Exploration of playa surface crusts in Qehan Lake, China through field investigation and wind tunnel experiments Postprint

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Abstract

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Full Text

Preamble

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Exploration of Playa Surface Crusts in Qehan Lake, China Through Field Investigation and Wind Tunnel Experiments

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Abstract: Globally, many lakes are drying up, leaving exposed lakebeds where wind erosion releases dust and sand rich in salt and harmful heavy metals into the atmosphere. Understanding the characteristics and spatial distribution of playa surface crusts is therefore important for recognizing the manifestation of salt dust storms. This study explored the playa surface crust types, their spatial distribution, and evolution in Qehan Lake, Inner Mongolia Autonomous Region, China, to understand the salt dust release potential of different crust types. We investigated various crust characteristics through field sampling and classified playa surface crusts into five types: vegetated areas, salt crusts, clay flats, curly crusts, and margins. Notably, curly crusts were distributed within clay flats and covered only a small area in Qehan Lake. We obtained the spatial distribution characteristics of playa surface crust types through supervised classification of remote sensing images and explored the salt dust release potential of crusts through wind tunnel experiments. Field investigation revealed that playa surface crust types exhibited a circum-lake band distribution from the lake interior to the shoreline, successively comprising vegetated areas, clay flats, salt crusts, and margins. This spatial distribution pattern was primarily controlled by playa hydrodynamics, soil texture, and groundwater. A significant negative correlation existed between crust thickness and electrical conductivity. Wind tunnel experiment results showed that the initial threshold friction wind velocity for salt dust release was higher in clay flats (0.7–0.8 m/s) than in salt crusts (0.5–0.6 m/s). Moreover, particle leap impact processes occurring under natural conditions may reduce this threshold value. Salinity was the main factor controlling the difference in the initial threshold friction wind velocity for salt dust release between clay flats and salt crusts. This study provides a scientific reference for understanding salt dust release from lakebeds, which may inform ecological restoration of dry salt lakes.

Keywords: playa surface crust; curly crusts; salt crusts; salt dust release; wind tunnel experiments; Qehan Lake

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1 Introduction

Lakes in arid and semi-arid regions have been affected by climate change and human activities in recent years, causing water bodies to dry up and lakebeds to become exposed (Tao et al., 2015; Micklin, 2016; Chun et al., 2017; Zhang et al., 2019). Drying saline lakebeds (Buck et al., 2011; Goldstein et al., 2017) further develop into playas, which are unique desert landscapes in arid and semi-arid areas (Peterson, 1980; Briere, 2000; Yechieli and Wood, 2002; Wurtsbaugh et al., 2017). Playa surfaces are often fluffy and highly vulnerable to wind erosion. During wind erosion events, dust may be transported over long distances, affecting the ecological environment of surrounding areas (Blank et al., 1999; Reynolds et al., 2007; Liu et al., 2011a; Zlotnik et al., 2012; White et al., 2015). Examples include Ebinur Lake in China (Liu et al., 2011b), the Aral Sea in Central Asia (Micklin, 2016), Sevier Dry Lake in the USA (Hahnenberger and Perry, 2015), and Lake Urmia in Iran (Mardi et al., 2018). The dust emitted by playas contains high concentrations of hazardous chemicals (heavy metals, salt ions, etc.) that might infiltrate the human body via air circulation and negatively impact health. Therefore, clarifying the dynamics of dust emissions from playa surfaces and their influencing factors is necessary to alleviate this environmental problem.

Soil crusts can be divided into physical and biological categories based on their formation mechanisms (Pagliai and Stoops, 2010). Playas are characterized by surface crusts that vary with weather and climate, and their morphology changes with surface temperature and soil moisture over time (Nield et al., 2015, 2016a). Crusts increase as the surface dries and cracks, affecting surface morphology (Valentin and Bresson, 1992). Playa surface crusts are sensitive to the surrounding environment and show rapid changes, especially during seasonal transitions (Nield et al., 2015). As crusts develop, surface aerodynamic properties change, which profoundly affects the emission of dust containing salt (salt dust hereafter). Therefore, quantifying surface crusts is essential for studying salt dust. Salt dust emission in playas is strongly influenced by surface soil moisture and crust types (Reynolds et al., 2007). Both high-frequency temporal dynamic changes and spatial distribution differences in surface crust morphology control the salt dust release potential (Nield et al., 2016b). The relationship between the physical and chemical characteristics of playa surface crusts, especially the type and form of salt crusts that affect wind erosion potential, is rather complex (Nield et al., 2016a). Factors affecting wind erosion resistance of surface crusts may include precipitation, temperature, soil texture, soil organic matter, salt type and structure, soil electrical conductivity (EC), and calcium carbonate equivalents (Sweeney et al., 2011; Nield et al., 2016a; Goldstein et al., 2017;

Motaghi et al., 2020).

Playa surface crusts have various forms, such as smooth crusts, weak botryoidal crusts, polygon crusts, and smooth salt crusts (Chico, 1968). Crust types have yet to be thoroughly investigated because playa surface crust characteristics differ across geographical areas. A systematic classification study of playa surface crust types is necessary to better quantify the effects of crustal properties on salt dust release. Cahill et al. (1996) revealed that stable salt-silt-clay crusts can form on the surface of Owen Lake, USA; polygonal crusts can then form after lake degradation, and salt dust can be further generated through the saltation-abrasion process. Different playa surface crust types exhibit heterogeneity and may show differences in dust release potential. Sweeney et al. (2011) investigated dust release from desert landscapes in the eastern Mojave Desert, USA, and found that the strongest dust release occurs at sandy playa margins. Motaghi et al. (2020) classified playa surface crust types into four categories: clay flats, clay flats-salt crusts, salt crusts, and salt crusts-clay flats. They calculated soil erodibility fractions for comparison and revealed that salt crusts are more stable and less susceptible to erosion. Contradictory to these results, a previous study showed that playas with sand-salt crusts are the most unstable type and prone to salt dust storms (Alkhayer et al., 2019).

In this study, we explored the characteristics and spatial distribution of soil crust properties of playa surface crusts in Qehan Lake, Inner Mongolia Autonomous Region of China through field investigation, and determined the salt dust release potential of major crust types through wind tunnel experiments. The main objectives are (1) to clarify the classification and spatial patterns of playa surface crusts and explain their causes; (2) to investigate which types of crusts are more prone to release salt dust; and (3) to investigate the effects of salt, water content, and soil texture on salt dust release. The results from this study may provide scientific reference to clarify the formation and evolution of surface crusts in playas and understand the situation of salt dust release for rational planning of ecological restoration projects in Qehan Lake.

2.1 Study Area

Qehan Lake (43°52′–43°58′N, 114°46′–115°02′E) is located in the southwest of Abag Banner, Xilin Gol League, Inner Mongolia Autonomous Region of China. The lake extends from southwest to northeast and is divided into two parts by an artificial dam, namely East Qehan Lake and West Qehan Lake (Fig. 1a [Figure 1: see original paper]). East Qehan Lake has an area of 28.0 km^2 and a maximum water depth of 7.2 m, while West Qehan Lake has an area of 80.0 km^2 and has gradually dried up with increasingly exposed lakebed since the early 2000s. To the south of Qehan Lake is the Hunshandake Sandy Land, and to the north is the Abag Lava Plateau. The Abag Lava Plateau is rich in acid volcanic clastic rocks, sedimentary rocks, sandstone, sandy mudstone, glutenite, mudstone, and other easily eroded rocks that are highly susceptible to leaching. Two seasonal rivers, the Gogusty River and Engel River, flow into East Qehan

Lake and West Qehan Lake, respectively.

Influenced by the Siberian highlands, the area has a temperate continental climate characterized by cold, dry, and windy conditions. The average annual precipitation is about 280 mm, with approximately 70% occurring from June to August. Seasonal waterlogging depends mainly on rainfall (Chun et al., 2017). Since the area is generally dry, potential evaporation is much greater than precipitation. Frequent windy weather, with wind speeds up to 15.0 m/s, affects the playa surface as it is highly vulnerable to wind erosion. Blowing salt dust often occurs over the playa surface (Fig. 1b). To solve this problem, *Suaeda glauca* was planted locally for ecological restoration and salt dust prevention. Salt dust is often captured in areas with normalized difference vegetation index (NDVI) values below 0.25, but this range is difficult to demarcate.

2.2 Soil Sampling and Processing

Measurement sites were marked along belt transects A (sites A1–A10), B (sites B1–B12), and C (sites C1–C12) (Fig. 1), with a total of 34 sampling sites. The geographical coordinates of each sampling site were recorded using a portable GPS (G120, UniStrong, Beijing, China) with an accuracy of 3.0 m. During field sampling, we found that crust distribution from the lakebed center to the lakeshore showed a zonal pattern, which facilitated investigation of crust regularity. Moreover, since no precipitation occurred during the sampling period, crusts did not change quickly enough to alter playa surface crust type. Soil crust thickness and hardness were measured on topsoil (0.00–10.00 cm) at each site using a vernier caliper with a precision of $±0.03mm(DL91300, DeliGroup, Ningbo, China)andapocketsoilpenetrometer(16−T0171, ZhuozhouTianpeng, Baoding, China), respectively.Measurementswererepeated10timesforeachsamp on July 7 and 8, 2019. Vertical downward pressure was applied to the pocket soil penetrometer at the sampling site to obtain a reading when the soil crust was broken. After that, one soil sample was collected at each sampling site using a soil auger, and a total of 34 soil samples were collected to measure soil water content, EC_1:$_5$ (the electrical conductivity of the upper clear layer for a soil-to-water ratio of 1:5), and soil particle size.

Soil water content was determined using the oven-drying method in the laboratory of the School of Ecology and Environment, Inner Mongolia University, Hohhot, China. Soil samples were air-dried in the laboratory for EC_1:$_5$ analysis. Specifically, the air-dried soil samples were passed through a 2 mm sieve, and approximately 50 g of soil was placed into a conical flask containing 250 mL of deionized water. The flask was then shaken mechanically for 30 min until soil salts were completely dissolved. After 24 h of resting, the supernatant was filtered using qualitative filter papers. The filtered clear liquid was controlled at 25°C, and EC_1:$_5$ was measured using a portable conductivity meter (Multi 3420, WTW, Weilheim, Germany). After natural air drying, 5 g of soil was added to a beaker and 10% H_2O_2 was added for heating reaction to remove organic matter, followed by the addition of 10% HCl for heating reaction to remove carbonate.

Additionally, 100 mL of deionized water was added and the supernatant was extracted after standing for 24 h. Finally, 2% sodium (hexa)metaphosphate was added as a dispersant, and soil particle composition was measured by a particle size analyzer (S3500, Microtrac MRB, Montgomeryville, USA) after shaking.

To investigate the effects of different playa surface crust types on salt dust release, we set five salinity class gradients for in situ soil sample collection using a soil three-parameter sensor (WET-2, Delta-T Devices, Cambridge, England) with three replicates per sampling site, resulting in a total of 15 soil samples for each site. In situ soil samples were collected in rectangular wooden boxes (50.00 cm × 30.00 cm × 10.00 cm), encapsulated in wooden boards, and wrapped in cling film and plastic on the outermost layer to reduce water evaporation. After encapsulation, the boxes were taken to the wind tunnel laboratory of Lanzhou University, Lanzhou, China, for further experiments.

2.3 Classification and Mapping of Playa Surface Crust Types

Combined with previous taxonomic studies on playa surface crusts, classification of the physical properties of soil crusts may effectively explain the impacts of playa surface crusts on salt dust release and help identify crust types that are more likely to release salt dust (Krinsley, 1970; Sweeney et al., 2011; Motaghi et al., 2020). According to Krinsley (1970), playa surface crusts can be categorized based on sediment surface features. Motaghi et al. (2020) also used this classification system and spatially mapped playa surface crust types of Lake Urmia in Iran with Landsat satellite image data and supervised classification algorithms. Thus, playa surface crusts in our study area can be classified and mapped using Sentinel-2 satellite images and supervised classification methods to clarify their spatial distribution characteristics. Sentinel-2 satellite images (mosaic function synthetic images from Google Earth Engine in 2019) were obtained (https://earthengine.google.com/), then classified and mapped with reference to sampling site location information from July 1 to 31. We classified playa surface crusts into salt crusts, clay flats, vegetated areas, curly crusts, and margins based on salt precipitation deposits, vegetation, compacted clays, and gravels (Krinsley, 1970; Sweeney et al., 2011; Motaghi et al., 2020). Due to the small size ($<100.0\ \mathrm{m}^2$) and fragmentation of curly crusts, their geographical distribution could not be clearly identified using satellite images.

2.4 Wind Tunnel Experiments

Salt dust release experiments were conducted in the wind tunnel laboratory of Lanzhou University, and the schematic diagram of the wind tunnel experiment is shown in Figure 2 [Figure 2: see original paper]. The detailed structure of the wind tunnel was described by Zhang et al. (2014). To simulate the real playa surface, we placed an artificial turf (length of 80.00 cm, width of 120.00 cm, and thickness of 1.00 cm) in front of soil samples in the wind tunnel experiments.

A groove (length of 50.00 cm and width of 30.00 cm) was constructed at the downwind axis of the wind tunnel section to facilitate placement of the soil sample box. The upper surface of the soil sample box was flushed with the wind tunnel surface to ensure experimental data accuracy, similar to the treatment described by Nield et al. (2016a). A sand collector was placed 20.00 cm behind the central axis of the soil sample box to measure horizontal dust flux; the collector consists of 14 rectangular sand collection ports (length of 4.00 cm and height of 1.50 cm) distributed along the vertical direction. The end of the sand collector was oriented downward at an angle of 30° to the horizontal dust flux to better collect soil particles into the bottom of the sand collector by gravity. The sand collector was weighed at the end of each wind tunnel experiment, and the horizontal dust flux was calculated. The wind tunnel rotors started at 6000 r/min and increased by 1000 r/min during each experiment for 180 s until the sand collector started to collect salt dust, and the sand collector was weighed before the speed was increased.

The soil samples in the wind tunnel experiments were divided into five groups (I, II, III, IV, and V, with mean $EC_1:_5$ values of 10.85, 7.21, 3.37, 2.30, and 8.70 mS/cm, respectively) and measurements were replicated three times for each soil sample. Wind velocity observed through the pitot tube can be converted into friction wind velocity (u*; m/s) using the logarithmic law of Prandtl-Karman (Prandtl, 1935):

$$u(z) = \frac{u*}{k} \ln\left(\frac{z}{z_0}\right)$$

where u(z) (m/s) is the wind velocity at height z (m) above the surface; k is the dimensionless von-Kármán constant with a universal value of 0.40; and z_0 (m) is the surface aerodynamic roughness.

2.5 Statistical Analysis

Pearson correlation coefficient was calculated using SPSS Statistics 26 (IBM, New York, USA) to analyze correlations among soil water content, $EC_1:_5$, crust hardness, and crust thickness. Bar graphs, box line plots, and scatter plots were illustrated using Origin 2022 (OriginLab, Northampton, Massachusetts, USA). The spatial distribution of playa surface crust types was plotted by ArcMap 10.8 (Esri, Redlands, USA).

3.1 Classification and Characterization of Playa Surface Crust Types

Figure 3 [Figure 3: see original paper] and Table 1 show the classification and characterization of playa surface crust types in the study area according to previous studies (Krinsley, 1970; Sweeney et al., 2011; Schoeneberger et al., 2012; Motaghi et al., 2020). The results indicated that the study area included five playa crust types: vegetated areas, salt crusts, clay flats, curly crusts, and margins. Compared to clay flats, the wider and deeper crustal cracks distributed in vegetated areas may be caused by higher silt particle content. Large cracks crossed two vertical horizons (trans-horizon cracks) on the surface of salt flats in vegetated areas, showing cracked crust with a depth greater than 3.00 cm overlying a compact unfractured silt deposit. The cracks themselves were mostly distributed nonlinearly, indicating many dry-wet cycles, and crack intersections were irregular (Tang et al., 2008; Goehring et al., 2010; Goehring, 2013). Vegetation growth in these areas may be attributed to a shallow water table that is conducive to plant growth. Salt crusts, clay flats, and curly crusts all exhibited reversible crust-related cracks, while vegetated areas were relatively more complex. The surface of salt crusts was smooth and enlarged, with salt crystal powder precipitating from evaporated salt around small cracks. Concave-up curling was the main feature of curly crusts that preferentially occurred around the perimeter of low-lying areas subject to microtopography, sometimes accompanied by ponding water. Margins were located at the edge of the playa surface, where sparse vegetation cover was insufficient to suppress salt dust phenomena when strong winds occurred.

3.2 Classification Statistics of Playa Surface Crust Types

Figure 4 [Figure 4: see original paper] shows differences in crust thickness, crust hardness, soil water content, and EC$_1$:$_5$ for each playa surface crust type. Crust thickness of vegetated areas, salt crusts, clay flats, and curly crusts mainly ranged between 0.50 and 0.70 cm, with higher values up to 1.00 cm or even larger in vegetated areas and salt crusts. In terms of crust hardness, salt crusts had the widest range of 0.30$\$\times10^{\{5\}-8.53\times10}\{5\}\$$ N/m^2. Vegetated areas had the greatest crust hardness values, while no significant difference in hardness was observed between clay flats and curly crusts. Curly crusts had similar hardness to other playa surface crust types that had been transformed by minerals into a horizontal “mat” or small polygonal plate. Regarding soil water content, four types were distributed from dry to wet (salt crusts, clay flats, curly crusts, and vegetated areas), with salt crusts and clay flats having lower moisture overall. The order of EC$_1$:$_5$ from high to low was as follows: salt crusts, clay flats, curly crusts, and vegetated areas. Salt crystals in salt crusts were the main source of EC in the topsoil. The EC$_1$:$_5$ of vegetated areas ranged from 1.00 to 3.50 mS/cm, indicating suitability for *Suaeda glauca* growth. Correlation results shown in Table 2 indicated a significant negative correlation between crust thickness and EC$_1$:$_5$ of the topsoil. Salt in the playa topsoil expanded the surface layer while decreasing the thickness of playa surface crusts, forming a thin, brittle crust containing salt sediments. This suggests that salt may be one of the main factors influencing surface crust thickness in Qehan Lake.

3.3 Spatial Distribution of Playa Surface Crust Types

Figure 5 [Figure 5: see original paper] shows the spatial distribution of playa surface crust types in Qehan Lake. A clear regularity was observed in this distribution, which can be summarized as vegetated areas, clay flats, salt crusts, and margins from the lake center to the lakeshore. Curly crusts were not mapped because of their small area and rarity on the playa surface.

Figures 6 and 7 indicate variations in crust thickness and hardness from the lake center to the lakeshore for the three belt transects (A, B, and C). Crust thickness showed no significant variation from the lake center to the lakeshore along belt transects A (except for A7), B, and C, and thickness was essentially the same but larger near the lakeshore (B11, B12, C11, and C12), as shown in Figure 6 [Figure 6: see original paper]. Crust thickness tended to increase from the lake center to the lakeshore and was more pronounced along belt transect C. Differences in crust thickness were primarily found at sampling sites located near the lakeshore (e.g., B11, B12, C11, and C12), which were mainly covered by smooth alluvium and large gravels. Crust thickness at these sites was relatively larger, ranging from 0.80 to 1.80 cm. A curly, thin crust was observed at site B4.

Crust hardness showed little change from the lake center to the lakeshore, as shown in Figure 7 [Figure 7: see original paper]. Therefore, we concluded that crust thickness was relatively uniform at sampling sites located in the lake basin, but crust hardness differed among sampling sites, similar to the results shown in Figure 4.

3.4 Relationship Between Crust Thickness and Hardness

As shown in Figure 8 [Figure 8: see original paper], a weak relationship existed between crust thickness and hardness. Crust hardness at sampling sites mainly ranged from 4.19$\times10^{5}$ to 8.91$\times10^{5}$ N/m^2, although hardness at A9, B12, and C10 was below 2.35$\times10^{5}$ N/m^2. The playa surface crust type of A9 and C10 was classified as salt crusts, and salt crust expansion might have contributed to their low hardness. Site B12 was classified as margins, located on the lakeshore with smaller hardness due to sandy soil. In terms of thickness, crust thickness at most sampling sites ranged between 0.40 and 0.90 cm, while thickness at sites A7, B11, C11, and C12 was larger than 1.00 cm. Sampling site A7 was identified as clay flats, and sites B11, C11, and C12 were margins. Excluding outliers, crust thickness showed a linear relationship with crust hardness.

3.5 Characteristics of Soil Samples for Wind Tunnel Experiments

EC$_{1:5}$, crust thickness, and soil water content of the five soil sample groups (I, II, III, IV, and V) were measured in the wind tunnel experiments (Fig. 9

[Figure 9: see original paper]). Crust thickness was highest in group III, while the difference in crust thickness was minimal for the other four groups. Soil water content also showed good gradient variation from high to low in the order of II, I, IV, V, and III. Specifically, soil water content was lowest for group III, and the difference within the group was not significant, mainly because of its high sand content and poor water retention capacity.

The physical properties of soil samples used in the wind tunnel experiments are shown in Table 3 . Good variety existed among soil samples in different groups based on sand or silt particle size. Sand particles of the five groups were sorted in ascending order as I, IV, II, V, and III, while silt particles were sorted in descending order as I, IV, II, V, and III. The soil texture category contained four types: silty loam (I1, I2, and I3), sandy loam (II2, IV1, IV2, and IV3), loamy sand (II1, II3, III1, V2, and V3), and sand (III2, III3, and V1), where 1, 2, and 3 represent the number of repeated samples in the wind tunnel experiments. The low silt and clay content of soil samples from clay flats used in the wind tunnel experiments might be because the samples used for particle size testing were collected at the end of the wind tunnel experiments, resulting in a relative increase in the size of fine particles blown away from surface crusts. The particle size distribution of clay flats from other sampling sites (Fig. S1) indicated that the soil texture of clay flats was silt with particle sizes ranging from 2 to 50 μm.

3.6 Horizontal Dust Flux

Figure 10 [Figure 10: see original paper] shows variation in horizontal dust flux with u* calculated from the sand collectors in the wind tunnel experiments. The horizontal dust flux of each soil group exhibited an exponential relationship with u. *The horizontal dust flux corresponding to the lowest u* was indicative of wind erosion resistance of soil samples. During the wind tunnel experiments, soil particles could be captured at u* of 0.6 m/s for groups I, II, and V, while for groups III and IV, soil particles could be collected at u* of 0.7 m/s. This indicated that crust-type clay flats (groups III and IV) had higher wind erosion resistance than salt crusts (groups I, II, and V). It is worth noting that for groups III2 and V3, after initial salt dust release, the horizontal dust flux decreased first and then increased exponentially, while groups II2 and IV3 showed a sudden increase in horizontal dust flux, both of which may be related to instantaneous destruction of soil crusts.

4.1 Spatial Patterns and Evolution of Playa Surface Crusts in Qehan Lake

Studying the taxonomy of lakebed (dry) crusts in different regions helps us understand crust formation mechanisms. In this study, playa surface crust types in dried Qehan Lake were classified into vegetated areas, salt crusts, clay flats, curly crusts, and margins. The surface type of West Qehan Lake showed a regular pattern from the lakeshore to the lake center, with outer margins surrounding the playa. This regular distribution pattern was also reflected in soil texture, as margins contained more coarse sands and gravels than the central area, indicating that hydrological processes would be the leading cause of sediment siltation. Margin formation is mainly dominated by surface runoff, resulting in coarser soil texture at surrounding zones away from the lake center, including sediments and gravels brought by runoff (Sweeney et al., 2011). When sediments are deposited into the playa due to water erosion, coarse sands with large gravels are deposited before fine particles (Luo et al., 1999). The higher crust hardness of margins may be due to gravels being filled with silt particles that act as cement, forming a concrete-like structure that increases crust hardness. The lack of interaction with groundwater and the coarse soil texture in this area result in poor water retention, further leading to low water content in the surface soil.

In Qehan Lake, salt crusts were mainly found in regions between playa margins and clay flats or vegetated areas, similar to results of Gutiérrez-Elorza et al. (2005) for the playa in the central-southern sector of the Duero Depression in Spain. It is generally accepted that the source of soil salinity is related to groundwater, and salt is deposited on the surface by capillary forces and intense evaporation (Hassani et al., 2021). The hydrodynamics of the lakeshore are likely the reason for salt crusts close to playa margins and the small area of the lake center. During precipitation events, surface water flows from the lakeshore into the lake center, but the flat lakebed cannot sustain responsive dynamics. The flowing water that erodes the lakeshore and external soil containing soluble salts infiltrates the bottom near the lakeshore as it cannot continue to flow toward the lake center, resulting in salt crust formation by raising the shallow water table in the zone between playa margins and vegetated areas (Luo et al., 1999; Zlotnik et al., 2012). The salt crusts of Qehan Lake mainly consist of soda salts, which are susceptible to deliquescence and moisture absorption, leading to a highly moist surface (Xisarula, 2011). The high level of sodium ions reduces soil particle binding, and fine-grained soil expands and disperses. This causes salt analysis to show heterogeneity, making the hardness range of salt crusts greater than that of other playa surface crust types. The surface crust of playas formed by the drying of extremely saline salt lakes may contain more salts, forming hard salt crusts with resistance to wind erosion (Nield et al., 2016a; Motaghi et al., 2020). Two possible reasons exist for the significant negative correlation between crust thickness and $EC_1:_5$ (salinity) in this study. First, soda salts lead to fluffy soil and reduce crust thickness; and second, the salt content is not enough to form a pure thick salt crust, but it is still higher compared to other playa surface crust types.

Vegetated areas were near the lake center (i.e., far from the lakeshore) and dominated by silty loamy soils, where fine soil particles tend to form reversible trans-horizon cracks under strong evaporation. Vegetated areas grown with *Suaeda glauca* can inhibit salt dust release production (Zhao et al., 2011). In this study, vegetated areas had dense growth of *Suaeda glauca* with root soils characterized by large mud cracks, which differed from other playa surface crust types, suggesting that vegetation growth may contribute to formation of large mud cracks. Large cracks in vegetated areas can facilitate preservation of alkali poncho seeds without being blown away, while reversible crust-related cracks in other playa surface crust types are less capable of preserving vegetation seeds.

The smooth surface of clay flats is sometimes accompanied by reversible crust-related cracks, although the available groundwater table is deeper than 2.0 m. Therefore, crust formation may ignore the influence of groundwater-soluble salts and mainly consider soil texture and evaporation conditions. Clay flats of Qehan Lake are mainly composed of sandy and silty loam involved in the formation process, similar to many other playas worldwide (Sweeney et al., 2011; Sweeney et al., 2016; Goldstein et al., 2017; Motaghi et al., 2020).

Curly crusts mainly appeared in low-lying areas of the lake basin and had relatively high humidity. A thin, high silt-content sedimentary layer temporarily formed at the bottom of turbid puddles, and the thin layer curled after rapid dehydration. The concave-up curling might be explained by the non-uniform distribution of horizontal forces generated by capillary force development (Tran et al., 2019). Mud curls are fragile and easily broken, thus providing base materials for salt dust transport (Stout, 2007).

4.2 Sand Dust Release from Different Playa Surface Crust Types

Generally, sand-sized sediments occurring in dry lakebeds are supplied by adjacent dunes or post-flood deposits that release salt dust from compacted clay or silt into the atmosphere and produce additional fine particles through leapfrog impact and creep abrasion processes (Gomes et al., 1990; Stout, 2003). Cahill et al. (1996) focused on crusted playa surfaces and regions of loose and coarse detrital particles (sand and dunes) in Owen (dry) Lake, USA, where salt dust was observed. Similarly, these areas existed in the Qehan Lake we studied. Coarse detrital particles appeared in the area near the lake center along belt transect C that lacks vegetation and is easily exposed to salt dust release. These coarse detrital particles were located at the junction of the lakebed and lakeshore in Qehan Lake. Sand-bearing sediments released salt dust from consolidated or compacted clay and/or silt into the atmosphere. These coarse detrital particles can cause discharge of fine dust particles from the lakebed and generate more fine dust by wind and sand abrasion. Nearby sand sources or deposition of fine sand after floods might also supply coarse detrital particles to the bottom of ephemeral lakes (Bullard et al., 2020).

Wind tunnel experiment results indicated that salt dust release from clay flats could only occur at higher u. *In nature, salt dust release may be mainly caused by human activities that destabilize surface structure or salt dust impact (Gill, 1996; Houser and Nickling, 2001; Reynolds et al., 2007). The impact of jumping sand grains on playa surface crusts can disintegrate fine or clay-sized particles from the surface (Gillett, 1979) or from the sand grains of saltation themselves*

(Krinsley and Doornkamp, 1973). Wind tunnel experiments conducted by Zhang et al. (2016) also showed that surface renewal through saltation and soil creep is important in limiting salt dust supply. However, in this study, the wind tunnel experimental conditions lacked the process of sand grain leap, which may increase the initial threshold of u for salt dust release. Our wind tunnel results showed a threshold of about 0.7–0.8 m/s for salt dust release occurring on clay flats, higher than that for salt dust release occurring on salt crusts (0.5–0.6 m/s). Similar results were observed by Sweeney et al. (2011) at the playa site in the Mojave Desert, which was interpreted as clay flat crusts having higher particle cohesion. However, the study of Motaghi et al. (2020) in Lake Urmia in Iran showed that the presence of a thin layer of crystalline halite on the salt crust surface, along with permanent shallow surface water and increased soil clay content, makes this crust type more stable and resistant to wind erosion than other playa surface crust types. Although salt crusts have an inhibitory effect on salt dust release, they become more fragile and more likely to break under continuous drought conditions and increasing aerosol concentrations (Borlina and Rennó, 2017). In addition to the protective mechanism of salt crusts, the thicker crusts of clay flats may also play a role in inhibiting salt dust release. The thick crusts formed by clay soil particles indicate stronger aggregation of soil particles, suggesting that the salt dust release process in clay flats is mainly influenced by the impact of leaping particles. In the wind tunnel experiments, large sand particle-containing clay flats produced thick crusts that were more stable (higher u*) than salt crusts. This may be explained by the fact that crust stability is increased by prolonged dry periods, while particle size may indirectly impact crust thickness. The soil water content of the wet soil layer limits salt dust release at a very low level since salt dust release increases after evaporation, so soil thickness becomes the main limiting factor; however, both will be dominated by saltation episodes and soil agglomerate fragmentation (Huang and Gu, 2009; Dun, 2019). Our results indicated that clay flats are more prevalent when fine dust is produced by particle abrasion, and heavy pulverization of particles is released from the crust surface. Therefore, under natural conditions, the threshold value of u* for salt dust release may be lower than that in wind tunnel experiments. We found that the initiation threshold value of u* for salt dust release in Qehan Lake was higher than the threshold (0.2–0.6 m/s) reported by Nield et al. (2016a) for soil samples taken from the Botswana Sua Pan in a wind tunnel laboratory at Trent University, Canada. A possible reason for this was the use of sand collectors in this study, which could not capture fine particles such as PM_{10}. However, our results are consistent with those of Sweeney et al. (2016), who demonstrated threshold values of u* in the range from 0.4 to 0.9 m/s and emission fluxes lower than 0.05 g/(m$\cdot$s) for salt dust emission measurements using the portable in-situ wind erosion laboratory (PI-SWERL) during the drought period in the Yellow Lake Playa of West Texas, USA.

5 Conclusions

Through a field survey of Qehan Lake in Inner Mongolia, China, we discovered that playa surface crust types could be classified into five categories (vegetated areas, clay flats, salt crusts, curly crusts, and margins), which showed a belt-like distribution around the lake. The order from the outside to the inside of the lake was margins, salt crusts, clay flats, and vegetated areas, while curly crusts were distributed in small areas within clay flats. This regular spatial distribution pattern was mainly controlled by playa hydrodynamics, soil texture, and shallow groundwater.

Crust thickness tended to increase from the lake center to the lakeshore and was more pronounced along belt transect C. Results also showed that crust thickness had a linear relationship with crust hardness when outliers were excluded. Therefore, crust thickness and hardness were good indicators for classification of playa surface crust types in the study area.

A significant negative correlation was observed between crust thickness and $EC_{1:5}$. Wind tunnel experiments showed that the initiation threshold of friction wind velocity (u*) for salt dust release was higher in clay flats (0.7–0.8 m/s) than in salt crusts (0.5–0.6 m/s). Thick crusts created by clay flats containing larger sand particles were more stable than those created by salt crusts. Salinity was the main factor controlling the difference in initiation threshold of u** for salt dust release between clay flats and salt crusts.

The main limitation of this study is that experiments were only conducted in wind tunnels rather than under natural conditions. Although we simulated outdoor and indoor conditions as much as possible when designing the experiments, the use of convenient on-site dust emission measurement systems (e.g., PI-SWERL) is recommended in future studies.

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Appendix

Fig. S1 Particle size distribution of soil samples belonging to clay flats that were not used in the wind tunnel experiments

Note: Figure translations are in progress. See original paper for figures.