Journal of Structural Geology 106 (2018) 70–85

Contents lists available at ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

# Microstructures in landslides in northwest China – Implications for creeping displacements?

M. Schäbitz[a], C. Janssen[a,*], H.-R. Wenk[b], R. Wirth[a], B. Schuck[a], H.-U. Wetzel[a], X. Meng[c], G. Dresen[a]

[a] GFZ German Research Centre for Geosciences, Telegrafenberg, Potsdam, 14473, Germany
[b] Department of Earth and Planetary Science, University of California, Berkeley, CA, 94720, USA
[c] Research School of Arid Environment and Climate Change, Lanzhou University, 222 South Tianshui Road, Lanzhou, 730000, China

ARTICLE INFO

*Keywords:*
Landslide
Microstructure
Texture
Pyrophyllite
Graphite
Grain size reduction

ABSTRACT

Microstructures, mineralogical composition and texture of selected landslide samples from three landslides in the southern part of the Gansu Province (China) were examined with optical microscopy, transmission electron microscopy (TEM), x-ray diffraction (XRD) and synchrotron x-ray diffraction measurements. Common sheet silicates are chlorite, illite, muscovite, kaolinite, pyrophyllite and dickite. Other minerals are quartz, calcite, dolomite and albite. In one sample, graphite and amorphous carbon were detected by TEM-EDX analyses and TEM high-angle annular dark-field images. The occurrence of graphite and pyrophyllite with very low friction coefficients in the gouge material of the *Suoertou* and *Xieliupo* landslides is particularly significant for reducing the frictional strength of the landslides. It is proposed that the landslides underwent comparable deformation processes as fault zones. The low friction coefficients provide strong evidence that slow-moving landsliding is controlled by the presence of weak minerals. In addition, TEM observations document that grain size reduction in clayey slip zone material was produced mainly by mechanical abrasion. For calcite and quartz, grain size reduction was attributed to both pressure solution and cataclasis. Therefore, besides landslide composition, the occurrence of ultrafine-grained slip zone material may also contribute to weakening processes of landslides. TEM images of slip-zone samples show both locally aligned clay particles, as well as kinked and folded sheet silicates, which are widely disseminated in the whole matrix. Small, newly formed clay particles have random orientations. Based on synchrotron x-ray diffraction measurements, the degree of preferred orientation of constituent sheet silicates in local shear zones of the *Suoertou* and *Duang-He-Ba* landslide is strong. This work is the first reported observation of well-oriented clay fabrics in landslides.

## 1. Introduction

Slip zones of landslides are natural shear zones produced by different stress configurations and propagate through different lithologies (Wen and Aydin, 2004). The composition and microstructures of landslide slip zones are fundamental for understanding the mechanisms of landsliding and shear behavior of soils (Skempton and Petley, 1967; Skempton, 1985; Wen and Aydin, 2004). Slope failure often depends on the complex interaction of tectonic activity, site morphology, variations in humidity, and geological factors such as presence of a weak glide plane, as well as texture and mineralogy of both the host materials and the slip zone. To understand the underlying mechanisms of landslides, a large number of studies have microstructurally examined slip zones (e.g. Wen and Aydin, 2003; Bhandary et al., 2005; Chen et al., 2014; Jia et al., 2014).

Some mechanisms involved in the formation of landslides may be similar to those that occur in fault zones. Particularly, the abundance of clay minerals in landslides may affect the mechanical properties of the slip zones similarly to clay-rich fault gouges (e.g. Warr and Cox, 2001; Saffer et al., 2001; Wen and Aydin, 2003; Bhandary et al., 2005; Moore and Rymer, 2007, 2012; Moore and Lockner, 2008; Collettini et al., 2009; Tembe et al., 2010; Schleicher et al., 2010; Holdsworth et al., 2011; Bradbury et al., 2011; Lockner et al., 2011; Janssen et al., 2014). Also, the critical earthquake magnitude required to trigger landslides may be affected by conversion of a flocculated (stable) clay structure to a dispersed (unstable) structure due to changes in pH of the pore fluid or creep-induced textural changes (e.g. Rosenquist, 1966; Loeken, 1971; Reves et al., 2006).

Microstructures (e.g. amorphous material/melt, brittle fracturing, dissolution-precipitation processes, intracrystalline plasticity, micro-

* Corresponding author.
*E-mail address:* jans@gfz-potsdam.de (C. Janssen).

https://doi.org/10.1016/j.jsg.2017.11.009
Received 10 May 2017; Received in revised form 9 November 2017; Accepted 17 November 2017
Available online 24 November 2017

pores, clay fabric) in the principal slip zone (PSZ) of landslides were formed by shear deformation due to dynamic slip and/or downslope movement by creeping. For example, the geometric patterns of the microstructures in the slip zone of the Shek Kip Mei landslide (Hong Kong, China) are similar to the S-C fabrics observed in tectonic shear zones (Wen and Aydin, 2003). Particle size reduction by crushing of grains and reorientation of grains by shearing generates an extremely fine-grained gouge in faults as well as landslides. Therefore, some deformation structures produced during faulting may help identify microstructures resulting from slope failure and landsliding.

Many quantitative studies of clay fabric intensity in natural fault zones, using X-ray texture measurements, have shown that sheet silicate fabrics in fault gouges are predominantly weak (e.g. Warr and Cox, 2001; Shimamoto et al., 2001; Solum and van der Pluijm, 2009; Haines et al., 2009; Schleicher et al., 2010; Wenk et al., 2010; Buatier et al., 2012; Janssen et al., 2012). The fabric strengths are generally much smaller than in shales, slates, and schists (e.g. Wenk et al., 2010; Haerinck et al., 2015).

So far, preferred orientation, also known as fabric or texture, of clay particles in landslides has been examined only by microstructural observations (e.g. Kawamura et al., 2007; Chen et al., 2014; Jia et al., 2014) and by a combination of microscopy and image analyses (Wen and Aydin, 2003, 2004, 2005). Chen et al. (2014) suggested that macroscopic sliding in the slip zone was most likely dominated by sliding of sheet silicate particles. Wen and Aydin (2003, 2004) recognized that porosity, particle-size distribution and particle orientation are key factors controlling the mechanical properties of landslide slip zones. During sliding induced by heavy rainfall, particle movement within the slip zone was governed by fluidized particulate flow, resulting in weak particle alignment or random particle orientation (Wen and Aydin, 2005). For example, microstructures of the Qinyu landslide slip zone, observed by SEM, mainly show a flocculated structure (Jia et al., 2014).

In this paper, composition, clay fabrics and microstructures from samples of three landslides in the southern part of Gansu Province (China) were examined. Samples were collected from the main slip layer and the surrounding damage zone. We analyzed deformation microstructures and determined fabric intensities of the clay gouge of the slip zone samples. For the first time, lattice-preferred orientation of constituent minerals in landslide samples was quantified using synchrotron X-ray diffraction measurements. The purpose of this investigation is to determine to what extent microstructures and/or composition influence the slip behavior of landslides. Finally, we compare the results with observations from well-investigated fault zones (San Andreas Fault, Chelungpu Fault) to discuss how the shared textural and compositional characteristics are indicative of common deformation processes. (e.g. Janssen et al., 2011, 2014).

## 2. Geological setting

The geography of Central China is affected by active mountain building that is associated with frequent occurrences of devastating earthquakes and mass movements (Bai et al., 2012; Sun et al., 2015). From more than 2000 medium and large landslides reported within Zhouqu and Wudu County, we selected three, *Xieliupo, Suoertou and Duang-He-Ba* landslide, for our study. *Xieliupo and Suoertou* landslides have experienced slow creeping deformation, threatening hundreds of thousands of people's lives in Zhouqu and Wudu County (Sun et al., 2015). The *Duang-He-Ba* landslide is a typical loess landslide, with loess moving on top of Silurian slates and phyllites bedrocks. These facts, together with excellent exposure conditions make them ideal candidates to study landsliding.

The three landslides investigated in this study are situated along the Bailong River Corridor in the southern part of the Gansu province (Fig. 1a; Jiang and Wen, 2014; Jiang et al., 2014; Yu et al., 2015). The Bailong River Corridor is a tectonically and seismically active region related to Himalayan orogenic deformation and one of the four most active areas of landslides and debris flows in China (Wang et al., 2013). It experienced two giant debris flows on August 8, 2010, as a result of a torrential rain. The debris flows destroyed half of the Zhouqu town and killed 1756 people (Tang et al., 2011).

The *Xieliupo* landslide (samples **X1-X9**) is located on the north bank of the Bailongjinag river (Figs. 1b and 2a). The geology of this area is mainly composed of Silurian slates and phyllites, Permian limestones, Devonian limestones and slates, and Quaternary loess deposits (Tang et al., 2011; Yu et al., 2015). The formation of the landslide is controlled by the active Pingding-Huama fault with a mean slip rate of 2.6 mm/year (Meng, unpublished data, Fig. 1b). The active *Xieliupo* landslide is about 2600 m long and 550 m wide with a thickness of 50 m (Jiang et al., 2014). Movement has been observed in the lower part of a slope whose toe was cut off for constructing the S313 provincial highway (Sun et al., 2015). The landslide moving/creep rate is several mm per year. In addition, an excavation pit provided a sample of clay gouge (slip zone) material from the neighboring *Suoertou* landslide (sample **S1**), which is also affected by the same long-term creep deformation. The lithological structure of both landslides and their linking to the active Pingding-Huama fault are the same (Figs. 1a–b and 2b), so we included the *Suoertou* gouge material in our analysis. *The Duang-He-Ba* landslide (samples **D1-D5**) is located in the southeastern tip of Zhouqu County, 20 km north-west of Wudu (Figs. 1a and 2c). Here, a river eroded a whole profile through a landslide down to its host rock and parallel to its movement direction.

## 3. Methods

Microstructures of all samples were studied using optical and transmission electron microscopy (TEM). Optical inspection of thin sections allowed us to identify representative areas characterized by fine-grained, clay-rich material potentially affected by fracturing and dissolution-precipitation processes. These areas were marked on high-resolution optical scans and prepared for TEM using a focused ion beam (FIB) device (FEI FIB200TEM) to avoid preparation-induced damage (Wirth, 2004, 2009). TEM was performed with a FEI Tecnai G2 F20 X-Twin TEM/AEM equipped with a Gatan Tridiem energy filter, a Fischione high-angle annular dark field detector (HAADF) and an energy dispersive X-ray analyzer (EDX). TEM diffraction patterns also provided a first indication for orientation and distribution of clay particles.

The crystallographic orientation of sheet silicates was determined from synchrotron X-ray diffraction images measured at the high-energy beam line ID-11C of the Advanced Photon Source (APS) at Argonne National Laboratory. Because of the high costs and the considerable amount of time necessary for this measurement, we selected only the most promising slip zone samples **S1** and **D3.** The method is described in detail in a tutorial (Lutterotti et al., 2013; Wenk et al., 2014). A monochromatic X-ray beam with a wavelength of 0.107863 Å and $1 \times 1$ mm in size was used to penetrate through a 1-mm thick slab of sample. Diffraction images were recorded with a Perkin Elmer $2024 \times 2014$ image plate detector. Seven images for each sample were measured at different sample tilt relative to the incident X-ray, from $-45^{\circ}$ to $45^{\circ}$ in $15^{\circ}$ incremental steps. These sample tilts are necessary to provide adequate pole-figure coverage. The X-ray beam was also translated parallel to the rotation axis over 2 mm to provide sufficient grain statistics. Images were then deconvoluted for phase fractions, crystallite size, and preferred orientation with the Rietveld method (Rietveld, 1969) implemented in the MAUD (Materials Analysis Using Diffraction) software (Lutterotti et al., 1997, 2013). Orientation distributions for sheet silicates obtained by the Rietveld method were exported from MAUD and further processed in BEARTEX (Wenk et al., 1998) to obtain pole figures, and to rotate and plot pole figures.

X-ray diffraction (XRD) was used to analyze fault rock composition of 11 samples (Table 1a–b). Samples were dried and ground to a fine powder (2g) before analysis. X-ray diffraction analyses were conducted