J. Geogr. Sci. 2011, 21(5): 771-790
DOI: 10.1007/s11442-011-0879-9

Structure and contents of layered classification system of digital geomorphology for China

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Abstract: This paper presents the structure and contents of a standardized layered classification system of digital geomorphology for China. This digital classification method combines landforms characteristics of morphology with genesis. A total of 15 categories of exogenic and endogenic forces are divided into two broad categories: morpho-genetic and morpho-structural landforms. Polygon patches are used to manage the morpho-genetic types, and solitary points, lines and polygons are used to manage the morpho-structural types. The classification method of digital morpho-genetic types can be divided into seven layers, i.e. basic morphology and altitude, genesis, sub-genesis, morphology, micro-morphology, slope and aspect, material and lithology. The method proposes combinations of matrix forms based on layered indicators. The attributes of every landform types are obtained from all or some of the seven layers. For the 15 forces categories, some classification indicators and calculation methods are presented for the basic morphology, the morphologic and sub-morphologic landforms of the morpho-genetic types. The solitary polygon, linear and point types of morpho-structural landforms are presented respectively. The layered classification method can meet the demands of scale-span geomorphologic mapping for the national primary scales from 1:500,000 to 1:1,000,000. The layers serve as classification indicators, and therefore can be added and reduced according to mapping demands, providing flexible expandability.

Keywords: digital geomorphology; classification system; morpho-genesis; morpho-structure; layered classification method

1 Introduction

Geomorphology involves the investigation of morphological processes, genesis, and characterization of the materials and age of the surface of the planet (Markov, 1957). Geomorphologic maps can represent information about natural conditions and resources, and the ecological and geographical environment, which are crucial for global or regional climate change identification, environmental protection and disaster monitoring, agriculture, forestry, water resources planning, regional land resource mapping, engineering construction, mili-

Received: 2011-01-20 **Accepted:** 2011-04-10
Foundation: Key Project of the National Natural Science Foundation of China, No.40871177; No.40830529; No.40971063
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tary and scientific research, and public education.

Research on geomorphologic classification methods can be used to answer important theoretical questions about geomorphology and geomorphologic cartography (Markov, 1957). According to the dominant forces that form surface characteristics, geomorphologic research can be divided into two branches, i.e. climate geomorphology and tectonic geomorphology. The former includes glacial, peri-glacial, aeolian and arid landforms. The latter includes volcanic-lava, gravitational, and tectonic landforms.

Classification research has long been used as the basis for mapping and application of geomorphology. In 1884, W.M. Davis developed the exterior genetic classification method, which used tectonics and erosion amount (Pan, 1961). In 1894, A. Penck introduced a classification method according to surface morphology indicators, which included six basic types (i.e. plain, mountain cliff, valley, concave ground and caves). Since then, many geomorphologists have presented about 50 related classification schemes. Pan (1961) translated, generalized, tabulated and presented all indicators, and comprehensively compared their differences and relative advantages among classification methods. In summary, the classification methods can be divided into four categories: only considering morphologic indicators, only considering genetic indicators, a combination of morphologic and genetic indicators, and artificially considering multi-indicators. Until now, most geomorphologists have used the combination classification method of morphologic and genetic indicators as one of the most reasonable approaches.

Nonetheless, genetic characteristics of modern geomorphologic entities are multi-sourced and multi-layered. The formation and evolution processes are dynamic and changeable, and spatial boundaries of types possess uncertain fuzziness. The relationship between geomorphologic types (i.e. morphology and genesis) is not simple (Chen, 1993). Thus, every geomorphologist has a different idea with regard to the morphology and genesis of geomorphologic characteristics. In addition, every classification method possesses different dominant indicators or factors, which may lack certain logicality and hierarchy. Thus, there is no general geomorphologic classification system, which can embody rational combinations of morphologic and genetic characteristics.

Before the introduction of geographical information systems (GISs) to geomorphology, manual geomorphologic classification analyses were complicated, time consuming and difficult to perform, especially when many geomorphologic indicators were included. In the late 1980s, the use of GISs became widespread in geomorphologic classification research, and GIS-software provided a tool for handling large spatial datasets. Such software also could provide a scientifically sound representation and spatial analysis of geomorphology (Gustavsson *et al*., 2008).

The combination of remote sensing (RS) and GIS technology within geosciences has greatly influenced traditional geomorphologic cartographic methods (Li *et al*., 2009; Zhou *et al*., 2009; David and Stephen, 1998). Remote sensing data are not only important sources to assist ground surveying, but are also important data sources, which can be presented at different scales according to particular needs, in contrast to traditional geomorphologic cartography methods. Data from different sources, such as digital elevation models (DEM), vegetation and geological maps, and remote sensing data can be integrated, overlapped and calculated in a GIS environment (Miliaresis and Argialas, 2000; Miliaresis, 2001; Miliaresis and Iliopoulou, 2004; Bishop, 2003; Bocco *et al*., 2001; Brian, 2000). Unlike traditional geomorphologic mapping methods, which depended on generalization from topographical maps and field surveying, GIS makes it possible for quantitative interpretation of geomorphologic information based on multiple data sources in a short time.

So, this paper presents a general classification system of digital geomorphology, which combines characteristics of morphology with genesis with layered attributes. This system was developed in parallel with a GIS geodatabase in China. Therefore, different information from every classification method can be easily performed and integrated in the ArcGIS geodatabase for the entire country. The layered classification methods can meet the demands of scale-span geomorphologic mapping for the national primary scales from 1:500,000 to 1:1,000,000. The classification indicators can be added and reduced according to mapping demands, which represents a flexible expandability.

2 Classification researches of genetic types

2.1 Genetic types

In China, systemic geomorphologic classification research has been conducted since the 1950s. Zhou *et al*. (1956) developed classification indicators that included morphologic characteristics (altitude and relief amplitude), tectonic, erosional characteristics and surface features. With this system, China was divided into six categories (i.e. plain, basin, plateau, hill, middle mountains and high mountains). This method was regarded as the first modern geomorphologic classification system in China.

Shen (1958) developed a genetic classifying method, which divided China into tectonic landforms, erosional-denudational tectonic landforms, erosional-denudational, accumulational and volcanic landforms. The Natural Divisions Working Committee (1959) of the Chinese Academy of Sciences divided Chinese landforms into eight categories: accumulational plains, denudational plains, high plains and plateaus, loess platforms and hills, erosional mountains (high, middle, low mountains), karstic mountains (middle and low mountains), glacial, frost and debris flowing high mountains and highlands, arid denudational mountains (middle and low mountains) and volcanic landforms.

In addition, China's National Atlas Compilation Committee (1965) divided Chinese landforms into three categories (i.e. accumulational plains, denudational plains and plateaus, denudational platforms and mountains). The Institute of Geography (1987a, 1987b) of the Chinese Academy of Sciences published an academic monograph regarding geomorphologic mapping specifications at 1:1,000,000 scale in China, consisting of 15 sheets at 1:1,000,000 scale of geomorphologic maps (in all 64 sheets of Chinese land territory of 1:1,000,000 scale). The monograph formed a preliminarily systematic classification matrix, the longitudinal indicators of which included 17 morphologic types based on altitude and relief amplitude. The latitudinal indicators included 10 genetic categories, and the mapping flowchart of geomorphologic maps at the 1:1,000,000 was standardized.

Through analyzing the classification methods mentioned above, major genetic categories of geomorphologic classification systems can be divided into exogenic and endogenic forces (Table 1), and, the resulting genetic classification method (Table 1) presents the 15 major genetic categories. Among them, 12 categories of endogenic forces include marine, lacustrine, fluvial, loess, karst, glacial, periglacial, aeolian, arid, artificial, biological and other

Table 1 Major genetic categories of geomorphologic exogenic and endogenic forces

Genetic categories	Genetic types	Genetic categories	Genetic types
1) Water-related forces	Marine (M) Lacustrine (L) Fluvial (F) Loess (H) Karst (K)	3) Arid and aeolian-related forces	Aeolian (E) Arid (A)
		4) Tectonic-related forces	Volcanic-lava (V) Gravitational Tectonic
2) Ice-related forces	Glacial (G) Periglacial (P)	5) Artificial and other-related forces	Artificial Biological Other

forces landforms.

According to modern genetic characteristics, spatial distribution location and present status, the genetic categories can be divided five broad categories, such as, water-related forces, ice-related forces, arid and aeolian-related forces, tectonic-related forces and artificial and other-related forces (Table 1).

Based on current conditions of land surfaces and the action properties of geomorphologic genesis, all forces can be divided into two major sub-genesis categories, i.e. erosional or denudational (uplifting) and accumulational (subsiding) landforms (Yang, 1993). Moreover, during the course of geomorphologic formation, some exogenic forces and/or endogenic forces can interact and form transitional types. For example, marine effect forces can be divided into marine accumulational, marine-alluvial and marine-erosional. Fluvial geomorphology can be divided into alluvial-marine, alluvial-lacustrine, alluvial, alluvial-pluvial, pluvial-lacustrine, valley and erosional-denudational. Table 2 presents accumulational, tran-

Table 2 Sub-genetic types of terrestrial geomorphology in China

Sub-genesis \ Genetic types	Marine	Lacustrine	Fluvial	Glacial	Peri-glacial	Aeolian	Arid	Loess	Karst	Volcanic-lava
Accumulation (subsiding) mountains	Marine Marine-alluvial	Lacustrine Lacustrine-alluvial	Alluvial-marine Alluvial-lacustrine Alluvial Alluvial-pluvial Pluvial Pluvial-lacustrine	Outwash Outwash gravel	Lacustrine	Aeolian-accumulated Aeolian-accumulated and alluvial	Salt lake Proluvial	Aeolian-accumulated and pluvial Tectonic-accumulated	Depositional Solutional depositional Solutional-alluvial	
Transitional			Valley	Valley	Valley		Valley	Erosional-accumulated Erosional-alluvial		
Denudation (uplifting) plain	Marine-erosional	Lacustrine-erosional	Erosional-denudational	Glacial erosional Erosional-denudational	Denudational	Aeolian-eroded	Denudational Erosional-denudational		Solutional erosional Erosional	Erosional-denudational

sitional and denudational types of sub-genesis categories for main 10 exogenic and endogenic forces of morpho-genetic categories. The amount and types of sub-genesis categories for every force are different, and they can be obtained by indirectly reasoning and analysis of geologic maps or field surveying.

2.2 Mapping approach of genetic types in ArcGIS

Based on the characteristics of distribution, shape, size, importance and mapping approaches for the different geomorphologic types, as well as vector data management in ArcGIS, the 15 major genetic categories mentioned in Table 1 can be divided into two categories, i.e. morpho-genetic and morpho-structural landforms (Figure 1).

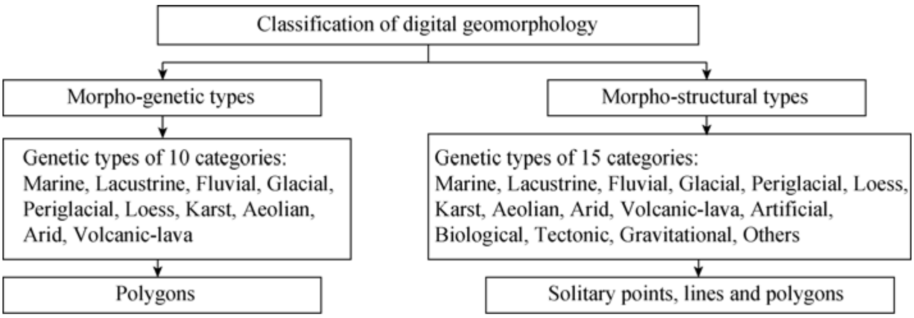

Figure 1 Mapping approach of digital land geomorphologic categories

Usually, polygon patches are used to manage the morpho-genetic geomorphologic types in ArcGIS. Different color values and symbols are utilized to discriminate polygon patches during the course of mapping. Solitary points, lines and polygons are used together to manage morpho-structural geomorphologic types in ArcGIS. Different color values and symbols are used to discriminate points, linear and polygon types of different landforms during the course of mapping.

Compared with the main 10 categories of genetic types in Table 1, the latter five categories (artificial, biological, tectonic, gravitational and other force landforms) usually influence over a relatively smaller scope, and form simple geomorphologic types. Thus, they usually are described by simple morpho-structural types based on solitary points, lines and polygons. The main 10 categories of genetic types in Table 1 possess both morpho-genetic and morpho-structural geomorphologic types. As a result, all geomorphologic types of different forces can be differentiated and managed in ArcGIS.

3 Morphologic types

Geomorphologic morphologies are major indicators of geomorphologic classification. The indicator types are many and varied. Among them, surface ground altitude and relief are the most essential morphologic indicators, including altitude, slope, aspect, and topographic relief. Most of these indicators can be calculated from DEM data by means of topographic algorithms and models (Irvin *et al*., 1997).

3.1 Basic morphology

While land and sea are two of the largest geomorphologic units on Earth, mountains and plains can be regarded as the largest geomorphologic units of land territories. China is located in the southeastern part of Eurasia, borders on the West Pacific Ocean and the South Asian subcontinent, and extends northwestward to the center of Asia. In this extensive territory, the relief undulates greatly, the altitude of which is paramount. At the extremes, the Himalayas, on the border between China and Nepal, are situated at 8844 m a.s.l, while the water surface of Aiding Lake in the Turpan Basin in Xinjiang is 154 m below sea level. The relief of China is high in the west and low in the east, and overall appears as a step-like slope, with high mountains, plateaus and large interior basins mainly distributed in the west, and lower mountains, hills and plains situated in the east (Zeng, 1985).

Geographers argue (Zeng, 1985; Li 1994; Chen, 1994) that the Chinese terrain possesses three apparent stages characterized by altitude values at 1000, 3500 and 5000 m. Furthermore, the altitude can be divided into four categories, which include low altitude (<1000 m), middle altitude (1000–3500 m), high altitude (3500–5000 m) and highest altitude (>5000 m) (Cheng *et al*., 2011).

Terrain relief is a controlling factor, which can depict relative terrain characteristics. Research has shown that relief values can be calculated from DEM or topographic contour lines and field surveying (Bishop *et al*., 2003). In addition, morphologic types based on relief values can be divided into seven categories: plains (<30 m), platforms (>30 m), hills (<200 m), low relief mountains (200–500 m), middle relief mountains (500–1000 m), high relief mountains (1000–2500 m) and highest relief mountains (>2500 m) (Institute of Geography, 1987a, 1987b).

Table 3 presents a classification of the basic terrestrial geomorphologic types of China. The horizontal coordinate is the value of altitude, and the longitudinal is terrain relief. The combination of altitude types and relief types together forms the basic 25 land terrestrial geomorphologic types.

Table 3 Classification of the basic terrestrial geomorphologic types of China (after Cheng *et al*., 2011)

Altitude relief	Low altitude (<1000 m)	Middle altitude (1000–3500 m)	High altitude (3500–5000 m)	Highest altitude (>5000 m)
Plain (<30 m)	Low altitude plain	Middle altitude plain	High altitude plain	Highest altitude plain
Platform (>30 m)	Low altitude platform	Middle altitude platform	High altitude platform	Highest altitude platform
Hill (<200 m)	Low altitude hill	Middle altitude hill	High altitude hill	Highest altitude hill
Low relief mountain (200–500 m)	Low relief low altitude mountain	Low relief middle altitude mountain	Low relief high altitude mountain	Low relief highest altitude mountain
Middle relief mountain (500–1000 m)	Middle relief low altitude mountain	Middle relief middle altitude mountain	Middle relief high altitude mountain	Middle relief highest altitude mountain
High relief mountain (1000–2500 m)	—	High relief middle altitude mountain	High relief high altitude mountain	High relief highest altitude mountain
Highest relief mountain (>2500 m)	—	—	Highest relief high altitude mountain	Highest relief highest altitude mountain

Notes: "—" no geomorphologic type represented

The classification values of altitude and relief are average values throughout the country. They can be adjusted according to regional characteristics. For example, the altitude classification of values possesses a ±500 m fluctuation scope, and thus represents the relief classification value.

Hills can be divided into low and high. The relief value of low hills less than 100 m in altitude, and of high hills is 100–200 m. Moreover, platforms can be divided into low and high, with a relief value for the former of less than 100 m, and a relief value of the latter of 100–200 m.

3.2 Morphologic types

Geomorphologic morphologic types can reflect genetic characteristics, the scope and area of which are less than the basic morphologic types, such as alluvial fan, flood plain, and terrace. Some typical geomorphologic morphologic types can be directly calculated or extracted from remote sensing imagery and DEM data (i.e. pluvial fans, longitudinal dune). Demoulin *et al*. (2007) developed an automated method to extract terraces from DEM in the Vesdre Valley in eastern Belgium.

Most morphologic types usually are extracted by manual interpretation based on multi-source data. Siart *et al*. (2009) combined digital elevation data (SRTM/ASTER), high resolution satellite imagery (Quickbird) and GIS for geomorphologic mapping of Mediterranean karst in Central Crete. Miliaresis (2001) used DEM and satellite imagery to classify and extract bajadas, etc.

3.3 Micro-morphologic types

Micro-morphologic types usually reflect detailed characteristics of large-scale geomorphologic maps, such as micro-highlands, depressions, lagoon depressions, coastal-lowlands, lake beaches, lakeshore lowlands, lake inlet delta plains, paleo-channel depressions, paleo-flood plains, and natural levees. Most of these are usually extracted by manual interpretation based on multi-source data, and they can be expressed as morpho-genetic geomorphologic types on large-scale maps. In contrast, they can be regarded as morpho-structural geomorphologic types on small-scale maps.

3.4 Slope and aspect

Slope and aspect are important topographic indicators. Usually, based on spatial analyst or 3D analyst modules in ArcGIS software, they can be calculated directly from DEM (Philip and Steven *et al*., 1998). Table 4 presents a slope classification status of geomorphologic entities. The types of slope values can be divided into seven categories according to the average value of plains and mountains. Since the slope and aspect values are continuous

Table 4 Slope classification method of geomorphologic entities

Slope surface types		Basic characteristics
Plain and platform	Flat	General less than 2°, inclining to the same direction, or to the center
	Sloping	General more than 2°, inclining to the same direction, or to the center
	Undulating	General more than 2°, possessing both same direction and facing direction
Hill and mountains	Gentle	Slope value is usual 7°–15°
	Mild	Slope value is usual 15°–25°
	Steep	Slope value is usual 25°–35°
	Extremely steep	Slope value is usual more than 35°

surfaces, they are average values of polygon patches within the geomorphologic units, which are manually interpreted (Institute of Geography, 1987a, 1987b).

The Shuttle Radar Topographical Mission (SRTM) data with 3-arc seconds spatial resolution free downloaded as the DEM data is used in this study, whose spatial resolution is 90 m, equal to 1:250,000. Through mosaicing, the whole SRTM-DEM data is obtained, and slope and aspect value is calculated in ArcGIS software.

4 Classification method of terrestrial digital geomorphologic types

Based on classification methods for every indicator mentioned above as well as the data management approach in ArcGIS, the classification scheme of terrestrial digital morpho-genetic geomorphologic types in China can be divided into seven layers (i.e. basic morphology and altitude, genesis, sub-genesis, morphology, micro-morphology, slope and aspect, material and lithology, Table 5) (Cheng *et al*., 2011). The former three layers are the fixed items, and the latter four layers are reference items, which are changeable according to actual geomorphologic mapping.

Table 5 Classification scheme of terrestrial digital geomorphologic types of China (morpho-genetic types) (after Cheng *et al*., 2011)

Morphologic types		Genetic types		Morphologic types			Material types
First layer		Second layer	Third layer	Fourth layer	Fifth layer	Sixth layer	Seventh layer
Basic morphology	Altitude	Genesis	Sub-genesis	Morphology	Micro-morphology	Slope and aspect	Material and lithology
Seven basic morphologic types	Four altitude types	Marine, Lacustrine, Fluvial, Glacial, Periglacial, Aeolian, Arid, Loess, Karst, Volcanic-lava	Changing according to genesis, being dividing to two types: uplifting/erosion, descending/ accumulation	Changing according to sub-genetic types	Changing according to morphologic types	Plain and platform: Flat, Sloping, Undulating Hill and mountain: Gentle, Mild, Steep, Extremely steep	Changing according to genesis, material and lithologic types
High precision DEM data RS data		Published geomorphologic maps, geologic data, Field, DEM, RS data		Published geomorphologic maps, geologic data, Field, DEM, RS data		High precision DEM, RS	Geologic data
Fixed items				Reference items (changeable)			

The layered classification methods meet the demands of scale-span geomorphologic mapping for the corresponding scales. The layers are classification indicators, which can be added and reduced according to mapping demands. This approach has flexible expandability. The method possesses five facets of the principles of geomorphologic classification, i.e. combining morphology with genesis, dominant factors, logic sequence, quantitative calculating, and complete system.

The main 10 genetic forces of terrestrial geomorphology in China can be obtained by means of manual interpretation from remote sensing imageries, and the spatial distribution pattern and characteristics are presented in Figure 2. Fluvial landforms, marine landforms and karst landforms are mainly distributed in eastern China. Glacial landforms and periglacial landform are mainly distributed in western China. Arid landforms, aeolian landforms and loess landforms are mainly distributed in northwestern China. The spatial distribution and sub-genesis characteristics of main 10 genetic forces are discussed in turn as follows.

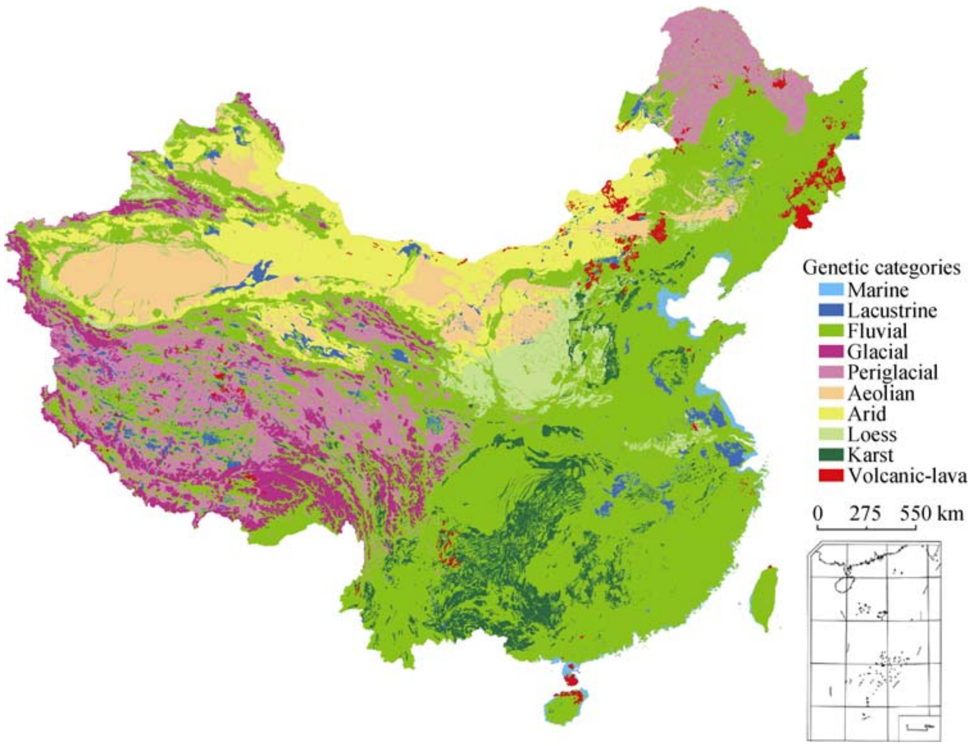

Figure 2 Spatial distribution of main 10 genetic forces of terrestrial geomorphology in China

4.1 Types of morphology and micro-morphology of marine landforms

Marine landforms are located in the coastal belt of East China (Chen, 1995; Wang, 1996). The basic geomorphologies of these landforms include plains and platforms, and they are located in the low altitude regions (Figure 2 and Table 6). The types of sub-genesis (third layer) include marine depositional, marine alluvial, marine erosional and marine depositional types. The types of morphology (fourth layer) include beaches, low terraces, depressions, delta plains, highlands, micro-highlands, platforms, high terraces, low platforms, and high platforms. Types of micro-morphology (fifth layer) are not temporarily classified.

Table 6 Types of morphology and micro-morphology of marine landforms

Basic morphologic types		Genetic types		Morphologic types	
First layer		Second layer	Third layer	Fourth layer	Fifth layer
Basic morphology	Altitude	Genesis	Sub-genesis	Morphology	Micro-morphology
Plain	Low altitude	Marine	Marine depositional	Beach, Low terrace, Depression	
			Marine alluvial	Delta plain, Depression, Highland, Micro-highland	
			Marine erosional	Low terrace, Platform	
Platform			Marine depositional	High terrace, Low platform, High platform	
			Marine erosional	Low platform, High platform	

4.2 Types of morphology and micro-morphology of lacustrine landforms

Lacustrine landforms are distributed throughout the Chinese land territories (Zeng, 1985), which are located in all the low, middle, high and highest altitudes (Figure 2 and Table 7). The basic geomorphologies include plains and platforms. The types of sub-genesis (third layer) include lacustrine, lacustrine alluvial and lacustrine erosional types. The types of morphology (fourth layer) include lake beaches, low terraces, lake beds, micro-highlands, depressions, delta plains, high terraces, low platforms, and high platforms. Types of micro-morphology (fifth layer) are not temporarily classified.

Table 7 Types of morphology and micro-morphology of lacustrine landforms

Basic morphologic types		Genetic types		Morphologic types	
First layer		Second layer	Third layer	Fourth layer	Fifth layer
Basic morphology	Altitude	Genesis	Sub-genesis	Morphology	Micro-morphology
Plain	Low altitude Middle altitude	Lacustrine	Lacustrine	Lake beach, Low terrace, Lake bed, Micro-highland, Depression	
			Lacustrine alluvial	Delta plain, Depression, Low terrace	
			Lacustrine erosional	Low terrace	
Platform	High altitude Highest altitude		Lacustrine	High terrace, Low platform, High platform	
			Lacustrine alluvial	High terrace, Low platform, High platform	
			Lacustrine erosional	Low platform, High platform	

4.3 Types of morphology and micro-morphology of fluvial landforms

Fluvial landforms are distributed throughout the Chinese land territories, except for the highest altitudes (Figure 2 and Table 8; Shen and Gong, 1986), and their basic geomorphologies include plains, platforms, hills, and low-, middle-, high- and highest-relief mountains. These are located in the regions of the low, middle and high altitudes. The types of sub-genesis (third layer) include alluvial marine, alluvial lacustrine, alluvial, alluvial pluvial, pluvial, pluvial lacustrine, valley, and erosional denudational landforms. The types of morphology (fourth layer) include delta plains, depressions, low terraces, micro-highlands, channels, flood plains, alluvial fans, splay fans, highlands, alluvial-pluvial fans, pluvial fans, debris flow fans, high terraces, low platforms, high platforms, low hills, and high hills. The types of micro-morphology (fifth layer) include river beds, channel islands, paleo-channels, low flood plains, high flood plains, paleo-channel flood plains, oxbow lakes, and micro-highlands of alluvial plains. Other types of micro-morphology of sub-genesis are not temporarily classified.

4.4 Types of morphology and micro-morphology of glacial landforms

Glacial landforms are distributed in the western Chinese mountain territories, except for at low altitudes (Shi *et al*., 2006). Their basic geomorphologies include plains, platforms, hills, and low-, middle-, high- and highest-relief mountains, which are located in the regions of the middle, high and high altitudes (Figure 2 and Table 9). The types of sub-genesis (third layer) include outwashes, outwash gravels, glacio-river valleys, glacial erosional areas, erosional denudational and periglacial landforms. The types of morphology (fourth layer) in-

Table 8 Types of morphology and micro-morphology of fluvial landforms

Basic morphologic types		Genetic types		Morphologic types	
First layer		Second layer	Third layer	Fourth layer	Fifth layer
Basic morphology	Altitude	Genesis	Sub-genesis	Morphology	Micro-morphology
Plain	Low altitude	Fluvial	Alluvial marine	Delta plain	
	Middle altitude			Depression	
	High altitude		Alluvial lacustrine	Delta plain	
				Depression	
				Low terrace	
				Micro-highland	
			Alluvial	Channel	River bed
					Channel island
					Paleo-channel
				Flood plain	Low flood-plain
					High flood-plain
					Paleo-channel
					Flood-plain
				Low terrace	
				Alluvial fan	
				Splay fan	
				Depression	Paleo-channel
					Oxbow lake
				Highland	Paleo-channel
					Micro-highland
			Alluvial pluvial	Alluvial-pluvial fan	
				Depression	
			Pluvial	Pluvial fan	
				Debris flow fan	
			Valley		
			Erosional-denudational		
			Pluvial lacustrine		
Platform	Low altitude	Fluvial	Alluvial	High terrace	
	Middle altitude		Pluvial	Low platform, High platform	
	High altitude		Erosional-denudational	Low platform, High platform	
			Alluvial pluvial	Low platform, High platform	
			Pluvial lacustrine	High terrace, Low platform, High platform	
Hill	Low altitude	Fluvial	Erosional-denudational	Low hill, High hill	
Low-relief mountain	Middle altitude				
Middle-relief mountain	High altitude				
High-relief mountain					
Highest-relief mountain					

clude terraces, floodplains, outwash fan plains, glacial barrier lakes, ridges and hillocks, monadnocks, hills and ridges, glacial pavements, glacial erosional lakes, low and high platforms, and low and high hills. Types of micro-morphology (fifth layer) of glacial landforms are not temporarily classified.

4.5 Types of morphology and micro-morphology of periglacial landforms

Periglacial landforms are distributed in the western and northeastern Chinese land territories

Table 9 Types of morphology and micro-morphology of glacial landforms

Basic morphologic types		Genetic types		Morphologic types	
First layer		Second layer	Third layer	Fourth layer	Fifth layer
Basic morphology	Altitude	Genesis	Sub-genesis	Morphology	Micro-morphology
Plain	Middle altitude	Glacial	Outwash	Terrace, Floodplain Outwash fan plain	
			Outwash gravel	Glacial barrier lake Ridges and hillocks Monadnock, Hills and ridges	
			Glacio-river valley	—	
			Glacial erosional	Glacial pavement, Glacial erosional lakes	
Platform	High altitude		Outwash gravel	Low platform High platform	
			Glacial erosional	Low platform High platform	
Hill			Outwash gravel	Low hill, High hill	
			Glacial erosional	Low hill, High hill	
Low-relief mountain			Erosional-denudational		
Middle-relief mountain					
High-relief mountain	Highest altitude		Periglacial		
Highest-relief mountain					

Table 10 Types of morphology and micro-morphology of periglacial landforms

Basic morphologic types		Genetic types		Morphologic types	
First layer		Second layer	Third layer	Fourth layer	Fifth layer
Basic morphology	Altitude	Genesis	Sub-genesis	Morphology	Micro-morphology
Plain	Low altitude	Periglacial	Lacustrine		
			River valley		
			Denudational	Depression	
Platform	Middle altitude		Erosional-denudational	Low platform, High platform	
Hill	High altitude			Low hill, High hill	
Low-relief mountain					
Middle-relief mountain	Highest altitude				
High-relief mountain					
Highest-relief mountain					

(Zhou *et al*., 2000), and their basic geomorphologies include plains, platforms, hills, and low-, middle-, high- and highest-relief mountains. These are located in the regions of all the low, middle, high and highest altitudes (Figure 2 and Table 10).

Types of sub-genesis (third layer) include lacustrine, river valleys, denudational areas, and erosional denudational landforms. Types of morphology (fourth layer) include lacustrine plains, river valley plains, depression, low and high platforms, and low and high hills. Types of micro-morphology of periglacial landforms are not temporarily classified.

4.6 Types of morphology and micro-morphology of aeolian landforms

Aeolian landforms are distributed in the northern Chinese land territories (Zhu *et al*., 1980), and their basic geomorphologies include plains, hills and low-relief mountains. These are located in the regions of main low and middle altitudes, and only small portions are located in the region of high altitudes (Figure 2 and Table 11). Types of sub-genesis (third layer) include aeolian accumulated and aeolian eroded landforms. Types of morphology (fourth layer), of aeolian landforms differ from the other landforms, and they include fixed, semi-fixed, shifting and shifting compounds for aeolian accumulated types. Types of morphology of aeolian eroded surfaces are not temporarily classified. In the plain categories, the aeolian accumulated types of micro-morphology include flat sand and low undulated sand land, and aeolian eroded types of micro-morphology include depressions and ripple plains.

Table 11 Types of morphology and micro-morphology of aeolian landforms

Basic morphologic types		Genetic types		Morphologic types	
First layer		Second layer	Third layer	Fourth layer	Fifth layer
Basic morphology	Altitude	Genesis	Sub-genesis	Morphology	Micro-morphology
Plain			Aeolian accumulated	Fixed, Semi-fixed, Shifting	Flat sand land, Low undulated sand land
			Aeolian eroded		Depression, Ripple plain
	Low altitude			Fixed	Coppice dune, Nest shaped dune, Longitudinal dune
				Semi-fixed	Coppice dune, Nest shaped dune, Honeycomb dune, Parabolic dune, Longitudinal dune, Honeycomb longitudinal dune, Dendritic dune, Compound dune chain
Hill		Aeolian	Aeolian accumulated	Shifting	Crescent sand ridge and dune chain, Lattice dune and dune chain, Scaly dune, Crescent sand ridge, Linear sand dune, Featherlike longitudinal dune, Star dune and dune chain, Star dune longitudinal dune
	Middle altitude			Shifting compound	Compound dune and dune chain, Compound longitudinal dune, Compound dome shaped dune, Compound chain dune, Compound dune with barkhans, Compound starlike chain dune, Complex starlike chain dune
	High altitude		Aeolian eroded		Yardan, Longitudinal landform, Wedge-shaped landform, Tower
Low-relief mountain			Aeolian accumulated	Shifting compound	Compound chain middle mega-dune, Complex starlike chain middle mega-dune, Complex starlike middle mega-dune with barkhans

In the hill categories, the aeolian accumulated types of fixed micro-morphology include coppice, nest shaped and longitudinal dunes. The semi-fixed types of micro-morphology include coppice, nest shaped, honeycomb, parabolic, longitudinal, honeycomb longitudinal, and dendritic dune, and compound dune chains. The shifting types of micro-morphology include crescent sand ridges and dune chains, lattice dunes and dune chains, scaly dunes, crescent sand ridges, linear sand dunes, featherlike longitudinal dunes, star dunes and dune chains, star dunes and longitudinal dunes. The shifting compound types of micro-morphology include compound dunes and dune chains, compound longitudinal dunes, compound dome shaped dunes, compound chain dunes, compound dunes with barkhans, compound starlike chain dunes, and complex starlike chain dunes. In addition, the aeolian eroded types of micro-morphology include Yardan, longitudinal landforms, wedge-shaped landforms, and towers.

In the low-relief mountain categories, types only include aeolian accumulated and shifting compound morphology, and types of micro-morphology include compound chain middle mega-dunes, complex starlike chain middle mega-dunes, and complex starlike middle mega-dunes with barkhans.

4.7 Types of morphology and micro-morphology of arid landforms

Arid landforms are distributed in northern Chinese land territories (Zhu *et al*., 1980), the basic geomorphologies of which include plains, hills, and low-relief, middle-relief and high-relief mountains, mainly located in the regions of low and middle altitudes, with only small portions located in the region of high altitudes (Figure 2 and Table 12).

Table 12 Types of morphology and micro-morphology of arid landforms

Basic morphologic types		Genetic types		Morphologic types	
First layer		Second layer	Third layer	Fourth layer	Fifth layer
Basic morphology	Altitude	Genesis	Sub-genesis	Morphology	Micro-morphology
			Salt lake		
Plain			Arid proluvial	Proluvial fan plain	
			Arid denudational	Low plain, High plain	
	Low altitude		Arid river valley		
Platform	Middle altitude	Arid	Arid proluvial	Low platform High platform	
			Arid denudational	Low platform, High platform	
Hill	High altitude			Low hill, High hill	
Low-relief mountain			Erosional-denudational		
Middle-relief mountain					
High-relief mountain					

Types of sub-genesis (third layer) of arid landforms include salt lakes, arid proluvial areas, arid denudational areas, arid river valleys and erosional denudational landforms. Types of morphology (fourth layer) include proluvial fan plains, low and high plains, low and high platforms, and low and high hills. Types of micro-morphology of arid landforms are not temporarily classified.

4.8 Types of morphology and micro-morphology of loess landforms

Loess landforms are mainly distributed in the Chinese Loess Plateau, and sporadically distributed upon the northern slopes of the Tianshan and Kunlun mountains (Zhang *et al*., 1989). The basic geomorphologies of loess landforms include plains, platforms, hills, and low-, middle- and high-relief mountains, mainly located in the regions of low and middle altitudes (Figure 2 and Table 13).

Types of sub-genesis (third layer) of loess landforms include aeolian accumulated and proluvial areas, tectonic accumulated areas, erosional alluvial landforms, and erosional ac-

Table 13 Types of morphology and micro-morphology of loess landforms

Basic morphologic types		Genetic types		Morphologic types	
First layer		Second layer	Third layer	Fourth layer	Fifth layer
Basic morphology	Altitude	Genesis	Sub-genesis	Morphology	Micro-morphology
Plain	Low altitude Middle altitude	Loess	Aeolian-accumulational and proluvial	Frontal mountain loess flatland	
			Tectonic-accumulational	Intermontane loess flatland	
			Erosional-alluvial	River low terrace	
				River valley plain	
			Erosional-accumulational	Loess inter-ridge	Unfragmented, Fragmented
				Loess terrace	
Platform	Low altitude Middle altitude	Loess	Erosional-alluvial	Loess terrace	Low terrace, High terrace
				Loess river high terrace	
			Erosional-accumulational	Loess platform	
				Loess fragmentized platform	
				Loess flat-topped ridge	
Hill			Erosional-accumulational	Loess hummock	
				long loess ridge	
				Loess mounded ridge	
				Loess mound	
				Low hill, High hill	
Low-relief mountain			Erosional-denudational		
Middle-relief mountain					
High-relief mountain					

cumulated and erosional denudational landforms. Types of morphology (fourth layer) include frontal mountain and intermontane loess flatlands, river low terraces, river valley plains, loess inter-ridges, loess terraces, loess river high terraces, loess platforms, loess fragmentized platforms, loess flat-topped ridges, loess hummocks, long loess ridges, loess mounded ridges, loess mounds, and low and high hills. Types of micro-morphology of loess landforms are classified for loess inter-ridges and loess terraces.

4.9 Types of morphology and micro-morphology of karst landforms

Karst landforms are mainly distributed in the southwestern Chinese pure limestone region, and also are sporadically distributed in other impure limestone mountain regions (Ren, 1983). The basic geomorphologies of karst landforms include plains, platforms, hills, and low-, middle-, high- and highest-relief mountains, mainly located in the regions of low and middle altitudes, with only small portions located in the region of high and highest altitudes (Figure 2 and Table 14).

The plain types of sub-genesis (third layer) of karst landforms include depositional, solutional alluvial, solutional depositional and solutional erosional landforms. The other types of sub-genesis of karst landforms relate to limestone purity, and include solutional erosional and erosional landforms. Types of morphology (fourth layer) include low and high platforms,

Table 14 Types of morphology and micro-morphology of karst landforms

Basic morphologic types		Genetic types		Morphologic types	
First layer		Second layer	Third layer	Fourth layer	Fifth layer
Basic morphology	Altitude	Genesis	Sub-genesis	Morphology	Micro-morphology
Plain	Low altitude	Karst	Depositional Solutional alluvial Solutional depositional Solutional erosional		
Platform	Middle altitude		Solutional erosional Erosional	Low platform, High platform	
Hill	High altitude		Solutional erosional Erosional	Low hill, High hill	
Low-relief mountain Middle-relief mountain High-relief mountain Highest-relief mountain	Highest altitude		Solutional erosional Erosional		

and low and high hills. Types of micro-morphology (fifth layer) of karst landforms are not temporarily classified.

4.10 Types of morphology and micro-morphology of volcanic-lava landforms

Volcanic and lava landforms mainly developed during the late Cenozoic, and mostly are distributed in three provinces of Northeast China, east of the Inner Mongolia Plateau, north of Shanxi, Jiangsu, Zhejiang, Guangdong, Hainan provinces in the southeastern China, Taiwan, west of Yunnan Province and north of the Qinghai-Tibet Plateau. Almost no volcanic deposits are preserved in the hinterland of mainland China (Liu, 1999).

The basic geomorphologies of volcanic and lava landforms include plains, platforms, hills, and low-, middle-, high- and highest-relief mountains, mostly located in the regions of low and middle altitudes, with only small portions sporadically located in the plateaus or mountains of high and highest altitudes (Figure 2 and Table 15). The plain types of sub-genesis (third layer) of volcanic and lava landforms include erosional denudational, arid, glacial and periglacial landforms. Types of morphology (fourth layer) include low and high platforms, and low and high hills. Types of micro-morphology (fifth layer) of volcanic and lava landforms are not temporarily classified.

Table 15 Types of morphology and micro-morphology of volcanic-lava landforms

Basic morphologic types		Genetic types		Morphologic types	
First layer		Second layer	Third layer	Fourth layer	Fifth layer
Basic morphology	Altitude	Genesis	Sub-genesis	Morphology	Micro-morphology
Plain Platform	Low altitude	Volcanic-lava	Erosional-Denudational	Low platform, High platform	
Hill	Middle altitude		Arid	Low hill, High hill	
Low-relief mountain Middle-relief mountain	High altitude		Glacial		
High-relief mountain Highest-relief mountain	Highest altitude		Periglacial		

4.11 Morpho-structural geomorphologic types

According to scope, area, and mapping scale, most morphologic types can be classified as morpho-structural landforms, including solitary polygon, solitary linear and solitary point types (Institute of Geography, 1987a, 1987b; Zhou, 2006; Li *et al*., 2009). Table 16 presents all morpho-structural landforms. There are about 300 types, including 105 types of solitary point landforms, 144 types of solitary linear landforms, and 50 types of solitary polygon landforms. These morpho-structural landforms types can be added or reduced according to the mapping demands, and some can transform into morpho-genetic types with the scale expanding, so, these landforms types can be expressed in the national primary scale of 1:1,000,000 in China.

5 Conclusions and discussion

This research presents a standardized classification method of digital geomorphology for China, which combines characteristics of morphology with genesis, exogenic with endogenic forces, and all forces are divided into 15 major categories. Among them, 12 types are endogenic forces including marine, lacustrine, fluvial, loess, karst, glacial, periglacial, aeolian, arid, artificial, biological and other forces; and three are exogenic forces including volcanic and lava, gravitational and tectonic types.

According to characteristics of distribution, shape, size, importance and mapping methods for the different geomorphologic types, and vector data management methods in ArcGIS, the 15 major genetic categories can be divided into two categories, i.e. morpho-genetic and morpho-structural landforms. Polygons patches are used to manage the morpho-genetic geomorphologic types in ArcGIS, and solitary points, lines and polygons together are used to manage the morpho-structural geomorphologic types in ArcGIS. Among the 15 force categories, the artificial, biological, tectonic, gravitational and other landform are usually described by simple morpho-structural types based on solitary points, lines and polygons. The other 10 categories of genetic types possess both morpho-genetic and morph-structural geomorphologic types. Thus, all geomorphologic types of different forces can be managed in ArcGIS.

The classification method of digital morpho-genetic geomorphologic types are divided into seven layers, i.e. basic morphology and altitude, genesis, sub-genesis, morphology, micro-morphology, slope and aspect, material and lithology. Among them, the former three layers are the fixed items, and the latter four layers are reference items, which are changeable according to actual geomorphologic mapping. The digital classification method constitutes a combination method of matrix form based on layered indicators. The attribute of every landform type can be combined and obtained from all or some of the seven layers. The layered classification method can meet the demands of scale-span geomorphologic mapping for the national primary scales from 1:500,000 to 1:1,000,000. The layers, serving as classification indicators, can be added and reduced according to mapping demands, which have flexible expandability.

The classification indicators and calculation methods of the basic morphology were detailed herein, including relief amplitude and altitude, slope and aspect based on DEMs. Also presented herein were the morphologic and sub-morphologic landforms of morpho-genetic types, such as marine, lacustrine, fluvial, glacial, periglacial, aeolian, arid, loess, karst, vol-

Table 16 Morpho-structural types of all genetic landforms

Genetic types	Solitary polygons types	Solitary linear types	Solitary point types
Marine landforms (M)	Lagoon, Rock beach	Shell ridge, Relict shell sand ridge, Tidal inlet, Paleo-shoreline, Coastal bar, Marine sand dyke, Marine sand spit, Transgression line, Marine cliff, Beach rock, Plain coast, Forward accumulation shore, Erosional coast, Delta coast, Stable coast, Sandy coast, Lava platform coast, Hill lough coast, Mountain lough coast, Suspended load flow, Bed load flow, Direction of sediment-load current, Direction of alongshore sea current, Spring tidal delta, Rise-fall tidal current	Shell ridge, Marine sand spit, Sea cave, Marine arch, Marine erosional platform, Marine erosional stone teeth, Sea stack
Lacustrine landforms (L)	Lakes	Paleo-lakeshore line, Lakeshore receded terrace, Lacustrine sandspit and gravel dike, Lacustrine sand dike, Lacustrine gravel dike, Lacustrine bank, Lacustrine terrace steep ridge, Lacustrine erosion bank, Lacustrine erosion's cliff	Small river and lake delta, Lacustrine sand spit, Lake erosional pillar, Lake erosional hole
Fluvial landforms (F)	Alluvial-pluvial fan plain, Ancient shoal on estuary, Pluvial fan plain, Debris flow fan, Shallow dissected river gully, Deeply incised river gully, Oxbow lake wash, Bulrush wash, Grass wash, Salina, Swamp	Colgully, Gully, Gully or young gully, Dry river gully, Ravine, Paleo-channel, Steep bank of river terrace, Steep bank front of terrace-platform, Flat-floored gully, Wide and shallow U-shaped gully, Narrow V-shaped gully, Mouth bar, Flat-floored valley, Steep cliff and steep slope on piedmont, Deeply incised glen, Canyon, Wide-bottom valley, Narrow gorge, Natural levee	Slope collapse, Alluvial-pluvial fan plain, Abandoned Yellow river mouth, Steep bank of river terrace, Knick point, Fluvial monadnock, Debris flow fan, Rapids, Meandering channel ridge
Glacial landforms (G)	Glacial gravel ridge, Paleoglacier, Glacial relic platform, Glaciofluvial relic terrace, Current glaciers	Glaciated trough, Glacial gravel ridge, Paleoglaciated trough valley, Arete, Modern snow line	Glacial lake, Cirque, Glacial gravel ridge, Paleoglaciated trough, Paleocirque firn basin, Horn, Arete, Contemporary cirque, Firn basin, Hanging valley, Drumlin
Periglacial landforms (P)	Permafrost marsh, Solifluction fan slope	Low limit of permafrost, Snow-eroded trough valley, Asymmetric valley located at the edge of snow	Involution mud, Frost mound, Permafrost marsh, Frost mound, Thermal lake basin, Thaw slumping, Solifluction terrace, Ice wedge and frost wedging relic, Rock glacier, Rock field, Rock stream, Clastration stream, Avalanche chute, Snow-scoured hollow, Rock slope
Aeolian landforms (E)	Coast sand dune and Aeolian sand land, Sand land, Sand hill and sand land, Sand dune	Prevailing wind	Wind erosional tower, Wind erosional Yardan
Arid landforms (A)	Cracked land, Salt crust land, Salt marsh, Salinization ground	Wind-erosional cliff, Dry gully, Dry valley	Ventifact, crack dried mud
Loess landforms (H)	Loess tableland top, Gully slope with mainly terrace area	Loess gully, Loess dry gully, Loess river gully, Loess ridge, Loess ridge top	Loess kettle depression, Loess hole, Loess bridge, Loess column, Loess tower
Karst landforms (K)	Peak cluster depression, Peak forest depression, Karst depression, Doline, Solution depression	Subterranean river, Karst valley, Blind valley	Penetrated cave, Exit and entrance of subterranean river, Peak cluster, Peak forest, Residual peak, Doline, Sinkhole, Cave, Clint-grike, Solution depression, Shaft, Earth forest
Volcanic-lava landforms (V)			Crater, Volcanic cone, Volcanic cone of crater lake, Volcanic cone of caldera, Volcanic of integrated crater, Caldrea, Lava stone ball, Lava depression, Mini-type lava platform
Graviational landforms			Rock fall, Talus, Landslide, Debris flow, Collapse

To be continued

Continued

Genetic types	Solitary polygons types	Solitary linear types	Solitary point types
Tectonic landforms	Fault triangle plane, Fault basin, Fault plain	Belt of plate junction, Anticlinal mountain ridge, Monohedral ridge, Monoclinal cliff, Earth junction and fracture zone, Earthquake crack, Fault, Fault cliff, Fault and insidious fault, Triangle fault plane, Fault scarp, Fault cliff and fault triangle plane, Fault basin, Tectonic dome hill, Geodesic faults, Conjectural faults, Synclinal ridge, Cenozoic depression, Cenozoic arched	Triangle fault plane, Fault scarp, Mesa, Dome summit
Artificial landforms	Pool, Artificial aquafarm, Reservoir, Saline basin	The Great Wall, Sidewall ruins of Genghis Khan, Levee, Sea dyke, River dyke, Karez	Port, Beach, Fossil excavation area, Well, Karez, Strip mine, Wharf
Biological landforms	Mangrove beach	Coral beach and coral reef, Fringing reef	
Other genetic landforms	Danxia, Planation surface	Steep ridge, Swell ridge, Rounded ridge, Tapering ridge line, Abutment ridge, Flat ridge, Inclined planation surface, Dome-shaped ridge line	Residual peak, Monadnock, Danxia, Granite peak, Monadnock, Shape peak, Mammoth and wooly rhinoceros fossil location, Rounded peak, Spring, Hot well, Mountain peak, Thermal spring

canic and lava landforms. The solitary polygon, linear and point approaches to characterize the 15 categories of morpho-structural landforms also were outlined.

In the 1980s, Loess and Karst landforms types were regarded as special material-related categories (Institute of Geography, 1987a 1987b), they did not belong to exogenic or endogenic forces, so, in this research, they can be divided into water-related forces categories.

This layered classification system was used during the course of the research and compilation of the geomorphological atlas of the People's Republic of China, and the classification method and indicators of Loess landforms referred to the research results (Zhang *et al*., 1989), which presented the erosional and accumulational characteristics in detail, so the classification system of Loess landforms is detail, layered indicators can be synthesized to meet demand of soil and water conservation in Loess Plateau in the future.

The classification method research is continually challenging with respect to the problem of how to embody the characteristics of morphology and genesis, as well as exogenic and endogenic forces, and how to classify and extract indicators. Hence the discipline requires additional future research, with each researcher modifying models according to his or her own interest and particular emphasis.

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