Zhu Cheng, Cui Zhijiu, 1992. The distribution and evolution of periglacial landforms in the source region of Urumqi River on the Tianshan Mountain. *Acta Geographica Sinica*, 47(6): 526–535. (in Chinese)

Zhu Junfeng, Shen Yuancun, 2004. Deserticluture in China. Beijing: China Forestry Publishing House. (in Chinese)

Zhu Junfeng, Zhu Zhenda, 1999. Desert Combating in China. Beijing: China Forestry Publishing House. (in Chinese)

Zhu Xiaxia, Zhang Hua, Zhu Yan *et al*., 2016. Forest community species diversity and the influencing factors in the rock stream periglacial landforms of Mt. Laotudingzi. *Plant Science Journal*, 16(1): 67–77.