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ORIGINAL ARTICLE

The variation of morphological features and mineralogical components of biological soil crusts in the Gurbantunggut Desert of Northwestern China

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Abstract Increasingly complex life forms were found in older biological soil crusts in the Gurbantaunggut Desert in Northwestern China. These crusts may play a critical role in mineral erosion and desert soil formation by modifying the weathering environment and ultimately affecting mineralogical variance. To test this hypothesis, variations in the morphological features and mineralogical components of successional biological soil crusts at 1 cm were studied by optical microscopy, SEM and grain size analysis. Concentrations of erosion-resistant minerals decreased with crust succession, while minerals susceptible to weathering increased with crust development. Neogenetic minerals were found in late stage crusts, but not in early stage crusts. Silt and clay concentrations were highest in early formation crusts and soil mean particle size decreased with crust succession. Cyanobacteria, lichen and moss were shown to erode and etch rocks, and secondary minerals produced by weathering were localized with the living organisms. Thus, more developed crusts appeared to contribute to greater mineral weathering and may be a major cause of mineralogical variance seen in the Gurbantunggut Desert. The greater activity and complexity of older crusts, as well as their improved moisture condition may function to accelerate mineral weathering. Therefore, protection and recovery of biological crusts is vital for desert soil formation.

Keywords Gurbantunggut Desert · Biological soil crust · Morphology · Mineral erosion

Introduction

Biological soil crusts are widespread in sparsely vegetated arid and semi-arid environments throughout the world and play a significant role in desert ecosystems (Belnap and Lange 2003). These specialized communities of cyanobacteria, mosses and lichens bind soil particles together, prevent soil erosion from water or wind, and accumulate carbon and nitrogen in desert soil (West 1990; Belnap and Gardner 1993; Belnap and Gillette 1997; Li et al. 2000, 2003; Hu et al. 2004; Zhang et al. 2006). Cyanobacteria are the first to colonize soil surfaces followed successionally by green algae, mosses and lichens. The occurrence of lichen crust is considered to be an index for stable landscape (Eldridge and Greene 1994).

Numerous studies demonstrated that the presence of biological soil crusts is correlated with specific surface soil physicochemical properties, such as mean soil size and clay content (Harper and Pendleton 1993; Belnap 1995; Pendleton and Warren 1995; Li et al. 2003). Crust formation alters soils by several mechanisms. One way that crusts change soil texture is by stabilizing airborne dust and

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concentrating clay and silt at the soil surface (Danin et al. 1989; Danin and Ganor 1991; Duan et al. 1996). Duan et al. (1996), however, found that airborne dust contains less silt and clay than the cyanobacterial crusts at the Tengger Desert. Biological soil crusts can also alter the soil environment by improving water-holding capacity and nutrient accumulation, and by increasing soil temperature (Belnap and Lange 2003; Li et al. 2003; She et al. 2004). These alterations may offer a more reactive erosion environment that accelerates production of desert soil. The accelerated weathering processes associated with crust formation may be more important to soil formation than plant dust-trapping mechanisms. In support of this, Ke Fu Da (1983) reported that crusts associated with higher mineral erosion rates led to formation of soil nutrients and various clay minerals, and a variety of neogenetic minerals formed in different environments by biogenic agents such as cyanobacteria or fungi (Boquet et al. 1973; Wright 1986; Monger et al. 1991; Amit and Harrison 1995).

Previous research of biological crusts focused on aspects of fertility (Harper and Pendleton. 1993; Belnap 1995; Pendleton and Warren 1995; Li et al. 2003), while the relationship between crust formation and accelerated mineral erosion and soil formation has mostly been studied in rock microbes and lichens. Soil fertility is preserved by stabilization against wind and water erosion created by greater organism biomass of late successional crusts (Belnap and Gillette 1997; Warren 2003; Zhang et al. 2006). Researchers found that cyanobacteria and lichen accelerate rock erosion through both physical means or chemical erosion from excretion of various organic acids (Chen et al. 2000; Brehm et al. 2005).

Biological crust effects on mineral erosion are complex and difficult to measure in the desert environment. This study examined morphological variation and analyzed changes in mineralogical components within successive crusts to establish the contribution of biological crusts in mineral erosion and soil formation in the Gurbantunggut Desert. The hypothesis was that changes in crust communities modify the weathering environment and create observable mineralogical variance.

Site descriptions, materials and methods

The study area

The Gurbantunggut Desert covers 48,800 km^2 in the center of the Jungger Basin, Xinjiang Uygur Autonomous Region of China (44°11′–46°21′N, 84°31′–90°00′E). It is the largest fixed and semi-fixed desert in China. The desert has a temperate continental climate with an annual precipitation of 70–150 mm (average = 80 mm) falling predominantly during spring (Wei and Dong 1997), and a mean annual evaporation of 2,607 mm. The annual average temperature is 7°C and the mean relative air humidity ranges from 50 to 60%. Wind speeds are highest during late spring, averaging 11 m/s, and the wind blows predominantly WNW, NW and N. The top sections of most dunes have a mobile crest, devoid of biological crust and covered with sparse vegetal cover that is dominated by *Haloxylon ammodendron* and *H. persicum*. The remaining dunes and the sandy interdunes are covered with different successional crusts and natural vegetation that is dominated by *Ephedra distachuya.* The dune and interdune sections have a vegetation cover of 20–30% and are considered stabilized.

Four types of biological crust are distributed throughout the Gurbantunggut Desert (Zhang et al. 2007): (1) light cyanobacterial crusts (light color, devoid of surface pigmentation; soft), (2) dark cyanobacterial crusts (black, relatively hard), (3) lichen crusts (permanent, very hard), and (4) moss crusts. Light cyanobacterial crusts are early successional stage crusts, while dark cyanobacterial crusts and lichen and moss crusts are late-stages crusts. A fifth surface type devoid of crust and abundant in the top of dunes served as control and is hereafter referred to as ‘shifting sand’. The cyanobacterial crusts (dominated by *Microcoleus vaginatus, M. paludosus, Lyngbya martensiana, Lyngbya martensiana*) are most abundant in the middle to the top of dunes; lichen-dominated crusts (dominated by *Collema tenax, Psora decipiens*, *Xanthoparmelia desertorum* and *Diploschistes muscorum*) are most abundant in the middle-down to interdune areas; and moss-dominated crusts (dominated by *Tortula desertorum* and *Bryum argenteum*) are scattered within the interdune areas (Chen et al. 2006). Human and wild animal disturbances have created a patched interdune interface with some light cyanobacterial crust. Minerals found throughout the Gurbantunggut Desert include quartz, feldspar, hornblende, picrite and mica (Qian et al. 2001).

Crust sampling

The selected research plot (44°32′30″N, 88°6′42″E) was a typical semi-fixed sand dune, approximately 30 m high with a 100 m wide interdune. Duplicate samples of superficial soil about 1.5 cm thick were collected from each of the four successional crust types and the non-crust shifting sand. Thin sections were made from all samples. Pieces of biological crusts were carefully sampled along the polygonal cracking for surface microscopic observations. Three duplicate soil samples were collected at 1 cm from the surface from each of the five sample types. Each sample was prepared for soil mechanical composition analysis.

Methods

Samples for thin sections were dried at 45°C for 48 h to remove the free water without killing cyanobacteria, lichen and moss. Undisturbed soil samples were impregnated with a mixture of 1,000 ml of Epoxy resin and 130 ml of catalyst (Triethanolamine), and saturated samples were dried at 65°C for 24 h (Gen and An 1978). The blocks of hardened soil were mounted on frosted microscope slides, cut to about 500 μm thickness using a diamond-edged saw, and then a polishing machine was used to reduce the thickness to about 30 μm, followed by hand polishing. Microstructure observations of thin sections were performed on an Olympus System Microscope (DP70, Models BX52), and mineral contents of the superficial layer (0–1 cm) were counted using a Nikon microscope (E-600). Microstructures of sand particles were observed on a LEO1430VP Scanning Electron Microscope.

The texture of the topsoil (0–1 cm layer mixed sample, with three replications in each type) was determined using a laser granulometer (MasterSizer2000, UK). Samples were treated with hydrogen peroxide to remove organic matter, and were then dispersed using ultrasound and sodium hexameta-phosphate.

Statistical analysis

Differences in mineralogical components among the five crust types were quantified using analyses of variance (ANOVA). Tukey's test was applied post hoc to distinguish between means at the different crust types. These procedures were performed on Windows-based *SPSS* 11.5th edition software (Chicago, IL, USA).

Results

Micromorphology of the biological crusts based on profile observations

Additional life-forms of increasing complexity became established near more developed crust types and resulted in higher biomass in these areas (Fig. 1). Cyanobacterial cover was not found in shifting sand samples (Fig. 1a). Light cyanobacterial crusts did not show an obvious cyanobacterial layer, however, patches of living microorganisms associated with fine particles were observed at the top of the surface layer (Fig. 1b). Profiles of cohesive dark cyanobacterial crust showed a 5 mm thick superficial layer formed of tightly packed sand and coarse silt particles, and a loosely packed lower layer of mostly sandy mixed particles (Fig. 1c). A thin lamina of living filamentous microorganisms associated with fine particles and showing a layer of tight flakes was observed at the top of the surface layer of the lichen crust. Green chloroplasts were seen in the flake structure and mycelium below the flake structure was in tight contact with sand particles. The largest biomass of dead organisms and adhered airborne sand particles was seen in the 4–8 mm layer of the lichen crust (Fig. 1d).

Morphological analysis of thin sections showed cyanobacteria eroded sand particles (Fig. 1b, c), lichen hyphae grew and penetrated sand particles vertically (Fig. 1e), and moss rhizoids penetrated into the sand particles (Fig. 1f).

Mineralogical composition

Sand particles in the 0–1 cm layer consisted of quartz, plagioclase, K-feldspar, hornblende, pyroxene, picritic basalts, zoisite, epidote, garnet, tourmaline, mica, zircon, hydrous mica, calcite, and magnetite. All samples contained quartz and feldspars (plagioclase and K-feldspar) as the major minerals, with contents ranging from 45 to 60% and 15 to 30%, respectively, together with minor quantities of hornblende and picritic basalts. Secondary minerals such as hydrous mica were found in late crust stages but were not found in shifting sand and light cyanobacterial crusts. The overall content of mica was less than 1%. Neogenetic minerals were co-located in soil with living organisms, and calcite was only found on lichen surfaces.

Minerals such as quartz and feldspar (plagioclase and K-feldspar) that are more resistant to erosion decreased with crust succession, whereas minerals that weather more easily, such as pyroxene and hornblende, increased with crust succession (Fig. 2). There is an apparent correlation between decreasing quartz content variability and crust development. The quartz content was significantly higher in shifting sand (56.1%) than in lichen (49%) and moss (49%) crusts. K-feldspar showed the same decreasing trend with succession. K-feldspar decreased significantly from a high in shifting sand (9.1%), to dark cyanobacterial crusts (8.5%), lichen (6.8%) and moss (5.3%). K-feldspar content was not significantly different among late-stage crusts. Plagioclase content did not vary markedly with crust succession with the exception of moss, which had significantly lower plagioclase content. Hornblende contents increased with crust development. All stages showed marked content increases over shifting sand (1.2%). Further, the content in lichen (2.0%) and moss (2.1%) was significantly higher than that in light cyanobacterial crusts (1.6%) and dark cyanobacterial crusts (1.9%). Pyroxene content did not change markedly with successional crusts. Hydrous mica content increased with crust succession. Both moss (4.6%) and lichen (4.1%) showed significant increase in mica when compared with dark cyanobacterial crust (2%) and light cyanobacterial crust and shifting sand, which did not contain mica.

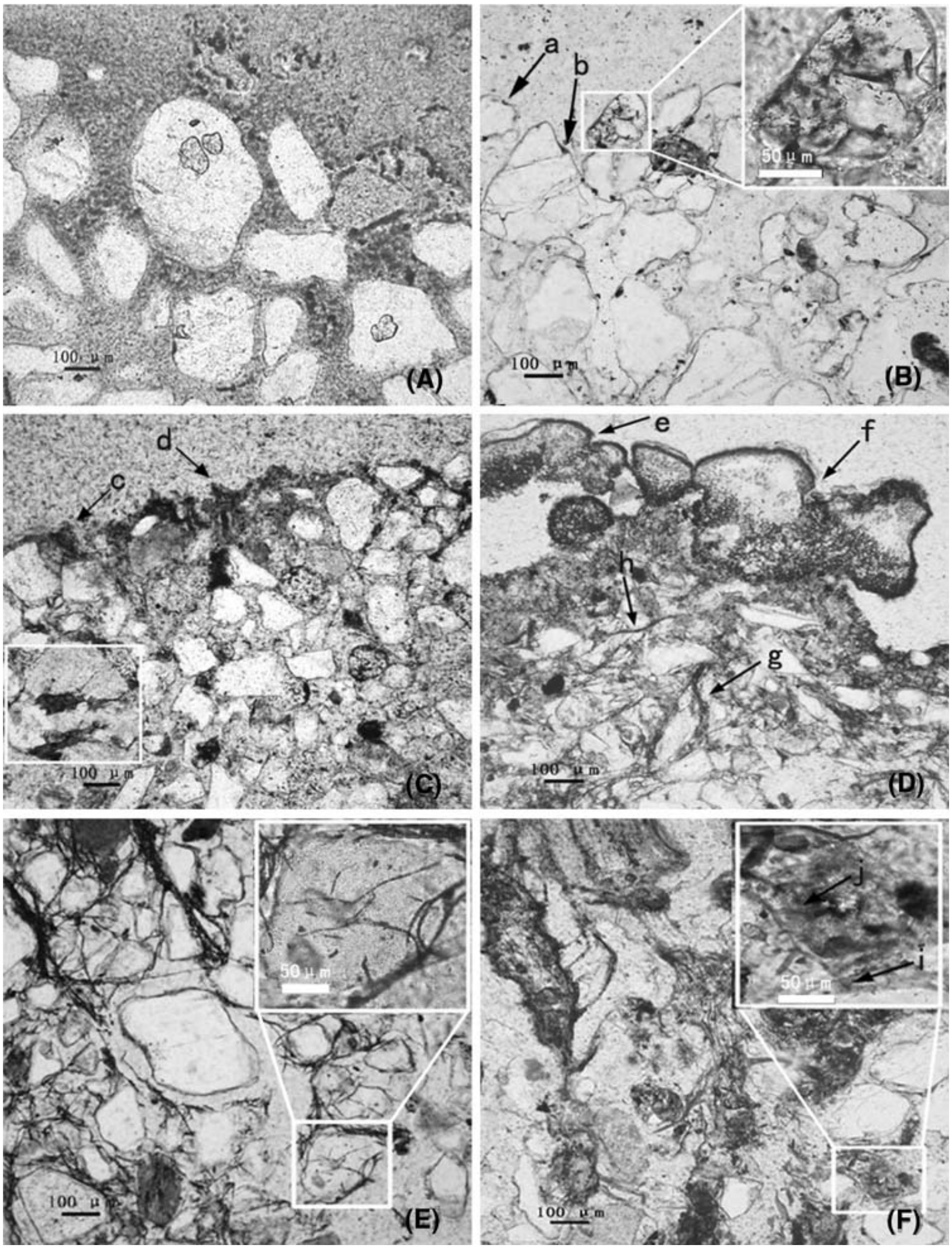

Fig. 1 Photomicrographs of vertical thin sections of studied soils. **a** Shifting sand, superficial layer of the profile without living microorganisms. **b** Light cyanobacterial crust devoid of continuous cyanobacterial layer, patches of living microorganisms located on the surface of sand particles (*arrows a* and *b*); sand particle eroded by living organism (*white frame*). **c** Dark cyanobacterial crust, superficial layer of the profile with a continuous layer of living micro-organisms (*arrows c* and *d*); sand particle eroded by living organism (*white frame*). **d** Superficial layer of lichen crust showing a layer of tight flakes (*arrows e* and *f*) and great biomass of hyphae (*arrows g* and *h*) in the sublayer. **e** Hyphae of lichen below flake structure and penetration of hyphae through sand particle (*white frame*). **f** The moss crust: moss rhizoids penetrated into the sand particles (*arrows i* and *j*)

Changes in soil texture

For sand, the mean particle size decreased with crust succession (Fig. 3) is in agreement with a similar trend observed in desert crusts developed over several decades (Duan et al. 2004; Li et al. 2002; Hu et al. 2000). Shifting sand, light and dark cyanobacterial crusts in the Gurbantunggut desert have a mean particle size >0.2 mm, whereas the crusts of moss and lichen have a mean particle size <0.2 mm (Table 1). Shifting sand was composed of 39% fine sand (0.05–0.25 mm), fine sand and >0.25 mm particles (61%), with little clay (<0.002 mm) and fine silt (0.002–0.05 mm). Therefore, it has high water permeability and poor water retention properties. Clay and fine silt appeared in all stages of crust succession beyond shifting sand. Fine sand (0.05–0.10 mm) content also increased during crust development; rising from 1.2% in shifting sand to 15.4 and 19.9% in the crust of lichen and moss, respectively. As a result of these changes, soil hygroscopicity and plasticity significantly improved.

Discussion

Morphology of biological crust

Soil profiles showed that living organisms are mainly in the layer of 0–10 mm with biological crusts. Light

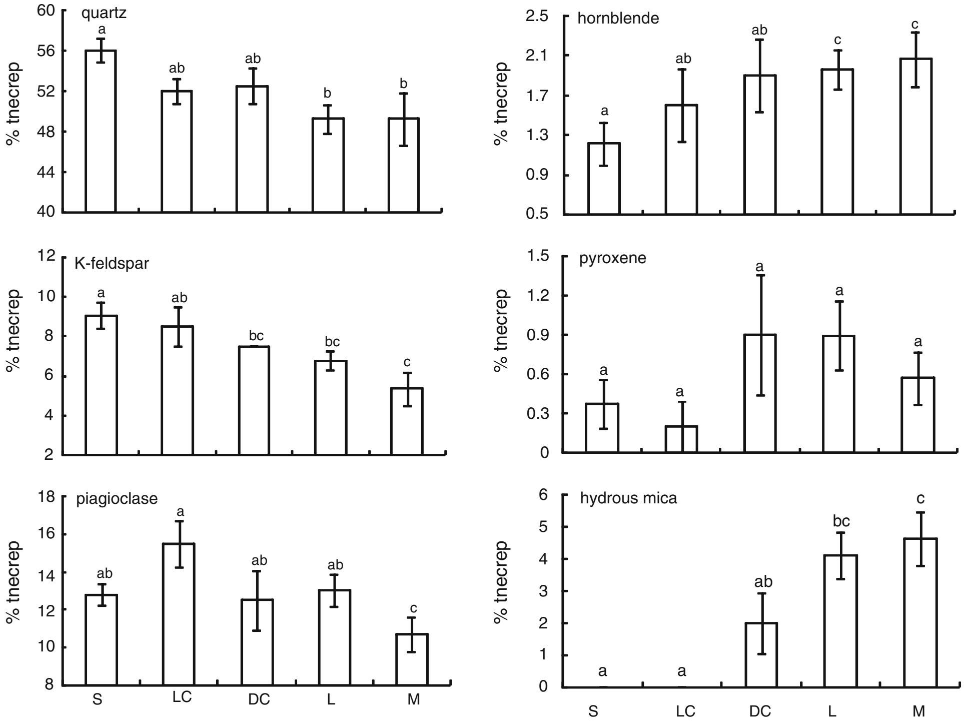

Fig. 2 Variance in the main mineral content of successional crusts. Abbreviations: *S* shifting sand, *LC* light cyanobacterial crust, *DC* dark cyanobacterial crust, *L* lichen crust, *M* moss crust

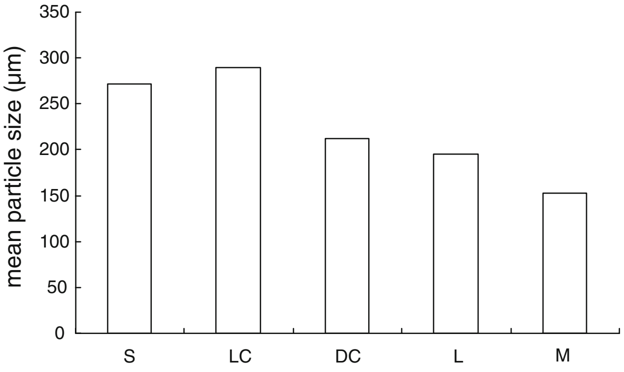

Fig. 3 Mean particle size (μm) of topsoil (0–1 cm) changed with crust succession. Abbreviations are as in Fig. 2

cyanobacterial crusts do not have a superficial layer. In late cyanobacterial crusts, the living microorganisms were mainly in the top soil 0–2 mm and formed a continuous cyanobacterial cover. Cyanobacteria were scarce in layers below 4 mm of soil. Cyanobacterial layers and sublayers of sand were found in western Niger (Issa et al. 1999), but were not found in dark cyanobacterial crusts in the Gurbantunggut Desert. Additionally, in contrast with descriptions from Shapotou (Hu et al. 2000) no mineral layer was found above the cyanobacterial layer in the Gurbantunggut Desert. Shifting sand was composed mainly of loose large grains. The light cyanobacterial crust formed an enhanced contact structure composed of fine mineral particles. Early cyanobacterial crusts become stabilized when cyanobacteria secret glutinous polysaccharides that bind the soil particles, whereas late cyanobacterial crusts achieve stabilization by secreting filamentous and glutinous polysaccharides (Zhang et al. 2006). At the lichen stage, the crusts bind sand particles tightly with mycelium to form a stable layer. Profiles of moss crusts showed a thick (10 mm) surface layer with sand particles bound and held by rhizoids, forming an extremely stable surface. Additional morphological studies with crusts of lichen and moss are needed to determine the mechanisms responsible for stabilizing sand.

Mineralogical composition and mechanical composition

Comparison of mineralogical composition characteristics during the early and late crust stages showed that erosion proceeds at different rates with successional stage. Research by Hu et al. (2000) showed that cyanobacterial crusts developed on shifting sands and stabilized for 3 years (Shapotou, China, Table 2) had decreased quartz content, while hydrous mica and kaolinite increased with crust development. Calcite and dolomite were found in soil crusts stabilized for 16 years and after 41 years of stabilization, crusts were dominated by lichens and mosses. Quartz and feldspar contents decreased and concentrations of secondary minerals such as hydrous mica, kaolinite and calcite increased (Hu et al. 2000). Consistent with their research, this study also found that mineral content in crusts of the Gurbantunggut Desert varied with crust

Table 1 Mechanical composition (%) of topsoil (0–1 cm) in different successional crust stages

Crust Types	Particle size (mm)						
	<0.002	<0.05	<0.1	<0.25	<0.5	<1	<2
Shifting sand	0.00	0.00	1.20	39.81	89.67	100.00	100.00
Light cyanobacterial crust	0.35	6.56	14.97	44.87	76.98	98.97	100.00
Dark cyanobacterial crust	0.02	4.32	15.01	61.20	91.96	100.00	100.00
Lichen crust	0.75	9.36	24.77	66.10	91.28	99.98	100.00
Moss crust	1.02	12.92	32.86	77.26	94.44	99.82	100.00

Table 2 Influences of different sand-fixing ages on soil mineralogical composition in Shapotou, China (%), from Hu et al. (2000)

Sand-fixing age (years)	Quality of crust		Original minerals (%)		Secondary minerals (%)			
	Thickness (mm)	Number of total algae, green algae/g dry soil	Quartz	Feldspar	Hydrous mica	Kaolinite	Calcite	Dolomite
0	–	517/0	50–55	30–40	5	5	–	–
3	3.30	67,000/2,680	40–45	30–35	15–20	15	–	–
16	1.60	58,920/2,940	45–50	20–25	15–20	10–15	1	3
33	3.40	92,100/6,450	45–50	20–25	15–20	10–15	3	–
41	5.20	82,458/6,200	30–35	15–20	20–25	20–25	3	1

succession. Original minerals such as quartz and feldspar decreased, whereas additional original minerals weathered more easily and concentrations of secondary minerals increased. Neogenetic minerals, such as hydrous mica in the Gurbantunggut Desert, and calcite and dolomite in Shapotou, were only found in the advanced stages of succession. This suggests biological crusts provide a better erosion environment and result in greater accumulation of secondary minerals than shifting sand.

During erosion, original minerals break down to smaller particle sizes and fine-sized clay mineral content increases. In shifting sands of Shapotou, clay (<0.005 mm) and fine silt (0.005–0.05 mm) were not found, however, concentrations of both clay and silt increased with crust development, at the same time mean particle size decreased (Hu et al. 2000). A similar trend was observed in present research, where clay content increased with crust succession. In lichen and moss crusts, higher proportions of fine silt and clay resulted in better retention of water and nutrient. Thus, erosional changes appear to be able to push the lower biological activity shifting sand ecosystem to a soil ecosystem of higher biological activity. This shift results in significantly accelerated mineral erosion.

The reasons for mineral content variance

Airborne dust captured by crust components was composed primarily of clay and secondary minerals. Mosses trap and fix dust among their caulidia (a stem with leaf-like structures). Cyanobacteria and lichens fix dust particles to their polysaccharide sheaths, which become sticky when wet. Trapped dust was thought to be important for creating a crust rich in clay and fine silt. However, Duan et al. (1996) found that biological crust composition was not consistent with trapped dust, suggesting the original mineral crust material does not derive directly from airborne dust. The results of this study confirmed that airborne dust is not a major mechanism for soil formation in the desert for the following four reasons. (1) Secondary minerals are produced in the process of mineral weathering. Secondary mineral hydrous mica was found in late successful crusts but was absent in shifting sand and light cyanobacterial crust (Fig. 2). At Shapotou, two secondary minerals, calcite and dolomite, were only found in late stage crusts stabilized longer than 16 years (Table 2). The higher content of secondary minerals found in advanced stages of succession in present study and others suggests a higher efficiency of mineral erosion in the later stages of crust development. (2) Cyanobacteria, lichen and moss were found to erode rocks (Fig. 1b, c, e, f, the eroding effect of living organisms; Fig. 4, the holes eroded by living organisms). Late stage lichen and moss had higher biomass and greater biological activities than cyanobacterial crusts, and their living organisms were in deeper soil layers. Thin section observation also confirmed that eroded mineral contents increased with crust succession, thus, late crust stages appeared to accelerate the effects of biological erosion. (3) Hydrous mica was primarily co-located with living organisms in the soil surface layer. The absence of this mineral in the deeper layers indicates lower biological

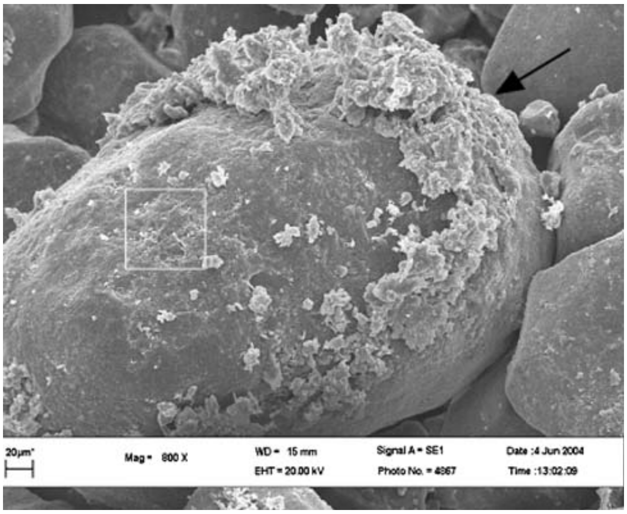

Fig. 4 The polysaccharides (*arrow*) produced by living organism and the eroding effect (*white frame*)

activity below the soil surface and suggests that lower mineral erosion occurs at deeper levels. Consistent with the present study, Danin et al. (1998) found biogenetic calcite concentrations increased from young to old in surface soil. No changes were found in subsoil, further suggesting that biogenic activity is a major reason for mineral variability. (4) Soil contents of nutrients, organic matter and secondary minerals increased during successional stages of formation (Li et al. 2002; Duan et al. 2004). Taken together, the data indicate that trapping of airborne dust alone is insufficient to explain the accumulation and formation of soil in the desert environment. Biological crusts alter the chemical, physical and biological environments that affect mineral weathering, and produce mineral content variation.

The effect of biological crusts on mineral erosion

The process of mineral erosion can be classified into physical, chemical and biological erosion. Factors affecting mineral erosion and soil formation include natural environmental processes and human activity. Climate (temperature and moisture), biology, topography, the original rock and time are the primary natural factors that affect soil formation (Ke Fu Da 1983). Development or recovery of biological crusts creates changes in the microclimate, resulting in increased biological activity. The surface temperature is higher in microbiotic crusts than in mobile dunes (She et al. 2004) and this change favors dew production (Li 2005; Liu et al. 2006). In natural ecosystems, dew serves as an important source of moisture for biological soil crusts, especially in desert environments, where water resources are limited (Jacobs et al. 1999). As a result, crusts can be maintained even when precipitation is <5 mm. The ability of advanced crusts to retain moisture and accumulate nutrients means these late developmental stages can affect mineral weathering to a greater degree than early crusts.

The biological activities of cyanobacteria, lichen and moss are the most important factor in mineral erosion. Calcite secretion by biogenic agents such as cyanobacteria or fungi increased with crust succession (Danin et al. 1998). Mineral surfaces are often affected by significant amounts of organic coatings (Krumbein and Dyer 1985) that are produced by bacteria, algae and fungi, as well as higher organisms that inhabit external and internal (fracture/fissure) surfaces of mineral substrates (Fig. 4; polysaccharides and the eroding effect). This research showed that erosion of mineral particles was accelerated by living organism binding, penetration and exploitation (Fig. 1b, c, e, f; biochemically as well as biophysically). Mineral nutrients leached in bioerosion could be immobilized and utilized by living organisms, resulting in a greater rate of crust succession. These results suggest that mineral erosion and formation of successive crusts is an interactive process.

Different types of living organisms occur in successional crusts. With crust development, the dominant organisms evolve in a sequence from bacteria or fungal to algae, lichen and moss, respectively. The biomass, secondary minerals, and clay content of biological crust components increases from the less-developed to the more-developed crusts. Clay is produced during weathering, so the existence of fine particles indicates different phases of weathering (Ke Fu Da 1983). Hu et al. (2000) suggested that changes in the numbers and species of algae were responsible for mineralogical component variety observed in crust succession at Shapoutou. However, late stage crusts (dominated by lichen and moss) at Shapotou did not have the highest concentration of algae (Table 2). The thin section observation showed that organisms in lichen and moss crusts are more productive than organisms in cyanobacterial crusts, and that algae penetrated large sand particles (Fig. 1a, b). Lichens, however, are more effective than algae in erosion of minerals as determined by decreased mineral concentrations measured in later crusts. Hyphae of lichen can physically break down quartz, however, in lichen-colonized granite, Prieto Lamas et al. (1995) found that the growth and penetration of hyphae occurs both vertically and horizontally and may exceed 4 mm, mainly via intergranular voids. Oxalic acid secreted by the mycobionts of many lichens is commonly considered to play a crucial role in chemical erosion of rocks and minerals. Lichen fungi can secrete other simple organic acids, such as citric and gluconic acids, which can also lead to the erosion of rocks through acidic attack and chelation. Biological crusts covering sandstone surfaces were shown to have bioweathering and protective effects (Souza-Egipsy et al. 2004). This research showed that biological crusts that develop on loose sand can also contribute to mineral erosion.

Conclusions

In the Gurbantunggut Desert, sand dunes covered by successional biological crusts showed enhanced topsoil recovery. Quartz and K-feldspar concentrations decreased and concentrations of secondary minerals such as hydrous mica increased in the later stages of crust development, with clay and fine silt content generally recovering more rapidly in the later stages. Soil section observations showed erosion and etching by cyanobacteria, lichen and mosses. The higher activities and greater complexities of late stage crusts, as well as better moisture conditions seen in these stages, may result in accelerated mineral weathering. The results presented in this paper highlight the importance of the formation of biological crusts to bioweathering processes and the ultimate transformation of original minerals in an arid environment. As a result, conservation of the biological crust is a vital issue in extremely arid desert regions.

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