Characteristics of Wenchuan earthquake and its geological hazard effects

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ABSTRACT: The eastern margin of the Qinghai-Tibet plain is seismically active, mainly due to a fault complex consisting of the Maowen fault, Yingxiu fault and Pengxian-guanxian fault. Since the late Cenozoic period, the rapid rise of the Qinghai-Tibet plain led the crustal material of the eastern edge to move to the southeast along the faults on a large scale. Minshan block structure and Long Men Mountain tectonic zone represented a strong nappe thrust movement along the east boundary of the Chuanqing slip block. Stress accumulated, contributing to a breakdown of the crust, and earthquakes. The shock speed, high-energy accumulation, and the reverse dextro-rotation of the earthquake fault resulted in several geological events. According to in situ investigations, typical geological events included thrust rock collapse, instability of deposits, and the reactivation of potential debris flows. A genetic model of these processes has been analyzed.

1.INTRODUCTION

Seismically active areas are located in the middle of the complex fault-fold belt from the northeast to the Long Men Mountain (Fig.1-1). The Long Men Mountain Fault Zone is spreading to the northeast, and its southwest begins near Luding to the northeast along Guanxian, Wenchuan, Guangyuan into Ningqiang in Shanxi, Mianxian areas, totaling 500 kilometers. The basic structural framework of Long Men Mountain Fault is comprised of three northeast compression-shear faults: the Maowen fault, Yingxiuwan fault and Pengxian-Guanxian fault from north to south. Seismic areas sit in the block border surrounded only by Maowen fault and Yingxiu fault, with the structural plane dip direction of the sub-region mainly to northeast compression-shear faults [4] [5].

The basic characteristics of the three main faults in Long Men Mountain can be summarized as follows:

- Maowen fault: The overall orientation is N30°-45°E/NW∠45°-80°, along the Jiangyou areas in the northeast; three main fault zones developing in parallel compose the Maowen fault which can be divided into the west, the middle and the east branch faults; the line of the Maowen fault is closer than the others; its tectonic ingredients are tectonic breccia, sheet rock, cataclasite, tectonic lens, miliolite or fault clay.
- Yingxiu fault: The overall orientation is N40°-60°E/NW∠50°-80°, with zone width 50 to 80 m, composed of crushed rock, sheet rock, miliolite and fault clay; it goes across the Min River in Yingxiu so that the Proterozoic Cheng River Jinningian granite (r_2^4) overthrusts on Triassic Xujiahe Formation (T_{3XJ}^3); it has characteristics of pressure or compression-shear.
- Pengxian-Guanxian fault: The overall orientation is N30°-60°E/NW∠40°-53°, with zone width of about 100 m, composed of crushed rock, sheet rock, miliolite and fault clay.

These three faults are compression-shear thrust faults, with morpho-tectonics being linear. Later in geologic time, tectonic activity has been relatively strong. Historically, moderately strong earthquakes occurred because of Maowen fault in Wenchuan, Yingxiu fault in Beichuan and Pengxian-Guanxian fault in Tianquan, Dayi. Under the control of these faults, secondary NE faults and fissures are developing.

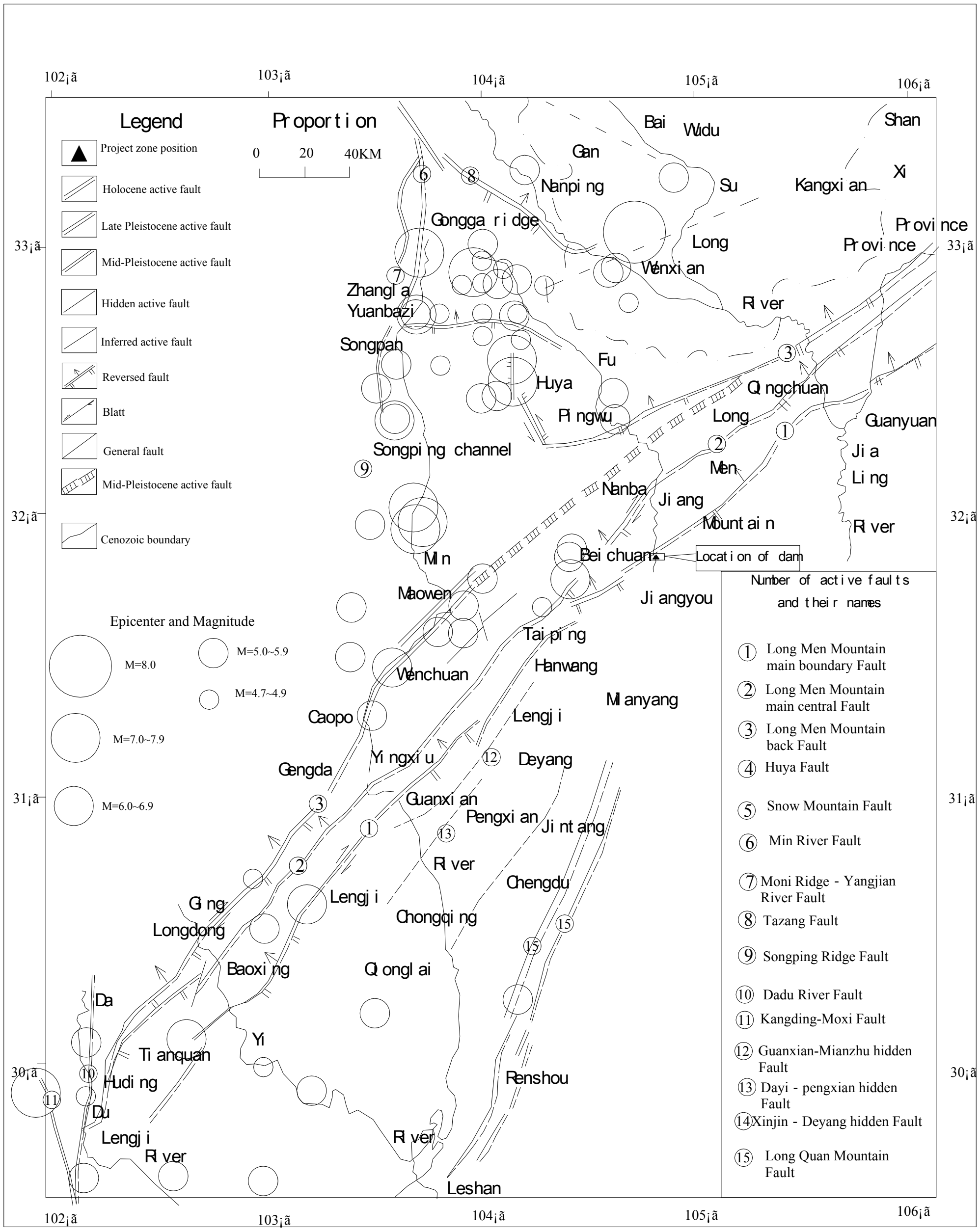


Fig. 1-1. The distribution map of regional geological tectonic framework and history epicenter

The conclusions show that the strike of these three main faults are around N30°-60°E, dipping to the northwest at an angle of 40°-70°. Fault zones are comprised of cataclasite rock, breccia, crushed rock, mortar rock and similar, of width several- to tens-of-meters, which are compression-shear thrust faults as shown on the linear image (Fig.1-2) [5].

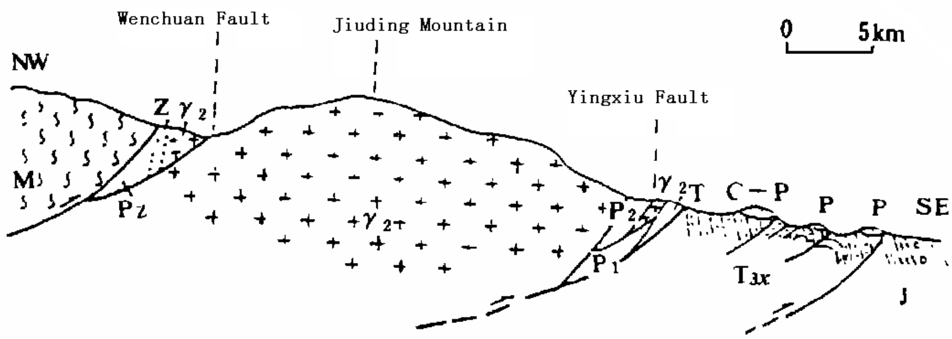
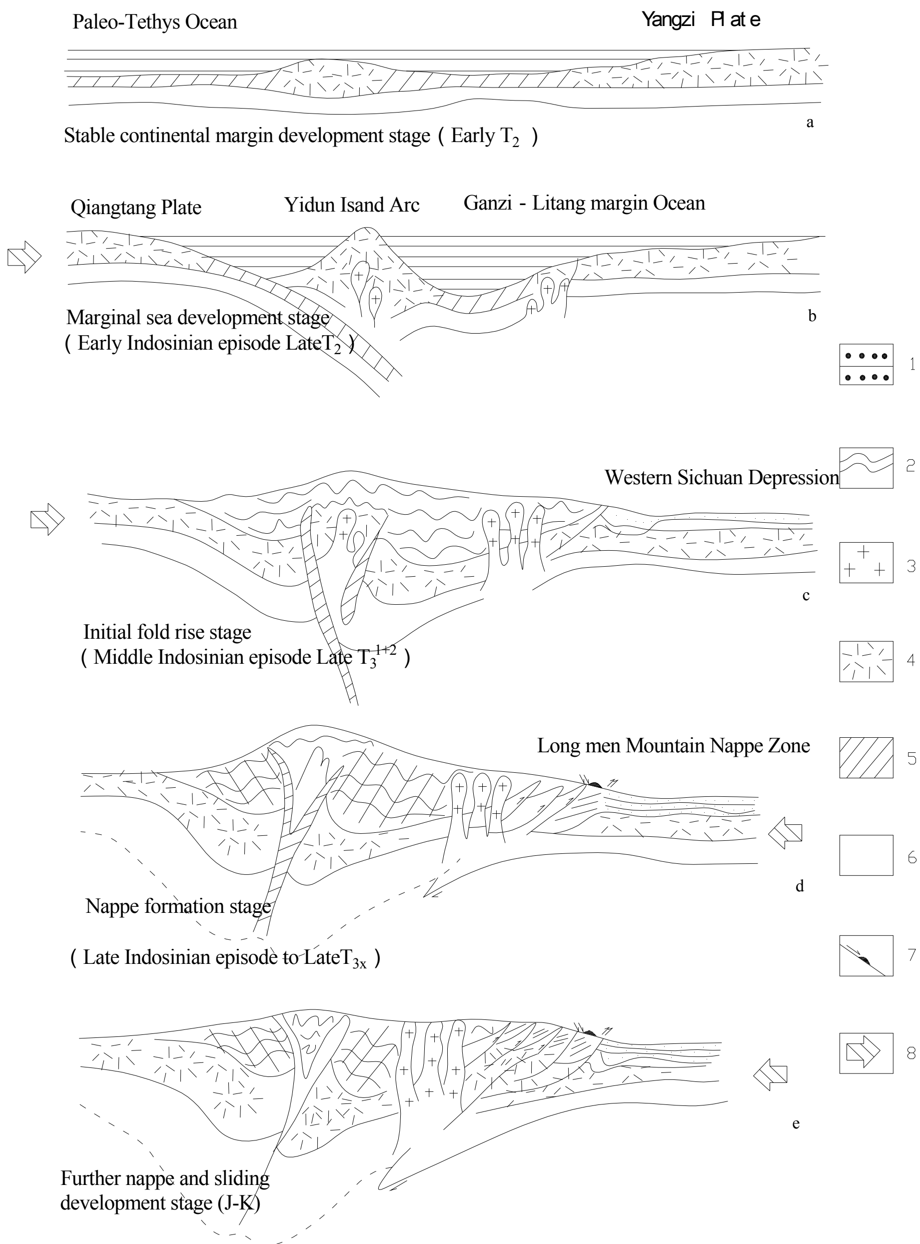


Fig. 1-2. Sectional diagram of the Long Men Mountain Fault zone

2. BASIC CHARACTERISTICS OF THE WENCHUAN EARTHQUAKE

The eastern edge of the Qinghai-Tibet Plate, previously called the Long Men Mountain region, includes the Min Mountain fault block and Long Men Mountain tectonic belt. The eastern and western borders of the Min Mountain fault block are the Huya fault and Min River fault, and southern and northern borders are cut by Long Men Mountain tectonic belt and the eastern Kunlun fault, which form a new uplift about 50 to 60 km from east to west, and 150 km from south to north. Long Men Mountain tectonic belt is mainly composed of the Wenchuan-Maowen fault, Beichuan-Yingxiu fault and Pengxian-guanxian fault. These 3 main faults compose a thrust belt of width 30 to 40 km, and it develops a large number of different sized klippes. The Long Men Mountain tectonic belt was on the Yangtze para-platform western edge before the Norian stage of Late Triassic period, and controlled the Early-Middle Triassic flysch turbidite sediment with a thickness of over 10,000 meters on the west side of the tectonic belt. Since the Norian stage of Late Triassic period, Long Men Mountain thrust from north to south, controlling development of the foreland basin. It gradually pushed forward, and thrust from northwest to southeast, with gravelly wedge-shaped megaclast appearing along the foreland basin's western edge cyclically and the emergence of the episodic sedimentary response of the foreland basin.

The rapid rise of the Qinghai-Tibet plain led the crustal material of the eastern edge to move to the southeast along the big arc faults on a large scale since the late Cenozoic period. The Minshan block structure and Long Men Mountain tectonic zone represented the strong nappe thrust movement as the east boundary of Chuanqing slip block. The regional tectonic stress field shows that north-south Indosinian squeezing movement has been changed to the Late Cenozoic northwest-southeast squeezing movement, with left lateral slip of Huya and Min faults and right lateral slip of Long Men Mountain tectonic belt. According to the profile section of Heishui-Chongqing-Xiushui western geonomy cross-section, conducted by the geophysical exploration team of the Sichuan Provincial Bureau of Geology and Mineral Resources (1990), the Long Men Mountain tectonic zone is in the location of the mutation of the lithosphere thickness, from the thickness of 95 km on Yangtze block to Songpan-Ganzi zone of 140 km. It shows that Long Men Mountain tectonic zone is a significant fault with a cutting depth up to the lithosphere. Especially in the west of Long Men Mountain tectonic zone which is about 20 km deep in the earth's crust, there exists a 3 to 5 km thick layer of low resistance which may be a deep detachment zone of the western Sichuan plateau, in line with the dominant seismogenic layer with a depth of about 20 km in this region. This can also be confirmed by the seismic tomography results. It can be concluded that because of the India-Asia plate convergence and the plateau crustal material under the force of gravity, the crustal material on the eastern edge moved to east along the slip plane, which was then changed into a brittle thrust movement in Long Men Mountain area. It formed a series of imbricate thrust rock-chips of shovel-type faults, which would be stacked from thrust wedges, thick in the east and thin in the west. The maximum thickness of the wedge is 10 km, and can be extended to 20 km. As a result, Long Men Mountain tectonic zone should be a typical foreland thin-skinned thrust [3], (Fig.2-1).



A schematic diagram of kinetics model evolution of the Lithosphere in Long Men Mountain orogenic Belt

1.T_3~KContinental facies bottom；2.Sedimentary and fold；3.Indosinian,Yanshan stage granite；4.Continental crust ；5.Ocean crust or transitional crust；6.Upper mantle；7.Sliding block；8.The direction of adjacent plate motion

Fig.2- 1. A schematic diagram of kinetics model evolution of the lithosphere in Long Men Mountain orogenic belt（after Luolizhi,1991）

Based on the above analysis, the Wenchuan earthquake resulted from the Indian plate moving to the north, and the Pacific plate to the west, pushing the Eurasian plate. The Indian plate's northward movement squeezed the Eurasian plate, causing the uplift of the Qinghai-Tibet

Plateau. The stress then accumulated, contributing to the breakdown of the crust, and to earthquakes. Sichuan Basin is a relatively stable block, and relatively hard. Its seismic wave propagation ability is also strong, which explains why the national Wenchuan earthquake was felt strongly nation-wide. As a result, the characteristics of this earthquake can be summarized: high magnitude, high energy, long duration main shocks and long duration aftershocks.

3. GEOLOGICAL HAZARDS INDUCED BY THIS EARTHQUAKE

3.1 Geological hazard effects induced by this earthquake

According to the in situ surveys and data collection, 5.12 Wenchuan earthquake-induced geological events include:

(1) Major landslide events: The earthquake triggered major landslides disasters that increased the earthquake damages, such as the Wangjiayan landslide in Beichuan, the new landslide from the middle school of Beichuan and the Donghekou landslide in Qingchuan [2]. According to preliminary estimates, this type of disaster occurred in more than 300 places.

(2) Landslides and the collapses: Along the severe earthquake zones on both sides of Yingxiu-Beichuan-Qingchuan fault zones, the earthquake triggered a great number of landslides and collapses, preliminarily estimated at as many as tens-of-thousands. Most material of the landslides had piled up high steep slopes and gullies. In the rainy season, it is easy to form new landslides and debris flow, which will threaten the choice of new resettlements [2].

(3) Potentially unstable slopes: The earthquake resulted in a large number of mountain cracks, and potentially quite subtly unstable slopes which formed a threat of disasters. It is difficult to estimate the number of losses [2].These potentially unstable slopes also constitute a major threat to new settlements. For example, in Pengzhou City, a large number of slag deposits in the upperstream of Ganxigou had formed potentially unstable slopes which provided sources of debris flow.

(4) Landslide-induced lake barriers: Parts of earthquake-induced landslides crashed into the river, with the bigger ones silting the entire river to form a landslide dam, which formed landslide-induced barrier lakes in the upper stream. More than 33 such lakes were formed, posing potential disasters [2].

3.2 Typical analysis of geological disasters

3.2.1 Thrust collapse

The main central fault of the Long Men Mountain is a early deep fault, which formed with the performance of tension at the beginning. Long Men Mountain fold belt formed with a normal fault changing to a thrust fault which pushed to the southeast. Due to the continuing northwestern tectonic stress, Long Men Mountain tectonic zone formed the expansion mode which gradually developed from northwest to southeast, i.e., from the rear of the nappe to the foreand which is the piggyback (or pre-expansion) expansion mode. It resulted in the superposition of the fold belt of imbricate combination model and the nappe. The Dabaiyan thrust collapse in the region based on the nappe (klippe) which was the front margin of Long Men Mountain fold belt, i.e., on the interface of middle Jurassic sandstone and shale limestone. The main collapse was gray rock (Fig.3-1).

After the Wenchuan earthquake occurred, Yingxiu-Beichuan faults thrusted, hanging limestone superposed on top of sandstone and the bedrock staggered slope to form a tiger-mouth cliff. Under gravity or surface water flows, hanging broken material slipped from the thrust and piled up under the cliff to form a colluvial wedge. Much material which was washed down by the surface water flow piled up near the tiger-mouth cliff. It would gradually fill up the tiger-mouth to form a colluvial wedge (Fig.3-2). The colluvial wedge had clear discontinuous sedimentary sections, stacked by many colluvial wedges [1] (Fig.3-3).

Fig.3-1. Overall perspective of thrusting collapse bodies of Dabaiyan

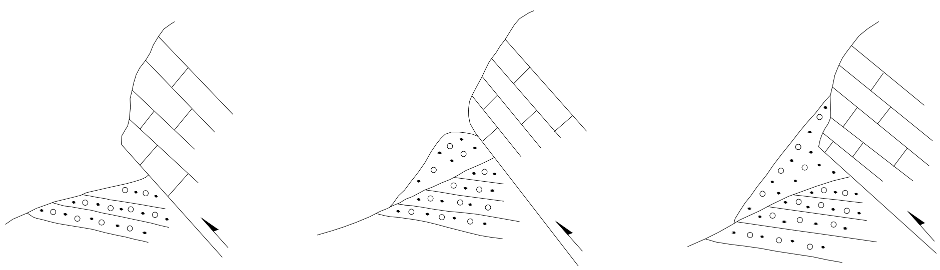


Fig.3-2. The forming model of thrusting collapse bodies of Dabaiyan

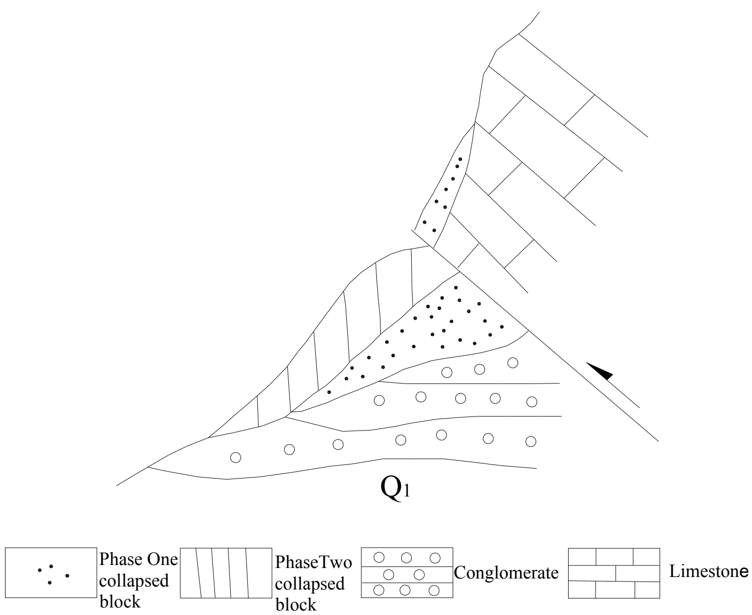


Fig.3-3. The packing and stacking model of thrusting collapse bodies of Dabaiyan

Through the analysis just presented, deposit material from Dabaiyan thrust collapse has provided a source of debris flow. In view of indirect threats to the human environment, we can take simple steps (slope protection, drainage, etc.) on the surface for protection.

3.2.2 Unstable deposit

Datuanbao deposit is on the right shore of Ganxigou in Pengzhou, which is 50 m from the upper course of Huaxi village, about 400 m from the landslide front, 200 m from the trailing edge. It is 200 m long along the main direction of sliding, with thickness 10 to 20 m, and sliding body size of 100×10^4 m^3. The structure of the bedrock is complex with development of joints in the slope. The main control surface of the structure is the tawny slate plane intercalated with coal seams, of the attitude N50°E/SE∠60°, belonging to the anti-slope (Fig.3-4). Due to this type of anti-dumping structural surface, the slope dumped, broke and then fell in the natural history to form a deposit (Fig.3-5). There were earthquake-induced landslides showing horizontal cracks of tension, with the following to explain their mechanism (Fig.3-6):

- Under the natural state, the slope showed dumping of a certain degree, but only limited to the front deformation in a small amount. This was the product of the process of the geological history.
- As the rock was sandstone intercalated with coal seams and shale, which was a soft rock, and under long-time pressure, the lower part showed compression deformation. First of all, upper layered slate appeared bedding separation and bending because of base compression deformation and gravity. The phenomenon of dumping began and gradually developed to the back margin. There were dislocation between bending plates and beams, and partial holes overhead. At the same time the trailing margin appeared drawing cracks, forming a local anti-level slope step parallel to the strike
- As time went on, the further development of deformation in the base of the slope began to result in partial collapses. In the big bending zone, the internal bending deformation began to form the intermittent drawing plane with the outside dip.
- Further developing deformation made this group of drawing planes to continue developing and link up with each other. At the same time the straight slope gradually pushed outside under the pressure of the dumping slope, *i.e.*, the emergence of the external drum of the slope. Dump-break deposit took shape then.
- Broken fragments of the rock collapse, piled up along the slope, was covered by Quaternary-covered slope wash and formed the deposit under the rain.
- In May 12, 2008 the Wenchuan earthquake resulted in partial-slip crack of deposit (Fig.3-7).

The dump-break deposit continued to develop and formed whole-slip damage in the end. As a result, the deformation mode of the anti-dumping slope is as follows: On the basis of inheriting the past dumping deformation, the deformation gradually transformed into the dump-break-deposit-slip deformation of the overall pattern.

Through this analysis, the landslide will result in a threat to the overall sliding during rain storms and other adverse conditions. It is proposed to fill the cracks of the landslide, to compact and to set drainages. The collected water on the surface of the landslide will be diverted, artificial foot excavation will be banned, and necessary measures to monitor the deformation will be taken.

Fig.3-4. The bedrock dumping phenomenon of Datuanbao deposit

Fig.3-5. Overall perspective of Datuanbao deposit

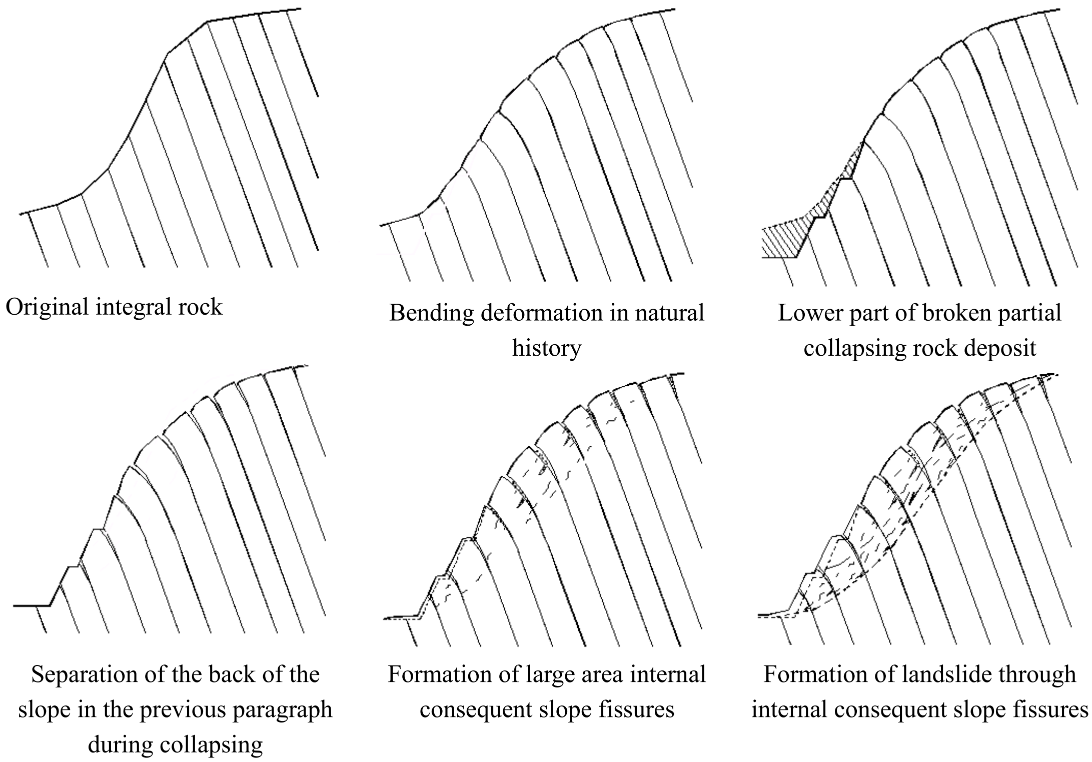


Fig.3-6. A schematic diagram of forming evolution of Datuanbao deposit

3.2.3 Potential debris flow

Ganxigou is located in the Sichuan Basin of the Qinghai-Tibet Plateau over the lower hill zone, the western margin of the basin is in the sub-tropical moist monsoon climate area. Abundant rainfalls provide much water for Ganxigou. Surveys of local villagers in recent years resulted in a policy of closing the hillsides to facilitate reforestation, and since 1993 there had not been any occurrence of large-scale landslides. In 2005 there were mountain torrents submerging downstream bridges and second bottoms in Ganxigou. Ganxigou was a mud-rock flow channel (Fig.3-8). As long as the upper stream can provide adequate loose material, Ganxigou may generate a debris flow disaster.

Fig.3-7. Banquette of Datuanbao deposit cracked because of the local slipping

Fig.3-8. Overall perspective of the flowing area of Ganxigou debris flow

After the Wenchuan earthquake, landslides and collapses were serious and the fragments piled up in the hillside areas, producing a large amount of debris flow sources. Through the investigation, Ganxigou in Pengzhou, there were 7 landslides, 6 collapses. Two landslides took place in the upper and middle courses. The volume of loose deposits was about 340 × 10^6 m^3, to provide an abundance of debris flow sources. Under heavy rainfall, Ganxigou might produce debris flows, threatening the downstream victims.

Based on years of rainfall data, the simulation results are shown in Table 3-1. When 20-year return debris flow occurs, velocity near the Huagong bridge is 3.9 m/s, with discharge 164 m^3/s. When 50-year return debris flow occurs, velocity near the Huagong bridge is 3.4 m/s, with discharge of 216 m^3/s. When 100-year return debris flow occurs, velocity near the Huagong bridge is 3.1 m/s, with discharge of 257 m^3/s.

Table.3-1 Velocity and discharge of the sectional Debris flow of Huagong bridge.

Design frequency	Rainstorm peak discharge Qp (m^3/s)	Unit weight rs (t/ m^3)	Peak discharge Qs (m^3/s)	Sectional velocity V (m/s)
5%	108	1.4	164	3.6
2%	135	1.5	216	3.4
1%	155	1.6	257	3.1

4. CONCLUSIONS

The Wenchuan earthquake occurred because the northward movement of the Indian plate squeezed the Eurasian plate, causing uplift of the Qinghai-Tibet Plate, and eastward movement to squeeze the Sichuan Basin at the same time. The stress accumulation contributed to breakdown of the crust, and earthquakes along the Long Men Mountain fault zone.

In the earthquake zone the shock speed, high-energy accumulation, and the reversed dextro-rotation of the earthquake fault characteristics occurred, which caused the development of secondary geological disasters, mainly major landslides, collapses and landslides, potentially unstable slopes and landsliding barrier lakes.

The typical geological disasters had thrust rock collapse, the instability deposit, and the revival of potential debris flows whose genetic model has been analyzed.

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