A polished and striated pavement formed by a rock avalanche in under 90 s mimics a glacially striated pavement

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A B S T R A C T

A polished and striated bedrock surface resembling a classical glacial striated pavement formed in 2009 in substantially <90 s beneath a rock avalanche on Jiweishan Mountain. Opportunities to closely examine such surfaces are rare, allowing researchers to speculate widely on basal rock-avalanche processes. We constrain future speculation by discussing signatures left on a basal sliding surface at a distance of 500 m from the headwall of this 2.2 km long rock avalanche. There are scratches, chatter marks and plucking scars on a surface of dolomitic black shale. They indicate frictional drag of particles in direct contact with the bed, causing relatively mild abrasion. Striations have beginnings and ends, vary in depth along their lengths, and do not always follow straight lines. These patterns suggest that the scratching particles moved about relative to one-another while confined in a deforming basal gouge. We used rotary shear equipment to experimentally shear both dry and saturated landslide gouge against intact shale from the sliding surface to create similarly grooved pavements under a realistic normal stress (1 MPa). Our observations and experiments suggested that the base of the landslide slid rapidly across this site on Jiweishan Mountain as a slightly erosive, initially water-saturated, dense grain flow with a low dynamic friction coefficient of about 0.1. Friction heated the base to about 800 °C, decomposing talc and dolomite to produce high-pressure live steam and carbon dioxide. What was left was a polished and grooved pavement highly reminiscent of a glacially striated pavement.

Available online 11 August 2018

1. Introduction

Shortly before 3:00 PM on June 5, 2009, a 7 × 10⁶ m³ rock avalanche fell from Jiweishan Mountain, Wulong county, China (Yin et al., 2011; Xu et al., 2010; Tang et al., 2014; Zhang et al., 2018). While inspecting the source area in 2015, we removed a locally thin cover of debris from the sliding surface to find a well preserved, polished and striated pavement (Fig. 1a) highly reminiscent of a classical striated rock pavement from beneath a glacier (Fig. 1b). It was distinctly different from the striated surfaces we had seen on fault-rupture surfaces, and beneath an un lithified clay-based slow-moving landslides (Fig. 1c). There is voluminous literature on the formation of glacial striae (e.g., Benn and Evans, 1998) (a Google search returns > 20,000 results for “glacial striations”) and much has been learned from them of basal glacier processes (e.g., Chamberlain, 1888). However, we have found no descriptive literature on basal rock-avalanche striae or pavements. The literature on rock-avalanche basal processes is largely speculative, with little evidential support of assumptions. Our study of the pavement on Jiweishan Mountain has been highly informative of the conditions that existed on several 2-m² portions some 50 m apart at the base of the 2009 rock avalanche for some portion of the 2-minute total duration of its movement. Our observations do not support much of the literature speculation.

We focus here on the small patch of pavement and not on the long run-out rock avalanche which is a continuing popular topic for researchers beyond those already cited. The Jiweishan landslide is worthy of global attention, as are many other Chinese landslides. We examined the pavement extensively in situ, and in the laboratory. We also conducted laboratory experiments on field-collected samples, making our own striated pavements to assist in better understanding how the pavement formed.

2. Setting

Shortly before 3:00 P.M. on June 5, 2009, after years of inferred creep deformation, a mass of about 13.3 million tons of limestone, dolomite and shale unexpectedly accelerated and slid rapidly along a weak shale interlayer in the coal-measure rocks on Jiweishan Mountain, Wulong County, China (Yin et al., 2011; Xu et al., 2010; Tang et al., 2014; Zhang et al., 2018). Although nearly a thousand townsfolk from the immediate area below the mountainside had long been evacuated to safety, >70 people were killed in the unanticipated giant rock avalanche which devastated the wider valley floor of Tiejiang
Creek, destroying farms and an underground iron mine within 90 s (Li et al., 2017). Jiweishan landslide is viewable in Google Earth, but unfortunately the image of 29 December 2014 is draped over pre-avalanche topography, giving a distorted 3-D view. An orthophotographic image of the landslide, geological cross-section I-I′ and oblique image of the sample area are shown in Fig. 2 and the location of the landslide in Wulong County and China is shown in Fig. 3.

Jiweishan Mountain is on the north-western limb of Zhaojiaba anticline where Lower Permian and Silurian coal-measure strata dip at 20–32° towards N15°W, almost parallel to the adjacent valley of Tiejiang Creek. Most of the landslide mass was made up of well indurated rocks from the Lower Permian Maokou Group consisting of mainly grayish-white thick-layered dolomitic limestone which forms the crest of the mountain above steep cliffs facing the valley. The lower part of the source mass is Lower Permian Qixia Group composed dominantly of dark grey and grey, medium-layered dolomitic limestone, interbedded with micritic dolomitic limestone. The steep cliffs below the landslide source mass expose grey limestone with a thickness of 90–95 m. The overlying layer is a 40-m thick, dark grey, largely limestone stratum. Near the top of the 40-m thick layer, there is a 30-cm thick particularly weak calcareous black shale interlayer which is quite variable in composition (Yin et al., 2011; Xu et al., 2010; Tang et al., 2014; Deng et al., 2014). The base of the landslide appears to have developed on the top of this shale, which contains variable proportions of talc (up to 95% by XRD). The eroded surface left by the landslide is shown in Fig. 2c.

On a visit to the landslide source area above the cliff on 11 May 2016 we inspected several areas of the exposed sliding surface. An area immediately below the headscarp has been exposed for at least 50 years. It became exposed by pre-rock-avalanche creep which began opening a deep crack which had grown to be 2-m wide by 1996 (Fig. 2e) (Yin et al., 2011). There are many calcite-filled slickensides distributed...
through the shale exposed at this site. These are described in detail by others (Deng et al., 2014; Tang et al., 2014). Tang et al. (2014) attribute them to the pre-2009 creep phase of movement, but we disagree, considering them to be bedding-plane shears from very much earlier and now extinct tectonic deformation that folded the rock mass. We found slickensides with calcite infillings to be widely distributed within shale interbeds in and around the landslide mass, and not confined to the basal shear surface of the landslide. Bedding-plane shears are a common occurrence in weaker beds in folded strata (eg., Skempton, 1985).

A second and larger area of exposures of the basal shale is illustrated in Fig. 1a. The location is circled in yellow in Fig. 2. It is approximately 500 m downslope from the landslide headscarp. The landslide basal shear surface in this area has been largely vacated by the rock-avalanche source mass, because the new surface slope is approximately at the angle of repose of the loose landslide debris. The texture of this surface was unlike the surface known to have been exposed by the earlier crack opening, and it had no calcite-infilled slickensides.

The polished surface that we infer the landslide slid on, is preserved on an in situ stratum of well indurated, very dark grey, dolomitic shale. It displayed well developed striae that were orientated symmetrically about the down-dip direction in the general direction of landslide motion (Fig. 1a). It is significant and curious that the dip direction and direction of sliding indicated by the striae lead obliquely into apparently blocking in situ rock, now forming a vertical cliff (Fig. 2c). A change in sliding direction is indicated by scratches on the...
cliff face, but lack of continuity of exposure across the landslide base currently prevents showing precisely where the change in direction occurs.

3. Observed physical damage

Three sets of striae were apparent on pavement hand specimens (shown in Fig. 4): one of them (indicated by a yellow arrow in Fig. 4a) formed later than the others which it is superimposed across. Only two sets were obvious in the field (Fig. 1a), however; 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. 4a, suggesting that what appeared to be two older sets on hand specimens was a single set with a variance of about 15°. 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. 1a and Fig. 4c). 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. A profile (A-A′) along the base of a deeper groove on one of the hand specimens (Fig. 4a) is shown in Fig. 5 along with a cross profile of adjacent grooves (B-B′).

The scratching “tools” which scored the pavement to make the striae, also left chatter marks along the bases of grooves. Two types of chatter marks are illustrated in Fig. 4b and c (indicated by red arrows). The most common type is caused by a “tool” making a single point contact with the pavement, while a rarer type is caused by a tool with two simultaneous point contacts, making parallel striae with paired chatter marks. Micro-scale images of the striae reveal little of the nature of the chatter marks (Fig. 6), which appear mostly to selectively penetrate a brittle, black material of probable organic origin, that has been graphitized by extreme frictional heat (and not revealed in X-ray diffraction analysis).

A very different type of chatter mark is illustrated in Fig. 7. This type was made by a much larger tool in the gouge, and the tool made only intermittent contact with the pavement. An unusual characteristic of penetrating cracks associated with these larger chatter marks was their highly irregular (hackly) crack surfaces (Fig. 7b).

4. Experiments

To determine possible frictional resistance at the base of the landslide and to create artificial striae for comparison, two groups of frictional shear experiments were conducted on shale collected from immediately below the pavement. One group of experiments used a
conventional soil-mechanics ring-shear apparatus; the other, a high-speed rotary shear machine developed for the study of fault mechanics (Ma et al., 2014). For the first group, we adapted a commercially available ring-shear apparatus (Wille Geotechnik ABS, a “Bishop-type” ring-shear apparatus), but filled the lower half of the circular shear box with an “intact” annulus of shale (outer diameter, 100 mm, inner diameter, 50 mm, and about 10-mm thick) shaped to fit in the shear box. Due to sample constraints, the annulus was made in two sub-equal parts, which behaved as one (most of the time) in the experiments. We used pieces of shale collected from immediately below the pavement (being unaware at the time, of its variable exposure to frictional heat during the landslide). The remainder of the shear box was filled with the <2 mm-size fraction of the gouge collected in the field from on top of the pavement. We conducted three ring-shear experiments across the possible range from wet to dry: one with fully saturated gouge sliding on rock; another with dry gouge on rock; and a third with wet rock on rock (using two annuli). Experiments with gouge were compacted following standard soil-mechanics procedure (e.g., Stark and Vettel, 1992) under a normal stress of 1 MPa (realistic for the landslide beneath 30–50 m of overburden, but also at the capacity of the equipment). Both wet- and dry-gouge experiments were sheared for up to 20 m of displacement at a nominal speed of 80 mm/min. A range of different shear displacement rates were applied to the rock-on-rock experiment (Table 1). The resulting striated samples were examined by eye and in more detail with a laser microscope (Olympus, LEXT OLS4500) which was also used to examine the field-collected samples. Grain-size distributions of the old and new gouges were measured in a laser sizer (Master sizer 2000).

Friction experiments were also performed on a rotary shear apparatus with capacity for higher speed (up to 2 m/s, the equipment located at the Institute of Geology, China Earthquake Administration, Beijing, is described in Ma et al. (2014)). We prepared three shale samples from Jiweishan Mountain. The sample assembly included two opposing cylinders made from the black shale. The cylinders were each 40 mm in diameter and 50 mm long. Rotary shear was carried out at a normal stress of 1 MPa and an “equivalent slip rate” (Han et al., 2007) of ~1 m/s. Temperature at the slip surface during rotation was monitored by a pair of thermocouples (Tn and Tf) mounted close to the sliding surface, respectively 4 mm and 8 mm from the sample boundary. The high-speed shearing was initially dry rock on rock, but quickly developed a

Fig. 4. Detailed views of hand specimens of Jiweishan landslide striated 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 are apparent. Yellow arrows point to a younger set of striae. The striae are neither straight nor parallel. The pavement was scratched and polished by sliding of a probably saturated, basal gouge containing a very widely graded mix of fine to coarse particles.

Fig. 5. Laser scan of pavement illustrated in Fig. 4(a) with longitudinal profile of deep scratch A-A′ and cross profile B-B′.
white powder gouge while emitting carbon-dioxide gas, and water vapour in an odiferous light grey dust cloud.

The sample set ups for the high-speed rotary and ring-shear experiments are shown schematically in Fig. 8.

5. Experimental results

5.1. Description of experimental striae

For the wet-gouge-on-shale ring-shear experiment, the striae are shown in Fig. 9a. This experiment reproduced many of the details seen on our field-collected samples. Just as on field-collected samples (Fig. 4), our experimental striae started and stopped irregularly. On Fig. 9a, i and ii are the start of fresh scratches from tools appearing against the surface from within gouge; iii is a chatter mark left by a larger scratching tool. iv is the relative direction of movement of the gouge in the ring-shear apparatus. Of course, most of the striae in the experiment followed the curvature imposed by the ring-shear apparatus, but some did not (such as i and ii in Fig. 9a).

Among other features on the experimental pavement, we observed micro-scale topography resembling miniature crag-and-tail glacial landforms. These features demonstrated a fluid-like, plastic or viscous motion of the basal gouge as it deformed around more abrasion-resistant obstacles (Fig. 9c and d, a quartz grain in this example).

The micro-morphology of the field-collected landslide striae (Fig. 9e) was very similar to the structure of the experimental striae (Fig. 9f). The shale illustrated in Fig. 9e had more abundant microshell fragments than that in Fig. 9f, while that in Fig. 9f had much black brittle material. The experimental pavements preserved more finer detail than did the field-collected Jiweishan pavement, however the black material on which the detail was preserved was very delicate, and may have been destroyed in the field by exposure to weathering since the 2009 event (Zhang and McSaveney, 2018). Other Jiweishan researchers remark on how hands were blackened while handling the shale (e.g., Deng et al., 2014; Yin et al., 2011). We also observed this phenomenon.

In the wet rock-to-rock ring-shear experiments, some larger chatter marks (Fig. 9b) were caused by rolling motion of a larger particle that had broken from the edge of one of the annuli, and which then caused further particles to be dislodged from the ensuing chain of chatter marks. This closely mimicked the plucking of shale seen on the field pavement, but on a much smaller (micro) scale.

Scanning electron microscope (SEM) images of the sliding surface of the sample from the high-speed rotary experiment are shown in Fig. 9g and h. Slickenside striae were observed on the sliding surface with an

<table>
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<th>Type of test</th>
<th>Shear rate (mm/min)</th>
<th>Shear distance (mm)</th>
<th>Residual Friction angle</th>
<th>Trend in friction angle</th>
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<tr>
<td>Ring shear test (Bishop type)</td>
<td>0.08</td>
<td>5</td>
<td>6°–7°</td>
<td>Increasing</td>
</tr>
<tr>
<td></td>
<td>0.8</td>
<td>50</td>
<td>6°–7°</td>
<td>Increasing</td>
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<td></td>
<td>8</td>
<td>200</td>
<td>7°–8°</td>
<td>Increasing</td>
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<td></td>
<td>80</td>
<td>5000</td>
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<td>Cyclic</td>
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<td></td>
<td>120</td>
<td>15,000</td>
<td>6°–7°</td>
<td>Cyclic</td>
</tr>
<tr>
<td>High-velocity shear test</td>
<td>1 m/s</td>
<td>150</td>
<td>5°–7°</td>
<td>Decreasing before stabilizing around 5°</td>
</tr>
</tbody>
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Fig. 6. Laser-probe-microscope images of a pavement striation. The lower image is a true-colour view of area marked by yellow square in upper image.

Fig. 7. Detail of large chatter mark adjacent to highly polished and striated surface. Right image is underside of sample in left image. It shows a series of hackly surfaced cracks (lower edge of sample) penetrating to depth of ~10 mm below the chatter-mark base.

Fig. 8. Schematic representations of the high-speed rotary and ring-shear experiment. The sample set ups are shown in Fig. 8.
average width of ~2–10 μm which were smaller than the striae of the slower ring-shear tests (Fig. 9c) and much smaller than the field ones (Fig. 4). The smaller widths reflected the much finer gouge produced in the high-speed experiment. No chatter marks were observed here.

5.2. Experimental mechanical data

The main mechanical data from the slower ring-shear experiments are shown in Fig. 10a-b. All slower experiments yielded relatively low residual friction angles. The lowest was for the rock-on-rock experiment and varied from about 5° to about 8° at different shear rates (Fig. 10b). This was little lower than that obtained for wet gouge on rock (about 9.5° to about 10.5°, Fig. 10a) and much lower than for dry gouge on rock (about 27° to 29° Fig. 10a). The rock-on-rock friction results were identical to results obtained by others for talc-rich fault rock (Moore and Lockner, 2008). The materials showed little frictional rate dependency over the experimental range of slower shear speeds.

The Wille Geotechnik ABS ring-shear apparatus was incapable of achieving the likely maximum shear deformation speeds experienced at the field site. The experimentally applied shear speeds, however, were within the range of speeds known to have been experienced at the field site (initial movement occurred over 50 years ago and rapid displacement did not occur until catastrophic failure began). The experimental loss of 0.3 mm of shale abraded from the annulus during 20 m of shear displacement was consistent with the field survival of most of the ~30 cm thickness of the shale stratum.

In addition to using conventional ring-shear apparatus, we also simulated shear in a high-speed rotary shear apparatus under 1 MPa normal stress and 1 m/s shear speed. These experiments were conducted on air-dried samples. The high-speed experimental results are shown in Fig. 10d. A peak friction angle of about 19.8° was attained after about 15 s of shearing. The friction angle next steadily decreased to about 11.3° over about a minute. Then, it decreased rapidly to about 3.5° over the next 10 s. After that, the friction angle increased slowly to about 6.6° over the next 50 s.

The low residual friction angle measured in the slower saturated rock-on-rock ring-shear experiment (5° to about 8°) was practically identical to the results obtained from the high-speed friction experiment (3.5° to about 6.6°). However, the highest temperatures reached in these experiments were hugely different. Temperature in the slower experiment was not measured, but the apparatus became only slightly warm to the touch (the large mass of steel around the shear box has high thermal inertia). In the higher speed experiment, however, the temperature reached to over 700 °C (Fig. 10c) and was hot enough to decompose talc and dolomite to release steam and carbon dioxide.
The landslide substrate had propagated through a rock mass in which the slickensides beneath the fast landslide presented hackly crack surfaces smooth fracture surfaces penetrating the bed rock, the equivalent basal sliding affected fractures penetrating into the landslide substrate. The valley floor divergence of up to 15° was occurring.

In summary, a polished and striated bedrock pavement beneath the deposit of the 2009 Jiweishan rock avalanche reveals that the landslide could move over its base with low frictional resistance as a dense granular flow, and leave striae seemingly identical to those left by glaciers, but formed in less than the two-minute duration of the entire landslide. The pavement substantially constrains hypotheses about the behavior of the granular debris in rock avalanches, including hypotheses relating to their high speed and long runout.

Acknowledgement

This research was supported by the National Basic Research Program of China: National fundamental scientific research grant (No. 41472273); and the Funds for Creative Research Groups of China (41521002). It is also supported by Young Researchers Funding of Sichuan Province (2016JQ0021). We also thank Huang Runqiu, Xu Qiang, Xiong Ran, Chen Zhiyi, Feng Shan, Zhu Xiaoran, Zhang Ming, Xiong Xionghong, Zhang Maoshu, Zhang Weifeng, and Zou Chunlei for their help in making this research possible.

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