Geological background for slope failures induced by the 2008 Wenchuan earthquake

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Abstract

The 2008 Wenchuan earthquake hit the mountainous areas characterized by steep topographic gradient between the Tibetan Plateau and the Sichuan Basin. Tremendous numbers of slope failures occurred along the Longmenshan Fault Zone. They include landslide, rock avalanche, debris-flow, and rock fall. Secondary disasters still threaten the areas especially along the Yingxiu-Beichuan Fault. The rock avalanche and rock fall are dominant in the southwest of the Longmenshan Fault Zone where Proterozoic granitic and highly metamorphosed rocks are distributed, while landslide and rock avalanche are dominant in the northeast where the Sinian and Paleozoic formations including phyllite, slate, sandstone, dolomite and limestone are distributed. Secondary disasters expected in the highly damaged region along the Longmenshan Fault Zone are debris flows and rock falls. Potential areas of those disasters could be identified by their geological and topographical characteristics

Keywords : slope failure, landslide, rock avalanche, debris-flow, rock fall, earthquake

1. Introduction

The 2008 Wenchuan earthquake occurred in the Longmenshan Fault Zone which is a tectonically active zone between the Tibetan Plateau and the Sichuan Basin (e.g. Burchfiel et al., 2008[1] ; Sasada, 2008[2]). It resulted in huge disasters in the mountainous areas, for example, approximately 15,000 slope failures were triggered by the earthquake (Xie et al., 2008[3]).

The authors integrated the geological literatures on the Longmenshan Fault Zones, and visited the earthquake-affected areas several times after the earthquake. They survey the geological information relating to the earthquake disasters, and discuss the geological background for slope failures in the Longmenshan Fault Zone in this paper.

2. Geology of the Longmenshan Fault Zone

2. 1 Tectonic setting and active fault movement

The collision between continents of India and Eurasia has been affecting the tectonics of the Longmenshan Fault Zone. The upper crust of the Tibetan Plateau extrudes onto the Yangtze Craton, resulting in the several large reverse faults and some nappe structures along the Longmenshan Fault Zone (Burchfiel et al., 2008[1]).

There are four active faults running parallel to the direction of NE-SW along the Longmenshan Fault Zone. They are named Guanxian-Anxian (Guanxian-Jiangyou, Pengguan) Fault, Yingxiu-Beichuan Fault, Wenchuan (Wenchuan-Maowen) Fault, and Qingchuan (Pingwu-Qingchuan) Fault in the order from the Sichuan Basin side to the Tibetan Plateau side (Densmore et al., 2007[4] ; Xu, X. et al., 2008[5] ; Xu, Z. et al., 2008[6]). All of them are reverse faults, which form a nappe structures in their Tibetan Plateau side (Burchfiel et al., 1995; Hou et al., 1995).

The geological disasters mostly occurred along the Yingxiu-Beichuan Fault and the Guanxian-Anxiuan Fault, where surface ruptures appeared coseismically at the earthquake (Yin et al., 2009[7]). The surface ruptures are observed in 240 km along the Yingxiu-Beichuan Fault, and in 72 km along the Guanxian-Anxiuan Fault. The vertical movement is dominant in both of the faults, and the maximum vertical displacement is 6.5 m, which was observed in Hankou near the southwestern end of the Yingxiu-Beichuan Fault. The lateral displacements are also observed along both the faults, but they are smaller than the vertical displacements (Li et al., 2008[8] ; Xu, X. et al., 2008[5]).

2. 2 Geologic structures of the Longmenshan Fault Zone

The Longmenshan Fault Zone is located along the boundary between the accretion prism of Triassic flysch sediments of Songpan-Ganzi Terrane in the Tibetan Plateau, and the Proterozoic basement and its overlying sediments of the Sichuan Basin in the Yangtze Craton (Fig. 1). The Yangtze Craton is one of the oldest continental crusts in China (Burchfiel et al., 1995[9]).

There are several nappes in the Longmenshan Fault Zone. They have long geologic history since Triassic (Sasada, 2008[2]). The repeated earthquakes have built the nappes as the results of extrusion of the upper crust of the Tibetan Plateau. There are two nappes in the Tibetan Plateau side of the Yingxiu-Beichuan Fault. They are named the Yingxiu Nappe mainly comprised of the Pengguan Massif of Proterozoic basement, and the Jiudingshan Nappe mainly of Paleozoic sediments. There is another nappe located in the elongated region between the Yingxiu-Beichuan Fault and the Guanxian-Anxiuan Fault. It is called Guanxian-Anxian Nappe.

2. 3 Nappe Structure

Yingxiu Nappe

The nappe thrusted up by the Yingxiu-Beichuan Fault in the southwestern region of the Longmenshan Fault Zone is called the Yingxiu

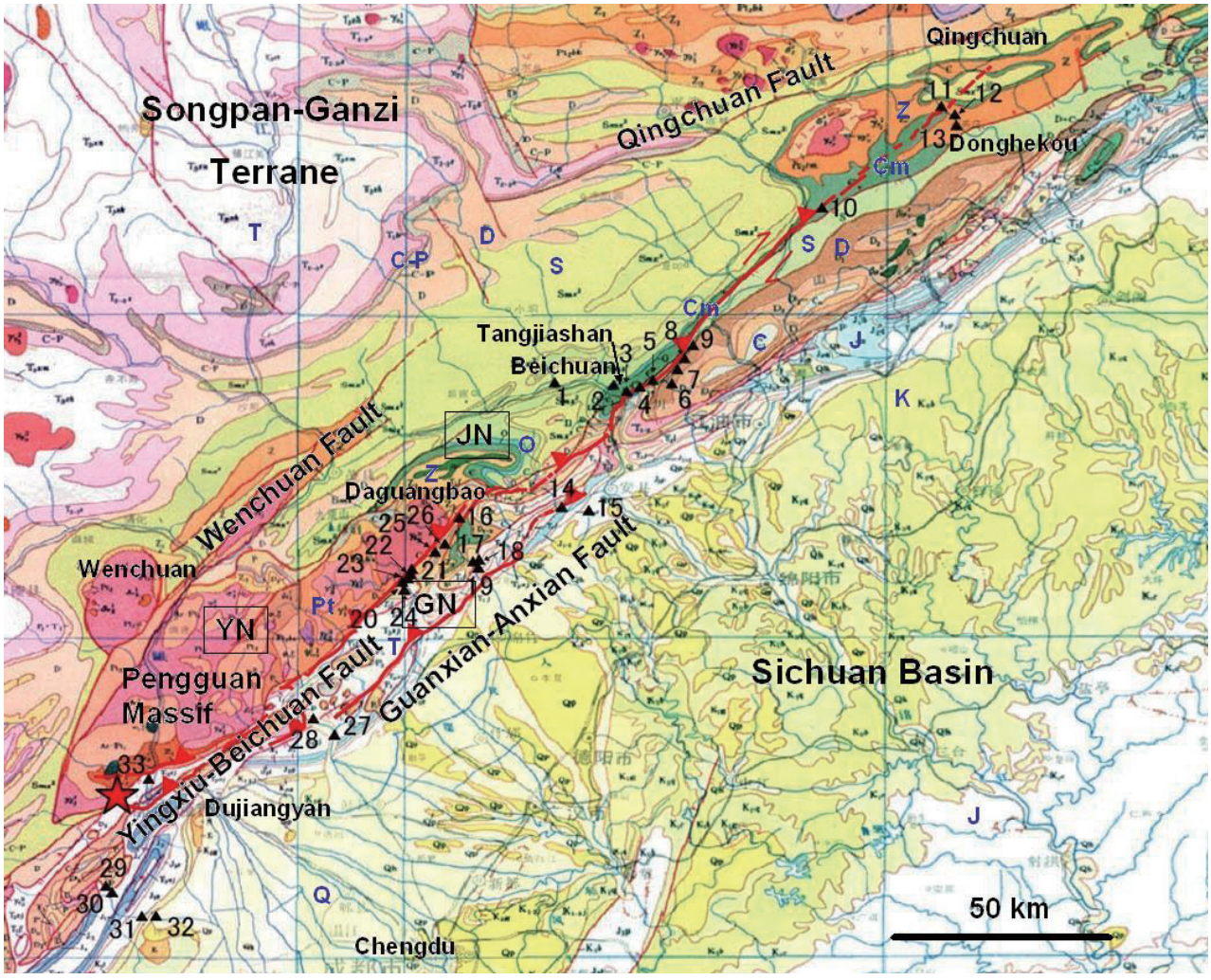

Fig. 1 Geological structures, surface ruptures and debris dams along the Longmenshan Fault Zone

Geology is referred from Geological Map of Sichuan Province of the People's Republic of China 1:1,000,000 (1991) [10]. Abbreviations of the geological eras and periods (blue letters): Pt: Proterozoic, Z: Sinian, Cm: Cambrian, O: Ordovician, S: Silurian, D: Devonian, C: Carboniferous, P: Permian, T: Triassic, J: Jurassic, K: Cretaceous, Q: Quaternary.
Surface raptures of the 2008 Wenchuan earthquake are referred from Xu, X. et al., (2008) [5]. Surface rapture is indicated by solid red line.
Distribution of debris dam is based on location map of debris dams (Yin et al., 2008[11]). Debris dams are indicated by solid triangle.
Nappes along the Longmenshan Fault Zone are indicated in abbreviations in an open square : YN: Yingxiu Nappe, JN: Jiudingshan Nappe, GN: Guanxian-Anxian Nappe.
Epicenter is indicated by red star.

Nappe. It is mostly occupied by the *Pengguan Massif*, which consists mainly of the Proterozoic granitic rocks and highly metamorphosed rocks of green schist and amphibolites facies (Fig. 1). The mylonitic rocks are distributed along the Yingxiu-Beichuan Fault and the Wenchuan Fault (Hou et al., 1995[12]; Xu, Z. et al., 2008[6]). The Pengguan Massif is the oldest geologic unit in the Longmenshan Fault Zone, indicating intensive upheaval and erosion through the thrust movements. The mountain slope of the Pengguan Massif is the steepest in the Longmenshan Fault Zone (Photo 1).

Jiudingshan Nappe

The nappe thrusted up by the Yingxiu-Beichuan Fault in the northeastern region is called the Jiudingshan Nappe (Fig. 1). It consists mainly of Sinian, Cambrian, Ordovician, and Silurian sedimentary rocks. The dolomite and limestone are present in the Sinian formations. The anticline and syncline structures are developed well with the axis parallel to the Longmenshan Fault Zone (Burchfiel et al., 1995[9]).

Guanxian-Anxian Nappe

The nappe thrusted up by the Guanxian-Anxian Fault is called the Guanxian-Anxian Nappe. There are molasses sedimentary rocks of Triassic and Jurassic with the folding axis parallel to the Longmenshan Fault Zone. Several klippes of limestone, dolomite and sedimentary rocks of Permian and Carboniferous are overlying the molasses deposits. They probably came from the Tibetan Plateau side (Hou et al., 1995[12]).

3. Characteristics of the disasters

3.1. Different types of disasters in different geology

The slope failures induced by the 2008 Wenchuan earthquake include rock avalanches, landslides, debris-flows and rock falls. The type of slope failures reflects the geologic structure and topography. As mentioned above, geology of the Tibetan Plateau side of Yingxiu-Beichuan Fault in the southwestern region in the Longmenshan Fault Zone is Proterozoic basement complex, and that in the northeastern region Sinian and Paleozoic sedimentary rocks (Fig. 1). The difference of the geology between both of the regions corresponds to different types of disasters, that is, rock avalanches and rock falls are dominant in the southwest, whereas landslides and rock avalanches are dominant in the northeast. Debris-flows occurred simultaneously at the earthquake and also occurred upon heavy rainfalls after the earthquake. Rock falls occurred simultaneously with the main shock and also with the aftershocks. The time sequence of those disasters is important to make counter measures for secondary disasters in the Longmenshan Fault Zone (Yuan, 2009[13]).

Photo. 1 The steep topography of the southeastern slope of the Longmenshan mountains.

The photo was taken at Xiaoyudong, where the bridge was collapsed as a result of the earthquake. There are so many slope failures on the mountain of granitic rocks of the Pengguan Massif.

3.2. Rock avalanches in the Pengguan Massif

As shown on the satellite imageries (Photo 2), the slope failures occurred mostly at the steep skirts of the mountains along the valleys. The strong motion of the earthquake detached the rocks from the slopes, and rock avalanches happened on steep and unstable slopes in the Pengguan Massif of granitic and highly metamorphosed rocks (Photo 3).

The reason why the Pengguan Massif is characterized by very steep slopes (Photo 1) is recent intensive upheaval and erosion which was resulted from the repeated thrust movements along the Longmenshan Fault Zone. Such tectonic movement is associated with subsidence in the Sichuan Basin side, which is called a foredeep. The thick Quaternary sediments are deposited in the foredeep in the Sichuan Basin just in front of the Pengguan Massif (Burchfiel et al., 1995[9] ; Jia et al., 2006[15]).

3.3. Landslides and rock avalanches in the Jiudingshan Nappe

The landslides and rock avalanches are dominant in the Jiudingshan Nappe where the anticlinal and synclinal structures are developed in the Sinian and Paleozoic sedimentary rocks. Especially, dip slope resulted in a big landslide like those at Daguangbao and Tangjiashan,.

The Daguangbao landslide is the largest one triggered by the 2008 Wenchuan Earthquake. The large volume of mass movement occurred on the low-angle dip slope of Sinian carbonate rocks. The Devonian and Carboniferous sandstone and dolomite also moved with the Sinian rocks. The landslide blocked a river to produce a debris dam (Huang et al., 2008 [16]). The rupture surfaces of rockslide showed rough surfaces with dimple-like depressions, which were made by dissolution of carbonate rocks. Earthquake tremor could be the most effective trigger breaking the contacts(Chigira et al., 2009[17]) .

The Tangjiashan landslide is also a dip slope type. The SE-dipping bedding plane of the Cambrian sedimentary rocks seems to slip widely and massive block of sedimentary rocks seems to slide coherently, based on the photo taken by Xinhua News Agency (2008). This landslide made the largest lake just after the 2008 Wenchuan earthquake.

The Donghekou 'landslide and debris-flow' occurred at the fault zone in which Cambrian slate

Photo. 2 Satellite imageries before and after the 2008 Wenchuan earthquake.

Location is near the city of Wenchuan. Slope failures are remarkably observed after the earthquake along the valley where the granitic and metamorphic rocks of the Pengguan Massif are exposed. These imageries are cited from "Topography of the earth viewed from the space" (Kato, 2010) [14] .

Photo. 3 Rock avalanche occurred near the epicenter of the earthquake to the west of Yingxiu.

Debris of the granitic rocks are thickly deposited along the valley. The Proterozoic granitic rocks of the Pengguan Massif are exposed on the slopes ahead.

and phyllite and Sinian dolomite and limestone appeared (Fig. 1 and Photo 4). This landslide was mainly affected by a fault trending of N50°E and 80-100 m wide. The total length of run-out is about 2400 m (Sun et al., 2009[18]).

3.4. Landslide and rock avalanche in the Guanxian-Anxian Nappe

The Guanxian-Anxian Nappe is elongated to NE direction between the Pengguan Massif and Sichuan Basin. The topographic relief of the Guanxian-Anxian Nappe is not remarkable as that of the Pengguan Massif. The klippe of Paleozoic limestone and dolomite from the Tibetan Plateau side overlaid the Triassic formations of folding structure. Small and medium scales of landslides occurred in low mountains of this nappe.

3.5. Debris dams in the Longmenshan Fault Zone

Some of the landslides and rock avalanches and associated debris flows resulted in debris dams especially along the Yingxiu-Beichuan Fault (Fig. 1). The debris dams were numbered 34 on June 15, 2008 just after the earthquake, and another 70 debris dams were found in the Sichuan Province, after that. The large debris dams like that of Tangjiashan were trenched to prevent breaching. Distribution of debris dam may mostly reflect distribution of the large slope failures relating to the earthquake.

4. Future disasters suggested from the geological point of view

It is important to point out that the secondary disasters expected in the highly damaged region along the Longmenshan Fault Zone are debris-flows and rock falls. Potential areas of those disasters could be identified by their geological and topographical characteristics.

Some debris flows deposits are the results of secondary movement of debris from rock avalanches and landslides (Photo 5). Both of the Pengguan Massif and the Jiudingshan Nappe especially along the Yingxiu-Beichuan Fault have high potential of such debris flows. They might block a river, and the debris dam itself has a risk of breaching. On the other hand, rock fall is a potential disaster on steep slopes especially in the massive rock dominant region where the granitic rocks or thick pile of sandstones are distributed.

5. Summary and conclusions

The slope failures induced by the 2008 Wenchuan Earthquake are rock avalanches, landslides, debris-flows and rock falls. The type of slope failures reflects the geologic structure and topography. The rock avalanche is dominant in the steep mountains of the Pengguan Massif of Proterozoic granitic and metamorphic complex. Landslides and rock avalanches are dominant in the Jiudingshan Nappe and Guanxian-Anxian Nappe of Sinian, Paleozoic and Mesozoic sedimentary rocks of phyllite, slate, sandstone, dolomite and limestone. The large slope failures are distributed mostly along the Yingxiu-Beichuan Fault.

Photo. 4 Landslide and debris flow at Donghekou

The sliding mass and debris of sedimentary rocks blocked the Hongshihe River.

Photo. 5 Secondary debris-flow deposit to the east of Beichuan.

Debris-flow was triggered by the heavy rain precipitated three months after the earthquake.

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2008年四川大地震で発生した斜面崩壊の地質学的背景

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（要　旨）

2008年の四川大地震は、原生代の地層を基盤にもつ揚子地塊と、海洋地殻の上に付加体堆積物が集積してできたチベット高原の地殻の境界にあたる竜門山断層帯で発生した。この断層帯では、チベット高原の地殻が、四川盆地の地殻の上にのし上がる運動が、三畳紀以来の長い期間に、繰り返し起こっており、結果的に大規模な衝上断層帯が形成されている。今回の地震も圧縮テクトニクスの場で発生したものであり、地表に現れた地震断層に沿ってチベット高原側の表層が最大6.5m 上方へと変位している。竜門山断層帯は長期間の断層運動に伴う隆起により、南西から北東に長く伸びる急峻な山地となっており、海抜500m の平坦な地形が広がる四川盆地とは対照的である。2008年四川大地震の震源断層（全長240km）は、四川盆地の縁及びこの急峻な山地の中を通っており、今回の地震で山岳地域においては、15,000 を超える箇所で斜面崩壊が発生した。

四川大地震により竜門山断層帯では、地すべり、岩屑流、土石流、落石といった斜面崩壊が発生したが、それらの発生はこの地域の地質構造及び地形と関係が深い。竜門山断層帯の南西部と北東部では斜面崩壊の様相が異なっており、南西部では岩屑流が卓越し、北東部では地すべりが卓越している。竜門山断層帯の南西部では、原生代の花崗岩及び高度の変成岩からなる揚子地塊の基盤を構成する古い岩石が急峻な山地と形成している。花崗岩等の塊状の岩石からなるという地質学的要因と、高角度の斜面という地形学的要因から、この地域での斜面崩壊では、岩屑流を発生させている。一方、北東部は竜門山断層帯に平行な褶曲軸を持つ震旦系、古生界、中生界の地層が分布しおり、地形は南西部ほど急峻とはなっていない。この地域には千枚岩、粘板岩、砂岩、ドロマイト、石灰岩等の堆積岩類が分布しており、流れ盤構造の場所に地すべりが発生している。とくに大光包、唐家山、東河口では地震に伴いきわめて大規模な地すべりが発生した。竜門山断層帯の斜面崩壊が起きた地域においては、引き続き二次災害に対する注意が必要である。岩屑流や地すべりの起きた場所やその周辺では土石流の発生の可能性があり、また、塊状の岩石である花崗岩や厚い砂岩が分布する地域では、急斜面において落石の危険性がある。

キーワード：斜面崩壊、地すべり、岩屑流、土石流、落石、地震