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

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ABSTRACT

Data on thermal decomposition constrain events around the transition on 5 June 2009 from creep deformation (over many decades) with sporadic rockfalls to catastrophic collapse of Jiweishan Mountain, China, which poured millions of tons of limestone rubble from a cliff top into the valley below, causing 79 deaths. We quantified frictional resistance (μ, 0.1–0.2) and rapid frictional heating using thermogravimetry, mineral alteration close to the sliding surface, and high-speed rotary experiments. The differential thermogravimetry (DTG) trough temperature varied from 794 ± 4 °C at the sliding interface to ~720 °C below 10 mm. We inferred that DTG trough changes reflected the substrate thermal history due to landslide frictional heating. X-ray diffraction (XRD) analysis showed thermal decomposition of talc (a major mineral in the shale at Jiweishan Mountain) to magnesium metasilicate (formation temperature of ~600 °C) and enstatite (formation temperature of 800–905 °C). The intensity of the enstatite XRD peak decreased with increasing depth below the sliding surface to disappear below 6.5 mm. Magnesium metasilicate appeared between 6.5 mm and 10.5 mm depth. We replicated the temperatures and mineral changes in high-speed rotary shear experiments. Heating above 800 °C at the sliding surface was confirmed by temperature measurements and thermal decomposition of dolomite to magnesium and calcium oxides in the shallowest samples (which could not have survived for 7 yr at our field site and thus were not detected in the field). We inferred that the slide surface was heated to at least 800 °C by frictional sliding and that the temperature below 10.5 mm depth did not rise above 600 °C. Evidence of dynamic localized recrystallization was found on both field and experimental sliding surfaces, which may be a further explanation for the ultra-low friction during the rapid sliding, besides the presence of a significant basal pore-gas pressure from CO2 and steam.

INTRODUCTION

It is generally believed that increase in temperature during slip can dramatically decrease the friction at the base of a large landslide and thus greatly affect its dynamic behavior (Voight and Faust, 1982). Much previous work on landslide and fault frictional heating has focused on the presence of melt rock, which is direct evidence of melting of rock at a sliding interface (Weidinger and Korup, 2009; Tsutsumi and Shimamoto, 1997; Di Toro et al., 2006). However, in most rapid landslides, melt rock is not found, although thermodynamics theory requires that frictional heating at the sliding surface must occur to some degree (Thompson, 1798).

Herein we used X-ray diffraction (XRD) and thermogravimetry (TG) to quantify the recent thermal history of substrate bedrock below a landslide sliding interface. We confirmed our findings experimentally using samples of shale from Jiweishan Mountain, China, in a high-speed rotary shear device. Our objectives were to quantify the frictional resistance and temperatures experienced during the sliding in A.D. 2009 on the bedrock interface beneath the large rapid Jiweishan landslide (Yin et al., 2011).
Maokou Group consisting of mainly grayish-white thick-layered dolomitic limestone, which forms the crest of the mountain above steep cliffs facing the valley of Tiejiang Creek. The lower part of the source mass is the lower Permian Qixia Group, composed dominantly of dark gray and gray medium-layered black dolomitic limestone interbedded with micritic dolomitic limestone (Fig. 1D; Yin et al., 2011). The steep cliffs below the landslide source mass expose gray limestone with a thickness of 90–95 m. This massive limestone is overlain by a 40-m-thick, dark-gray, largely limestone stratum. Near the top of the 40-m-thick layer, there is a 30-cm-thick, particularly weak, black calcareous shale interlayer on which the rupture surface was formed, as shown in Figure 1D (Yin et al., 2011).

MATERIALS AND METHODS
We examined exposures of the sliding surface above the cliff in May 2016. The surface is preserved on a stratum of well-indurated, dark-gray, dolomitic shale and displays well-developed scratches in the direction of landslide motion (Figs. 1B and 1C; more details are provided in the Data Repository, including Fig. DR5). These clearly indicate that the landslide moved in close frictional contact with its base. The surface was highly reminiscent of a striated pavement from beneath a glacier. In addition to examining the obvious evidence of erosion and physical damage to the exposed bedrock (Fig. 1B; Fig. DR5), we also sought evidence of damage from the frictional heat that must have been generated as the landslide slid over the pavement. We took samples of the exposed stratum back to the laboratory where we determined mineral and temperature stable phases in the samples, attributable to frictional heat generated by the landslide movement. We repeated the TG tests using material from a nearby site B (Fig. 1B), also on the sliding surface, ~2 m distant from site A. Four samples (samples [12]–[15]) were cut from known depth increments. DTG curves for them are shown in Figure 2B. They showed the same characteristic DTG trough shifts. The variation in maximum temperature of the respective DTG troughs with sample depth for the 14 samples is shown in Figure 2D. The DTG trough temperature varied linearly with sample depth from an extrapolated 794 ± 4 °C at the sliding interface to ~720 °C below a depth of ~10 mm. We considered a possibility that changes in the DTG trough might have resulted from exposure of the surface to weathering since 2009. We conducted TG analyses of a further three samples (samples [16]–[18]) of the shale lithology (Fig. 2C). These samples were chosen to have possibly different exposure durations. Sample [16] was comparatively minimally weathered, as it was taken from what appeared to be a relatively freshly broken (dark gray) surface. Sample [17] had a light-gray color and appeared to be a more-weathered material. Sample [18] was a sample of the fine gouge on the sliding surface, and had had precipitation runoff passing through it since June 2009. The DTG trough temperature of sample [16] (807.9 °C) was higher than that of the other two samples in Figure 2C, and sample [18] had the lowest temperature (783.1 °C) among the three samples. We inferred that weathering was not the reason for the shift of DTG trough temperature.

Characterization of Thermal Decomposition Due to High-Speed Sliding
In order to understand the shift of DTG peak trough with depth of sample and the evidence of phase transformation during frictional heating, we obtained XRD spectra for samples [1]–[10]. The spectra from different sampling depths are given in Figure 3A. The results show that the shale contains dolomite, talc, feldspar, and faujasite as major minerals, and an appreciable amount of enstatite and magnesium silicate. With increasing depth below the slide surface, there is varying influence of the characteristic XRD peaks of enstatite and magnesium silicate (Fig. 3A). This confirms the presence of high-temperature intermediate products as deduced from DTG. From 1 to ~5.5 mm depth, the intensity of the XRD peak at 27.5° (2θ) attributed to

RESULTS

Thermogravimetric Analysis of Sliding-Surface Material
In the differential TG (DTG) curves, we use the first derivative of the mass change with temperature. Figure 2A shows DTG curves of the samples. The troughs of the DTG curves allow the specific temperature characteristics of the different mineral components to be more accurately determined than the parent TG curves. At the different sampling depths, similar DTG curves were obtained. However, with decreasing depth of sample, the DTG trough temperature occurred at a higher temperature, while the area of the DTG trough increased gradually. We deduced that the shift of the DTG trough temperature related to increased content of high-temperature stable phases in the samples, attributable to frictional heat generated by the landslide movement. We repeated the TG tests using material from a nearby site B (Fig. 1B), also on the sliding surface, ~2 m distant from site A. Four samples (samples [12]–[15]) were cut from known depth increments. DTG curves for them are shown in Figure 2B. They showed the same characteristic DTG trough shifts. The variation in maximum temperature of the respective DTG troughs with sample depth for the 14 samples is shown in Figure 2D. The DTG trough temperature varied linearly with sample depth from an extrapolated 794 ± 4 °C at the sliding interface to ~720 °C below a depth of ~10 mm. We considered a possibility that changes in the DTG trough might have resulted from exposure of the surface to weathering since 2009. We conducted TG analyses of a further three samples (samples [16]–[18]) of the shale lithology (Fig. 2C). These samples were chosen to have possibly different exposure durations. Sample [16] was comparatively minimally weathered, as it was taken from what appeared to be a relatively freshly broken (dark gray) surface. Sample [17] had a light-gray color and appeared to be a more-weathered material. Sample [18] was a sample of the fine gouge on the sliding surface, and had had precipitation runoff passing through it since June 2009. The DTG trough temperature of sample [16] (807.9 °C) was higher than that of the other two samples in Figure 2C, and sample [18] had the lowest temperature (783.1 °C) among the three samples. We inferred that weathering was not the reason for the shift of DTG trough temperature.

Figure 2. Thermogravimetric analyses of field samples. A: First derivative (deriv.) of thermogravimetric mass change of samples [1]–[10] from various depths at sample site A. B: First derivative of thermogravimetric mass change of samples from sample site B at various depth increments (samples [12]–[15]). C: First derivative of thermogravimetric mass change of weathering samples [16]–[18]. D: Variation of maximum temperature (temp.) of trough of differential thermogravimetric (DTG) curve with sampling depth below sliding surface.
We deduced that the enstatite and magnesium silicate phases shown in Figure 3A came from talc decomposition due to heat generated by friction during the landslide. The sampling depth and the temperature experienced during the landslide show an inverse relationship, wherein the closer the sample to the sliding surface, the higher the temperature experienced, and vice versa. We deduced from the XRD results that the surface samples (from 0 to 6 mm depth) may have briefly experienced temperatures up to 800 °C during the landslide, and the temperature from 6.5 mm to 10.5 mm below the surface did not rise above ~600 °C at any time (in the small sampled area shown in Fig. 1B).

Based on the XRD results, at 630–850 °C, the sample mass loss shown in Figures 2A–2C was mainly attributable to the overlapping steps of decarbonation of dolomite and dehydration of talc (Ptáček et al., 2014). The following reactions may take place at for talc at 630–850 °C:

\[2\text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_2 \rightarrow 2\text{Mg}_2\text{Si}_2\text{O}_3 \text{ (anhydrous magnesium silicate)} + 2\text{H}_2\text{O} \text{ (gas)}, \]

\[2\text{Mg}_2\text{Si}_2\text{O}_3 \rightarrow 3\text{Mg}_2\text{Si}_3\text{O}_5 \text{ (enstatite)} . \]

The following reactions may take place for dolomite at 750–800 °C (Ptáček et al., 2014):

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

and at 840–950 °C:

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

Besides the XRD spectra, SEM images of the shale also showed evidence of thermal decomposition systematically decreasing with increasing depth in the shale. On the sliding surface of the sample, we found nano-scratches on the submicron plates of an aluminosilicate phases shown in Figure 3A came from talc decomposition due to heat generated by friction during the landslide. The sampling depth and the temperature experienced during the landslide show an inverse relationship, wherein the closer the sample to the sliding surface, the higher the temperature experienced, and vice versa. We deduced from the XRD results that the surface samples (from 0 to 6 mm depth) may have briefly experienced temperatures up to 800 °C during the landslide, and the temperature from 6.5 mm to 10.5 mm below the surface did not rise above ~600 °C at any time (in the small sampled area shown in Fig. 1B).

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through the crystal and left nano-bubbles of calcium and magnesium oxides on the crystal surfaces in the experimental sample (Fig. 4J). These oxide nodules were not seen in the field samples probably because with water and time, both of these oxides are soluble and absorb CO₂ to revert to carbonate.

Laboratory Simulation and Analysis

We also conducted high-speed friction experiments on three samples of the black shale from near the sliding surface on Jiweishan Mountain, using the rotary shear apparatus at the Institute of Geology, China Earthquake Administration, Beijing (see the Data Repository). The sample assembly included two opposing cylindrical host samples created from the shale. Rotary shear was carried out at a normal stress of 1 MPa and “equivalent slip rates” (Tsutsumi and Shimamoto, 1997) of 1 and 2 m/s. The sample cylinders were 40 mm in diameter and 50 mm long. Temperature at the slip surface during rotation was monitored by a pair of thermocouples (T₁ and T₂) mounted close to the sliding surface, respectively located 4 mm and 8 mm from the sample boundary (see the Data Repository; Fig. DR6). Three representative experiments at a normal stress of 1 MPa and slip rates of 1 and 2 m/s are shown in Figures 4A–4C. In the experiment shown in Figure 4A, with a normal stress of 1 MPa and slip rate of 1 m/s, a peak friction coefficient of ~0.38 was attained after ~7 m of shearing. A comparatively slow weakening process was observed, and the lowest friction coefficient was ~0.06. We obtained a maximum temperature of ~700 °C after ~45 m of shear displacement. With further displacement, there was a slow cooling to ~400 °C and then heating again, gradually to ~420 °C. However, the recorded temperature can only be taken as a lower bound of the real temperature on the slip surface because of the complex evolution of slip zones (e.g., width and exact location, and their changes with slip). Furthermore, the measured temperature changes in the later stages may partly result from the energy sink of the endothermic decomposition reactions, which buffer or suppress the frictional temperature rise (Brantut et al., 2011). In another 1 MPa and 1 m/s test (Fig. 4B), we obtained a peak friction coefficient of ~0.79, which was then followed by a rapid weakening process. The lowest friction coefficient obtained was ~0.19 (Fig. 4B). For the experiment at 1 MPa and 2 m/s, the peak and lowest friction coefficient were respectively ~0.65 and 0.1 (Fig. 4C). The variation in the mechanical data for the different experiments mainly lies during the period of peak friction during initial displacement, which can be attributed to the heterogeneity of the samples and the complexity of the pulverization process of shale during initiation of slip. Once cooled to room temperature, one side of the slip surface was examined with SEM (Fig. 4E). The surface was striated. Striae ridges were composed principally of recrystallized wollastonite (Fig. 4G) while the troughs contained agglomerated nanoparticles (Fig. 4H) adhering to recrystallized, heat-altered host rock, as determined from microprobe analysis. Aligned polygonal grains and curved grain boundaries (Mitchell et al., 2015) were also observed (Fig. 4F), which were ~40x larger than similar structures seen on the field sample (Fig. 3C). A section of the cylinder immediately below the sliding surface was also examined by SEM (see the Data Repository; Fig. DR7). Evidence of thermal decomposition was observed on calcite and dolomite crystals, which were dotted with nano-spheroids. Those illustrated in Figures 4I and 4J were located ~3 mm below the sliding surface. The mushroom-like or red blood cell–like structures (Fig. 4J) were possibly deflated bubbles of CaO and MgO after emission of CO₂ gas formed through thermal decomposition of dolomite.

Fourteen small samples were cut from the cylindrical host at cumulative increments of ~1 mm from the sliding surface for XRD. Representative XRD analyses are illustrated in Figure 4D. The results show that the bulk of the cylinder >5 mm from the slip surface contains unaltered calcite, dolomite, quartz, and talc as the major minerals, with only a minor amount of enstatite. Closer than 5 mm from the sliding surface, there is replacement of talc with enstatite and decomposition of dolomite and calcite to magnesium and calcium oxides. These XRD results give further support to the results obtained from the field samples shown in Figure 3A.

CONCLUSIONS

For the first time in the study of large rapid landslides, we have quantified the thickness of the zone affected by heating and the highest temperature reached on the sliding surface of the 2009 Jiweishan landslide. Thermogravimetry and mineral alteration indicate a maximum surface temperature of 794 ± 4 °C. Direct field evidence of the thermal decomposition of sliding-surface materials including talc and dolomite was found to a depth ~6.5 mm below the sliding surface.

ACKNOWLEDGMENTS

This research was supported by the National Basic Research Program of China, the funds for creative research groups of China (41521002), and the basic research funds (41790433). It is also supported by young researchers funding of Sichuan province (2016JQ0021). We are grateful for helpful comments by S.L. Ma. We thank M.S. Feng for his technical assistance in SEM analyses. We thank Reginald Hermanns and Antoine Lucas for their constructive comments.

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Manuscript received 28 August 2017
Revised manuscript received 3 November 2017
Manuscript accepted 7 December 2017
Printed in USA

226
www.gsapubs.org | Volume 46 | Number 3 | GEOLOGY

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