Effect of moisture and temperature conditions on the decay rate of a purple mudstone in southwestern China

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ARTICLE INFO

Article history:
Received 1 August 2012
Received in revised form 10 October 2012
Accepted 3 November 2012
Available online 10 November 2012

Keywords:
Rock decay
Mudstone
Moisture and temperature interaction
Moisture alternation
Temperature alternation
Freeze–thaw

ABSTRACT

Soil formation and geomorphology are primarily influenced by the rock decay, which in turn is strongly determined by moisture and temperature conditions. However, it remains unclear whether rock decay is dominated by thermal stresses or by hydration disintegration, and there is little information on mudstone decay rate in southwestern China. This study hypothesized that rock decay is dominated by hydration mechanism, and focused on the physical decay characteristics of typical purple mudstones using a combination of field and laboratory-based experiments. The bedrock of a Penglaizhen group (J3p) in Yanting County, Sichuan Province, southwestern China, was exposed and covered with nylon fabric in situ. Soil depths of 10, 20, 40 and 60 cm were laid on this nylon fabric in 2003, and the decay rate (the quantity of clastic particles <2 mm that were decayed from the bedrock, in t km−2 yr−1) under the nylon fabric was measured both in 2005 and 2009. In addition, fresh mudstones sampled from the Matoushan group (K2m), the Tuodian group (J1t) and the Lufeng group (J1l) in Yuanmou County, Shuangbai County, and Lufeng County of Yunnan Province, southwestern China, respectively, were subjected to alternating applications of moisture, temperature and their interaction (seven treatments) in the laboratory, and their decay ratios (the mass of decayed rock of <2 mm clastic particles to sampled rock mass, in percent) were measured in 2010. In the field, the decay rate of the bedrock showed a significant (p<0.05) positive relationship with both the daily moisture and temperature variation at the interface between the soil and bedrock. In the laboratory, results showed that the effect of moisture variation, but not temperature alternation, on rock decay was apparent, suggesting that purple rock decay is dominated by hydration mechanism. Freezing–thawing in particular affects the sampled rocks, because it causes more spalling and fracturing. The J1t rock had the highest decay ratio because it had the highest clay mineral content and porosity of the three rock types. Hierarchical clustering analysis suggested that the variation of moisture content and H2O phase (solid or liquid) within rock plays a key role in rock decay processes. Both field and laboratory studies consistently showed that the alteration of wetting–drying and freezing–thawing, as well as moisture content, substantially influenced rock decay.

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1. Introduction

It is well-known that moisture and temperature are important for a wide range of ecological and environmental processes, including the rock weathering process that greatly influences soil formation and geomorphology (Elliott, 2008; Mol and Viles, 2010; Coombes, 2011). Rock weathering was recently termed as “rock decay” by Hall et al. (2012) because it has come to mean different things to different people, and hereafter rock decay was used in paper. These basic ecosystem processes also influence CO2 consumption (Li and Zhang, 2002). Therefore, understanding the effects of moisture and temperature alternation on rock decay can therefore enhance our understanding of the effects of global climate change on soil formation and geomorphology (Elliott, 2008).

To date, rock decay is known to be caused by various factors, including natural and anthropogenic ones (Weiss et al., 2007; Sumner et al., 2009), and many studies have been conducted on the effect of moisture and temperature conditions on rock decay. However, rock decay mechanisms have been a topic of debate for almost a century. The question is whether rock decay is dominated by thermal stresses or hydration decay (Moores et al., 2008). Most researchers (Cantón et al., 2001; Bozzano et al., 2006; Hoerlé, 2006; Hall, 2007; Huang, 2007; Warke, 2007; Elliott, 2008; Moores et al., 2008; Doostmohammadi et al., 2009; Mol and Viles, 2010; Saad et al., 2010) consider that rock
decay is mainly determined by rock moisture conditions, while some researchers (Sumner et al., 2007; Hall et al., 2008; McKay et al., 2009) find temperature to be the dominant factor, and yet others (Oyama and Chigira, 2000) consider oxygen to be the most important. However, details on rock decay rate are notably absent (Sumner et al., 2009), and few studies have been carried out on mudstone decay. Previous studies on rock decay have mainly focused on the independent effect of moisture or temperature or mineral composition of rocks, but have rarely considered the impact of moisture and temperature or moisture and temperature interaction on rock decay at the same time. Thus, there is inconsistent knowledge on the role of moisture and temperature in the processes of rock decay, and it is implied that the factors of moisture and temperature should be considered simultaneously in study the rock decay. As Hall (2007) pointed out, thermal conditions alone are not adequate to indicate the occurrence or absence of freeze–thaw events in the absence of some indication of the presence of water and that it actually froze.

Some studies (Gale et al., 2009; Jacob and Winner, 2009; Kang et al., 2009; Rijnsdorp et al., 2009; Crozier, 2010) have shown that climate change can influence ecological processes and the environment. Modeling studies show that rock decay proceeds more quickly with increasing temperature as a result of the influence of the activation energy on mineral dissolution kinetics at warmer temperatures (Banwart et al., 2009; Reinds et al., 2009). Likewise, Muller and Wust (2006) apply the deposit-geochemical method and find that increased precipitation results in increasing physical decay. Hall et al. (2012) recently noted that the issues that confront rock decay researchers are centered upon the behavior of rock materials and much less upon climate variability. In most area of China, climate will became warmer and moister (Ding et al., 2006). However, there is little available information about the effect of these predicted varying moisture and temperature conditions on decay of purple mudstone of southwestern China, making it difficult to predict the future fate of these rocks and geomorphology in the context of a changing global climate. In order to bridge this knowledge gap, this study investigates the possible influence of moisture and temperature conditions on rock decay in the field and laboratory to further understand the mechanism of rock decay. Our objectives are to determine: 1) the rock decay characteristics of purple mudstone under variable moisture and temperature conditions in field and laboratory conditions; and 2) the contribution of moisture and temperature factors to the rock decay process.

2. Methods and materials

2.1. Site description

The field site was located at Yanting Station, a station belonging to the China Ecology Research Network (CERN), situated at 31° 16′ N, 105° 27′ E, in the middle–north of Sichuan Province, southwestern China (Fig. 1). The topography is hilly and the climate is subtropical, with an annual average temperature of 17 to 18 °C and rainfall of 800 to 1000 mm. Most of the precipitation occurs during the rainy season, from May through to August (Li et al., 1991). The main crops are rice (Oryza sativa L.), wheat (Triticum aestivum L.), corn (Zea mays L.), rape (Brassica napus L.), and sweet potato (Ipomoea batatas L.). The soil is classified as purple soil (termed Regosols in the taxonomy of the Food and Agriculture Organization of the United Nations (FAO), and Entisols in U.S. taxonomy) – a lithologic soil without distinct pedogenic horizons (orthent) – which is derived from the mudstone of the Penglaizhen group (J3p); its basic physiochemical properties are as described by Liu et al. (2009).

Purple soil is one of the most important soil types in southwestern China. More than 75% of this soil type in China is found in the region of the upper Yangtze River, particularly in the Sichuan and Yunnan provinces (Liu, 2008). Purple soil is characterized by high productivity, fast decay and severe erosion. Its parent rock, especially for mudstone, is easily decayed and very soft, and readily develops structural, diagenetic and decayed cracks. Under alternating warm–cool and wet–dry conditions, the physical decay rate of purple mudstone is much higher than that of other types of parent rocks. It has been estimated that the decay rate of an exposed purple mudstone in the field is about 15800 t km\(^{-2}\) yr\(^{-1}\) (He, 2003).

2.1.1. Plot construction procedure and treatments

Eight plots measuring 4 m × 2 m were established (Fig. 2); all of the soil in each plot was removed to expose the bedrock. The bedrock was manually leveled to create a 17.6% slope, and rock of the original unlevelled surface was scraped and removed to maintain the same natural bedrock surface in plots. The boundary walls of the plots were constructed with bricks and extended by 20 cm into the bedrock surrounding each plot. Runoff and sediment collection tanks were constructed at the end of each plot (Liu et al., 2009). All the created clastic particles were removed away before overlaying the soil, and all plots were constructed by the same method to make effective comparison between soil thickness treatments. Finally, the bedrock inside the plots was covered with nylon fabric with a pore diameter of 0.149 mm to prevent the soil laid on the top of the bedrock from leaching into it. The soil previously removed from each plot was then manually overlaid on the nylon fabric and packed according to its original bulk density to the desired soil thickness (the purple soil is a parent material-dependent soil, its soil structure does not vary significantly and thus this is feasible). Four soil thickness treatments were utilized (10, 20, 40, and 60 cm), with each treatment being repeated twice, analogous to moisture and temperature treatments in the laboratory. The construction was completed on 15th May, 2003.

2.1.2. Measurement of rock decay rate

The decay rate of the leveled bedrock was measured inside the walls. Because mudstone is a lithologic product developed from sedimentary rock, purple particles <2 mm are usually considered to be soil particles (in contrast to rock particles) (Li et al., 1991; Zhu et al., 2008). Therefore, we used the quantity of clastic particles <2 mm that decayed from bedrock to represent the decay rate in t km\(^{-2}\) yr\(^{-1}\). The decay rates of the different treatments were measured on 1st to 3rd November 2005 and 7th to 9th October 2009 using the following procedure:

1. the soil overlaid on top of the nylon fabric was carefully removed to expose the bedrock;
2. an area of 2.0 × 1.0 m\(^2\) on the bedrock was selected in each plot;
3. the decayed bedrock was scraped;
4. the decayed bedrock collected was air-dried and then sieved through a 2-mm sieve to measure the moisture content of the <2 mm particles using the gravimetric method; and
5. decay rates were calculated.

2.1.3. Measurement of rock decay rate

Soil moisture was measured using time domain reflectometry (TDR), and temperature was measured with a thermometer at the interface between the soil and the bedrock. Measurements were taken at 08:00 h and 14:00 h on the 10th, 20th and 30th (28th for February) of every month both in 2005 and 2009. Daily variations in temperature and soil moisture were calculated using the values measured at 08:00 h minus those measured at 14:00 h, and the magnitude of the variations was taken to be the absolute values of these differences. The average and standard deviation (SD) of the data were calculated using Microsoft Excel 2010.
Fig. 1. Graph showing the sampling and experimental sites.

Fig. 2. A picture of the field experiment showing the various covered soil thickness in plot.
2.2. Laboratory experimental methods

2.2.1. Materials

The mudstone samples used in the laboratory experiments were obtained from the Matoushan group (Km) (25° 38' 28.7" N, 101° 54' 18.5" E, at an elevation of 1370 m), the Tuodian group (J1l) (24° 41' 50" N, 101° 37' 14.7" E, at an elevation of 1928 m) and the Lufeng group (J1l) (25° 08' 40.3" N, 102° 02' 55.3" E, at an elevation of 1563 m), all in the Chuxiong district of Yunnan Province, southwestern China (Fig. 1). The topography of the sampled district is hilly, and the climate is subtropical, with an annual average temperature of 13 to 16 °C and rainfall of 900 to 1100 mm. Most of the precipitation occurs during the rainy season, from June through August. The main crops are rice, wheat, corn, rape and sweet potato (He, 2003). All the mudstone samples used in the laboratory experiments were completely immersed in distilled water for more than 12 h to saturate the rocks were determined by atomic absorption spectrophotometry.

2.2.2. Treatments

The laboratory study examined three factors that influence rock decay: moisture, temperature, and the moisture and temperature interaction between them. Moisture treatments were assessed by soaking the rock for a certain length of time that was determined according to a pre-determined relationship between rock moisture content and soaking time. This relationship was established by measuring the rock moisture content after being soaked at room temperature (about 40 °C), until the moisture content no longer changed with soaking time. In this study, we found the sample was saturated after immersed in water for 12 h. Temperature treatments were used to simulate annual temperature fluctuations in Yunnan County. The highest ground temperature is 76 °C and the lowest is −5 °C (data from Yunnanmou meteorological station, 2003–2010). The moisture and temperature interaction was represented by different combinations of moisture and temperature. To eliminate the effect of man-made mechanical vibration in the process of rock decay, each sample was independently placed into a single nylon (2 mm pore diameter) bag to undergo treatment. During December 2010, the samples were subjected to seven treatments (A to G) of different combinations of moisture and temperature (Table 1).

Five temperature treatments were applied to the saturated rock samples, including: constant temperatures of 40 °C (Treatment A) and 76 °C (Treatment B); daily natural temperature variation (Treatment C); extreme temperatures of 2 to 76 °C variation (Treatment D); and −5 to 40 °C variation (Treatment E). All samples were first completely immersed in distilled water for more than 12 h to saturate them prior to being subjected to the temperature treatments. For Treatment A, the samples were placed in a drying oven set at 40 °C to dry for 12 h, and the samples for Treatment B were placed in a drying oven set at 76 °C, also to dry for 12 h. Treatment C samples were subjected to daily natural fluctuations in temperature. For Treatment D, the samples were first placed in a 2 °C refrigerator for 6 h, until they achieved thermal equilibrium, and were then heated to dry at 76 °C in an oven for 10 h. Similar procedures were used for Treatment E, with the corresponding extreme temperatures of −5 °C (for four hours) and 40 °C (for 12 h).

The completed procedure for each treatment was referred to as a cycle, and the samples were determined to be dry when the mass, after being placed in the oven, was less than its mass before wetting. There were 39 cycles for all of the above treatments because the weathering of some samples was complete after this number of cycles. After each cycle, clastic materials of < 2 mm (materials leaked out of nylon bag) were collected and weighed, and referred to as the decayed mass of the sample, and the percentage of decayed mass relative to the sample mass was referred to as the decay ratio in %.

2.2.3. Measurements of physicochemical properties of parent rocks

Presence of the elements K, Na, Ca, Mg and Mn (Table 2) in parent rocks were determined by atomic absorption spectrophotometry. p was measured using the molybdenum blue photometric method; Si using the gravimetric-molybdenum blue photometric method; Al using fluoride replacement; Fe using the dichromate volumetric method; and Ti using the hydrogen peroxide photometric method (Ministry of Geology and Resources, 2002). Minerals were determined using X-ray diffraction (Zhang and Fan, 2003). Hydric determinations were used to identify porosity (Molina Ballesteros et al., 2011).

2.3. Data analysis

Multiple comparisons of the decay ratio were used to compare the effects of each treatment and mudstone type quantitatively. Next, the treatments were classified into groups according to the hierarchical clustering method. Least significant difference (LSD) tests were performed using SPSS 11.5 to determine whether the decay ratio means were significantly different between the treatments or mudstone types or groups. A model of the relationship between variables was constructed after comparing the regressive determination parameters by Sigmaplot 8.0 software.

3. Results and discussion

3.1. Field experiment

Field measurements revealed that the rate of bedrock decay, decreased with increasing soil thickness, the relationship between the decay rate and soil thickness exhibiting a significant (p=0.01) exponential relationship (Fig. 3). The maximum decay rate was over 4000 t km⁻² yr⁻¹, and the minimum rate was approximately 1000 t km⁻² yr⁻¹. Statistically significant differences were found between the decay rates at soil thicknesses of 10 and 20 cm and at soil thicknesses of 40 and 60 cm (Table 3). These results can be attributed to the apparent variation in moisture and temperature at the interface between the soil and bedrock. Moisture content and its daily variation tended to decrease with soil thickness. There was a significant difference between the moisture content at soil thickness of 10–20 cm and that of 40–60 cm. Although temperature slightly increased with soil thickness, no significant difference was observed.

<table>
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<tr>
<th>Temperature treatment</th>
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<td>Constant temperature 40 °C</td>
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<td>Treatment F</td>
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<tr>
<td>Constant temperature 76 °C</td>
<td>Treatment B</td>
<td>Treatment C</td>
<td>Treatment D</td>
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<td>Daily natural temperature variation</td>
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<td>Extreme temperature variation 2 to 76 °C</td>
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<td>Extreme temperature variation −5 to 40 °C</td>
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3.2.1. Comparisons of rock decay ratios under different moisture and temperature variation and moisture content.

Our study showed that the decay rate can increase greatly. Our study showed that the decay rate rising to a maximum with increasing daily temperature and moisture variation was significantly higher (p<0.05) than those of Treatments A, B, C, D and E, implying that wetting–drying under high water content or saturation conditions substantially accelerated rock decay. The ratios of Treatments E and D were significantly higher (p<0.05) than those of Treatments A, B, and C, suggesting that the combination of wetting–drying and heating–cooling cycles apparently hastened rock decay. Furthermore, the ratios of Treatment E were significantly higher (p<0.05) than those of Treatment D for the rocks of J1l and J3t, indicating that freezing–thawing has a significantly positive effect on rock decay.

Moisture conditions have been highlighted as significant to determining the rate of rock decay (Elliott, 2008; Mol and Viles, 2010). The role of water in rock decay mainly involves the dissolution of cementing carbonate and clastic feldspar, crystallization of salt minerals and the formation and transformation of ferric oxide and ferric hydroxide (Bozzano et al., 2006; Huang, 2007), as well as increasing pore pressure and capillary tension, and reducing frictional and fracture energy (Doostmohammadi et al., 2009). All these factors cause rocks to crack during decay processes; crack growth is primarily a function of water content in rock (Moores et al., 2008). Therefore, in Treatments F and G, it was observed that exfoliation occurred only at the surface of the rocks because of the low moisture content in the rock, resulting in cracks developing more slowly and lower decay ratios. However, when the rocks of Treatments A, B, C and D were soaked in water to saturation-level and these were combined with high temperature or temperature alterations, large cracks were observed to develop in the rocks, causing them to crumble into different-sized blocks and fragments to be continually exfoliated from the rock surface. Hence, the decay ratio was high under saturation conditions. When the rocks experienced temperature ranges from −5 °C to 40 °C, (i.e., combined actions of wetting–drying and heating–cooling as well as freezing–thawing), cracks and fissures developed quickly, and the rock soon disintegrated into small pieces. Hence, the decay ratio was highest in Treatment E. Our results again documented that frost splitting in particular affects sedimentary rocks, in which it causes more spalling and fracturing (Saad et al., 2010).

For the three types of rocks, the decay ratios of the parent rocks were determined to be ranked in the following order (from highest to lowest): J1l > K3m > J3t. The rock of J1l decayed considerably faster than the other parent rocks. Rock decay was influenced by both moisture and temperature conditions and the rock material composition.
The chemical and mineral composition of the rocks resulted in the differences in decay ratios. The SiO₂ content in the three types of rocks was high but variable (Table 2). Generally, rocks with high SiO₂ are harder and more difficult to decay (Li et al., 1991; Shi et al., 2009). The SiO₂ content of J1l rocks (59.6%) is higher than that of K2m (58.9%) and J3t (54.2%) rocks, and thus J1l rocks had the lowest decay ratio. Normally, Al₂O₃ forms the main basic component of clay minerals. CaO, MgO and K₂O are the basic components of secondary clay minerals. Mudstones contain a high proportion of clay minerals (Jiang et al., 2006; Matsukura et al., 2007), and can expand and shrink rapidly during the wetting–drying process (Sarman et al., 1994; Warke, 2007; Doostmohammadi et al., 2009; Shi et al., 2009), especially in the case of Montmorillonite and Illite. It has been found that rocks can disintegrate as a result of cyclic swelling and shrinking of the clay minerals they contain (Newman, 1983; Einstein, 1996; Pejon and Zuquette, 2002). Additionally, porosity is another major factor in rock decay, for it controls not only the movement of the fluids throughout the rock mass, but also the processes at work (Molina Ballesteros et al., 2010, 2011). Thus, a higher clay mineral content and porosity in rock result in a higher decay ratio; J3t rock therefore had the highest decay ratio because it had the highest clay mineral content and porosity of the three rock types. Thus, J3t was most easily decayed, followed by K2m and J1l. These results again suggested that the decay ratio is closely related to the material composition of the rock (Liu and Lu, 2000), and especially to its clay mineral content (Wu et al., 2006).

3.2.2. The influence of the different factors on the rock decay

Hierarchical clustering was used to analyze the decay ratios of the three types of rock for each of the different treatments, in order better to understand how they were affected by different factors (Fig. 6). The decay ratios of the three types of rocks in the seven treatments were divided into three groups. The treatments in which rocks were moistened but not saturated (Treatments F and G) belonged to Group I. The treatments that involved water saturation and constant temperatures of 40 °C and 76 °C, daily natural temperatures and extreme temperatures of 2 to 76 °C (Treatments A, B, C and D) comprised Group II. The treatment with water saturation and extreme temperatures of −5 to 40 °C (Treatment E) formed Group III. The results suggested that the primary reason for the differences in decay ratios between the groups was the degree of water saturation and temperature variation, and the primary factor affecting hierarchical clustering was water content, while alternating freezing–thawing cycles played an important but secondary role.

Multiple comparisons (Fig. 7) showed that the decay ratios of the three types of rocks were in the order (from highest to lowest) of Group III > Group II > Group I. Although there was no significant difference (p > 0.05) between the decay ratios of Group I and Group II for J1l, significant differences (p < 0.05) were found for the other rock types.
rock groups (K_{2m} and J_{3t}). The decay ratios of Group I (0.08%, 0.06% and 0.13%) were apparently lower than those of Group II (0.17%, 0.11% and 0.40%) for K_{2m}, J_{3l} and J_{3t}, respectively, i.e., the decay ratios of K_{2m}, J_{3l} and J_{3t} in Group II increased by 55.2%, 51.1% and 67.5% when compared with Group I, respectively. There were differences both in temperature and moisture conditions between Group I and Group II. In fact, although the decay ratios followed the order of Treatment D > C > B > A, there was no apparent difference in decay ratios between Treatments A, B, C and D (Table 4), in which temperature clearly varied, suggesting that the variation in decay ratio caused by temperature (Treatments A and B) or temperature variation (Treatments C and D) was not significant. Consequently, the significant difference between Group I and Group II is mainly caused by the difference in moisture content, i.e., moisture conditions played a greater role than temperature did in rock decay processes.

The decay ratios for Group III were significantly higher than for other groups (Fig. 6), indicating that the decay of mudstone under freezing–thawing treatments was faster than under other treatment conditions, and that alternating freezing and thawing promoted rock decay. The average decay ratios of Group III for K_{2m}, J_{3l} and J_{3t} were 0.27%, 0.24% and 0.64%, respectively, i.e., the decay ratios of Group III increased by 39.0%, 53.2% and 37.5%, respectively, when compared to Group II. Seemingly, these significant differences resulted from the temperature variation (−5 to 40°C); actually, those caused by freezing–thawing of water. Freezing of water within rocks resulted in irreversible stress damage (Delage and Lefebvre, 1984; Lienhart, 1988), creating wide and deep cracks inside the parent rocks (Bloom, 1997; Hale and Shakoor, 2003) which continually disintegrated into small rock debris. Thus, it is the variation of moisture content and H_{2}O phase (solid or liquid) within rock that plays a key role in rock decay processes, and not temperature alternation. Because it has been suggested that the magnitude of thermal stresses is not generally sufficient to fracture rocks catastrophically (Moore et al., 2008).

4. Conclusions

The rate of bedrock decay decreased with increasing soil thickness in the field. Differences in moisture content and temperature were found to be the primary reasons causing the significant differences in decay rates of the rocks at different soil thickness. Decay rate was significantly related to daily temperature and moisture variation and fitted well to an exponential model. Laboratory results showed different degrees of moisture and temperature action led to different decay ratios of the three types of rocks. Hierarchical clustering analysis separated the rocks into three groups with significant differences in their decay ratios. Water was recognized as having a more important contribution to the process of rock decay than temperature; and the variation of moisture content and H_{2}O phase (solid or liquid) within rock was found to play a key role in rock decay processes, rather than temperature alternation. Under similar moisture conditions, freezing–thawing greatly promoted rock decay, compared to other treatments. J_{3t} rock showed the highest decay ratio because of its highest clay mineral content and porosity amongst the three rock types.

Acknowledgments

The authors are grateful for financial support from the National Natural Science Foundation Committee of China (Grant No. 40971168) and the One Hundred Young Persons Project of the Institute of Mountain Hazards and Environment, Chinese Academy of Sciences (Grant no. SDSQB-2011-01), and honestly thank the anonymous referees for their detailed comments.

References


Fig. 7. Multiple comparisons of the decay ratios of the sampled rock (different letters following the values of mean ± standard deviation in each chart group indicate the significant difference at the p = 0.05 level between the groups).

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