Rapid Weathering and Salt Water Migration Processes near a Slope Surface in Plio-Pleistocene Mudstone Badlands in Southwest Taiwan

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Abstract

High rates of surface wash erosion and rapid weathering of impermeable mudstone form barren badlands consisting of sharp ridges and dense gully networks on steep slope surfaces under the humid subtropical climate with distinct dry and rainy seasons in southwest Taiwan. We analyzed pore water chemistry, swelling of the mudstone, and monitored water contents and salt contents near the slope surfaces, and revealed the weathering and erosion processes of the mudstone, as follows. The mudstone, which contains salty interstitial water and has low permeability, is dried with developed desiccation cracks during dry seasons. The salty interstitial water migrates from the depth to the surface and condensed with salt, which precipitate near the slope surfaces. Water from occasional rainfall immediately infiltrates down to the depth along open fractures, dissolving precipitated salts. During rainy seasons, on the other hand, interstitial water of rock increases in amount and is diluted, increasing the osmotic pressure, which expands bulk volumes, and closes desiccation cracks. Diluting the interstitial water by meteoric water finally disperses the rock-forming grains due to chemical osmosis. This dispersed surface material is rapidly removed by surface wash during subsequent rainfalls in the rainy season, and next cycle of weathering starts again.

Keywords: erosion, weathering, Plio−Pleistocene mudstone, badlands, in-situ monitoring

1. Introduction

High rates of surface wash erosion and rapid weathering of the mudstone predominantly occur and develop sharp ridges and v-shaped gullies on steep slope surface in badlands in Taiwan (Fig. 1, Lee et al 2007; Nakata and Chigira 2009; Higuchi et al. 2013, 2014). Since the mudstone has lower permeability and low resistivity to the erosion, the rainwater cannot penetrate into deeper depth immediately, and surface wash erosion predominantly occurs during heavy rain. Such high rates of erosion and sediment yield cause environmental problems as well as poor use of land.

During the rapid weathering, volumetric change of the mudstone causes initiation and closure of cracks near the slope surface and essentially associates with rapid weathering processes in badlands (Howard 1994; Faulkner et al. 2004; Higuchi et al. 2014). However, the detailed water and salt content migrations during each rainfall event and mechanical volume changes of the mudstone have not been revealed. Therefore, we here discuss migration of water and salt contents at each rainfall event, and the rock swelling, and summarize the weathering and erosion processes.

2. Study area

The barren badland landforms widely distribute in the middle of the Erhjen River basin in southwestern foothill of Taiwan, where is

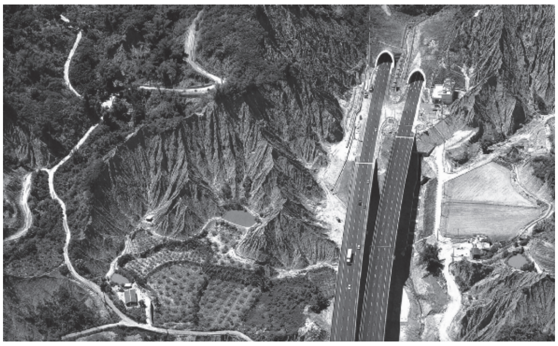

Fig. 1 Photograph of badlands around study area. The National express way in the center of the photo goes through the mudstone area.

underlined by Plio−Pleistocene mudstone of the Lower Guting-keng Formation. In this area, multiple erosional river terraces of middle−late Holocene paleo-floodplain, which forming calcareous coarser sandstone surface of a few to several tens meters thick, cover the weakly resistant mudrock and are covered by vegetation due to higher resistivity to the surface erosion. Tropical typhoons commonly bring disastrous floods to the basin where is undergoing extremely rapid tectonic uplift (Hsieh and Knuepfer 2001). After the abandonment of the paleo-floodplain of around 2 ka, river bottom incision due to the uplift and subsequent lateral surface erosion have extended wide badlands (Hsieh and Knuepfer 2001).

The studied slope is located in typical badlands of Tian-liao county, 20 km east of Tainan in southern Taiwan (Fig. 2, Higuchi et al. 2014), where the climate is humid sub-tropical with a rainy season from May to August and a dry season from September to April. The slope surface was covered by friable crust that was a few centimeters thick and that became desiccated with open fractures in the dry season. Beneath the crust, some of the desiccation cracks penetrated to depths of 20−30 cm but no cracks extended to 40 cm deep. The bedrock comprises impermeable, dense mudstone (siltstone) as low as <0.2−0.3 of void ratios, and whose properties are reported in Higuchi et al. (2013, 2014) as follows. In dry season, the slope surface is dried and precipitates salts along the opened fracture surfaces with decreasing water content and with increasing rock hardness. After the dry season, hard rainfall moistens the rock with dissolving the precipitated salts and decreases the rock hardness significantly with developing lower bulk density and higher porosity near the slope surface in the early rainy season. This deteriorated surface is eroded as high as 9 cm/y in average in the subsequent late rainy season.

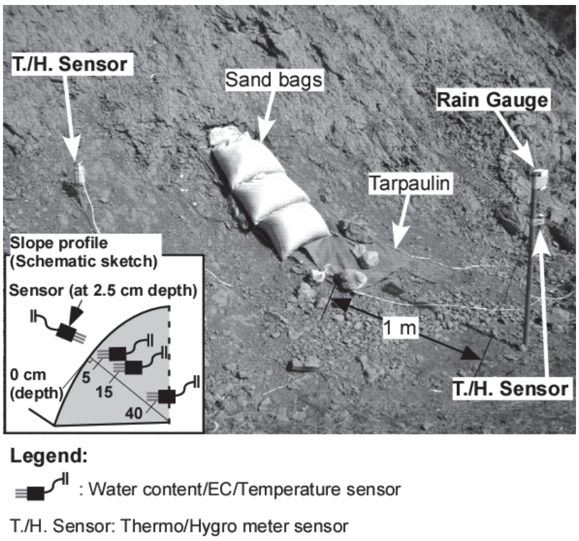

Fig. 2 Photograph of monitoring site and schematic sketch of setting of sensors.

3. Methodology

Swelling tests were performed for the mudstone by initially cutting a fresh mudstone disc (5 cm in diameter, 2 cm in height) from a block by drilling and dry saw. The disc was placed in a consolidation test machine and loaded to a stress of 50 kPa before immersion in 8% salt water or pure water. Strain was monitored for 50 hours.

From November 2009 to March 2011, temperature, water content, and pore water EC (Electrical Conductivity) were monitored at and below the slope surface with simultaneous measurements of rainfall and air humidity/temperature in front of the slope (Fig. 2, Higuchi et al. 2014). The slope, which had been artificially cut several years prior to the measurements, faced southeast, was inclined at 50°, and lacked vegetation. The detailed technique for installing the sensors and monitoring instruments were described in Higuchi et al. (2014).

The 5TE sensor that we used for the monitoring cannot measure pore water EC in

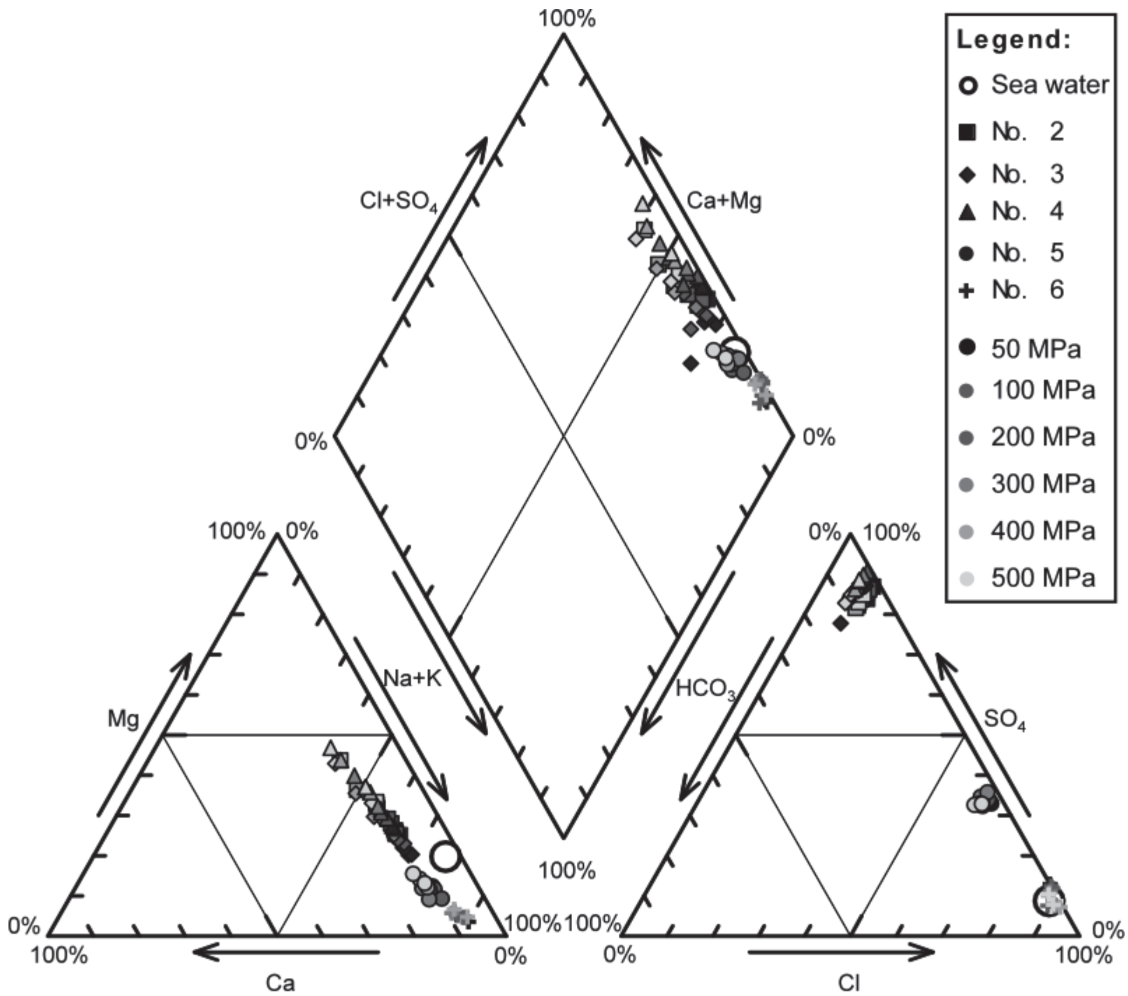

Fig. 3 Piper diagram of extracted pore water of the mudstone at each loading pressure.

extremely dry soil because the derived equation referred from Hilhorst (2000) is not available when the water is bound to the soil rather than being free. We calculated the minimum water content for the application of the Dirksen and Dasberg (1993) equation, which gives the relationship between the minimum water content and the specific surface area of soil. We measured the specific surface area of the mudstone as 19.6 m^2/g using the BET (Brunauer-Emmett-Teller) method and obtained a minimum water content of 0.006, which was much lower than the water contents observed during field monitoring.

The extraction of interstitial water was made using a uniaxial compression water-extraction apparatus developed by Kiho et al. (1999). Extracted water was filtered with a 0.45 μm filter before analysis using an EC meter (B-173; Horiba Corporation), a pH meter (B-212; Horiba Corporation), and an ion chromatography device (761 compact IC; Metrohm Corporation).

4. Results

3.1 Chemistry of the Extracted Pore Water and Swelling

Extracted water volumes from the samples ranged from 0.3 to 4.8 ml at each pressure increment, bringing the total volume to 17–25 ml for each sample. Pore waters contained high amounts of sodium and chorine ions, and had similar compositions to that of sea water (Fig. 3). The chemical composition changed with increasing of the loading pressure from 200–300 MPa, in especially sample No. 2, 3, 4, which have higher SO_4 contents. At the higher loading, the pore water decreased Na+K and increased Ca+Mg.

The swelling test showed that the mudstone swelled 5% in pure water and 4% in salt water (Fig. 4). The larger swelling in pure water may reflect chemical osmosis, as discussed below. The normal

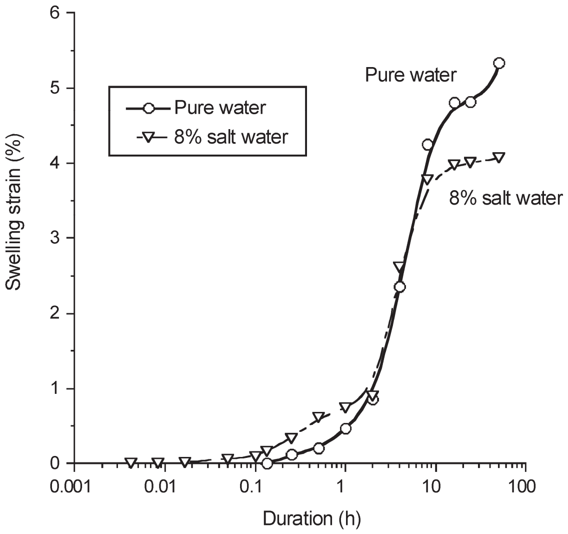

Fig. 4 Volumetric changes in mudstone by using pure and salty water during the swelling test under a normal stress of 0.5 kg/cm^2.

pressure of 0.5 kg/cm^2 corresponds to the pressure at 2.3 m depth when the density of rock is 2.2 g/cm^3, as obtained by Higuchi et al. (2013).

3.2 Monitoring of water contents, pore water EC, and precipitation

The seasonal changes in water content and pore water EC were described in Higuchi et al. 2014, the detailed responses of these properties to rainfall events from dry season to the rainy season were as follows. On 23−24 April 2010 in the dry season, 30 mm of rainfall occurred with three steps in the cumulative curve of rainfall amounts (marked as a−e in Fig. 5). Water contents before the rainfall were 0.02−0.1 with the lowest value at 2.5 cm depth. During precipitation, water contents increased from 0.02 to 0.1 at 2.5 cm depth with breaks corresponding to steps a, b, and c (Fig. 5), from 0.05 to 0.07 at 5 cm depth with a break corresponding to step c, from 0.07 to 0.12 at 15 cm depth with breaks at steps c and d (e), and from 0.1 to 0.14 at 40 cm depth with breaks at steps c and d. The water content breaks thus moved downwards through the material. Pore water EC before the rainfall was 2−3 dS/m at depths of 2.5−15 cm, and was 10 dS/m at 40 cm depth. During the precipitation, EC at 2.5 cm depth gradually increased from 2 to 10 dS/m, and at 5 cm depth increased from 3 to 8 dS/m with two peaks at b and c. At 15 cm depth, EC increased from 2 to 9 dS/m with a very small peak just after step e. In contrast, at 40 cm depth, EC peaked immediately after step c, then decreased and recovered reach >10 dS/m.

Between 10 and 20 June 2010 in the early rainy season, 200 mm of precipitation occurred with a maximum intensity of 17 mm per 10 min (Fig. 6). During this rainfall event, intense precipitation (>5 mm per 10 min) continued, and the total was 10 times larger than the dry season's total precipitation. Water contents were 0.1−0.16 before the rainfall (Fig. 6). During the precipitation, the water contents increased from 0.1 to 0.28 at 2.5 cm depth and from 0.15 to 0.29 at 5 cm depth. In contrast,

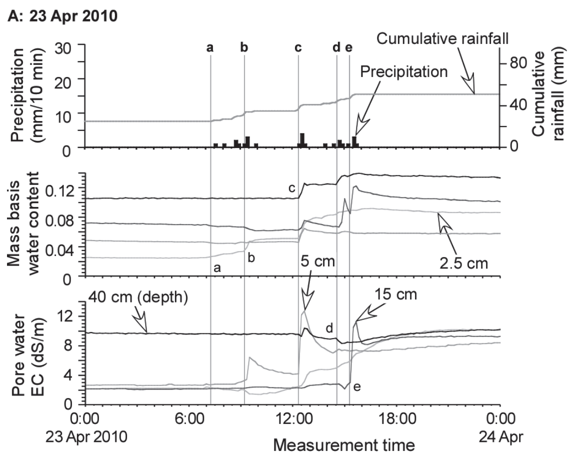

Fig. 5 Changes in water content and pore water EC for the rainfall event of 23 April 2010.

The vertical lines indicate breaks in values of cumulative rainfall.

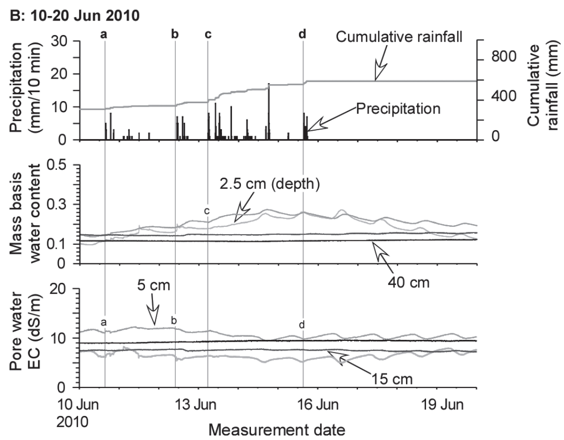

Fig. 6 Changes in water content and pore water EC for the rainfall event of 10−20 June 2010.

The vertical lines indicate breaks in values of cumulative rainfall.

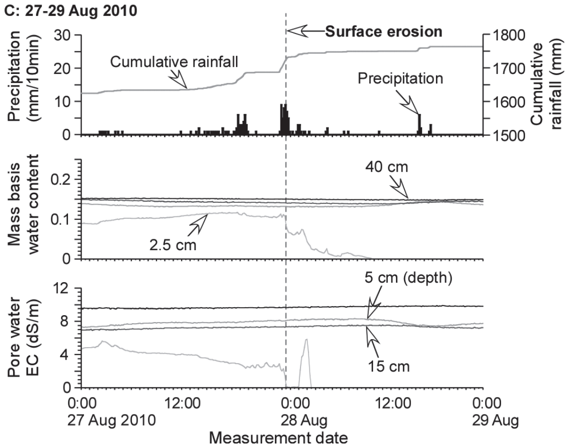

Fig. 7 Changes in water content and pore water EC for the rainfall event of 27–29 August 2010.

The dashed line indicates the timing of the surface erosion identified by the abrupt change of the values at 2.5 cm depth.

water contents at 15 and 40 cm depths increased by only 0.01 after rainfall ceased. EC values varied from 7 to 12 dS/m before the rainfall, and decreased from 8 to 5 dS/m at 2.5 cm depth and from 12 to 9 dS/m at 5 cm depth during the precipitation. In contrast, at 15 cm and 40 cm depths, the values of EC were 7 and 9 dS/m, respectively, and increased by only a small amount during the rainfall.

On 27–28 August 2010, 150 mm of precipitation occurred with a maximum of 9 mm per 10 min (Fig. 7). Water contents before the event were 0.09–0.15, with the lowest occurring at 2.5 cm depth. During the precipitation, only water content at 2.5 cm depth increased, from 0.09 to 0.12; the water contents at other depths did not respond to the rainfall. During the precipitation, EC at 2.5 cm depth increased to 6 dS/m then decreased to 2 dS/m. In contrast, at 5, 15, and 40 cm depths the EC was almost constant at 7–10 dS/m. At 2.5 cm depth, the measured values of both water content and EC showed radical change, which started 00:30–10:30 on August 28, which suggests the timing of sensor disturbance and displacement due to surface erosion.

5. Discussion

In dry season in the several weak rainfall events, during which there was a dramatic response of water content and pore water EC values (in April). The water contents at 15 cm depth increased in response to the rainfall event, which had a maximum intensity of 5 mm per 10 min, equivalent to 8×10^{-4} cm/s, much higher than the permeability of rock matrix (10^{-8} cm/s; Lee et al. 2007). Rainwater probably traveled along open cracks further than 40 cm depth, as supported by water content changes during the rainfall in April (Fig. 5). The vertical shifting of changes in water content suggests that first the surface portion became saturated then water infiltrated through open cracks to reach the deeper parts of slope material. Void ratio of the fresh mudstone from a nearby slope measure 0.2 (Higuchi et al. 2013), which is equal to a mass-basis saturated water content of 0.08. The mudstone at 40 cm depth might have slightly higher water contents than the assumed saturated water content.

In the early rainy season, the mudstone near a slope surface increases in water content much higher than saturation (Figs 5). Subsequently, after the early rainy season, the increase in water contents propagated to 40 cm depth (Higuchi et al. 2014), where water contents measured 0.16–0.18 after June and when water contents at 15 and 40 cm depths scarcely responded to rainfall (Figs 6 and 7). The very weak response at depth to rainfall events may be a result of the closure of desiccation cracks near the slope surface by the swelling of rocks. The void ratio of rocks from depths of 20–30 cm on a nearby slope measure 0.2 (Higuchi et al. 2013), which suggests that the mass-basis water contents at saturation at these depths is 0.08. In contrast, the monitored water contents at depths of 20–40 cm were about twice that value, which suggests that the rock volume at 40 cm depth might have increased by absorbing more dilute water than pore water in the dry season.

Abrupt increase in pore water EC near the slope surface (2.5 and 5 cm) occurred during intermittent rainfall events like those in Dry season (April) (Fig. 5), when EC increased sharply and then decreased gradually. The sharp increase in EC may be due to the dissolution of precipitated salts on fracture surfaces (Higuchi et al. 2014). While after the rainfall events, EC decreased gradually at the surface (Fig. 5), when evaporation and salt precipitation most likely occurred. But that salt

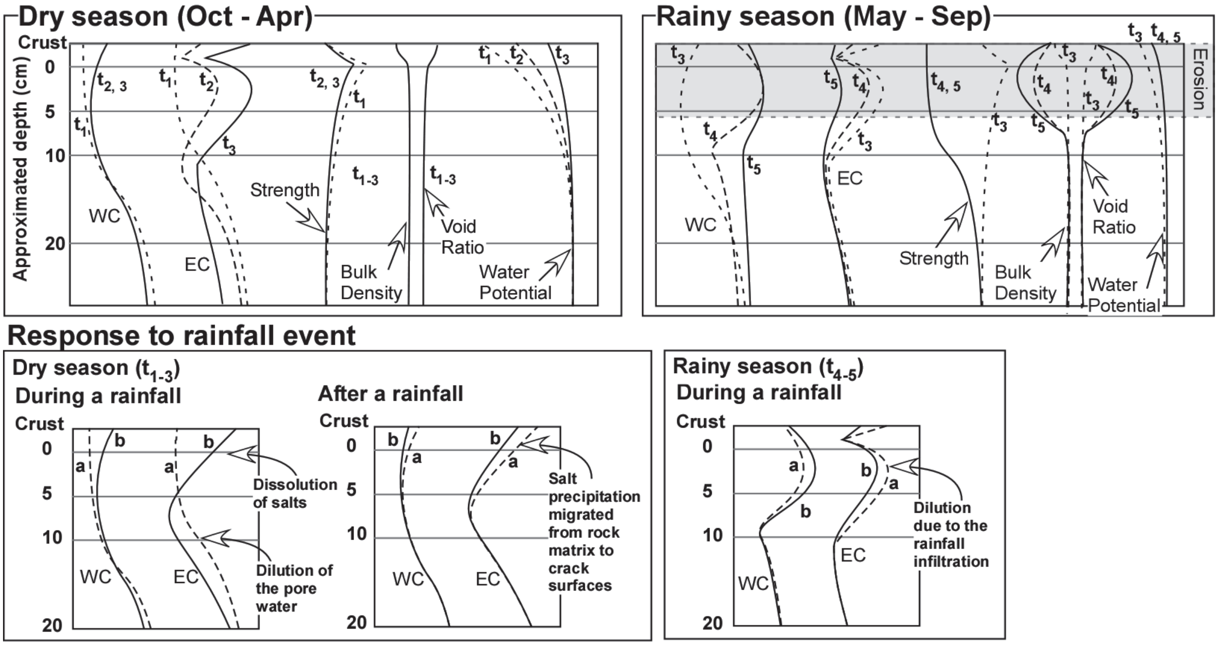

Fig. 8 Schematic sketch of the changing physical property profiles of the mudstone beneath the slope surface during the dry and rainy seasons.

t_1: dry season without precipitation; t_2: after sparse precipitation during the dry season; t_3: late dry season after wetting and drying; t_4: beginning of the rainy season; t_5: after precipitation in the early rainy season (just before erosion). EC: Electrical Conductivity; WC: Water Content. The depths 5, 10, and 20 cm are indicative averages based on the monitoring data and on the results of Higuchi et al. (2013, 2014).

crystallized on fracture surfaces and salt in the pore water of the rock matrix may have migrated to the surface and therefore have decreased (Higuchi et al. 2014). In the early rainy season, EC at 2.5 and 5 cm depths increased to their highest recorded levels and thereafter decreased. During the rainy season, the immediate responses of pore water EC to rainfall events were limited to the shallow parts of the slope material (Figs 6 and 7). The aforementioned changes in both water content and EC strongly suggest that open desiccation cracks, which formed during the dry season, were closed at the beginning of the rainy season. This crack closure was observed in the field and could be caused by the swelling of rocks by water adsorption. As shown by swelling experiments (Fig. 4), the mudstone swelling occurs without expandable clay minerals and the larger swelling occurs with immersion of pure water, suggesting that the chemical osmosis-induced swelling occurs. The mudstone has compacted fabric (0.2< void ratio) and soluble salts, that can form overlapping of ionic double layer on negatively charged particle surface during immersion because of the narrower pore openings. That can inhibit passage of ions, thereby the rock acts as semi-permeable membrane (Marine and Fritz 1981). The salty interstitial water of the mudstone would presumably cause larger infiltration of surface fresh water during rainfall due to unequal ionic concentration like osmotic membrane. Therefore, the mudstone most likely disperses (dissociates) mudstone-forming grains and subsequently swells the volume at the slope surface where salts concentrated during heavy rain in the rainy season.

On the basis of the above discussion of the changes in both water content and EC, we here discuss the overall scheme of weathering and erosion processes as seasonal phenomena (Fig. 8). In the early dry season, mudstone is dried significantly near the slope surface (labeled t_1 in Fig. 8). Desiccation cracks form near the surface, and are particularly abundant to a few centimeters in depth. Water potential gradient brings salt water from depth to the surface and the evaporation of the water deposits salt on fracture surfaces (Higuchi et al. 2014). During the following late dry season, water potential is greatest at 15 cm depth, and therefore water movement follows the potential gradients at depth greater than 15 cm depth. At depths shallower than 15 cm, water ascends according to the potential gradients but water vapor may return to 20–40 cm depth and condense under the cooler conditions there. Water from intermittent rainfall in the late dry season flowing down open cracks may be another source of water. Salt precipitation occurs as a result of the migration of salt from the inner matrix to cracked surfaces when the slope surface material is dried. Rainfall in the dry season increases moisture content in surface cracks and dissolves the precipitated salt (labeled t_2 and t_3 in Fig. 8). After rainfall, water content decreases because of drying and the migration of dissolved salt to surface cracks. In the early rainy season, rainfall causes water contents near the slope surface to increase up to much higher than saturation (Higuchi et al. 2014) (labeled t_4 to t_5 in Fig. 8). This increase in water content dilutes pore water and probably increases the chemical osmotic pressure and affects pore size enlargement. The surface fresh water during rainfall most likely disperses (dissociates) the rock-forming grains due to unequal of ionic concentration with the interstitial salty water and subsequently swells the volume. The enlargement of pore sizes is more common near the surface, as identified in pore size distribution curves for drilled cores (Higuchi et al. 2013). Peak pore sizes ranged from 0.04 to 0.06 μm in rock deeper than 20 cm and measured 0.1 μm with an additional peak at 0.3 μm at depths shallower than 10 cm. The high water contents and pore size enlargement act to weaken rock near the slope surface, as indicated by tests of needle penetration resistance in drill core material (Higuchi et al. 2013). High amounts of rainfall in the rainy season precede increases in water content, salt water dilution, pore size enlargement, and deterioration in the surface layer (after t_5 in Fig. 8), with the surface layer finally being removed by predominant surface wash erosion.

6. Conclusions

We measured for the pore water chemistry, mudstone swelling and time series fluctuations of water content and pore water EC near the slope surface in badlands in Taiwan, and revealed the mudstone mechanical properties and weathering processes near the slope surface, as follows.

In the dry season, near the mudstone slope surface, the mudstone of low water content develops desiccation cracks. Rain water from occasional rainfalls immediately moves down to the deep along open fractures, dissolving precipitated salts near the slope surface. The mudstone is essentially impermeable so that the rainwater cannot infiltrate immediately into the rock matrix. After the dry season, water content of the mudstone increases and closes opened cracks due to swelling near slope surface during heavy rain in the early rainy season. This crack closure prohibits penetration of water to the deeper depth, and consequently, water concentrates at the slope surface with dilution during heavy rain. In the heavy rain, dilution of salty interstitial water during the infiltration of surface fresh water disperses rock-forming grains due to chemical osmosis. This deteriorated part would be removed during surface wash in the late rainy season. After the rainy season, stripped surface is dried and starts to be weathered again.

Acknowledgements

Eiji Nakata of Central Research Institute of Electric Power Industry (CRIEPI) is acknowledged for his help of measuring the pore water chemistry and for his advice in the field and laboratory. Prof. Yuki Matsushi of the Disaster Prevention Research Institute of Kyoto University is acknowledged for his advice in the field and laboratory. Prof. Yen-Hua Chen of the National Cheng-Kung University is acknowledged for her help of measuring the BET specific surface area. Prof. Hun-Ming Lin of the National Cheng-Kung University is acknowledged for his help in the field.

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