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# Landslide Developmental Characteristics and Response to Climate Change since the Last Glacial in the Upper Reaches of the Yellow River, NE Tibetan Plateau

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**Abstract: The upper reaches of the Yellow River in northeastern Tibetan Plateau are geohazards areas. The evolution of the Yellow River, chronology of some landslides, and spatiotemporal distribution characteristics of super large scale and giant landslides within the region are summarized using paleoclimate evidence, and the relationship between the intensive landslide period and climatic changes since the Last Glacial period is analyzed. It is concluded that (1) Super large scale and giant landslides are distributed widely within the region, particularly in the Qunke-Jianzha basin. (2) The chronological sequence of landslides is established by dating the slip zones of landslides and analyzing the relations between landslides and their overlying or underlying loess formations. Five landslide development periods are determined: 53–49 ka BP, 33–24 ka BP, 10–8 ka BP, 5–3.5 ka BP, and the present. (3) These correspond closely to warm and wet periods during the last 100,000 years, i.e., two weak paleosol development stages of Malan loess deposited during the last Glacial period in the Chinese loess Plateau, $L_{1-4}$ and $L_{1-2}$ that belong to the marine oxygen isotope stage 3, the last deglacial period, the Holocene Optimum, and the modern global warming period. (4) Landslide triggers may be closely linked to warm and wet periods related to rapid climatic transitions.**

**Key words: landslide, developmental characteristics, climate change, upper reaches of the Yellow River, response**

## 1 Introduction

The response of landslide development to paleoclimate change is a focused issue among scientists from various countries, and has been critical for geological disasters (Burbank et al., 1996; Mauro et al., 2004; Farrokh et al., 2006; Yin et al., 2010). Climatic implications on landslide recurrence have been reported in China, Argentina, Austria, Great Britain, Italy, Poland, Spain, and Switzerland (Alexandrowicz, 1993, 1997; Ibsen et al., 1997; Lateltin et al., 1997; Margielewski, 1998; Starkel, 1997; Flageollet et al., 1999; Mauro et al., 2004; Chen et al., 2005; Armelle et al., 2006; Ding et al., 2006; Geertsema et al., 2006; Yin et al., 2010). In documents from the 1970s and 1980s, specific types of landslides were described and ascribed to specific climatic conditions. It was indicated that climate change had influenced, either directly or indirectly, the occurrence of mass wasting processes (Lan et al., 2003). Scholars concluded that since the Late Glacial period, intensive landslide developmental periods were concentrated mainly during interglacial warm and humid climatic phases and periods of extreme rainfall. Other researches focused on the development of landslides related to meltwater, geological effects of glacial processes, coastal erosion and climate change, as indicated by landslide activity events (Wen et al., 2005; Long et al., 2008; Zhang et al., 2013; Zhu et al., 2013).

Due to intense tectonic deformation and climate fluctuations, the upper reaches of the Yellow River, located in the northeastern (NE) Tibetan Plateau, became a geologically disaster-prone region where numerous landslides, debris flows, and other geological phenomena occurred (Zhang et al., 2000; Yin et al., 2010). Recently, large and deep-seated landslides have been recognized

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within this region, and many super large scale and giant landslides have been identified based on their huge volume and size, wide distribution, the severe damage and the complexity of their dynamic mechanisms. It represents a significant hazard to mountain communities because of the loss of lives and the damage of infrastructures (Qiao et al., 2000; Yan et al., 2000; Huang, 2003, 2009; Qin et al., 2012). Recently, primary investigations into geological disasters within the region were concluded, which provided basic data for each landslide, including length, width, thickness, residual volume, elevation and type. Furthermore, some important landslides were dated to reveal specific landslide development periods.

This paper focuses on the super large scale and giant landslides in the region that were triggered by climate changes (rainfall and moisture). Based on regional paleoclimatic, active tectonics and landslide chronology, the temporal characteristics of intensive landslide development since the last glacial are identified and discussed, and the relationship between major landslides activities and climate change is analyzed.

## 2 Geological Settings

### 2.1 Geomorphology

The study area is located in the upper reaches of the Yellow River in the NE Tibetan Plateau, which is a transition zone between the Tibetan Plateau and Chinese Loess Plateau. It lies between the geographic region of the Animaqing Mountain (6282 m) and the Guanting basin (1750 m). The Yellow River has wound along canyons from west to east since the middle Pleistocene period. In the region the Jishixia gorge was cut apart by the “Kunlun-Yellow River tectonic movement” since 1.1 Ma BP, then was eroded in traceability towards, when the 0.06 Ma BP and 0.015 Ma BP(Cui et al., 1997, 1998), the Songbaxia gorge and Longyangxia gorge were cut apart respectively due to the “Republican movement”. The topography is shown in Figure 1, and the region consists of a series of basins (i.e., the Gonghe, Guide, Qunke-Jianzha, Xunhua, and Guanting basins) and gorges (i.e., the Longyangxia, Laxiwaxia, Lijiaxia, Gongboxia, and Jishixia gorges). The difference in altitude of the mountain slopes is usually in excess of 900 m. With the continuous uplift of the Tibetan Plateau and the continuing erosion of the Yellow River valleys, a lot of extensive development of high and steep slopes had formed and resulted in the occurrence of super large scale and giant landslides due to free space in the front leading edge since the late Pleistocene.

### 2.2 Stratigraphy

The species of stratigraphic outcropping within the region are diverse, including pre-Neogene strata of the Proterozoic, Paleozoic, Devonian, Carboniferous, Permian, Triassic, Jurassic, and Cretaceous, and the Paleogene and Neogene strata have a widest distribution (Li et al., 2011). The lithology comprises mainly red mudstone, sandstone, siltstone, and conglomerate, which are distributed mostly within the gorge areas. Across the entire area, the Tertiary mudstone is the predominant slip-prone stratum, which is located in the Xunhua, Qunke-Jianzha, and Guide basins. The Quaternary strata are distributed mainly within the Gonghe basin, with few in some other river valleys and mountain basins (Fig. 2), and the loess of the Quaternary strata is shallow and represents another slip-prone stratum within the region.

### 2.3 Geotectonics

The development of geotectonically active faults is due to the strong compressional deformation effects of the Tibetan Plateau and there are many major faults aligned NWW–NW (290–310°) and NNW (330–345°). These structures include folds of regional or local extent and the Lajishan–Jishishan Mountain fault and west Qinling fault are the largest faults within the region. Evidence of neotectonic movements of the Guanting and Qunke-Jianzha basins (i.e., earthquakes, reverse or strike-slip faults) has been found and these movements might possibly be attributed partially to landslides formation since the late Pleistocene. Generally, geomorphological features are related strictly to the underlying geological structure of the slopes. Morphostructurally, the uplift of the Tibetan Plateau and the subsequent erosion processes of the Yellow River have led to the burial of previous geological structures and thus, they have largely defined the present landscape. Particularly prominent within the study area are landforms due to slope movements. Ancient and more recent tectonic stresses have obviously caused movement of rock masses prone to landslide. To some extent, the internal dynamical geological conditions have enhanced the development of landslides caused by intense tectonic activity.

### 2.4 Paleoclimatic change

The paleoclimatic records of the Guliya ice core of the Tibetan Plateau and the Malan loess of the Loess Plateau are considered similar to that of the upper reaches of the Yellow River, as they have all undergone similar climatic changes in NW China. Therefore, it is possible to carry out a comparative analysis on the temporal distribution of landslides within the region, to identify possible relations between landslides and climate changes occurring in the late interglacial and Holocene periods. Although paleoclimatic studies within the region are lacking, the

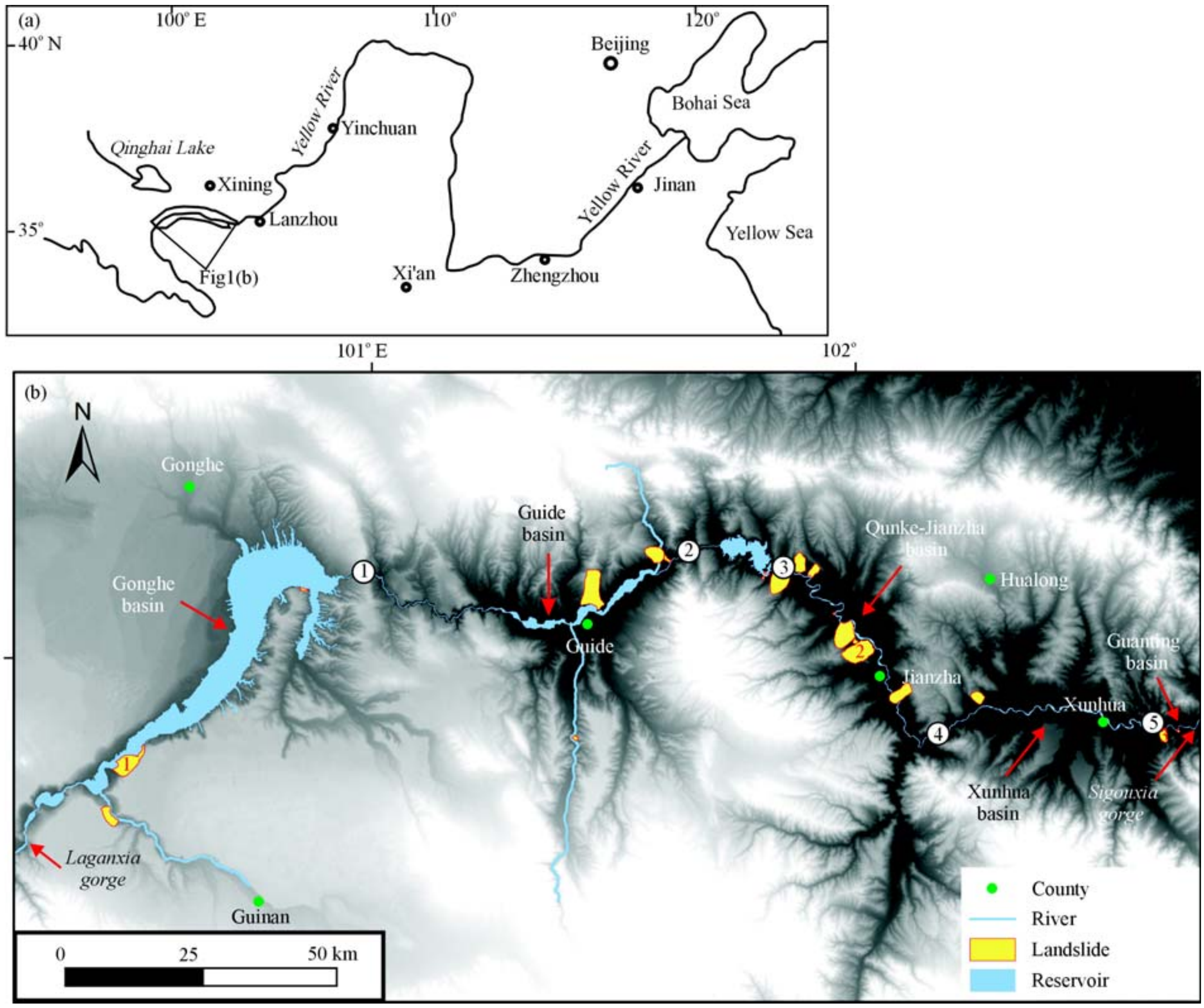


Fig. 1. Location and geomorphological sketch of the study area

(a), Location of the study area of the Yellow River; (b), Map of geomorphology and landslide distribution. 1, Baicitan landslide; 2, Xiazangtan landslide; 3, Gelongbu landslide; ①, Longyangxia gorge; ②, Songbaxia gorge; ③, Lijiaxia gorge; ④, Gongboxia gorge; ⑤, Jishixia gorge

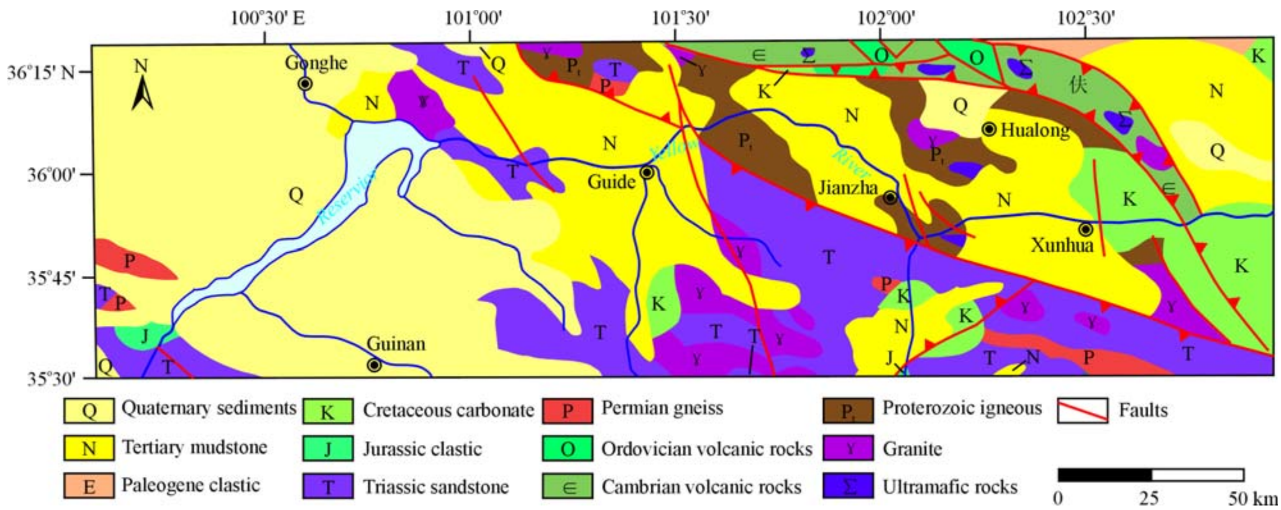


Fig. 2. Geological and tectonic structural map of the study area (modified after geological map of Qinghai Province, 2005)

sequence of climatic changes induced by regional and global events during this period may be considered similar to those reconstructed by other authors for the Tibetan and Loess Plateaus.

For the purpose of this research, the climatic frames presented mainly by the Guliya ice core (Thompson et al., 1997; Yao et al., 1997) and SPECMAP (Imbrie et al., 1984) are used. In short, these results show that following the marine isotope stage (MIS)-5a, peak warm period occurred between 80,000 and 75,000 cal BP, when the temperature was higher than the modern climate by about 3 °C. Commencing at about 40,000 cal BP, a subsequent increase of precipitation occurred, followed by a period in the NE Tibetan Plateau with temperatures about 2–4 °C higher than present, which is equivalent to the late MIS-3 of the last glacial period. Finally, at around 10,000 cal BP (the boundary of the last glacial and the Holocene), a sudden climatic change occurred, causing a considerable increase in both precipitation and temperature (Fig. 3). In response to the rising temperatures, the plateau produced a large amount of glacial meltwater which caused significant erosion to both sides of the Yellow River.

## 3 Landslide Developmental Characteristics

Over 20 super large scale and giant landslides, differing in type, size, and degree of activity have been identified and mapped in the upper reaches of the Yellow River (Yin et al., 2013a). Because of the influence of topography, lithology, active tectonics, climate change, and other environmental factors, the landslide distribution displays an imbalance within the region. For example, landslides are located on both sides of the main stream of the Gonghe, Guide, Qunke–Jianzha, Xunhua, and Guanting basins, but they are more prevalent on the south bank than on the north. The reason behind this phenomenon is the difference in lithology. Another characteristic within the region is that 70% and 56% of the super large scale and giant landslides are distributed on concave banks and river bends of the Yellow River, respectively, which is because of lateral erosion by the river and canyon bedrock topography.

Field surveys have suggested that most of the super large landslides occurred in Tertiary mudstones, which provides a wealth of material conditions suited to landslide development. Recently, it was established that landslide masses found within the study area are attributable mainly to the fall of mudstone and bedrock from the mountains on both sides of the Yellow River. Through drilling holes, it has been determined that some landslide masses are characterized by a thickness exceeding 100 m and a spatial extent of several square kilometers. At present, the deepest surfaces of landslides are in most cases dormant, whereas those that are more superficial are subject to recurrent reactivation.

According to statistics, landslides are distributed within the basins on both sides of the Yellow River, and the number of giant landslides (with mass residual volume greater than $1 \times 10^8$ $m^3$) is eleven, which gives a total landslide mass residual total volume of $60.96 \times 10^8$ $m^3$. The number of super large scale landslides (with mass residual volume of between $1 \times 10^7$ and $1 \times 10^8$ $m^3$) is nine (Table 1). Of all the basins, the greatest number of landslides, the largest amount of residual mass, and the largest density strength are found in the Qunke-Jianzha basin, which is composed mainly of Tertiary mudstone.

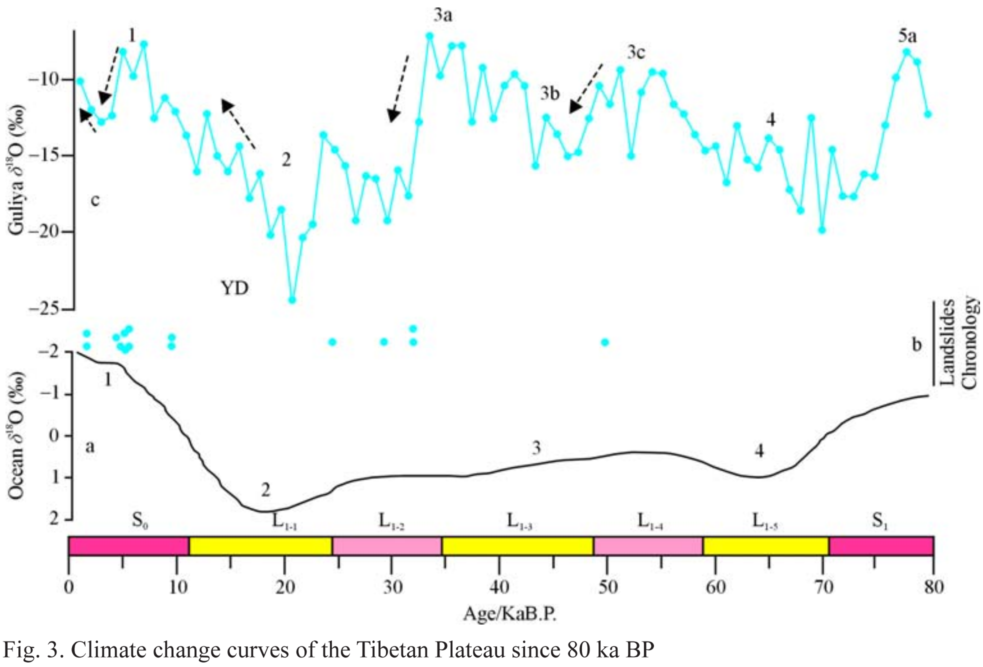


Fig. 3. Climate change curves of the Tibetan Plateau since 80 ka BP

(a), Marine oxygen isotope curve (Imbrie et al., 1990); (b), Landslide chronology; (c), Guliya ice core curve (Yao et al., 1997). $S_0$ and $S_1$ are the Holocene paleosol and late Pleistocene soil layers respectively; $L_{1\text{-}1}$, $L_{1\text{-}3}$, and $L_{1\text{-}5}$ are the loess layers; $L_{1\text{-}2}$ and $L_{1\text{-}4}$ are the poorly developed soil layers (Qin et al, 2008)

**Table 1 Statistics of super large and giant landslides in the upper reaches of the Yellow River**

| ID | Landslide name | Location | Longitude | Latitude | Average elevation/m | Relative elevation/m | Residual mass volume /×$10^8$$m^3$ | Average angle of slope/° |
|---|---|---|---|---|---|---|---|---|
| H1 | Mangla river | Gonghe basin | 100°26′18″ | 35°43′56″ | 2956 | 418 | 1.20 | 42 |
| H2 | Baicitan | | 100°30′07″ | 35°49′11″ | 2862 | 538 | 2.84 | 40 |
| H3 | Chana | | 100°48′49″ | 36°05′38″ | 2723 | 350 | 1.27 | 35 |
| H4 | Ashigong | Guide basin | 101°34′01″ | 36°09′07″ | 2570 | 556 | 1.60 | 40 |
| H5 | Xijitan | | 101°27′06″ | 36°03′44″ | 2472 | 240 | 8.40 | 30 |
| H6 | Tangsecun | Qunke-Jianzha basin | 101°48′55″ | 36°05′27″ | 2525 | 790 | 1.20 | 35 |
| H7 | Quhetankou | | 101°56′12″ | 36°00′28″ | 2180 | 700 | 0.17 | 51 |
| H8 | Kangyang | | 101°57′20″ | 36°00′05″ | 2365 | 715 | 10.60 | 42 |
| H9 | Xiazangtan | | 101°58′51″ | 36°08′51″ | 2358 | 300 | 15.05 | 30 |
| H10 | Zhihuqiedong | | 102°03′45″ | 35°54′36″ | 2153 | 608 | 0.10 | 20 |
| H11 | Shengguotan | | 101°53′12″ | 36°06′32″ | 2239 | 730 | 0.48 | 30 |
| H12 | Xiaqiongsi | | 101°53′46″ | 36°06′04″ | 2450 | 300 | 0.35 | 30 |
| H13 | Lannitan | | 101°58′58″ | 35°59′55″ | 2164 | 372 | 0.86 | 20 |
| H14 | Suozi | | 102°03′41″ | 35°54′40″ | 2040 | 250 | 13.55 | 48 |
| H15 | Shange | Xunhua basin | 102°32′53″ | 35°46′43″ | 2050 | 400 | 1.08 | 25 |
| H16 | Chaligang | | 102°21′12″ | 35°53′57″ | 2175 | 500 | 0.39 | 25 |
| H17 | Tangjiakatan | | 102°14′20″ | 35°14′20″ | 2200 | 305 | 2.40 | 30 |
| H18 | Mengda | Jishixia gorge | 102°38′19″ | 35°49′48″ | 1945 | 250 | 0.16 | 18 |
| H19 | Gelongbu | | 102°36′45″ | 35°49′46″ | 1980 | 875 | 1.19 | 51 |
| H20 | Badashan | Guanting basin | 102°55′03″ | 35°22′05″ | 2075 | 350 | 0.66 | 35 |

Several large scale uplifts of the Tibetan Plateau and the erosive activity of the Yellow River have led to the abundance of high and steep slopes within the region, which provide plenty of scope for topographically induced landslide formation. Furthermore, the rift-basin sedimentary red clays of the Paleogene and Neogene afford a wealth of material conditions suited to landslide development.

Our analysis shows that the morphological spatial distribution of landslides can be divided into eight categories: round-backed armchair-like and semi-elliptical shaped, dustpan shaped, dumbbell shaped, tongue shaped (including long tongue, rectangular, mat, stepped shape), saddle shaped, long-arc shaped, and triangular shaped. For example, the flat patterns of the Xiazangtan and Kangyang landslides look like armchair and semi-elliptical shapes, respectively (Fig. 4). The length and width of landslides are generally about 1500–2500 m; however, the length and width of the landslide masses are extended in different directions. The thicknesses of landslides are commonly more than 25 m. The average elevations of the landslides are mainly between 2400 and 2800 m, and the relative elevation differences between the front sheer opening and the back trailing edge are about 300–700 m with a peak of 875 m. The highest concentration of the average slope angle is about 15–25°, and a good linear relationship exists between the average slope angle, relative elevation difference, and the length of landslide mass.

Another characteristic of most ancient and old landslides is that the sliding distance is great, representative of high-speed remote landslides, which blocked the Yellow River, leaving a large amount of landslide residual mass on the other side (Wu et al., 2009), e.g., the Gelongbu landslide (Fig. 5a) located in the Jishixia gorge and the Suozi landslides located in the Qunke-Jianzha basin.

## 4 Landslide Chronology within the Region

The landslide chronology within the study area since the interglacial period at 79900±6000 a B.P. has been studied (Zhou, 2010). The basins and valleys of the Yellow River have been affected by several landslide processes that have changed the morphological features significantly. Research performed in recent years has led to the typological and chronological characterization of the various landslides found within the region (Yin et al., 2013b).

### 4.1 Landslide chronology: method and results

The best method for determining landslide developmental chronology is to obtain samples from the sliding zone soil. The China Geological Survey undertook many engineering geological drilling borings in several landslides, e.g., the Xiazangtan and Shengguotan landslides, to acquire samples from the sliding zone soils, and then determined the chronology using optically stimulated luminescence (OSL) or electron spin resonance (ESR). However, the thicknesses of most landslide masses within the study area are huge and the landslide sliding zone soils cannot be obtained directly. Therefore, indirect methods (Fig. 6) were used to infer the ancient or old landslide developmental periods. For example, the method of superimposing the relationship between the overlying and underlying loess and the landslide mass was used, whereby chronology samples were obtained from the loess located at the bottom or top of landslide mass. Moreover, samples of sediments were found in the bottom of

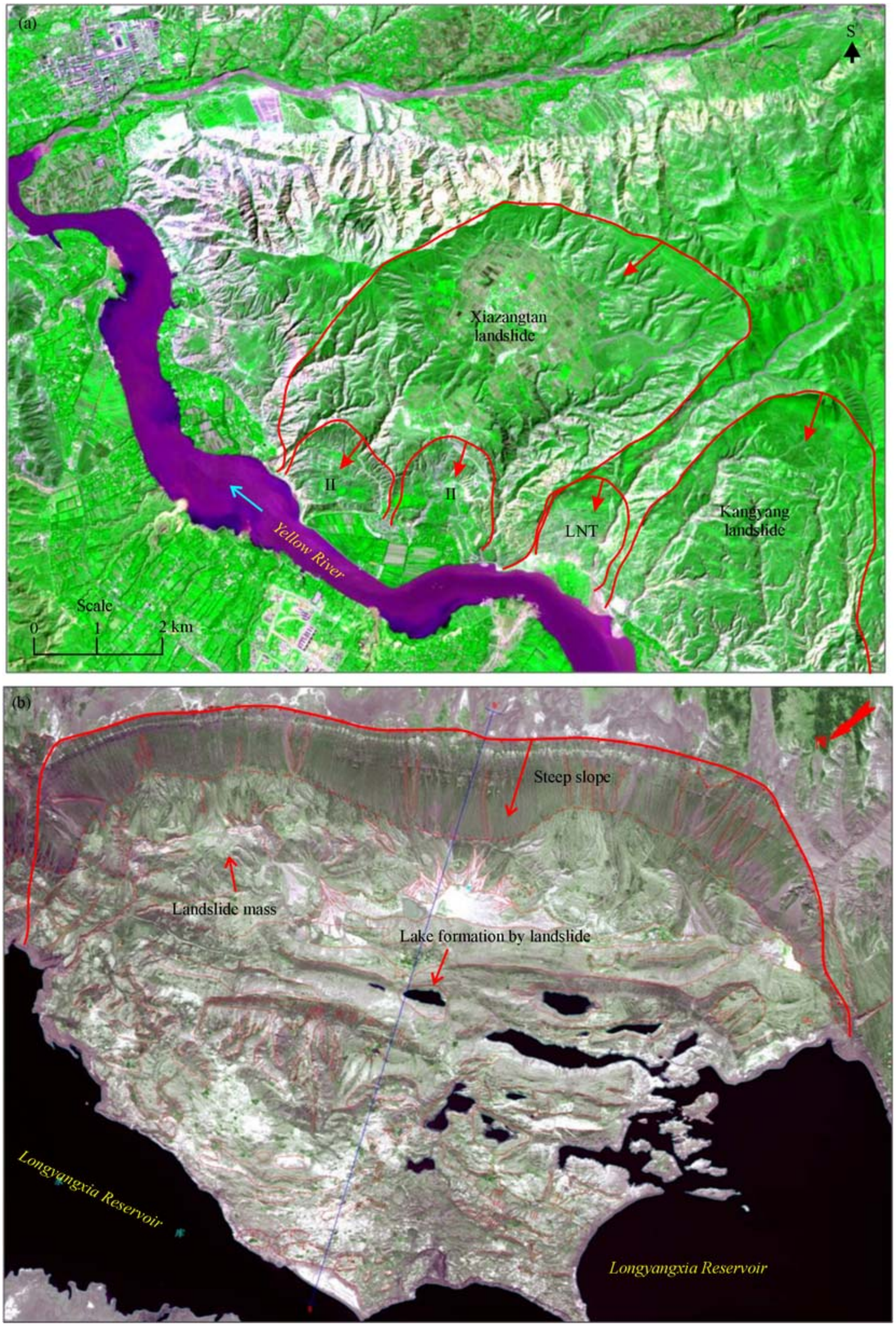


Fig. 4. Remote sensing of landslides and representative flat patterns

(a), The ZY-1 02C image of the Xiazangtan landslide (first phase) and front edges of two sub-scale landslides (second phase), the Kangyang landslide, and Lannitan landslide (LNT). The flat pattern of the Xiazangtan landslide (first phase) and Kangyang landslide appear as armchair and semi-elliptical shapes; we define their patterns are round-backed armchair-shaped and semi-elliptical, respectively; (b), QuickBird image of Baicitan landslide. The back trailing edge is very steep and the landslide mass relatively flat. The entire mass gives the appearance of a dustpan, so we called this the dustpan pattern. The red lines and arrows show the boundary and sliding directions of the landslide; the blue arrow shows the direction of flow of the Yellow River.

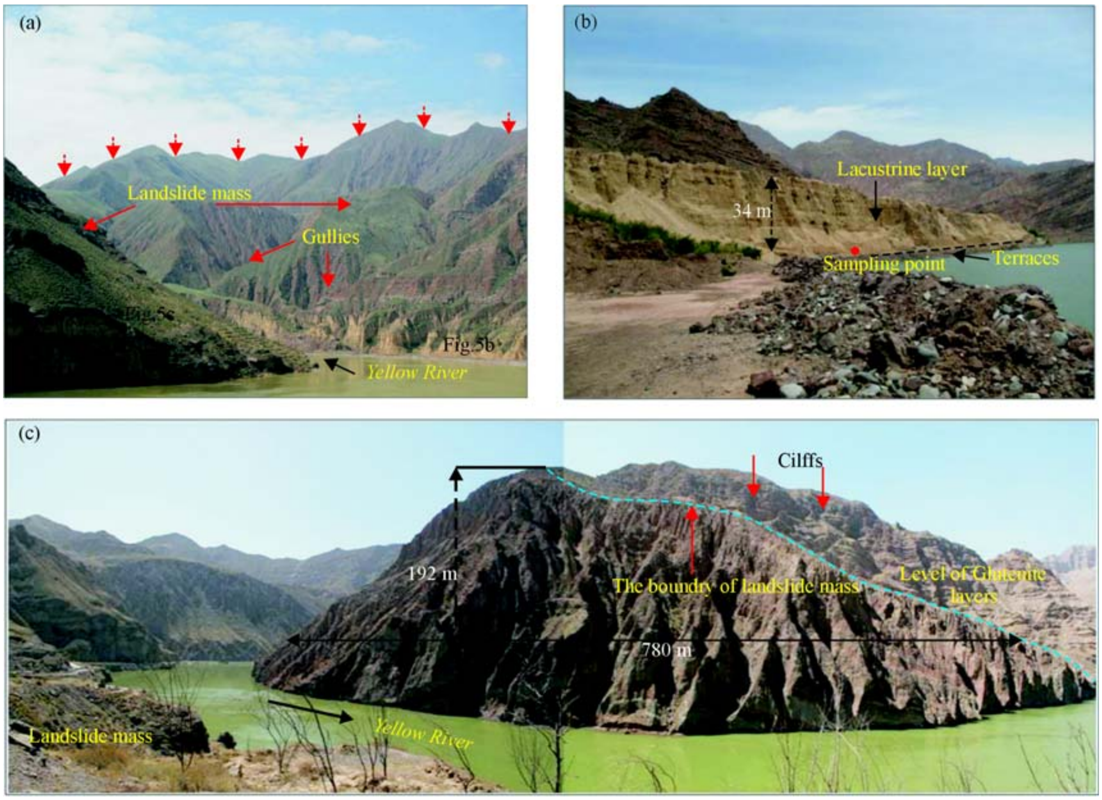


Fig. 5. View of Gelongbu landslide (April 16, 2012).
(a), Landslide mass and flat pattern on the right bank of the Yellow River. The dotted red arrows show the boundary of the landslide; (b), The sampling point is located at the bottom of Lacustrine layer and top of river terraces; (c), Landslide mass and flat pattern on the left bank of the Yellow River.

lacustrine deposits (Fig. 5b) that were the result of the damming of rivers by landslides. Because these sediments are rich in organic matter that had been buried by the landslide deposits, conventional radiocarbon dating allowed the chronological reconstruction of the mass wasting processes that occurred within the study area.

The formation and evolution of terraces on the Yellow River within the same basin generally follow similar formation processes; thus, their formation periods should be similar. If the ancient landslides are covered by the same river terraces at different locations within the same basin, then their formation ages can be inferred as approximately the same. However, in some regions, the terrace relationships are not clear because of uplift of the plateau, the Yellow River lateral erosion, or other powerful internal and external geological reasons. Therefore, the elevations of the front sheer openings of the landslides or the neighborhood terraces are used, which are known to synthesize landslide chronology. Detailed landslide investigations and dating allowed the

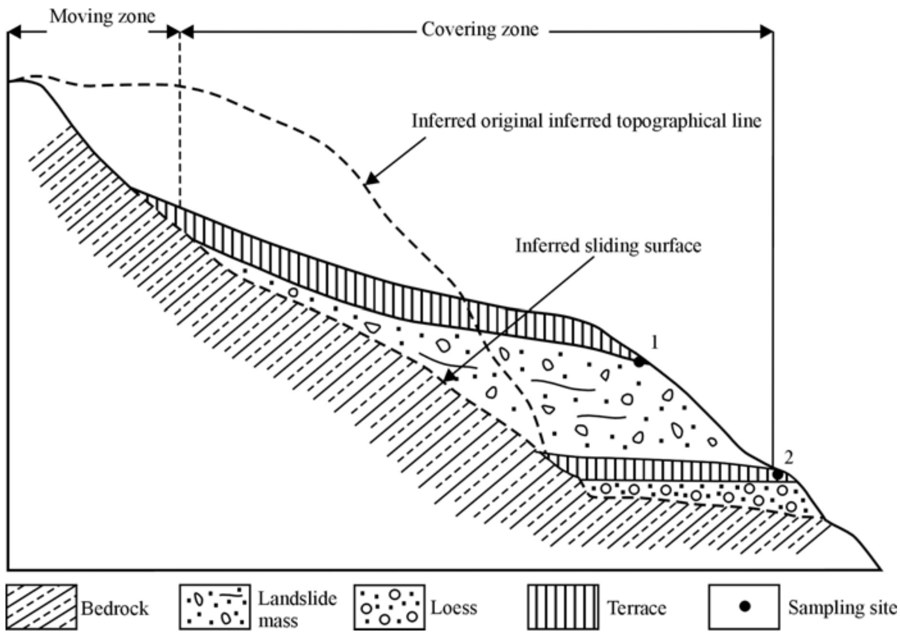


Fig. 6. Schematic of indirect acquisition of chronology samples from landslides within the study area.
1 indicates the landslide formation age before the loess sediments and 2 indicates the opposite.

geomorphological evolution of the valleys to be outlined (for landslide location and dating information, see Fig. 1 and Table 2).

The distribution of the oldest obtained ages ranges from 53,000 to 49,000 cal BP and concerns the massive mudslides, such as the Xiazangtan landslide (at present dormant), which modified the valley's morphology considerably, and some slides or flows that are still active, such as the Lannitan landslide. A significant example of a mudslide is presented by the Xiazangtan landslide, which affected the southern bank of the Yellow River around 49,000 cal BP. The landslide body was partially reactivated at 28,000 years BP. Similar evolution patterns were reconstructed for the Gelongbu landslide that is located in the Jishixia gorge. As for the Gelongbu landslide, lacustrine deposits formed after the damming of the loess were also dated. Some landslides date to the early Holocene, such as the Zhihuqiedong landslide (Zhou, 2010), which was probably originally triggered in the late Glacial period and has recurrent activity that continues to the present.

### 4.2 Landslide developing periods

Landslide chronology and results of field investigations indicate five periods of landslides development within the region:

**(1) 53–49 ka BP**

The first phase of development of the Xiaangtan landslide was established as 49,000±5000 a BP (ESR) by testing the samples of drilled sliding zone soils, which covered the forth terrace of the Yellow River. The OSL age of the Chaligang landslide, which lies in the same basin as the above, was estimated to be 53,000±4000 a BP, according to previous analysis results, and regional comparisons found many landslides that were located on the forth terrace, such as the Xiaqiongsi landslide. A comprehensive analysis of the ancient landslide age revealed an age of between 53 ka BP and 49 ka BP, which is equivalent to the $L_{1\text{-}4}$ (Loess) period of the late Pleistocene.

**(2) 33–24 ka BP**

The ESR ages of the Shengguotan and Xiazangtan landslides and the OSL ages of the Kang Yang and Tangsecun landslides were 24000±2000 a BP, 28000±2000 a BP, 33200±2500 a BP, and 32900±2400 a BP, respectively, which are all located within the Qunke-Jianzha basin. The field investigation found that these ancient landslide masses covered the third terrace of the Yellow River. Based on these ancient landslide developmental ages, it is considered that the period 33–24 ka BP was the second period of landslide activity, which corresponds to the loess-paleosol climate cycles $L_{1\text{-}2}$ of the late Pleistocene.

**(3) 10–8 ka BP**

The $^{14}C$ age of the bottom of the lacustrine layer that was caused by the Gelongbu landslide, shows that the landslide event occurred at 9100±40 a BP. Some details demonstrate that the Zhihuqiedong and Jishixia landslides occurred at 9711±35 a BP (Zhou, 2010) and 8500 a BP. Therefore, this period may represent an old landslide event, which corresponds to the transition between the last deglacial and Holocene periods.

**(4) 5–3.5 ka BP**

The OSL dates of the Xijitan second phase, Mengda, Badashan, and Zhajiao landslides were estimated as 4900±400 a BP, 3700 a BP, 4600±400 a BP, and 4572±29 a BP, respectively. Therefore, it is inferred that some old landslides may have occurred around 5000–3500 a BP, which corresponds to the Holocene Megathermal period.

**(5) Recent years**

In recent years, due to the gradual increase of human activities and consequent global warming, the already

**Table 2 Chronology and record dating of landslides in the study area**

| ID | Landslide name | Landslide type | Sample code | Sample type | Site of collection | Depth (m) | Conventional age (BP) | Paleoclimatic significance | Data source |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Shengguotan | mudstone | SGT | red clay | excavation | 35 | 24000±2000 (ESR) | low | |
| 2 | Xiazangtan I | mudstone | XZT-1 | red clay | excavation | 102 | 49000±5000 (ESR) | high | |
| 3 | Xiazangtan II | mudstone | XZT-2 | red clay | excavation | 99 | 28000±3000 (ESR) | low | |
| 4 | Lannitan | mudstone | LNT | | historical materials record | | 2005 | | |
| 5 | Kangyang | mudstone | KY | red clay | excavation | 9 | 33200±2500 (OSL) | high | |
| 6 | Xijitan | mudstone | XJT-2 | red clay | excavation | 12 | 4900±400 (OSL) | high | Zhou, 2010 |
| 7 | Tangsecun | mudstone | TSC | red clay | excavation | | 32900±2400 (OSL) | high | |
| 8 | Mengda | mudstone | MDX | wood | excavation | | 3700 | | Liu, 2008 |
| 9 | Gelongbu | sedimentation in dam lake | MRP | loess | excavation | 2.7 | 9100±40 ($^{14}C$) | high | |
| 10 | Chana | | CN | | historical materials record | | 1943 | | |
| 11 | Baicitan | semi-consolidated | BCT | wood | excavation | | 5000 (OSL) | high | Li, 2006 |
| 12 | Badashan | | BDS | red clay | excavation | 4 | 4600±400 (OSL) | high | |
| 13 | Chaligang | | CLG | | excavation | | 53000±4000 (OSL) | high | |
| 14 | Zhajiang | translational rock slide | ZJA | | excavation | | 4572±29 ($^{14}C$) | high | Zhou, 2010 |
| 15 | Zhihuqiedong | | ZHQD | | excavation | | 9711±35 ($^{14}C$) | high | |

fragile geological environment of the region has experienced serious damage. Some ancient (old) landslides have been triggered by rainfall and engineering activities, such as the Lannitan landslide that occurred on August 25, 2005 because of heavy rainfall. Another example is the Chana landslide, located in the Gonghe basin, which was activated by the freeze-thawing mechanism on February 7, 1943.

## 5 Landslide Development Periods in Response to Climate Change

Of all the factors that control the development of landslides, geomorphological change and evolution of the climatic environment, caused by the uplift of the Tibetan Plateau, were the crucial triggers within the region. The landscape change was caused by regional crustal movements and tectonic activities, which are endogenic geological processes that provide essential free space for ancient (old) landslides (Li et al., 2008). The amount of precipitation caused by climate change played a direct role in triggering landslide development.

During the late Pleistocene or the MIS-5e period in the Quaternary, the climate of the Tibetan Plateau presented a warm, humid, and severely fluctuating climate (Yao et al., 1997). The period also marked the beginning of the last interglacial period. Under the influence of this event, precipitation increased significantly, and due to the uplift of the Tibetan Plateau, river erosion in the upper reaches of the Yellow River accelerated, incising large-scale high and steep valleys that provided the free space necessary for extensive landslide development.

According to previous paleoclimatic studies of the Guliya ice cores from the ancient great lakes of the Tibetan Plateau and the $L_1$ loess stratigraphy of Weinan since 12.5 ka BP (Yao et al., 1997; Qin et al., 2009), every significant period or transition stage is associated with significant variations in precipitation and strong climatic fluctuations.

Based on the characteristics of the developmental periods of landslides and the climate change record, it is believed that the periods of landslide development are very closely related to climate change within the region since the last interglacial period. A detailed analysis is given in the following:

**(1) 53–49 ka BP**

Previous studies have suggested that the Tibetan Plateau belongs to the MIS-3a of 58 ka BP (Yao et al., 1997; Shi et al., 2002). The pollen records of western Sichuan also show extremely high temperatures about 58 ka BP (Tang 2009). Following this, the temperature began to rise and precipitation increased. The increased amount of glacial meltwater and rainfall caused unprecedented erosion of both sides of the Yellow River. The first phase of ancient landslides occurred at about 53–49 ka BP, triggered by the melting of the glaciers and the rainfall. This corresponds to the period of loess-paleosol $L_{1\text{-}4}$. The first phase of the Xiazangtan landslide, the Xiaqiongsi landslide, and the Xintan landslide located in the Three Gorges Reservoir area, also occurred during this period (Zhang et al., 2005) (Fig. 7).

**(2) 33–24 ka BP**

The weak warm stage of 33–24 ka BP was a period of high temperature and precipitation, or a “strong summer monsoon event” (Shi et al., 2002). It reveals a warm and humid climate anomaly, which is different from the Antarctic Vostok record during this period, and corresponds to the ancient landslides in the $L_{1\text{-}2}$ loess stratigraphy. In this period, precipitation increased significantly, ancient lake areas enlarged, and ancient vegetation development was equivalent in extent to that of the interglacial period. Therefore, the second phase of ancient landslides was triggered by rainfall around 33–24 ka BP. This conclusion is consistent with landslide group formation mechanisms in northwestern Argentina (Trauth et al., 1999) and the Three Gorges Reservoir area (Zhang et al., 2005) (Fig. 7).

**(3) 10–8 ka BP**

The Younger Dryas event appeared about 11 ka BP, which was the final cold event of the last glacial period, during which $\delta^{18}O$ values decreased and ice volume increased. However, 10.5 ka BP marked the end of the cold event. The temperature was warmed rapidly in the Tibet Plateau and entering the Holocene period, precipitation and glacial meltwater increased and the erosive activity of the Yellow River strengthened again. Therefore, the third phase of old landslides occurred in the early Holocene. This phase is also reflected in the United Kingdom (Ibsen et al., 1997), the Carpathians of Poland (Alexandrowicz et al., 1993, 1997), the Cantabrian Mountains of Spain (Diez et al., 1996), the Swiss Alps (Lateltin et al., 1997; Wilson et al., 2003), and the Dolomites in Italy (Mauro et al., 2004), indicating that this landslide event might have been a response to a global phenomenon (Fig. 7).

**(4) 5–3.5 ka BP**

Under the control of the warm and wet environment of the Holocene Optimum that was around 5000–3500 a BP, precipitation increased significantly, which together with the temperature and small-scale monsoon initiated some ancient landslides. During this period, landslides and debris flows developed widely across the plateau, especially giant landslides that blocked the Yellow River and formed dammed lakes. Therefore, the fourth phase of

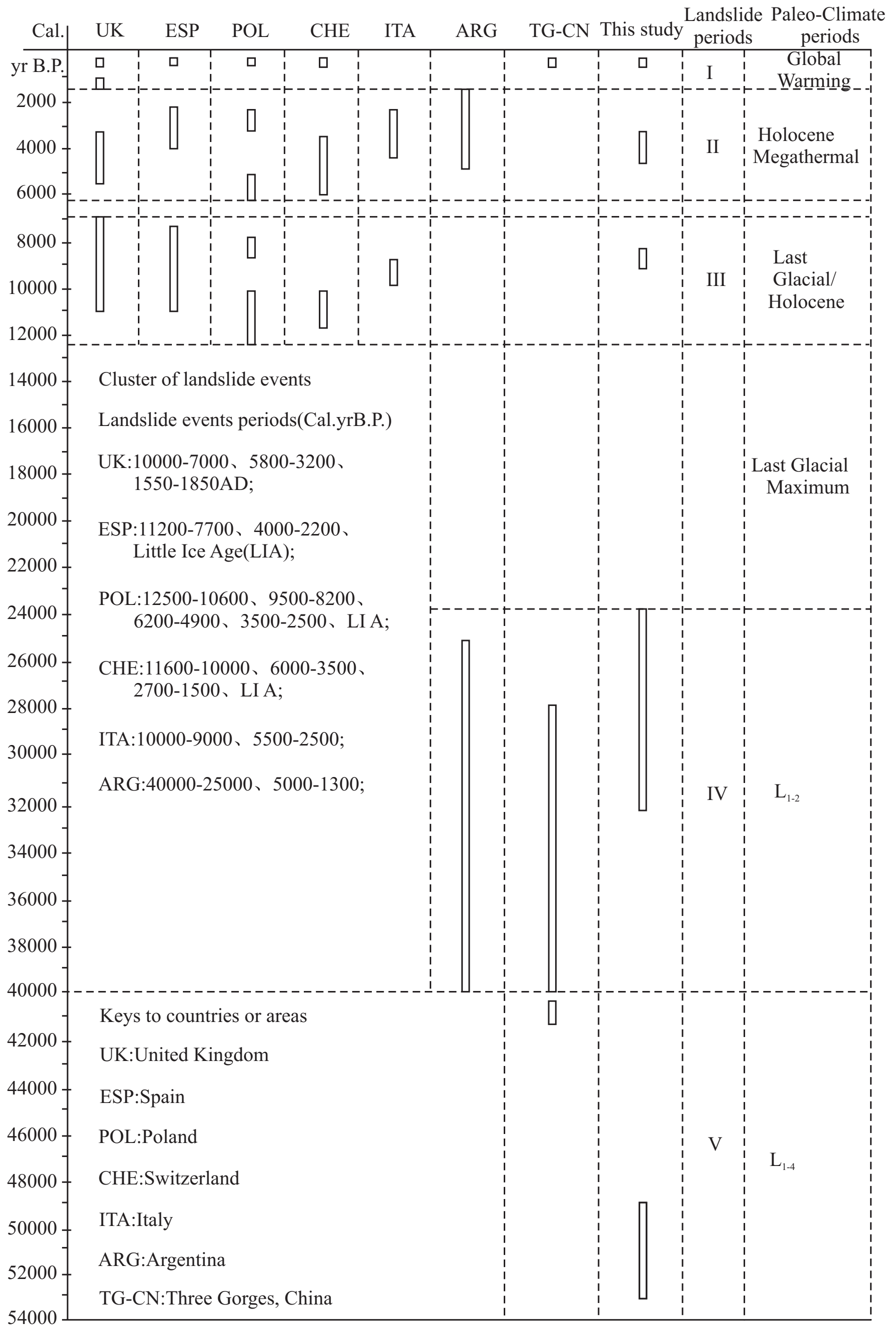

Fig. 7. Diagram of main landslide developmental stages and response to paleoclimatic periods

old landslides was triggered by climate change (Yin, et al., 2013a). Similar to the third phase, this event is also reflected in the United Kingdom, Poland, Spain, Switzerland, Italy and other places around the world (Fig. 7).

**(5) Recent years**

In recent years, landslides within in the region have been triggered by continuous rainfall, short periods of heavy rainfall, and by snow meltwater. The landslides have largely been re-disintegration or re-sliding of ancient or old landslides, such as the Chana giant landslide and the Lannitan super-large landslide.

## 6 Conclusions

In this research, based on paleoclimatic evidence, the evolution of the Yellow River, and the chronology of some landslides, together with the characteristics of the spatiotemporal distribution of super-large and giant landslides of the region, have been discussed. The relationship between the temporal occurrence of landslides and climatic changes since the Late Glacial period has been analyzed and our conclusions are as follows:

(1) The developmental characteristics of landslides within the region are presented as large-scale volumes, multiple evolution stages, and dense distributions, controlled by the uplift of the Tibetan Plateau, lateral erosion of the Yellow River, and the topography and lithology of the different sedimentary basins and gorge areas.

(2) The ESR, OSL and $^{14}C$ chronology results show that there were five phases of active landslide development within the region: 53–49 ka BP, 33–24 ka BP, 10–8 ka BP, 5–3.5 ka BP, and the present.

(3) Landslide developmental stages correspond closely to warm and wet periods during the last 100 ka, i.e., two weak paleosol developed stages of Malan loess of the Late Glacial period in the Chinese loess Plateau $L_{1\text{-}4}$ and $L_{1\text{-}2}$ that both belong to the MIS-3, the last deglacial period, the Holocene Optimum, and the present period of global warming.

(4) Factors that trigger landslides might be closely linked to global climate change, because landslides developed mainly during warm and wet climatic periods and at times of rapid climatic transition.

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