Evidence of overpressure at the base of huge landslide

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Abstract. Overpressuring from generation of CO₂ gas caused by thermal decomposition of basal carbonates can raise pore-fluid pressure and reduce friction during landsliding. We used thermogravimetry and dilatometry to determine the evidence of raised pore-fluid pressure from carbonate thermal decomposition at the base of the 2009 Jiweishan landslide. Results from thermal expansion experiments showed that the rock undergoes expansion and thermal fracture. At a heating rate of 20 °C/min, the coefficient of linear thermal expansion increased sharply at 807.3 °C and reached a maximum of 36.6×10^-6 °C^-1 at 827.3 °C. DTG data show that the temperature of the maximum thermal decomposition rate of calcite is 852.5 °C. The evidence showed that CO₂ gas can produce great pressure during the rapid sliding process of Jiweishan landslide, and it is conducive to reduce the effective normal load. In addition, thermal fracture may be an explanation for the ultra-low friction during the rapid sliding by reducing the strength of the rock at the sliding surface and making it more easily entrained.

1. Introduction

Huge rock avalanches as large volume, long-runout, high-speed dense granular flow is one of the most dangerous natural hazards (Heim, 1932; Pudasaini and Hutter, 2007; Lucas et al., 2014; Pudasaini and Miller, 2013, Keefer and Larsen, 2007), which caused thousands of loss of lives every year. A main concern of rock avalanche flow dynamics is the understanding the physic process of the long-out distances and high-speed movement, which can improve the prediction of maximum landslide extension and velocity. More recently, overpressuring from generation of CO₂ gas caused by thermal decomposition of the basal carbonates is considered to be a cause of ultra-low friction (Anders et al., 2000; Mitchell, 2015; Hu et al., 2018, 2019), and Hu found the direct field evidence of calcite thermal decomposition in Jiweishan landslide. However, the hypothesis is lack of direct evidence for gas pressure.

Herein we used thermogravimetry and dilatometry to determine the evidence of raised pore-fluid pressure from carbonate thermal decomposition at the base of the 2009 Jiweishan landslide.

2. Geological setting of the landslide

Jiweishan landslide is located on JiweiShan (Cock tail mountain), Wulong County, Chongqing, China. It occurred about 3:00 PM on June 5, 2009, with a volume of 5×10⁶m³ and 74 people were killed (Yin et al. 2009; Xu et al., 2010).

JiweiShan is an oblique thick stratified limestone mountain, and the sliding rock mass is on the top (Fig 1). The sliding rock mass was composed of the strata of the Maokou Group (P₅m) and Qixia
Group (P1q) of the Lower Permian, which were mainly consisted of grayish-white thick-layered micritesand and gray medium-layered bituminous limestones, and strata dip at 21° into anacinal slope, towards N15°W.There are many weak interlayers of bituminous and calcareous shale in the Maokou Group and Qixia Group (Fig 2) (Xu et al.,2010).

The east side of the sliding rock mass is a steep cliff with a height of 50 ~ 150m, and the south and west sides are cut and separated by two large steep cracks T0 and T1, respectively. These two cracks are connected with the weak interlayer downward, so that the sliding rock mass and stable bedrock barrier are separated to form a driving block (Fig 1). The weak interlayer of black calcareous shale with a thickness of about 30cm, about 40m below the top of the cliff, is the sliding surface of this landslide (Tang et al., 2014).

Before failure, the driving block had undergone a long-term creep deformation under the action of gravity. At the beginning, motion was directly down the true dip angle (N15°W) of the weak interlayer...
at the bottom of the driving block, and then it changed to the N10°E after being blocked by the stable bedrock barrier on the west side, and continue to push the key block along this direction (Fig 1). Under the huge thrust of the driving block, the shear strength of the weak interlayer at the bottom gradually lose, and the key block sheared the karst zone T2 and sheared out from the leading edge, then, the failure happened (Xu et al., 2010; Tang et al., 2014).

In the process of failure, the rock mass disintegrated very quickly and fell more than 50 m from the cliff into the Tiejiang creek, spilling across the valley to run up the opposite valley slope. Deflected by this opposing slope, a high-speed debris flow formed an about 2.2 km long deposition area along the Tiejiang creek (Fig 1). The whole sliding process lasted less than 1 min (Xu et al., 2010).

3. Materials and methods
We sampled the calcareous shale from an out crop near to the Jiweishan sliding surface. It had a similar composition to the original shale at sliding surface, but without frictional heating caused by the landslide.

We examined the thermal expansion behavior of the shale by measuring the linear thermal expansion, using a NETZSCH DIL 402 PC thermal expansion analyzer at heating rates of 3°C min⁻¹, 5°C min⁻¹, 11°C min⁻¹, and 20°C min⁻¹ from 25 to 1000°C. Four samples were cut into 5×5×25mm blocks which oblique with bedding for linear thermal expansion measurement. In addition, samples were ground to fine powder for XRD and TG-DTA analyses of the mineral composition and thermal reaction.

4. Results and discussion

4.1. Mineral composition
We determined the sample mineral compositions using XRD spectra. The results showed that the Jiweishan calcareous shale contained calcite (83.7%), dolomite (10.4%), quartz (4.95%) as major minerals, and a small amount of talc and gmelinite (Fig 3).

Fig 3. X-ray diffraction (XRD) analysis of field sample. a: Annotated XRD spectra of sample. b: Quantitative analysis from profile-fitted peaks of original sample. c: Quantitative analysis from profile-fitted peaks of original sample after separation. Cal-Calcite, Dol-Dolomite, Q-Quartz, Tal-Talc, Gme-Gmelinite.

4.2. Thermal reaction analysis
As can be seen from the TG figure, the curves of each heating rate are similar, and there is a large mass loss (about 42.28%) in the temperature range of 630-850°C (Fig 4). In this temperature range,
DTA curves form an obvious endothermic valley, indicating that mass loss was caused by endothermic thermal decomposition reaction. Combined with XRD results and temperature range, mass loss was mainly caused by decarbonation of dolomite and calcite, the reactions may take place for dolomite at 750–800 °C:

\[
\text{MgCa}(\text{CO}_3)_2 \rightarrow \text{CaCO}_3 + \text{MgO} + \text{CO}_2
\]

(1)

and at 840–950 °C (Ptáček et al., 2014):

\[
\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2
\]

(2)

![Fig 4. Thermal analyses of samples.](image1)

**Fig 4. Thermal analyses of samples.** a: Thermogravimetry (TG) of samples at different heating rate. b: First derivative (deriv.) of thermogravimetry (DTG) of samples at different heating rate. c: Differential thermal analyses (DTA) of samples at different heating rate.

In the thermogravimetric experiment, with increasing heating rate, the DTG trough temperature occurred at a higher temperature, while the value of the DTG trough decreased gradually. At a heating rate of 10°C min⁻¹, the minimum mass change rate was about -6%, and the corresponding temperature was 817.5°C. At a heating rate of 20°C min⁻¹, the minimum mass change rate was about -10%, and the corresponding temperature was 852.5°C (Fig 4). The larger the mass loss rate was, the faster the thermal decomposition was and the faster the CO₂ generation was.

4.3. Thermal expansion analysis

Fig 5 shows the relationship between thermal decomposition reaction and thermal expansion. It can be seen that when the temperature continued to rise and reached about 630 °C, sample began to lose
weight as the carbonate decomposed. When the temperature reached to about 807.3°C, the coefficient of linear thermal expansion rose sharply then continued to increase along with intensification of the carbonate decomposition reaction, reaching a maximum 36.6×10^{-6}°C^{-1} in the whole experiment at about 827.3°C. At that time, the corresponding DTG curve approximately reached a minimum value, indicating that the thermal decomposition reaction rate and CO₂ generation rate were approximately maximum.

![Graph](image)

**Figure 5. Thermogravimetric experiments and thermal expansion experiments at 20°C min⁻¹.**

The thermal expansion of rock is the result of mineral thermal expansion and rock thermal fracture (Cooper and Simmons, 1977). However, at the stage of thermal decomposition, calcite generated calcium oxide and carbon dioxide, the linear expansion coefficient of calcium oxide was far less than that of calcite. So it can be considered that the surge of thermal expansion in the thermal decomposition stage is the result of thermal rupture, which is facilitated by the production of a large amount of carbon dioxide gas. The sudden increase of the coefficient of linear thermal expansion at this stage appears to be closely related to the generation of CO₂ gas. After the experiment, many cracks were produced due to thermal expansion (Thirumalai and Demou, 1970).

Above all, it can be seen that the thermal expansion behavior of the shale during the heating process, especially during the generation of CO₂ gas, significantly promoted expansion of the sample—direct evidence of the formation of overpressure. This indicated a condition for the formation of elevated pore-fluid pressure at the bottom of the sliding rock mass, which could greatly reduce the frictional resistance at the sliding surface. Strong thermal fracture was generated in the process of thermal expansion. This was capable of destroying the rock structure and reducing the strength of the rock, making the sliding surface more easily entrained, which could also play a role in reducing frictional resistance (Iverson, 2005; Iverson and Reid, 2011). However, in the natural environment, the rock mass at the sliding surface bears a great load, while no load was applied to the sample in the experiment. The coefficient of linear thermal expansion under such large load conditions in landslides may not be able to achieve laboratory results, but the generation of CO₂ gas during the landslide and the ability of overpressure causing by CO₂ gas are load-independent, and under the condition of high load, it is easier to form a closed environment, which is conducive to the accumulation of CO₂ gas (Cooper and Simmons., 1977; Voight and Faust, 1982).

Another three samples were tested at different heating rates and the coefficient of linear thermal expansion of the samples at different heating rates had somewhat similar curve trends (Fig 6a), the maximum coefficient and its corresponding temperature increased linearly with the increase in heating rate (Fig 6b). CO₂ gas escaped as it generation, when the heating rate was larger, the rate of CO₂ generation was greater than the rate of escape, and could accumulate to larger pressure in the pores and cracks in the rock and augment the coefficient of linear thermal expansion. Therefore, it can be
inferred that the more intense the decomposition reaction of calcite, the faster the generation of carbon dioxide gas, and the higher the pore-fluid overpressure. Therefore, it can be inferred that the more intense the decomposition reaction of calcite, the faster the generation of carbon dioxide gas, and the higher the pore-fluid overpressure.

The sliding process at Jiweishan landslide was transient, its frictional heating was at very high rate. Therefore, on the basis of these experiments, we can infer that CO$_2$ gas was generated by thermal decomposition of calcite and dolomite during the sliding process, which tended to generate higher pore pressure in the rock at the sliding interface and so reduced the sliding frictional resistance.

![Figure 6. Thermal expansion of samples. a: The coefficient of linear thermal expansion curves at different heating rates. b: The maximum coefficient of linear thermal expansion at different heating rates.](image)

5. Conclusion

For the first time in the study of large landslide with high-speed and long run-out, we have obtained direct evidence of overpressure from generation of CO$_2$ gas caused by thermal decomposition of basal carbonates in Jiweishan landslide by using thermal analysis method. The thermal analysis results show that the significant increase of the coefficient of linear thermal expansion of rocks related to the generation of CO$_2$ gas is the result of overpressure. Under the extremely rapid heating rate, the thermal decomposition of minerals releases CO$_2$ gas during the sliding process of Jiweishan landslide, resulting in a sharp increase of pore pressure and a significant decrease of effective normal load. Simultaneously with the thermal expansion, thermal fracture is generated, making the sliding surface easily entrained, also contributed to the lubrication.

References

[1] Anders, M.H., Aharonov, E., Walsh, J.J. 2000. Stratified granular media beneath large slide blocks: implications for mode of emplacement. Geology, 28, 971–974.

[2] Cooper, H. W., Simmons, G., 1977. The effect of cracks on the thermal expansion of rocks. Earth & Planetary Science Letters, 36(3), 404-412.

[3] Heim, A. 1932. Der Bergsturz und Menschenleben, Fretz and Wasmuth, Zurich, pp. 185-218.

[4] Hu, W., Huang, R. Q., Mcsaveney M., Zhang, X. H., & Shimamoto, T., 2018. Mineral changes quantify frictional heating during a large low-friction landslide. Geology, 46(3).

[5] Hu, W., Huang, R., Mcsaveney, M., Yao, L., Xu, Q., Feng, M., & Zhang, X. H., 2019. Superheated steam, hot CO$_2$ and dynamic recrystallization from frictional heat jointly lubricated a giant landslide: field and experimental evidence. Earth and Planetary Science Letters, 510, 85-93.

[6] Iverson, R.M., 2005. Debris-flow mechanics. In: Jakob, M., Hungr, O. (Eds.), Debris Flow Hazards and Related Phenomena. Springer-Verlag, Berlin, pp. 105–134.

[7] Iverson, R. M., Reid, M. E., Logan, M., Lahusen, R. G., & Griswold, J. P., 2011. Positive feedback and momentum growth during debris-flow entrainment of wet bed sediment.
[8] Keefer, D.K., Larsen M.C. 2007. Assessing landslide hazards, Science, 316(5828), 1136–1138.
[9] Lucas, A., Mangeney, A., Ampuero, A.P. 2014. Frictional velocity-weakening in landslides on Earth and on other planetary bodies, Nature Communications, 5(1), 3417.
[10] Mitchell, T.M., Smith, S.A.F., Anders, M.H., Di Toro, G., Nielsen, S., Andrea, C., Beardg, A.D. 2015. Catastrophic emplacement of giant landslides aided by thermal decomposition: Heart Mountain, Wyoming, Earth and Planetary Science Letters, 411, 199-207.
[11] Pudasaini, S.P., Hutter, K. 2007. Avalanche Dynamics: Dynamics of Rapid Flows of Dense Granular Avalanches, 537 pp.
[12] Pudasaini, S.P., Miller, S.A. 2013. The hypermobility of huge landslides and avalanches, Engineering Geology, 157, 124-132.
[13] Ptáček, P., Lang, K., Šoukala, F., Opravil, T., Bartoničková, E., and Tvrdík, L., 2014. Preparation and properties of enstatite ceramic foam from talc: Journal of the European Ceramic Society, v. 34, p. 515–522.
[14] Tang, H.M., Zou, Z.X., Xiong, C.R., Wu, Y.P., Hu, X.L., Wang, L.Q., Lu, S., Criss, R.E. and Li, C.D., 2016. An evolution model of large consequent bedding rockslides, with particular reference to the Jiweishan rockslide in Southwest China. Engineering Geology, v186, p.17–27.
[15] Thirumalai, K., Demou, S. G., 1970. Effect of reduced pressure on thermal - expansion behavior of rocks and its significance to thermal fragmentation. Journal of Applied Physics, 41(13), 5147-5151.
[16] Voight, B., and Faust, C., 1982. Frictional heat and strength loss in some rapid landslides: Géotechnique, v. 32, p. 43–54.
[17] Xu, Q., Fan, X. M., Huang, R. Q., Yin, Y. P., Hou, S. S., Dong, X. J., & Tang, M. G., 2010. A catastrophic rockslide-debris flow in Wulong, Chongqing, China in 2009: background, characterization, and causes. Landslides, 7(1), 75-87.
[18] Yin Y.P., Wang F. W., Sun, P., 2009. Landslide hazards triggered by the 2008 Wenchuan earthquake, Sichuan, China. Landslides, 6(2):139-152.
[19] Yin, Y. P., Sun, P., Zhang, M., and Li, B., 2011, Mechanism of apparent dip sliding of oblique inclined bedding rockslide at Jiweishan, Chongqing, China: Landslides, v. 8, p. 49–65.