Optically Stimulated Luminescence (OSL) Chronology of the Dehenglong Landslide from Longyang Gorge to Liu jia Gorge along Upper Yellow River, China

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Abstract: Giant landslides are common along the upper Yellow River from Longyang Gorge to Liu jia Gorge, and some of them even blocked and dammed the upper Yellow River. Chronology is inevitable in studying the mechanism of giant landslides. Controversy exists about the chronology of those giant landslides, and some have not yet dated. The Dehenglong landslide is the largest one among them. In this study, OSL samples were collected from lacustrine silty sediments and loess directly overlying the landslide sediments, as well as fault sediments related to the landslide. This landslide yielded an age of 89 ± 8 ka, which is identical with the fault age of 73 ± 5 ka at two sigma errors. The agreement of a topographic analysis and the absolute age of landslides imply that the formation of the Dehenglong landslide is strongly correlated with the tectonic activity.

Key words: landslide, OSL, Upper Yellow River in China, Qinghai-Tibetan Plateau

1 Introduction

Landslides are often related to mortality and economic loss in mountainous regions (Dai et al., 2002; 2004) by destroying villages and towns. Various external stimuli might trigger this mass movement, such as earthquakes, intense rainfall, rapidly stream erosion or water level changes. Understanding the mechanisms and the geomorphic threshold of landslides will help develop an effective landslide risk assessment and appropriate management strategies. Controversy still exists in the geomorphic thresholds of paleolandslides in the northeastern margin of the Qinghai-Tibetan Plateau (QTP). Yin et al. (2010, 2013) and Li et al. (2007) suggested that landslides occurring nowadays were mainly induced by human activities such as excavation of slopes from road cuts and building sites or deforestation; the occurrence of later period of paleolandslides was attributed to extensive rainfall in the Holocene with a warm and wet climate (Li, 1991), torrential rainfall causes a rapid increase in shear stress along with a decrease in shear strength of slope-forming materials; The early period of landslides were triggered by the Gonghe Movement (~150 ka) (Li, 1991) that resulted in the cutting of the Longyang Gorge with a depth of 800–1000m. However, Zhou (2011) claimed paleolandslides occurring in recent 500 years were induced by torrential rainfall, those in 50 ka and 30 ka by both torrential rainfall and earthquakes, and those in 80 ka and 50–0.8 ka by earthquakes.

A variety of triggers should be taken into the consideration of the occurrence of paleolandslides in the QTP, and an improved chronology on the timing of landslides in the Late Pleistocene may help differentiate between tectonic and climate factors. Most of previous chronologies of paleolandslides were using thermoluminescence (TL) dating. Previous TL ages indicate that paleolandslides in the QTP occurred during three periods: the last 100 years, between 18 ka and 29 ka, and 4 ka (Li et al., 2007). Other chronologic methods have been used to estimate the age of paleolandslides, including lichenometry (Porter and Orombelli, 1981; Rapp and Nyberg, 1981; Innes, 1983) and dendrochronology.
(Shroder, 1978; Ostertamp et al., 1987; Braam et al., 1987). Due to radiocarbon ages in the range of 30–40 ka BP and frequently lack of terrestrial organic materials and low total organic carbon content, it is hard to establish reliable 14C chronologies for the paleo-landslides in the QTP.

Recently, optically stimulated luminescence (OSL) dating has been widely applied in dating landslides, and reliable chronologies have been obtained. OSL dating, which addresses the last light-exposure event, can date sediments from a few decades to >100 ka old. Solar resetting is a prerequisite for accurate OSL dating. Luminescence dating from palaeo-landslide respectively in the Three Gorges in China (OSL ages) (Chen et al., 2008) and Gobi-Altay mountains in China (infrared stimulated luminescence ages) seemed to be well-bleached (Balescu et al., 2007). OSL samples from shear surfaces have been dated (Ma et al., 1992; Ji et al., 1993; Ji et al., 1994; Lang et al., 1999; Carobene et al., 2006), but the OSL signal of these sediments are often insufficiently solar reset (Clarke et al., 2003; Fuchs et al., 2009; Fuchs and Lang, 2009); OSL chronologies of landslides have been reported in the study area by Yin (2010) and Zhou (2011). However these luminescence dating results of 24 ka and 34 ka, 5 ka, and today (Yin et al., 2010) and 80 ka, 50 ka, 30 ka, 10–0.8 ka B.P., 0.5 ka B.P. (Zhou et al., 2010) are not in agreement with each other.

In this study, we investigate the applicability of quartz OSL dating for seven samples collected from sediments related with Dehenglong landslide and another sample from Dehenglong fault deposits that possibly triggered landslide along the upper Yellow River. After examining the OSL characteristics and their possibility of resetting, the chronologies of landslides were established and the possible triggers of landslides were discussed as well.

2 Study Area

Our study area (N: 35°32′09.33″, E: 102°42′27.23″ Fig. 1) is located in the western Gansu province and eastern Qinghai province, at the transient between the Loess Plateau and the Tibet Plateau (Li, 1991). The upper Yellow River originates in the northeast QTP and descends through a series of Tertiary basins in the QTP, including Gonghe Basin, Guide Basin, Jiaozha-Quanke Basin and Xunhua Basin from west to east. The upper Yellow River incised deeply (more than 600 m) into a series of intermontane basins and bedrock ranges (Cradock et al., 2010), while the QTP experienced intense upheaval caused by the uplift of Tibetan Plateau since the Mid-Quaternary. Deep landscape dissection by the Yellow River on the northeast QTP has caused narrow, high-relief river gorges, including Gongbo gorge, Longyang Gorge, Liujia Gorge and Jishu Gorge. A plentiful of giant landslides, a by-product of rapid incision initiated by regional uplift (Ouimet et al., 2007), often occurred in these high-relief, narrow river gorges.

Dehenglong landslide is located on the left bank of the Yellow River in Jianzha County with a total volume of 14.35×10⁸ m³. The basement rock from which the landslides rotate is a Neogene red mudstone with overlying unconsolidated Quaternary sediments. There are about twelve faults (Fig.1b) from Longyang Gorge to Liujia Gorge along upper the Yellow River, some of which are currently active (Li et al., 2011). The head scarp of Dehenglong landslide is mainly controlled by Dehenglong fault and the frontal edge of Dehenglong landslide is controlled by Jian zha dong fault, both of which are segment faults trending NNW (Fig.1b). Both these faults are derived from the boundary between Qilian Mountain massif and Western Qinling Mountain massif, and still active recently, with a record of Mt 4.5 earthquake in 1958. Because of earthquake, the head scarp of Dehenglong landslide fractured along with the NNW Dehenglong fault. Dehenglong landslide dipped toward East, dammed the Yellow River and deposited on both banks of the upper Yellow River.

3 OSL Dating

3.1 Sampling sites

The Dehenglong landslide extended down the valley and blocked the river flow. Narrowing of the river channel facilitated deposition of sediment on the landslide body during flood periods. Large depressions behind the landslide were infilled with silty lacustrine sediments which have been later re-incised due to headward erosion of the Yellow River. In an attempt to date this palaeo-landslide, OSL samples have been collected from the lacustrine sediments directly overlying the landslide mass. These OSL age from the base of the lacustrine sediments could provide the age for the landslide event. Dating loess overlaying on the surface of the landslide after the end of the movement will also give a minimum age and provides a constraint on OSL ages from the lacustrine sediments.

About thirty m of sediments is deposited in the lake formed post the landslide (Fig.2a). The uppermost stratum of this section (N: 35°55′38.8″ E 102°04′23.0″, 2237m a.s.l.) is a ~10 m thickness of loess. Beneath the loess is a ~20 m thickness of lacustrine sediments with mm-to-cm scale laminations. Three samples were collected from the lacustrine sequence from bottom to top: DHL2-1, DHL2-2, and DHL2-3. DHL2-1 was collected at the bottom of
the lacustrine sediment which is the lowest contact between the lake deposits and the landslide units. Age of DHL2-1 sample will provide a close, but minimum age for Dehenglong landslide.

On the other bank of Yellow River and opposite Dehenglong landslide, a multitude of gneiss agglomerates are exposed in the field. Some with a volume of $1 \times 2 \times 1$ m$^3$ can be found. These gneiss agglomerates is the same material as the Dehenglong main body of landslide mass, which indicates that gneiss agglomerates traveled from the landslide main body on the other bank of the Yellow River. Therefore, two samples (DHL3-1, DHL3-2) (Fig.2b) are collected from a loess section (N: 35°54′19.6″ E: 102°01′53.4″2304m a.s.l.) overlying on landslide body on the other bank of Yellow River. These OSL age estimates should thus provide a minimum age for the landslide event.

The Dehenglong landslide initiated by an earthquake and dammed the Yellow River probable at high velocity towards the other bank of Yellow River. The landslide mass displaced and deformed terrace sediments. Such a great shock rendered the landslide mass squashed vertically into the terrace sediments of Yellow River, thus the Tertiary red mudstone of landslide mass and terrace sediments were smashed together. Sample DHL1-1 and Sample DHL1-2 (Fig.2c) were collected from vertical terrace accumulations (N: 35°55′29.7″ E: 102°01′46.8″ 2110m a.s.l.). Here, the terrace accumulations were tilt and overlain by the landslide mass. These two samples are another strong evidence for the fact that Dehenglong
landslide had ever dammed the Yellow River and the landslide mass deposited on the other bank of Yellow River.

Dehelong landslide is supposed to be controlled by Dehelong fault that derived from the boundary between Qilianshan mountain massif and Western Qinling Mountain massif. On this Dehelong fault, gneiss of late Proterozoic upthrusts red mud of Neogene where some round breccias can be found. Sample DHLF-1 (Fig.2d) is dark brown fault gouge, mostly composed of red mud of Neogene and part of gneiss of late Proterozoic era. It can be inferred that sample DHLF-1 is possibly sufficient to reset the OSL clock because that silken slides are easily found on the sample DHLF-1, suggesting that this sample is likely to experience high stress. OSL samples were collected by hammering steel tubes into freshly-cleaned sections. The tubes were then wrapped in black plastic bags.

3.2 OSL sample preparation and measurement methods

Coarse samples were firstly sieved to remove grains coarser than 300 μm at the Luminescence Dating Laboratory, Qinghai Institute of Salt Lakes, Chinese Academy of Sciences, and the raw ones were treated with 30% H₂O₂ and 10% HCl to remove organic matter. Then grains (38–63μm) were selected by dry sieving and treated with 35% H₂SiF₆ for two weeks to dissolve feldspars (Lai, 2010), followed by 10% HCl acid to remove fluoride precipitates (Lai et al., 2007; Lai and Wintle, 2006). And infrared (IR) stimulation was used to check the purity of quartz extract. Samples that showed obvious IRSL signals were treated again with 35% H₂SiF₆. At the end of the single aliquot regenerative-dose (SAR) routine, a regeneration dose (Rᵣ) equal to the first regeneration dose (Rᵣ) was also added to checking the IR signal, that ensure efficient removal of feldspar contamination that might
cause the change in the shape of the growth curve for quartz OSL (Lai and Bruckner, 2008) and age underestimation. Quartz grains were then mounted on the centre part (0.5–0.6 cm in diameter) of a stainless steel disc (1.0 cm in diameter) by silicone oil.

OSL measurements were carried out on a Risø TL/OSL-DA-20 reader. Laboratory irradiation was using a $^{90}\text{Sr}^{90}\text{Y}$ beta source built into the Risø reader. Detection was through 7.5mm Hoya U-340 filter in front of the photomultiplier. The dose rate of the beta source was calibrated for 38-63μm quartz grains. The blue light emitting diodes ($\lambda=470\pm20$ nm) for 40s at $130^\circ\text{C}$ was used for stimulation, and ninety percent dose power was used. Signals of the initial 0.64s of stimulation were integrated for growth curve construction after subtracting background (last 5s).

The cosmic ray dose rate was estimated according to Prescott and Hutton, 1994, and alpha value for quartz grains of 38-63μm was taken as 0.035±0.003 (Lai et al., 2008). The concentration of U, Th, and K were measured by neutron activation analysis in China Institute of Atomic Energy in Beijing. Water content of all samples was assumed to be 10±5 %.

4 Equivalent Dose Determination

4.1 Luminescence characteristics

According to the equivalent dose (De) plateau for temperatures from 220°C to 260°C in the preheat plateau test of sample XZT-3 from Xiazangtang landslide which is near Dehenglong landslide in the study area (Guo, 2012), preheat in this test was using 260°C for 10s, and cut-heat 220°C for 10s after De plateau test. The SAR protocol was adopted for De determination (Murray and Wintle, 2000) and the SAR sequence used a preheat of 260°C for 10s, a cut-heat of 220°C for 10s and a test dose of 11.1Gy. Fig.3 shows OSL decay curves of Nature dose (N), test dose (TD=11.1), regeneration dose of 400 Gy and 0 Gy for sample DHL1-1, as well as a growth curve of an aliquot. The fast component is dominant in the OSL signal can be seen from that OSL signal quickly decreasing during the first second stimulation indicates.

As recommended by Murray and Wintle (2003) SAR protocol for De determination, a dose recovery test was carried out for samples DHL2-2 and DHL3-1. Six aliquots for each sample were exposed to blue LED stimulation at 130°C for 100s to remove acquired charge during burial, and each aliquot was then given a laboratory dose of 300.53 Gy for DHL2-2 and 199.91 Gy for DHL3-1. The aliquots were then measured using SAR protocols to obtain a De values, giving an average of 284.39 Gy for DHL2-2 and 195.73 Gy for DHL3-1. The ratio of the measured to given dose is 0.95 and 0.98 (within 10%), indicating that the SAR protocols are internally consistent (Wintle and Murray, 2006), and the De measured from naturally dosed material is credible.

4.2 Determination of $D_s$

Combining both SAR (Murray and Wintle, 2000) and Standard growth curve (SGC) (Roberts and Duller, 2004; Lai et al., 2007; Long et al., 2010) methods, De could be determined. In the SAR protocol, six aliquots were measured for each sample. Data from SAR protocol were used to construct a SGC for an individual sample. Then another 10–14 aliquots under the same measurement condition as SAR procedure were measured to determine the natural signal ($L_N$) and the OSL of test dose ($T_N$). Each value of $L_N/T_N$ was then matched in the SGC to obtain a $D_s$. Table 1 shows that all De determined by the SGC are in agreement with Des by the SAR protocol, indicating that the SGC could be used for De determination for all samples in upper Yellow River. The mean of SAR Des and SGC Des is the final De for each sample.
5 Dating Results and Discussions

5.1 Dating results

Table 1 shows the sample information and OSL dating results, and Fig.2 shows the OSL ages. The calculated ages fall within the range from 62 ± 5 ka to 89 ± 8 ka.

Samples DHL2-1, DHL2-2 and DHL2-3 were collected from the lacustrine sediments of Dehenglong landslide, and OSL dating yielded ages of 89:±8 ka, 71 ± 7 ka and 66 ± 6 ka which are in stratigraphic order and indicate that the Dehenglong landslide occurred at about 89 ±8 ka.

Samples DHL3-1 and DHL3-2, which yielded 66 ± 5 ka and 62 ± 5 ka, were collected from Quaternary loess deposit overlaying the landslide mass on the other bank of Yellow River, opposite Dehenglong landslide. These age estimates are consistent with optical ages from lacustrine sediments (DHL2-1, DHL2-2, and DHL2-3).

Quartz grains yielded optical age of 68 ± 5 ka and 74 ± 8 ka (DHL1-1 and DHL1-2) from vertical terrace accumulations on top of the landslide mass. The age of DHL1-1 and DHL1-2 were almost the same with the ages of DHL 2-1, DHL2-2 and DHL2-3 which indicates that the terrace sediments were pushed to be vertical by the landslide mass when the long runout giant landslide occurred. These two samples are another evidence for the fact that Dehenglong landslide had ever dammed Yellow River.

The fault gouge was mostly composed of red mud of Neogene and part of gneiss of late Proterozoic era. There is no residual in TL at 400°C in the case of high friction (Ma et al., 1992), and resist to zero at deposition is more effective for OSL than for TL (Aitken, 1998). Thus, sample DHLF-1, collected from the fault gouge, is presumed to be zeroed in term of OSL and yielded 73 ± 5 ka. At two sigma errors, the age of DHLF-1 is coherent with the ages of DHL-1 obtained from lacustrine sediments. In other words, Dehenglong landslide occurred simultaneously with the shock of Dehenglong fault, it is likely that Dehenglong landslide triggered by the shock of Dehenglong fault. Thus, Dehenglong landslide would be an earthquake-triggered landslide.

5.2 Discussions for landslide triggers

For triggers of most large landslides, seismic shaking and intense monsoon precipitation events are the most likely triggers (Barnard et al., 2001). With regard to the mechanism of Dehenglong landslide, it may be mainly related to earthquakes. The conformity of chronology constraints for Dehenglong landslide and the age of Dehonglong fault (at two sigma errors) suggest that Dehenglong landslide was triggered by earthquake. Besides, most landslides triggered by earthquake have a prominent characteristic of rapid and long runout mass (Kong et al., 2009; Han et al., 2009). So does Dehenglong landslide.

Tectonically, active mountain belts always experienced seismic landslides (Keefer, 1994). The fact that the QTP has experienced intense upheaval caused by the uplift of Tibetan Plateau since Mid-Quaternary (Cradock., et al., 2010), offers Dehenglong landslide a geologic background to be a seismical landslide. ~ 1.0 Ma when the Jishi Gorge was cut, Huanghe (the Yellow River) Movement rendered the VI terrace 900m high above the river level in Xunhua Basin (Li, 1991).

At the beginning of the late Pleistocene, Gonghe movement cut the Longyang Gorge 800-1000m deep. Around 80 ka, the beginning of the second stage of Gonghe movement (Zhou, 2011), the QTP experienced a strong uplift and structural deformation (Zhao et al., 2003), and several seismic landslides have been identified previously in the QTP. In Guide basin, Deqiansi-Ashengong fault derived from Qinghai nanshan-Western Qinling Mountain Fault and its latest tectonic movement in 80 ka (Q.E.A., 1989) not only induced Xijitan landslide (80 ± 5 ka OSL age, 8.4×10^3 m^2) and Ashengong landslide (80 ± 6 ka OSL age, 1.6×10^5 m^2), but also affected the 79.9 ± 0.6 ka thermal event of fault gauge to the south of Ashengong landslide in the east Guide basin and caused an incision of 41 m in the west of Guide Basin (Zhou, 2011). In Xunhua Basin, the Yiheilong fault (93 ka) and Deqianshi fault (80.56 ka) incised two terraces with a total height of 64m. Less than 10 km away from the Deqiansi-Ashengong fault, there are Kangyang landslide (33.2 ± 2.5 ka~86 ± 7 ka) (Guo, 2012), Xiaozangtang landslide (80 ± 9

Table 1 Environmental radioactivity and OSL dating results

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Depth (m)</th>
<th>K (%)</th>
<th>Tb (ppm)</th>
<th>U (ppm)</th>
<th>Water Content (%)</th>
<th>Dose rate (Gy/ka)</th>
<th>Aliquot Number</th>
<th>D$_{10}$ (Gy)</th>
<th>OSL Age (ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DHL1-1</td>
<td>0.3</td>
<td>1.48±0.05</td>
<td>10.32±0.27</td>
<td>2.3±0.14</td>
<td>10:5</td>
<td>2.68±0.19</td>
<td>6±14$^a$</td>
<td>195.5±4.3</td>
<td>68±5</td>
</tr>
<tr>
<td>DHL1-2</td>
<td>1.1</td>
<td>1.79±0.05</td>
<td>11.25±0.30</td>
<td>2.84±0.14</td>
<td>10:5</td>
<td>3.10±0.22</td>
<td>4±14$^a$</td>
<td>244.3±20.8</td>
<td>74±8</td>
</tr>
<tr>
<td>DHL2-1</td>
<td>2.5</td>
<td>1.88±0.05</td>
<td>11.95±0.31</td>
<td>5.33±0.18</td>
<td>10:5</td>
<td>3.75±0.26</td>
<td>6±10$^a$</td>
<td>353.7±19.1</td>
<td>89±8</td>
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<tr>
<td>DHL2-2</td>
<td>3.0</td>
<td>2.24±0.06</td>
<td>13.87±0.34</td>
<td>6.06±0.20</td>
<td>10:5</td>
<td>4.32±0.3</td>
<td>6±14$^a$</td>
<td>352.3±22.8</td>
<td>71±7</td>
</tr>
<tr>
<td>DHL2-3</td>
<td>0.4</td>
<td>2.05±0.06</td>
<td>15.08±0.38</td>
<td>4.84±0.18</td>
<td>10:5</td>
<td>3.95±0.27</td>
<td>6±10$^a$</td>
<td>282.6±12.5</td>
<td>66±6</td>
</tr>
<tr>
<td>DHL3-1</td>
<td>0.9</td>
<td>1.65±0.06</td>
<td>11.01±0.30</td>
<td>3.13±0.15</td>
<td>10:5</td>
<td>3.16±0.21</td>
<td>6±14$^a$</td>
<td>221.5±6.0</td>
<td>66±5</td>
</tr>
<tr>
<td>DHL3-2</td>
<td>1.5</td>
<td>1.80±0.06</td>
<td>10.5±0.28</td>
<td>2.81±0.14</td>
<td>10:5</td>
<td>3.20±0.23</td>
<td>6±14$^a$</td>
<td>211.1±8.4</td>
<td>62±5</td>
</tr>
<tr>
<td>DHLF-1</td>
<td>0.4</td>
<td>2.13±0.06</td>
<td>9.62±0.27</td>
<td>10.94±0.28</td>
<td>10:5</td>
<td>4.83±0.33</td>
<td>6±14$^a$</td>
<td>378.9±8</td>
<td>73±5</td>
</tr>
</tbody>
</table>

Note: * aliquot number used for SAR, † aliquot number used for SGC.
ka) (Guo, 2012) and Tangse landslide (32.9 ka) (Zhou, 2011). In Jianzha Basin, Dehenglong fault (73 ± 5 ka) is identical with Deqiansi-Ashengong fault (OSL age 79 ± 1 ka) (Zhou, 2011) at the southern boundary of Ashengong landslide in the east of Guide Basin. All of the above faults belong to Zhamashan-wendudashi fault which is one limb of Qilian Mountain Massif and Xiqingling Mountain Massif. Therefore, Qinghai Tibet Plateau experienced a strong uplift and structural deformation ~80 ka ago (Zhou, 2011). To a certain degree, this ~80 ka tectonic movement would bring about a multitude of tense earthquakes. For Dehenglong landslide, since DHL2-1 (89 ± 8 ka) obtained from lacustrine sediments is coherent with age of DHLF-1 (73 ± 5 ka) at two sigma errors, Dehenglong landslide is likely to be closely related to this 80 ka tectonic movement. Ground shaking induced by earthquake had a great influence upon the formation of main ruptures, which finally provide the rifts and slip surfaces for potential landslides.

For torrential trigger, the Dehenglong landslide occurred at 89 ± 8 ka, which happened at the period of marine isotope stage (MIS) 5 with optimum precipitation and temperature conditions (Wu et al., 1999). The last interglacial palaeosol S1 in Tuxiandao (TXD) section in Xining Basin shows that S1 correlates with MIS 5, on the basis of the S1 pedostratigraphy in Chinese loess. For torrential rainfall, on the one hand, intense rainfall during MIS5 is responsible for the rapid growth of pore pressure and for the loss of the apparent cohesion of thin soils resulting in failure within the soil material or at the contact with the underlying impermeable bedrock. On the other hand, long duration and less intense rainfall periods allow the steady rise of the groundwater table and the occurrence of deep failures through the reduction of shear strength of affected materials (Zezer et al., 2005).

However, we infer that ground shaking caused by earthquake was the origin of the gigantic Dehenglong palaeolandslide. Integral with the rainfall gradually permeating into these ruptures, the high speed slip was accelerated in later stage and higher water table allowing fluidization of the base clays, finally bringing about the basal shear surface of this mass movement. Humid climate just functions as an accelerator to trigger the landslide (i.e. pre-existing fracturing, and gypsumiferous clays under the landslide mass). Therefore, it confirms that Dehenglong is a seismic landslide, occurring occurred under wet conditions.

6 Conclusions

In this study, seven OSL samples were collected form Dehenglong landslide along the upper Yellow River in China and OSL results show a good agreement with geomorphological features.

(1) The Dehenglong lacustrine sediments formed post the landslide, and the OSL results show that the lacustrine sedimentation started at about 89 ± 8 ka, suggesting that the sliding event took place during the period of MIS 5 when climate became warmer and wetter.

(2) We suggest that earthquakes could be the cause of the Dehenglong landslide, in terms of the agreement in the chronologies of its lacustrine sediments and the Dehenglong fault at two sigma errors.

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