Earth and Planetary Science Letters 481 (2018) 284–289

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Is air pollution causing landslides in China?

Ming Zhang [a,*], Mauri J. McSaveney [b]

[a] Faculty of Engineering, China University of Geosciences, 388#, Lumo Road, Wuhan, Hubei Province 430074, PR China
[b] GNS Science, PO Box 30368, Lower Hutt, 9040, New Zealand

ARTICLE INFO

Article history:
Received 13 May 2017
Received in revised form 17 October 2017
Accepted 23 October 2017
Available online xxxx
Editor: J. Brodholt

Keywords:
acid rain
landslide
mining activity
microorganism
organic matrix

ABSTRACT

Air pollution in China often exceeds "unhealthy" levels, but Chinese air is not only a threat from being breathed: the pollutants may also be causing fatal landslides. Very acid rain from severe air pollution falls widely in southwest China, where coal is a major energy source. We discuss where acid rain may provide an unsuspected link between mining and the fatal 2009 Jiweishan landslide in southwest China; it may have reduced the strength of a thin, calcareous, black sapropelic shale in Jiweishan Mountain by removing cementing carbonate minerals and sapropel matrix. Mining beneath the potential slide mass may not have directly triggered the landslide, but collapse of abandoned adits drained a perched aquifer above a regional black-shale aquiclude. Inflow of acid, oxygenated water and nutrients into the aquiclude may have accelerated the reduction of strength of the weakest rocks and consequently led to rapid sliding of a large rock mass on a layer of weathered shale left composed largely of soft, and slippery talc.

1. Introduction

The rapid industrial development that brought an economic miracle to China since 1978 has come at a major environmental cost: the level of air pollution in China can often be described as "unhealthy" or "very unhealthy" (for example see http://aqicn.org/city/beijing). One of the consequences of air pollution is acid rain. Especially in southwest China, where coal combustion is one of the main energy sources, the air pollutants in addition to fine particulates are SO_2 and NO_2 (Hu et al., 2010), which are major contributors to acid rain. Between 1986 and 2014 in Chongqing, for example, the minimum rainfall pH was 2.8 in 2012 and the average was between 4.3 and 5.0. The proportion of rain-days with acid rain (pH <7.0) in the yearly total number of rain-days has varied between 33.3 and 95.0% (Hu et al., 2010; CEPB, 1998–2014) (Fig. 1). Table 1 lists the main acid-rain components in Chongqing (Feng and Ogura, 1998; Liao and Tang, 2000; Tang et al., 2013).

Although some scientists have shown that rock physical properties can be gradually altered by acid rain reacting with constituent mineral such as calcite and illite (Gupta and Ahmed, 2007; Taghipour et al., 2015) and by microbial weathering (Buss et al., 2005; Wilson, 2005; Shelobolina et al., 2012), few studies have discussed a direct relationship between acid rain and a landslide. Zhao et al. (2011) studied the action of acid rain on clay minerals from the slip zone of a reservoir landslide in the Three Gorges Reservoir in China, and found a transformation of illite to smectite which decreased the shear strength of the sliding-zone soil. However, they did not further link their laboratory experiments with a failure mechanism of a landslide. We suggest in this paper that the disastrous 2009 Jiweishan rock avalanche in Wulong County, Chongqing (Fig. 2), was caused by the coupled actions of tectonism, mining activities, karstification, acid rain, and microbial decomposition. Acid rain may have played a key role in reducing the sliding resistance along the potential failure surface: it supplied nutrients to microorganisms capable of decomposing the matrix of sapropel, and it was capable of dissolving calcite cement from the interbedded shale layer on which the landslide failure surface eventually

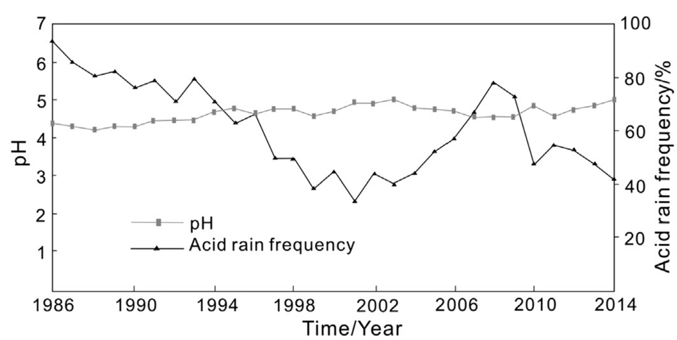

Fig. 1. Variation in rainfall mean pH and proportion of rain-days with pH < 7.0 (acid-rain frequency) between 1986 to 2014 in Chongqing, China (Hu et al., 2010; CEPB, 1998–2014).

* Corresponding author.
E-mail address: zhangming8157@126.com (M. Zhang).

https://doi.org/10.1016/j.epsl.2017.10.045
0012-821X/

Table 1
Major ions in Chongqing rain water (Feng and Ogura, 1998; Liao and Tang, 2000; Tang et al., 2013) and from spring water sampled from adjacent to the Jiweishan rock avalanche (mg/l).

	SO_4^{2-}	NO_3^-	Cl^-	Na^+	K^+	Ca^{2+}	Mg^{2+}
Collected from references	12.08–4.83	0.93–6.29	0.98–3.62	0.49–1.40	0.61–4.25	2.45–26.7	0.24–1.52
Spring water	15.41[a]	3.842	0.485	0.559	0.133	52.924	6.537

[a] Some spring-water SO_4^{2-} comes from acid-sulfate weathering of pyrite in the shale interbeds.

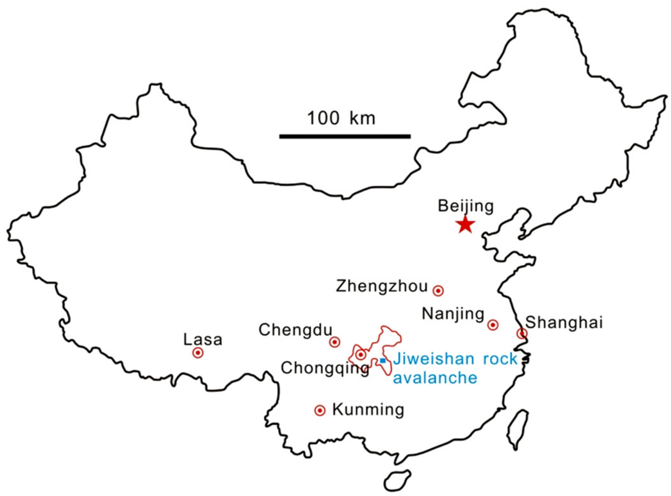

Fig. 2. Location of Jiweishan rock avalanche (29°14.4′N, 107°26′E) in Wulong County, southern China.

formed. Without calcite and organic matter, the shale becomes a predominantly soft talc powder, which has low frictional resistance (Moore and Lockner, 2008).

Our re-investigation of this already much studied landslide was spurred by the apparent absence of an identified landslide-triggering event: an absence possibly due to a long delay of many decades between obvious potential triggers and the occurrence of the disastrous landslide. The apparent lack of an initiating event led to an unfortunate misdiagnosis of the potential outcome. The diagnosis was for continuing dangerous rockfalls affecting a limited area at the foot of the cliff where a small town was located. Potentially more than 700 lives were saved by the timely relocation of Tekuang Town, but 74 lives were lost when a failure occurred that was very much larger than predicted, and had a long runout down valley, through occupied mine facilities and farmland (Yin et al., 2011).

Using the benefit of hindsight, we searched for a subtle landslide explanation involving slow, progressive loss in strength over a wide area. In this, we sought evidence from a wide range of disciplines eventually including landslide science, mining technology, geology, biology, biochemistry and atmospheric pollution.

The hypothesis we present in this paper of a plausible progressive failure mechanism for the Jiweishan landslide suggested an unexpected developing landslide risk that may be emerging in southern China. This risk is associated with widely distributed carbonate rocks with interbedded shales and the escalating problem of air pollution in China. But the developing risk may not be unique to China: similar lithological combinations of carbonates with shale interbeds occur in North America, Europe and elsewhere in Asia, in heavily industrialized nations with varying degrees of polluted air and problems with acid rain.

2. Widely distributed limestone slopes in southwest China

Many rock slopes in southwest China comprise gently to tightly folded, thick-bedded Permian to Triassic limestone and dolomite with interbedded shale units. These carbonate rocks often overlie mudstone or siltstone, which contain layers of ore-grade hematite or coal with thicknesses up to 2 m (Fig. 3). Of course, the hematite and coal are mined (Xu et al., 2010; Yin et al., 2011; Wang et al., 2015).

In the humid, subtropical climate of southwest China, a karst landscape has developed on the thick carbonate rocks following their folding and uplift since the late Cretaceous period (Liu and Xie, 2010). On the more erodible, softer units, the land surface has eroded more rapidly to leave steep limestone cliffs with slope angles >60° and even near vertical. On the cliff faces, contact surfaces between the shales and limestones are particularly unstable (Yin et al., 2011; Wang et al., 2015) leading to many rockfalls, some block slides and very rarely, large rock avalanches.

Mining of the ore-grade hematite (as below Jiweishan Mountain) and coal layers (Yin et al., 2000) has been active since the 1920s, leaving a legacy of mined-out areas, which in places affects the stability of their overlying rock mass. At Jiweishan Mountain, collapse of old mines had deformed the overlying rock mass (Fig. 3). Mining changes the state of stress around mined-out areas (Parise and Lollino, 2011; Zheng et al., 2015) and deformation here has involved collapse of the roof and wall of gobs and tunnels. Cracks have propagated into the overlying rock, even to the ground surface. Drainage through cracks greatly changed the flow of groundwater (Libicki, 1982; Rapantova et al., 2007). Groundwater previously trapped above shale aquicludes (Yin et al., 2011) then drained into the mines through cracks. Until the facilities were destroyed by the rock avalanche, water was pumped from the active adit 1 to keep it dewatered.

The largely historical mine collapse (from the late 1950s) was previously reasoned insufficient to have triggered the large failure at Jiweishan Mountain on its own (Yin et al., 2011), and we do not dispute this finding. The Chinese government, however, has strengthened the management and inspection of mines in recent years, including minimizing the deformation of overlying rock masses through strict controls.

The troublesome shale interbeds are between 10 and 30 cm thick, and composed of calcite, quartz, clay minerals and sapropel (fine organic material) in somewhat variable proportions. Fig. 4A shows the X-ray-diffraction-determined mineral components of the shale immediately beneath the basal sliding surface of the Jiweishan rock avalanche. Some layers contain more abundant shell fragments and others more sapropel. Using a CS844 carbon &sulfur analyzer, we measured total organic carbon (TOC) in 4 samples from around the basal failure surface. TOC ranged between 0.46 and 1.9%, but a TOC of 13% is also reported from the basal shale (Deng et al., 2014). Tests using extraction and a Leica Transmission/Reflected Light Fluorescence Microscope indicate an organic-rich matrix in the shale that is mainly sapropel (coming from microorganisms such as algae, fungi and bacteria) and vitrinite (coming from advanced plants and animals). Centimeter-scale vitrinite lenses occur sparsely. Folding of southwest China's thick carbonate sequence has induced many slickensided bedding-plane shears widely in the weak shale interbeds and they are conspicuous at Jiweishan Mtn (Fig. 4B). For this reason, such shale interbeds would be largely at residual shear strength, were it not for some post-deformational diagenesis (Deng et al., 2014). Any process which undoes the dia-