Formation mechanisms of the ancient giant basalt landslide in Yanyuan County, China

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Abstract. This study examined the Boli ancient landslide to improve the general understanding of the formation of ancient basalt landslides in the Emeishan large igneous province, China. The morphological, geomechanical, and structural features of the landslide were studied to reconstruct its characteristics. Field investigations, interpretations of remote sensing imagery, and topographical analyses were conducted to assess its formation mechanisms and to clarify the structural, geological, and geomorphological contexts in which the landslide developed. Inherited brittle tectonic features such as fault and joint sets determined the location, geometry, and development of rock slope failures. The Maijiaping thrust fault that cuts through the landslide area was found to be the major controlling factor in its evolution. The ductile tectonic features and sedimentary rock intercalations in the study area created the basal sliding surface for the landslide as it has weak mechanical properties and is hydrophilic unlike the surrounding basalt rock masses, resulting in a landslide-prone structure in the basalt slope.

1. Introduction
Ancient giant landslides are widely distributed in tectonically active areas, such as southwestern China and are often triggered by intense seismic activity or other exogenic factors. The predisposing factors include adverse tectonic conditions and weak rock mass structures[1]. Although ancient landslide deposits can remain stable or meta-stable for centuries, they can be reactivated by events such as rainfall, runoff, and changes in flow concentration[4]. Basalt landslides, in particular, have been formed throughout geologic history. The Emeishan basalt landslides are widespread in southwestern China because of regional tectonic movements, local lithology, and geology, and external triggers. The reactivation of ancient basalt landslides is particularly frequent during rainy seasons and poses significant threats to human life and the natural environment.

The relationship between the tectonic features and large landslides has been an issue of concern worldwide[6]. Scheidegger clarified the mechanism of landslide genesis using examples from the Chinese Himalayas and noted that the orientation of mass movements was preset by current local tectonic stress[10]. Martel emphasized that tectonic conditions significantly influenced landslide formation and development[11]. The evolution of landslide hazards is thus closely related to tectonic movements, fault activities, and resultant earthquakes. Intensive fracturing and faulting due to tectonic activities are also considered key factors in delineating landslide-prone areas.

Tectonic features along slopes have preferential paths of erosion or sliding; these paths can control the overall slope morphology[12]. The numerous ancient giant basalt landslides in southwestern China are often controlled by the tectonic conditions and features that are predisposed to their formation. These ancient landslides have similar characteristics and formation mechanisms. However, although tectonic activity has been widely recognized as a particularly important geological factor for landslide formation, most of the tectonic activity can only be identified and qualitatively studied based on
experience. This is because the corresponding fault-related tectonic activity, with the exception of earthquakes, cannot be identified easily. Therefore, little research has been conducted on the generation and evolution of tectonic features and landslides under tectonism. To improve understanding of the instability mechanisms of basalt landslides in southwestern China, the Boli ancient landslide (BAL) was studied to assess the predisposing factors and triggers for tectonically related ancient basalt landslides in the study area. The emphasis was on the geological structure and composition of the ancient landslides. Field investigations, experiments, and interpretations of remote sensing imagery were used to examine the characteristics, contributing factors, and formation mechanism of the BAL. This study clarified the role of tectonic features in the development of ancient landslides and thus improved the understanding of the development of basalt landslides in southwestern China.

2. Regional geological setting

The study area is in Boli Village, which lies 48 km to the west of Yanyuan County, China. It is a part of the western section of the Yanyuan–Lijiang platform-margin geotectogene located along the center of the Sichuan–Yunnan rhombic fault block (Fig. 1). This fault block had formed via compression during the Cenozoic collision between the Eurasian and Indian plates[13] at the western and eastern boundaries of the Jinping–Xiaojinhe and Jinhe–Qinghe fault zones, respectively. The landslide area lies between the north–east-striking Woluohe and Maijiaping faults. The Woluohe Fault has an outcrop length of 37 km; it strikes NE 40°–50° and generally dips steeply southeastward. The Maijiaping Fault has an outcrop length of 42 km; it too strikes NE 40°–50° and dips 60°–70° southeastward. The fault fracture zone is well developed, and many small lakes and depressions are located along the zone. The southern margin of the ancient landslide area is in the immediate vicinity of the Maijiaping thrust fault in Taozi Village. The BAL is situated in the Jiami River basin, which is dominated by large valleys surrounded by mountains, forming a typical central mountain landform. The study site is situated on the right bank of the central section of the Taozi gully and contains a nearly northeast–southwest-flowing tributary of the Jiami River; the latter is 15 km long. The lithology of the exposed rock in the study area comprises mainly Upper Permian Emeishan Formation (P₂β) basalt, which dominates the landslide source in the southern part of the study area. The basalts are underlain by sandstone, and shale is interlayered with coal in the Upper Permian Leping Formation (P₂l) in the northern and eastern parts.

Figure 1. Location of the study area, distribution of the local drainage system, and major faults and historical earthquakes in the area surrounding the Boli ancient landslide. ① Jinping–Xiaojinhe Fault, ② Jinhe–Qinghe Fault, ③ Xiajiami Fault, ④ Maijiaping Fault, ⑤ Jinplingshan Fault, and ⑥ Yanyuan Fault.
3. Characteristics of the Boli ancient landslide

3.1. Zoning characteristics
The Boli ancient landslide (BAL) has a tongue-shaped planform morphology, with a maximum lateral width of 900 m. It is 2540 m long in the sliding direction and covers a total area of 2.47 km². Its total volume is $7.41 \times 10^7$ m³. Figure 2 shows that the elevation of the main scarp is about 3105 m. The gradient of the slope is about 43°; in contrast, the slope of the deposition is about 11°. Field investigations and interpretations of remote sensing imagery allowed the evaluation of the main scarp boundary, which is clearly visible on the source area because of a 455-m difference in height. The boundary of the deposits, however, is covered by later accumulations and is thus difficult to distinguish. Field investigations and remote sensing imagery revealed traces of the fault crossing the central section of the BAL and showed that the landslide originated on the hanging wall thereof. Further field investigation, geological mapping, and analysis of remote sensing imagery allowed the identification of three distinctive zones characterized by diverse signs of deformation, geological materials, and geomorphic expression (Fig. 2) in the BAL mass. This section briefly describes each zone that affected the interpretation of landslide behavior.

3.1.1. Source area
The initial sliding area of the BAL is the upper part of the slope, which has an armchair-shaped headscarp and an overall sliding direction of 15° (Figs. 2 and 3). The elevations of the crown and toe are 3105 and 2617 m, respectively. The length along the sliding direction of the source area is 946 m, and its width and area are 750–1200 m and 0.98 km², respectively. The geomorphology of the BAL, as inferred from the terrain on both flanks of the source area (Figs. 3b and 3c), suggests that the initiation of the landslide caused the slope and ancient ridges in this area to slide together. Therefore, based on the extrapolation from the mountains that still stand in the surrounding region, the basalt that moved and disintegrated during the landslide was 60–70 m thick on average. Thus, the volume of the basalt rock mass prior to failure was $0.59–0.69 \times 10^7$ m³. The original inclination of the headscarp was 25°–30°, and the current slope of the steep headwall is 15–43°, with a steep–gentle–steep shape in the main sliding direction. Extensive slickensides were also observed in this area (Figs. 3d and 3e). The back wall is composed primarily of Emeishan basalt (Figs. 3f and 3g), with three major sets of joints with attitudes of $40–43^\circ \angle 70–75^\circ$, $60–65^\circ \angle 75–80^\circ$, and $335–340^\circ \angle 82–85^\circ$. The basalt rock mass underwent rising that created several tectonic cracks. These cracks, together with columnar joints and a highly weathered area of stress relaxation, resulted in the fractured basalt structure. In the lower part of this area, a series of descending beaded springs developed because of the saltation of the terrain resulting from the sliding movement. Two sub-source areas formed here; the initial landslide occurred below the ridge, while the second one occurred along the slope of the angle of saltation in the central section (Fig. 3a).

3.1.2. Sliding area
This area is approximately 1340 m long and 400 m wide and covers 0.53 km²; it has an average depth of 15 m (Fig. 2). The elevation of the vertical drop is 300 m. The rock mass slope here is almost perpendicular to the initial direction in which the landslide moved. An intense impact occurred here, creating a large mass of fractured rock that subsequently formed a rock avalanche. A clear at a higher elevation on the right-hand margin and one at a lower elevation on the central area indicate the occurrence of an impact and a swerve-sliding movement. The sliding mass underwent weathering, denudation, precipitation, and aggradation throughout its geological history. Therefore, the deposits in this area show abundant brecciation and clayization with a lithology dominated by basalt gravel.

3.1.3. Deposition area
The displaced sliding mass of the BAL was mainly deposited below the scarp in the central section (Fig. 2). The deposition area is 900 m long in the sliding direction and 950 m wide, and it has an average depth of 30 m. It has a gentle slope of approximately 11° and a fan-shaped planar geometry.
(Fig. 2). Four exploratory trenches were drilled into the leading edge of this area to determine the thickness and composition of the landslide deposits (Fig. 4). At the leading edge, an unconsolidated layer of 2–3 m covers the gravel. The particle size of the rock debris far from the rear of the landslide is small, and it increases in size as it approaches the landslide area.

3.2. Characteristics of the deposited material
The original characteristics of the slope changed significantly with the evolution of geological processes and anthropogenic activity. Results of drill hole and trench tests showed that the Quaternary deposits in the landslide area are composed mainly of two layers (Fig. 5). The first is silty clay with gravel, composed mainly of highly viscous clay particles and approximately 30–45 m thick. The content of breccia and gravel ranges approximately 5–25%, and the particle size is 10–110 mm. The parent rock is basalt. The soil consists of diluvium that has been greatly disturbed by human activities such as cultivation. The second layer is composed of argillaceous gravel, with a rock block and gravel content of 50–60% and a particle size of approximately 10–100 mm. The lithology is mainly stomatal or amygdaloidal basalt, with an argillaceous rock content of 20–30% and sand content of 20–30% and a thickness of approximately 5.0–50.3 m. The inlaid structure consists of skeleton particles and argillaceous sand, indicating that the debris material in the ancient landslide rock mass was transformed into argillaceous material by weathering and that the residual rock block formed gravel and breccia.

Figure 2. Longitudinal and transverse sections of the Boli ancient
landslide in the landslide area.

Figure 3. Landslide source area. a: Oblique view; b: the left-hand segment; c: the right-hand segment; d–e: clear slickensides on the sliding bed; f: bedrock; and g: back wall.

Figure 4. Landslide deposits revealed by drilling exploratory
trenches in the middle section of the deposition area.

4. Tectonic constraints on the BAL

Few previous studies have focused explicitly on the influence of inherited tectonic discontinuities (e.g., faults and joint sets) in the development of slope instabilities. Consequently, the relationship between tectonics and slope mass movement has not yet been defined clearly. Inherited tectonic structural configurations induced by regional tectonics can markedly influence the development of slope deformations\textsuperscript{[14]}. Brittle tectonic features (e.g., persistent bedding planes, faults, and regional joint sets or foliation) can determine the location, geometry, and development of rock slope failures\textsuperscript{[17]}. Meanwhile, ductile tectonic features can create weak zones and control the morphology of failure surfaces\textsuperscript{[18]}.

4.1. Brittle tectonic features

The Maijiaping thrust fault is considered the major controlling factor of the BAL; it has an overall trend of NE 40°–50°, a southeastward dip, and a dip angle of 60°–70°. The fault line is relatively straight on the plane, and the change in attitude is not obvious. There are Upper Permian strata in both walls of the fault; the hanging wall contains Permian Emeishan basalt; and the foot wall contains sandstone, argillaceous siltstone, and shale interlayered with limestone as well as coal from the Leping Formation. Field investigations show that fault outcrops occur in the central part of the landslide area (Fig. 6). Fault breccias several tens of centimeters wide occur near the fault plane; the fault fracture zone has an influence range of several meters to tens of meters wide and exhibits strong silicidation. Exposed springs in the fault zone are perennial sources of water. The fault zone also contains straight and cross-structural planes with clear brecciation. The arrangement of the derived minor fissures near the fault indicates that the fault moved mainly in a vertical direction; its two walls have a sinistral slip tendency. The fault-fractured breccias are often stacked by new ruptures, indicating that multi-stage tectonic activity occurred throughout the geological history of the area. Field investigations confirmed that the fault runs primarily through the valley that extends along the fault line. Moreover, the location and northeastward orientation of the topographic scarp is close to the fault zone. Thus, the current topography and local topographic relief of the study area are closely related to the Maijiaping Fault.

4.2. Ductile tectonic features

The BAL is located in the western area of the Emeishan large igneous province\textsuperscript{[19]}, which formed in the Early to Late Permian because of massive and multi-stage volcanic eruption. The Emeishan basalt strata in this area show characteristics of delamination that reflect the terrestrial eruption environment: dense massive basalt at the bottom, amygdaloidal and stomatal basalt in the center, and microlithic basalt at the top, interlayered with sedimentary rocks. The sedimentary rock intercalations in this area are thick and characterized by several layers because of the many eruption cycles, long intermittence period, and palaeoenvironment of the continental lakes. These characteristics indicate the ductile features of the terrain. The sedimentary rock intercalations developed in the basalt series in the source area with montmorillonite and other hydrophilic clay minerals; they appear as magenta mudstone intercalations (Fig. 7). These intercalations are liable to soften and disintegration in a saturated state, weakening the interlayer bonding within the basalt rock mass. Furthermore, the widely developed fissures and cracks in the rock mass in the source area enable groundwater and surface water infiltration. The strength of these sedimentary intercalations is reduced, as a consequence, and the hydrostatic pressure within the sliding zone increases the sliding force along the slip surface. Thus, the slope has a tendency to undergo deformation and failure.
Figure 5. Typical dual structure observed in the drill cores.

Figure 6. Fault fractures in the landslide area.
5. Conclusion

This paper presents a detailed description of the failure mechanisms of the BAL. Field investigations and experiments were conducted and remote sensing imagery were interpreted to analyze its characteristics and the tectonic model and to study the factors contributing to its formation. The main conclusions are as follows:

1. The BAL is a giant basalt landslide induced by several factors, including the Maijiaping thrust fault, intercalation of mudstone, and a landslide-prone slope structure. The BAL was divided into three zones based on various deformation signs, geological materials, and geomorphic features.

2. Failure mechanism analysis indicates that the Maijiaping thrust fault is of primary importance to the evolution of the unstable slope. The source area of the BAL is the hanging wall of this fault. Because of successive thrusting motions, stress was concentrated therein, while compressive fault activity caused the fragmentation of the basalt rock mass. This, combined with the columnar joints of the structure, caused the development of numerous tectonic cracks and fissures that were mostly perpendicular to the fault plane.

3. The presence of sedimentary rock intercalation in the Emeishan basalt created a favorable sliding zone for the landslide. A weak interlayer formed in the volcanic eruption interval; the eruption environment comprises continental facies.

4. Ancient basalt landslides are closely related to the historical tectonic activity in the study area. The tectonic fractures and the steep relief of the terrain also provide a setting for future basalt slope deformation and failure. Inherited brittle and ductile tectonic features greatly influenced the development of the landslide; therefore, even if the joint sets observed did not contribute directly to the failure mechanism, they were related to the initial detached boundary condition of the landslide.

6. References

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