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SUPPLEMENTARY INFORMATION

Mineral changes quantify frictional heating during a large low-friction landslide

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This file provides supporting information for the article "Mineral changes quantify frictional heating during a large low- friction landslide" by Hu et al. Topics covered include:

1. Details of the sequence of the movement of Jiweishan landslide (Figure DR1, Figures DR2, DR3, DR4);
2. Details of the experimental methods
3. Detailed description of sliding surface striae (Figure DR5)；
4. Details of measurement of temperature (Figure DR6)；
5. Micro-structure of test cylinder transverse to the sliding surface (Figure DR7).

1. The sequence of the movement of Jiweishan landslide

By 1969, residents of Teukung Town, Wulong County, Chongqing, China had become concerned about the risk to their homes and families from rocks falling from the high limestone bluffs of Jiweishan Mountain (Yin et al., 2011). The Wulong County geological authority assessed the risk and advised relocation of the town from immediately below the mountainside. By 2001, relocation of 841 people to a new site was safely accomplished, but a rockfall risk remained for road users and farm workers.

Authorities continued to monitor and advise on the instability of the cliff, successfully warning of a number of rockfalls. On the morning of the June 2, 2009, Re Guangmu, the local monitoring person, watched a 1,000 m^3 rockfall (Xu et al., 2010). Mr Re continued watching as the falling rocks stopped abruptly in the road where the evacuated village formerly had been located. At about 6:00 P.M. on June 4, 2009, another rockfall with a volume of 3,000 m^3 collapsed from the same cliff area. The collapsed area of 2 June was enlarged and extended to the middle and lower part of the front of the cliff (Tang et al., 2016).

An inspection at 9 AM on June 5, 2009 assessed that a larger rockfall from the June 4 site was imminent. The area likely to be at risk from a larger rockfall was cleared and closed to access. Around 2:50 P.M. on June 5, 2009, a mass of about 13.3 million tonnes of limestone unexpectedly accelerated, broke into many small fragments and poured from the clifftop onto the valley below. The huge block had suddenly transformed into a giant rock avalanche which devastated the wider valley floor of Tiejiang Creek, destroying farms and an iron mine with workers underground (Yin et al., 2011; Tang et al., 2016; Xu et al., 2010). Seventy-four people were killed in the disaster.

In the ensuing post-disaster investigation, the immense landslide was found to be 3 orders of magnitude larger than the predicted event (Xu et al., 2010). The larger mass was found to have slid rapidly along a weak shale interlayer in the coal-measure rocks on Jiweishan Mountain (Yin et al., 2011; Tang et al., 2016; Xu et al., 2010). The accelerating movement appeared to have moved almost parallel to the cliff face instead perpendicular to the cliff which was the anticipated fall direction. The reason that the original county investigators had made such an error in prediction was not adequately explained but was attributed to the outcome being beyond their previous experience.

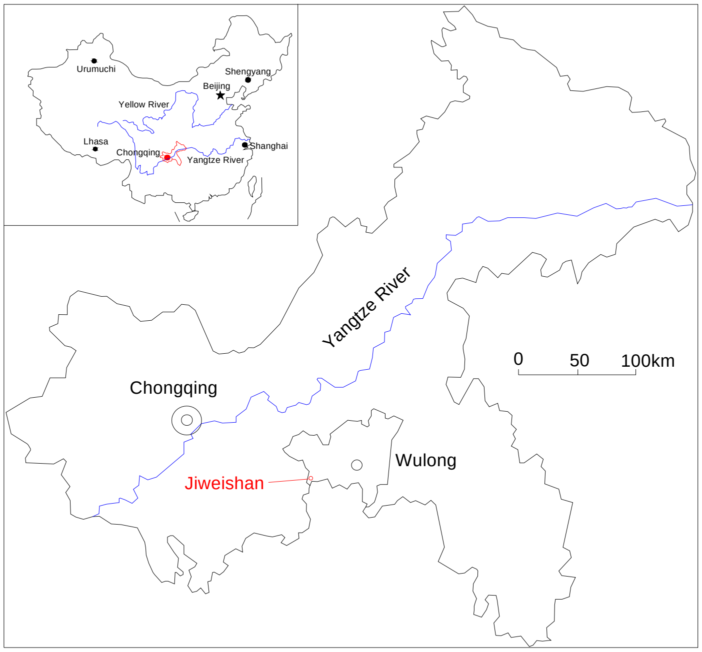

Figure DR1 The location of Jiweishan landslide.

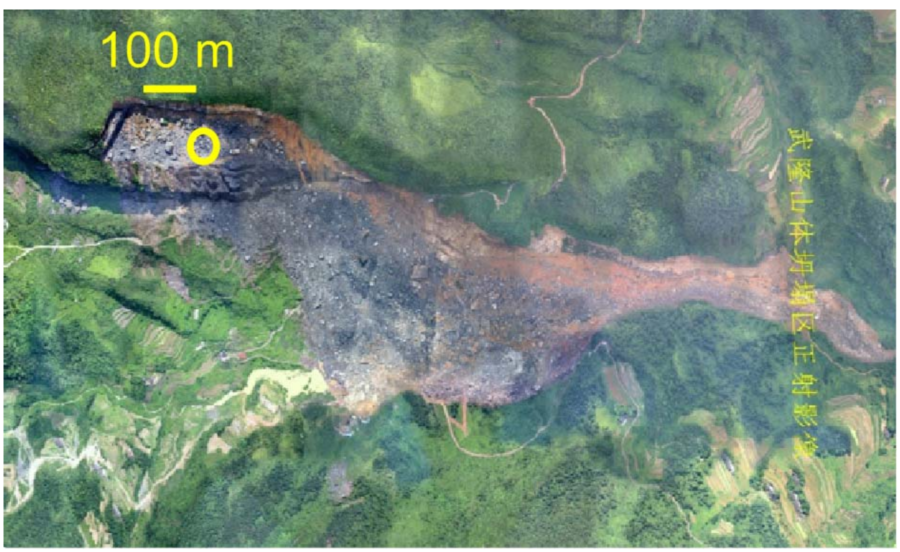

Figure DR2 Orthophotographic image of the Jiweishan landslide. The area where we sampled the basal sliding surface in the landslide source area is circled. The landslide runout is to the north (right in image)

Figure DR3 Oblique image of sample area after sliding. Circle marks location where samples were collected for analysis.

Figure DR4 Oblique image of the slope before sliding. A crack up to 2 m wide and perpendicular to the cliff face had formed before 1996 after collapse of old mine adits. We and others (Xu et al., 2010; Yin et al., 2011; Tang et al., 2016) infer creep deformation of the slope over many years until June 2009.

2. Details of the experimental methods

Thermogravimetric tests

Thermogravimetry (TG) or Differential thermal analysis (DTA) is a method of thermal analysis in which changes in physical and chemical properties of materials are measured as a function of increasing temperature (with constant heating rate), or as a function of time (with constant temperature and/or constant mass loss). DTA can provide information about chemical phenomena including chemisorptions, desolvation (especially dehydration), decomposition, and solid-gas reactions (Coat and Redfern, 1963) (e.g., oxidation or reduction).

We obtained conventional TG-DTA measurements using a Netzsch STA409PC simultaneous thermal analyzer at a heating rate of 10°K min^{-1} from 30 to 900°C. This TG-DTA system heats a finely ground sample mass of about 25 mg, in an alumina sample pan, in an atmosphere of Argon flowing at 30 mL min^{-1}, whilst temperature and mass are very precisely monitored. Temperature calibration was performed prior to the analyses.

X-Ray diffraction

The mineral composition of the samples was examined by X-ray diffractometer (Rigaku D/MAX-IC) equipped with Ni filter. It generates a beam of CuKa radiation (k = 0.1546 nm). The operational settings for all the XRD scans were voltage: 40 kV, current: 30 mA, range: $10<2\theta<70°$, scanning speed: 0.6°/s.

High-speed friction tests

High-speed friction experiments were performed on three samples from Jiweishan mountain using the rotary shear apparatus at the Institute of Geology, China Earthquake Administration, Beijing (Ma et al., 2014). Each experiment was conducted on a pair of solid cylindrical specimens of the shale. The diameter and length of each specimen were 39.5 to 39.8 mm and about 50 mm, respectively. We used solid- rather than hollow-cylindrical specimens because the latter cannot support high normal stress. To prevent thermal fracturing of the specimens due to rapid and inhomogeneous frictional heating on sliding, we mounted an aluminium sleeve (~1.3 mm thick) around each specimen and a narrow gap was left between the two aluminium sleeves to avoid metal-to-metal frictional contact. Our friction tests all were conducted with initially bare contact surfaces of solid rock cylinders without pre-insertion of gouge between the specimens.

SEM analysis

Scanning electron microscopy (SEM) enables examination of surfaces at much higher magnification than optical microscopy because of the much smaller wavelength of electrons compared to visible light. SEM imaging and energy-dispersive X-ray spectroscopy (EDS) analysis were performed on a Quanta250 FEG and Oxford INCAx-max20 system at the State Key Laboratory of oil and gas reservoir geology and exploitation, Chengdu University of Technology. The imaging in SE and BSE modes and EDS analyses were performed at an accelerating voltage of 15 kV in the SEM. The samples from the sliding surface of the landslide and from the high-speed friction experiments were examined on pristine surfaces after gentle cleaning with water and coating with a thin gold film.

3. Detailed description of sliding surface striae

A sample was taken from the sliding surface (Fig. 1B) to get detailed of information of striae. Three sets of striae were apparent on pavement hand specimens (shown in Fig.DR5): one of them (indicated by a yellow arrow, Fig.DR5(A) obviously formed later than the others that it is superimposed across. Only two sets were obvious in the field where one set of broader deeper grooves was crossed diagonally at an angle of about 30° by a set of smaller, shallower grooves. This latter set corresponded with the youngest set in Fig. DR5, suggesting that what appeared to be two older sets on hand specimens may be a single set with a variance of about 15° degrees. The spacing between striae of similar size in the field varied across at least three orders of magnitude from about 1 mm to 1 m (compare their spacing in Fig. 1B and Fig.DR5(A)). Individual striations began and ended irregularly and striation lengths and depths varied widely. Some continued down the 2-m long gentle slope of the entire exposed field outcrop, while others were much shorter than a hand specimen. The scratching “tools” which scored this pavement to make the striations, also left chatter marks along the bases of grooves. Two types of chatter marks are illustrated in Fig.DR5 (B) and DR5(C) (indicated by red arrows). The most common type was caused by a “tool” making a single point contact with the pavement, while a rarer type was caused by one with two point contacts, making parallel striae with paired chatter marks.

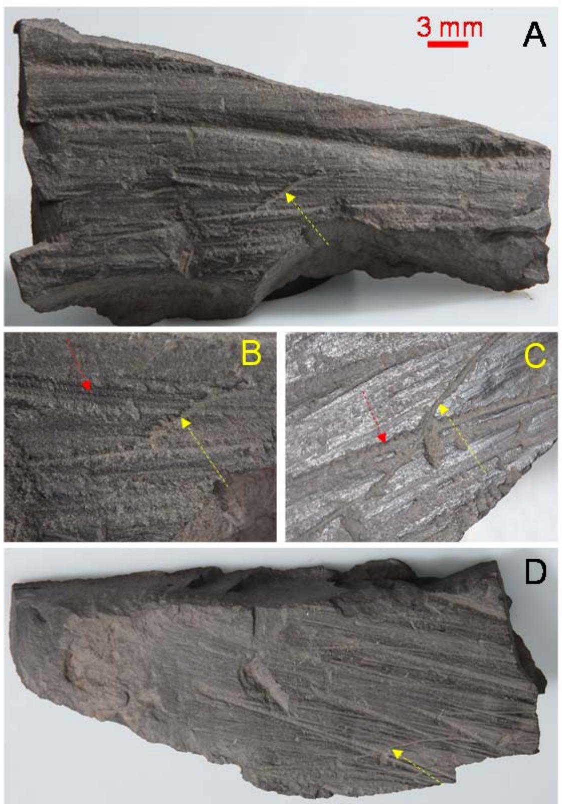

Figure DR5 Detailed views of hand specimens of pavement. Direction of landslide movement is from left to right. Many of the deeper and fresher striae show evidence of stick-slip motion in the form of chatter marks (indicated by red arrows) left by scratching tools. Two striae-trend directions were evident. Yellow arrows point to a younger set of striae. The striae were neither straight nor parallel. The pavement was scratched and polished by sliding of very hot (~800°) basal gouge containing a fractally graded mix of fine to coarse particles. Frictional resistance was initially reduced by the presence of talc, but ultimately by high-pressure gas (CO_2, and live steam) and a dynamically recrystallizing layer.

4. Measurement of temperature

Thermocouples were used to measure the temperature on the sliding surface. A thermocouple is an electrical device consisting of two dissimilar conductors forming electrical junctions at differing temperatures. A thermocouple produces a temperature-dependent voltage which can be calibrated to measure temperature. Thermocouples are a widely used type of temperature sensor. To measure temperatures on the sliding surface during shear, manually welded Ni-Cr thermocouple wires, insulated by corundum tubes, were embedded into the lower (stationary) cylinder that had been drilled beforehand at radial distances of 4mm and 8mm from the edge (Fig. DR6). We glued the thermocouples with high-temperature cement near the surface of the cylinder and with epoxy at the remote end, setting the welding points (<0.5mm in diameter) exactly on the grinding end surface of the cylinder (Chen et al.,2016).

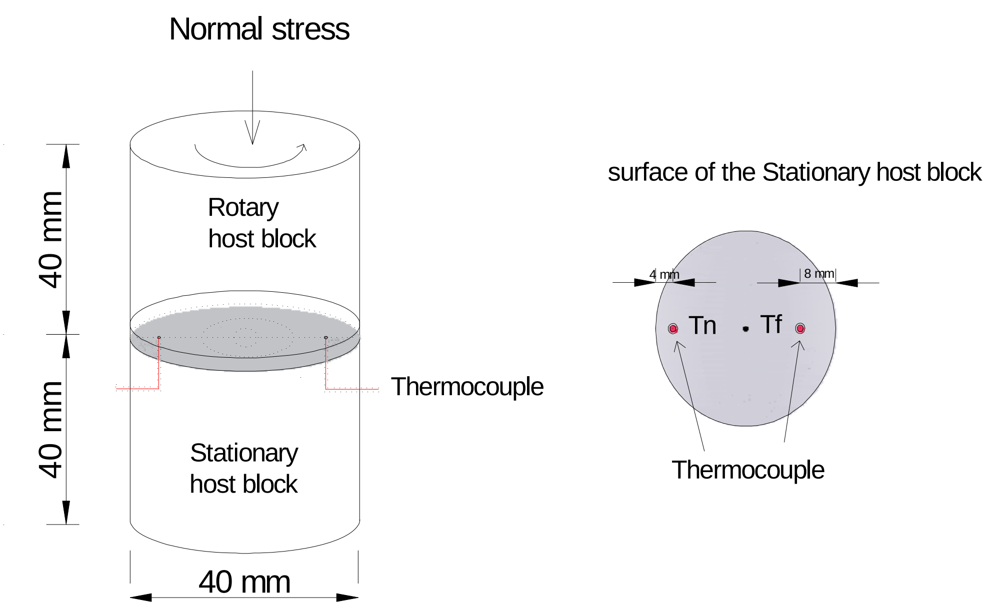

Figure DR6 Sketch of the high speed rotary experiment and positions of thermocouples.

5. Micro-structure of test cylinder transverse to the sliding

A 0.6mm section of the cylinder adjacent to the sliding surface also was examined under SEM: a 12-µm-thick surface gouge of agglomerated nanoparticles is shown covering intact, but heat-altered host rock (Fig. DR7). The chemical composition of the agglomerated gouge (by electron probe) was identical to the intact-but-altered rock, and is inferred to be derived from it.

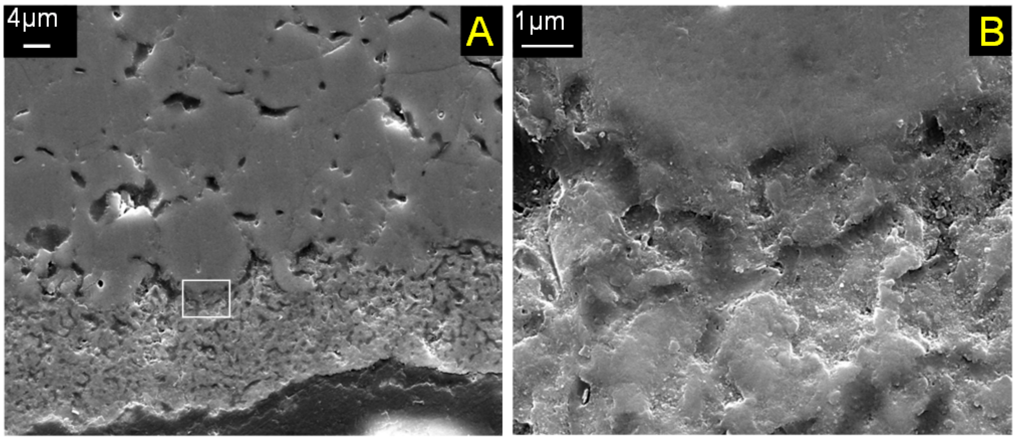

Figure DR7 Micro-structure of test cylinder transverse to the sliding

A. A SEM image of a 0.6mm section of the test cylinder transverse to the sliding. **B**. View of the rectangle outlined in white in Fig. DR7(A) at higher magnification. Together they show a 12-μm thick layer of surface gouge of agglomerated nanoparticles covering intact, but heat-altered recrystallized host rock. Electron-microprobe analysis shows that chemical composition of the agglomerated gouge is identical to the intact-but-altered rock.

References Cited

Chen, J.Y., Niemeijer, A., Yao, L., Ma, S.L., 2016, Water vaporization promotes coseismic fluid pressurization and buffers temperature rise: Geophysical Research Letters, v44, P.2177-2185, https://doi.org/10.1002/2016gl071932.

Coats, A.W., and Redfern, J.P., 1963, Thermogravimetric analysis. A review: Analyst

(London), v. 88, p. 906–916, https://doi.org/10.1039/an9638800906.

Ma, S.L., Shimamoto, T., Yao, L., Togo. T and Kitajima, H.,2014, A rotary-shear low to high- velocity friction apparatus in Beijing to study rock friction at plate to seismic slip rates: Earthquake science, v 27,469–497, https://doi.org/10.1007/s11589-014-0097-5.

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, https://doi.org/10.1016/j.enggeo.2014.08.021.

Xu, Q., Fan X.M., Huang, R.Q., Yin, Y.P., Hou, S.S., Dong, X.J. and Tang, M.G., 2010, A catastrophic rockslide-debris flow in Wulong, Chongqing, China in 2009: Background, characterization, and causes: Landslides, v7, p.75–87, https://doi.org/10.1007/s10346-009-0179-y.

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, 49–65, https://doi.org/10.1007/s10346-010-0237-5.