Contribution of underlying terrain to sand dunes: evidence from the Qaidam Basin, Northwest China Postprint

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Date: 2021-12-30T18:39:24+00:00

Abstract

Underlying terrain strongly influences dune formation. However, the impacts of underlying terrain on the dune formation are poorly studied. In the present research, we focused on dunes that formed in the alluvial fans and dry salt flats in the Qaidam Basin, Northwest China. We quantified the dunes' sediment characteristics on different types of underlying terrain and the terrain' effects on the surface quartz grains by analyzing grain-size distribution, soluble salt contents and grain surface micro-textures. Results showed that barchan dunes were dominated by medium sands with a unimodal frequency distribution, whose peak corresponded to the saltation load. Linear dunes were mainly composed of fine sands with a bimodal frequency distribution, whose main peak represented the saltation load, and whose secondary peak represented the modified saltation or suspension load. Sand was transported from source area by running water (inland rivers) over short distances and by wind over relatively longer distances. Thus, quartz grains had poor roundness and were dominated by sub-angular and angular shapes. Surface micro-textures indicated that dune sands were successively transported by exogenic agents (glaciation, fluviation and wind). Soluble salt contents were low in dunes that developed in the alluvial fans, which represented a low-energy chemical environment, so the grain surface micro-textures mainly resulted from mechanical erosion, with weak micro-textures formed by SiO2 solution and precipitation. However, soluble salt contents were much higher in dunes that developed in the dry salt flats, which indicated a high-energy chemical environment. Therefore, in addition to micro-structures caused by mechanical erosion, micro-textures formed by SiO2 solution and precipitation also well developed. Our results improve understanding of the sediment characteristics of dune sands and the effects of underlying terrain on dune development in the Qaidam Basin, China.

Full Text

Preamble

Contribution of underlying terrain to sand dunes: evidence from the Qaidam Basin, Northwest China

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Abstract

Underlying terrain strongly influences dune formation, yet its impacts remain poorly understood. This research investigated dunes formed on alluvial fans and dry salt flats in the Qaidam Basin, Northwest China, by quantifying sediment characteristics across different terrain types and analyzing their effects on surface quartz grains through grain-size distribution, soluble salt content, and grain surface micro-texture analysis. Barchan dunes were dominated by medium sands with a unimodal frequency distribution whose peak corresponded to the saltation load, whereas linear dunes consisted mainly of fine sands with a bimodal distribution whose main peak represented saltation load and secondary peak represented modified saltation or suspension load. Sand was transported from source areas by running water (inland rivers) over short distances and by wind over relatively longer distances, resulting in quartz grains with poor roundness dominated by sub-angular and angular shapes. Surface micro-textures indicated successive transport by exogenic agents (glaciation, fluviation, and wind). Soluble salt contents were low in dunes developed on alluvial fans, representing a low-energy chemical environment where grain surface micro-textures resulted primarily from mechanical erosion with weak features formed by SiO_2 solution and precipitation. In contrast, dunes on dry salt flats exhibited much higher soluble salt contents, indicating a high-energy chemical environment where micro-textures from mechanical erosion coexisted with well-developed features from SiO_2 solution and precipitation. These results improve understanding of dune sand sediment characteristics and terrain effects on dune development in the Qaidam Basin.

Keywords: dune; grain-size distribution; soluble salts; surface micro-texture; Qaidam Basin

Introduction

Sandy deserts are primarily located in hyper-arid and arid regions worldwide, as well as in some coastal areas. They represent regional depositional centers for sediments and contain diverse types and scales of sand dunes, extensive sand sheets, and wide inter-dune areas (Lancaster, 2013). Regional sand transport systems consist of three components: sand source areas, transport pathways, and depositional sinks (Lancaster et al., 2015). The main factors controlling these components include sand supply, availability of erodible surface sand, and wind transport capacity (Kocurek and Lancaster, 1999). Regional aeolian landform studies demonstrate not only the morpho-dynamic processes controlling different dune types (Dong et al., 2004, 2010) but also clarify dune sediment characteristics to reveal provenance and transport pathways (Muhs et al., 2003; Li et al., 2015; Qian et al., 2020).

These issues have been primarily addressed by comparing the mineral and chemical element composition of dune sands with surface sediments from potential source areas, an approach successfully applied in desert provenance studies globally (Xu et al., 2010; Scheidt et al., 2011; Garzanti et al., 2013; Hu and Yang, 2016; Zhang et al., 2020). These studies indicate that clastic materials are produced by weathering and denudation, with fluvial, alluvial, and lacustrine sediments providing material for sandy desert formation (Wu, 2010). However, the effects of exogenic agents beyond water and wind during sand transport from source areas to sinks, as well as the influence of underlying terrain on dune sand formation processes, require further clarification.

The Qaidam Basin desert is China' s sixth-largest desert and the highest in elevation, featuring extensive wind erosional and depositional landforms (Zhu et al., 1980). Simple and sporadic dunes dominate the landscape, though their provenance and dominant transport pathways remain poorly understood. Aeolian sands are mainly composed of quartz and feldspar, with quartz grains being most resistant to physical and chemical alteration. Feldspar is softer and more vulnerable to erosion, and its decreasing content provides evidence of post-formation sediment evolution. Consequently, quartz sand grains preserve abundant information about their sedimentary environment (Bristow and Livingstone, 2019). Aeolian sands are crucial for understanding Quaternary paleogeographic evolution in the Qaidam Basin, particularly since the Last Glacial Maximum (Zeng et al., 2003; Yu and Lai, 2014; Yu et al., 2015).

Chen and Lü (1959) proposed that Qaidam Basin aeolian sands originated from the Tarim Basin, though this lacked subsequent experimental confirmation. Recent research suggests dune sand mineral assemblages result from transport of piedmont alluvial-diluvial deposits from surrounding mountains and exposed lacustrine sediments following Qarhan Salt Lake desiccation (Bao and Dong, 2015). Du et al. (2018) found through geochemical analysis of different grain-size fractions that coarse components (75–500 m) derived from local fluvial and alluvial-diluvial deposits, while fine components (<75 m) came from the Tarim Basin. Li et al. (2018, 2020) determined that both gobi surface sediments and yardang corridor sands could supply material for linear dunes on the northern Qarhan Salt Lake margin, with these sands originating from granite and granodiorite in the Qilian Mountains. However, few studies have examined quartz sand grain surface micro-textures as evidence of provenance and transport pathways

(Dong et al., 2017a).

Linear and barchan dunes are the most common types in the Qaidam Basin, with linear dunes primarily found in dry salt flats around Qarhan Salt Lake and barchan dunes mostly in alluvial fans along piedmont zones (Zhang et al., 2018). Building on previous research, this study focused on linear and barchan dunes developed on different underlying terrain (salt flats vs. alluvial fans) in the Qaidam Basin, analyzing sedimentary characteristics (grain-size, soluble salt content, roundness, and surface micro-texture) of quartz sand grains. Feldspar particles were excluded due to their vulnerability to physical and chemical erosion, which makes them unreliable for provenance tracing. We compared sedimentary characteristics between dunes on salt flats and alluvial fans and discuss how underlying terrain influences these aeolian sands.

2.1 Study Area

The Qaidam Basin is the largest intermontane fault basin on the northeastern Tibetan Plateau, encircled by the Kunlun Mountains to the south and west, the Altun Mountains to the northwest, and the Qilian Mountains to the northeast (Fig. 1). Surrounding mountains range from 4000 to 5000 m a.s.l., while the basin floor averages 2800 m a.s.l. across an area of 12×10^{4} km^2. As a typical endorheic basin, it features a convergent drainage system with rivers originating in surrounding mountains and feeding saline lakes in the central-southern basin. The basin contains China' s highest elevation and largest yardang field in its northwestern region (Li et al., 2016). Climate is hyper-arid, with mean annual precipitation ranging from 100 mm in the southeast to less than 20 mm in the northwest, and mean annual potential evaporation exceeding precipitation by more than 100 times (Han et al., 2014). Sand and dust storms occur frequently from March to May, with a frequency of 40 d/a under prevailing northerly and northwesterly winds (Yu and Lai, 2012).

Aeolian landforms cover up to 3.4×10^{4} km^2 in the Qaidam Basin, with depositional landforms covering 1.3×10^{4} km^2 and erosional landforms covering 2.1×10^{4} km^2 (Dong et al., 2017b). Dunes have developed on two main underlying terrain types. The first comprises alluvial fans, particularly in the Qimantagh Mountains piedmont (Fig. 1), where barchan and barchan chain dunes dominate, reaching 5–10 m in height and migrating 20 m/a in the prevailing wind direction (Zhu et al., 1980). The second comprises dry salt flats surrounding Qarhan Salt Lake, dominated by linear dunes up to 30 m high (Zhou et al., 2012). These linear dunes are more stable than barchans, with elongation rates of 4–10 m/a (Qian, 1986).

2.2 Methods

Based on differences between the two terrain types, we studied barchan dunes (BD01 and BD02) on north-slope alluvial fans of the Lvliang Mountains and linear dunes (LD01–LD03) plus one barchan dune (BD03) on salt flats around

Qarhan Salt Lake (Fig. 2). Surface sediment samples were collected from barchan crests (Fig. 3a) and from linear dunes along topographic transects perpendicular to dune orientation at four positions: base of SSW (south-southwest) slope, crest, base of NNE (north-northeast) slope, and inter-dune area (Fig. 3b). A total of 15 samples were collected: one crest sample per barchan site and four samples per linear dune site.

Each sample comprised surface sediments from a 20 cm$×$20 cm area to a depth of 2 cm, weighing approximately 500 g. Grain-size distribution was analyzed using a Malvern Mastersizer 2000 at Shaanxi Normal University. Grain-size parameters included mean grain-size (Mz, ϕ), sorting (σI), skewness (SKI), and kurtosis (Kg), calculated graphically using Folk and Ward (1957) methods. Soluble salt content was determined from dried residue mass. Quartz sand grain surface micro-textures were examined using a Mineral Liberation Analyzer (MLA 650, FEI Company), with a total of 476 quartz sand grains observed for roundness and surface micro-textures across all 15 samples. Roundness was determined following Powers (1953), and surface micro-textures were interpreted using Krinsley and Doornkamp (1973) and Xie (1984).

3.1.1 Grain-Size Distribution

Grain-size distribution is affected by both sand source and subsequent transport and deposition processes. Contents of different grain-size fractions varied greatly among dune and inter-dune deposits and between dune types (Table 1). Dune surface sediments were dominated by fine and medium sands, averaging 30.49% and 28.05% respectively, compared to 15.33% and 11.46% for coarse and very fine sands. Inter-dune sediments between linear dunes were dominated by silt (28.35% average), followed by similar fine (18.25%) and very fine sand (17.60%) contents. Barchan dunes showed the highest medium sand content (59.32% average), with fine and coarse sands averaging 28.26% and 11.36% respectively. Linear dunes had the highest fine sand content (31.24% average), followed by medium sand (17.63%), with similar coarse and very fine sand contents (16.66% and 15.15% respectively).

3.1.2 Frequency Curves

Frequency curves for the two barchan dunes (BD01 and BD02) on Lvliang Mountains alluvial fans showed unimodal distributions with main peaks between 200 and 300 m (Fig. 4). Their cumulative frequency curves exhibited a single segment representing saltation load (particles between 100 and 500 m). In contrast, the third barchan dune (BD03) on dry salt flats in the Sebei area showed a bimodal distribution with a main peak between 300 and 500 m and a secondary peak between 40 and 60 m forming a fine tail. Its cumulative curve displayed two segments representing modified saltation load (63–100 m) and saltation load, with the boundary near 120 m.

Linear dune grain-size distribution curves varied greatly by position. Crest sediments showed clear bimodal distributions with main peaks between 100 and 200 m (saltation load) and secondary peaks between 10 and 20 m (suspension load), the latter forming a fine tail similar to BD03. Their cumulative curves included two segments: a gentle slope for suspension load and a steep slope for saltation load. Toe-of-slope sediments also exhibited bimodal distributions, but with main peaks between 200 and 500 m (saltation load) and secondary peaks between 20 and 100 m (suspension/modified saltation load). Their cumulative curves similarly consisted of two segments, though suspension and modified saltation loads were mixed. Inter-dune sediment curves were more complex, with wider, flatter frequency curves showing obvious bimodal distributions. Most cumulative curves included two segments, but boundaries among suspension, modified saltation, and saltation loads were ambiguous, indicating poor sorting (Fig. 4).

3.1.3 Grain-Size Parameters

Relationships between Mz and other parameters differed among dune types and sample positions (Fig. 5). As Mz coarsened for dune surface sediments, σI gradually increased and SKI shifted from strongly positively skewed to nearly symmetrical, while Kg showed no clear trend. Sorting was strongest for barchan dunes on alluvial fans, followed by barchan dunes on dry salt flats, with linear dunes showing the poorest sorting. Grain-size frequency curves for barchan dunes and the SSW slope sample of linear dune LD03 were nearly symmetrical, while other sediments showed positively skewed distributions with fine tails, particularly for LD01, possibly influenced by underlying terrain.

3.2 Soluble Salt Content

Soluble salt contents showed striking contrasts between the two terrain types (Table 1). Barchan dunes on Lvliang Mountains alluvial fans ranged from 0.03% to 0.13%, while the barchan dune on dry salt flats near Sebei reached 0.90%. Linear dunes exhibited much higher values: 5.09%–10.83% at LD01, 0.65%–18.39% at LD02, and 0.65%–7.92% at LD03. Salt content also varied by position: 0.65%–9.14% at toes, 1.42%–5.09% at crests, and 7.92%–18.39% in inter-dune areas. Inter-dune areas had the highest salt contents, followed by crests, with slope toes lowest—attributable to higher coarse grain content at toes having lower surface area and thus holding less salt.

Soluble salts bind silt and clay particles, increasing sediment cohesion, so underlying terrain salt content may control dune development through cohesion effects. Figure 6 shows the relationship between sand content and total silt, clay, and salt content. For barchan dunes, total silt, clay, and salt ranged from 0.03% to 1.81% (mean 0.65%). Linear dunes ranged widely from 1.53% to 39.70% (mean 13.85%), with inter-dune sediments highest at 34.42%–57.77% (mean 49.48%). A strong, statistically significant negative relationship existed between sand content and total silt, clay, and salt content.

3.3.1 Roundness

Quartz sand grain roundness provides abundant information about exogenic agents and transport distance. We classified roundness as rounded, sub-rounded, sub-angular, and angular. Rounded and sub-rounded grains typically indicate long-distance transport or strong hydrodynamic forces, as repeated impacts remove angular features. Sub-angular and angular grains retaining some angular features suggest short-distance transport, weak hydrodynamic forces, or glacial shaping. Aeolian quartz grains are usually well-rounded, while aqueous grains show medium to slight roundness, and glacial grains have the poorest roundness.

Dune sands exhibited poor roundness, dominated by sub-angular and angular grains with relatively low sub-rounded and rounded contents (Table 2). Barchan crests averaged 41.27% sub-angular, 38.37% sub-rounded, 10.32% angular, and 10.05% rounded grains. Linear dunes averaged 42.23% sub-angular, 28.45% angular, 24.88% sub-rounded, and only 4.45% rounded grains. Inter-dune sediments showed the poorest roundness, with angular and sub-angular grains totaling 80.75% and sub-rounded and rounded grains only 19.25%.

3.3.2 Surface Micro-Textures

Surface micro-textures on quartz sand grains reveal sedimentary history and transport agents. Aeolian environments produce crescent- and dish-shaped depressions, pockmarked pits, and upturned cleavage plates. Glacial environments develop conchoidal fractures, cleavage planes, striations, and impact pits. Subaqueous environments create polished surfaces with V-shaped depressions and straight or bent impact grooves. Chemical environments (with strong chemical reactions) form solution and precipitation structures: strong SiO_2 solution creates pits, grooves, and scaly exfoliation, while SiO_2 precipitation forms siliceous spheres, scales, films, or botryoidal precipitates (Table 3; Fig. 7).

Scanning electron micrograph analysis revealed all micro-textures from mechanical transport by glacial, fluvial, and aeolian forces, plus SiO_2 solution and precipitation effects (Fig. 7). However, specific micro-texture combinations and frequencies varied greatly among environments and dune types (Fig. 8). Barchan dunes (BD01 and BD02) on Lvliang Mountains alluvial fans were dominated by aeolian transport micro-textures, with high frequencies of crescent- and dish-shaped depressions. Glacial and fluvial micro-textures were second most frequent, while chemical environment features were less common. This indicates that piedmont alluvial sediments were transported by glacial and fluvial forces, then deposited at mountain slopes and transformed into barchan dunes under wind influence.

In the Sebei area, V-shaped depressions and subaqueous polished surfaces from fluvial transport were most common, though typical aeolian micro-textures like dish- and crescent-shaped depressions also occurred frequently, indicating strong aeolian activity. Chemical environment micro-textures were better developed than in alluvial fan barchans, suggesting these quartz grains experienced a warmer paleoclimate. Thus, Sebei barchan sands likely underwent short-distance glacial transport, then long-distance transport by strong hydrodynamic forces, followed by strong aeolian transport combined with chemical etching and precipitation due to the area' s windy climate and high soluble salt content in underlying terrain.

Linear dunes contained particles with all surface micro-textures from glacial, fluvial, aeolian, and chemical forces, but chemical micro-texture frequency was much higher than in barchan dunes (Fig. 8), attributed to their proximity to Qarhan Salt Lake. At LD01, aeolian micro-textures (crescent- and dish-shaped depressions) accounted for 40.97% of the total, followed by fluvial features (V-shaped depressions and straight impact grooves) at 29.60%. Chemical and glacial micro-textures totaled 15.87% and 13.56% respectively. LD02 showed higher aeolian micro-texture frequencies than other sites, attributed to longer wind transport distances. LD03 showed higher chemical process frequencies than other sediments due to its location on the Qarhan Salt Lake northern margin (Fig. 2). Spring snowmelt can expand lake area into inter-dune zones (Fig. 9), concentrating soluble salts at former dry salt flat surfaces through capillary action and causing strong chemical etching and precipitation in nearby dune sands. Fluvial micro-texture frequency was slightly higher than at other sites, suggesting linear dune sands were first transported into the basin by glacial and fluvial processes, then moved by wind to their current salt flat locations where chemical etching and precipitation occurred.

4.1 Influence of Underlying Terrain on Dune Development

Aeolian dune formation and development are influenced by local wind regime, sand supply, and underlying terrain (Pye and Tsoar, 2009). The Qaidam Basin is a closed inland fault basin dominated by northerly and northwesterly winds. Linear and barchan dunes in the Sebei area developed under a broad unimodal wind regime (Li et al., 2020), while barchan dunes in the Lvliang Mountains piedmont were mainly influenced by northwesterly winds (Fig. 3a). These dune types coexist on the western Qarhan Salt Lake margin (Lü et al., 2018), indicating that wind regime alone cannot explain their formation. Aeolian sands in the Qaidam Basin mainly originated from fluvial and lacustrine sediments (Bao and Dong, 2015; Du et al., 2018), giving barchan and linear dunes similar provenance, but their underlying terrain was quite distinct.

Barchan dunes are mainly distributed in surrounding mountain alluvial fans, whereas linear dunes occur primarily in modern salt lake dry salt flats. Although Sebei area barchan dunes developed on ancient lake dry salt flats, their crest soluble salt content was similar to alluvial fan barchans. However, linear dunes had much higher soluble salt content than barchan dunes, particularly in inter-dune areas where values were hundreds of times greater (Table 1).

Surface soluble salt contents in alluvial fans and ancient lake dry salt flats were much lower than elsewhere. Both terrain types are flat with limited loose sand supply, so barchan dunes developed under unimodal wind regimes (Wasson and Hyde, 1983). In contrast, dry salt flats around modern salt lakes allow soluble salts to concentrate at the surface through running water and evaporation, with much higher silt and clay contents (Table 1). Both factors increase sediment cohesion. When wind carries loose sand and salt particles to modern dry salt flats, these particles are captured by cohesive finer particles, forming initial topographic obstacles around which dunes develop. With continuous sediment supply and unimodal wind regimes, these obstacles gradually grow in length and height, eventually developing into linear dunes (Rubin and Hesp, 2009). Our results suggest that different environmental settings, particularly soluble salt content differences in underlying terrain, were important factors determining dune type development.

4.2 Transport Pathways and Sedimentary Environments for Dune Sands

Denudation clastic sediments from surrounding mountains produced by weathering represent the ultimate provenance of various aeolian depositional landforms in the Qaidam Basin. However, the exogenic agents transporting these sediments cannot be confirmed until quartz sand grains accumulate into dunes. Due to quartz' s widespread distribution and physical-chemical stability, its surface micro-textures—produced by mechanical erosion from exogenic agents and by chemical etching and precipitation—remain visible for long periods (Vos et al., 2014), preserving abundant information about transport agents and sedimentary environments.

Glacial-force micro-textures like conchoidal fractures and cleavage planes appeared in all samples, though weakened in some, indicating dune sands underwent glacial transport before entering the basin (Gao et al., 1995). Glacial tills concentrated in mountain erosion channels under gravity and slope runoff, then were transported by running water and deposited in piedmont zones to form alluvial fans, during which fluvial micro-textures like V-shaped depressions and impact grooves became well developed. With continued mountain uplift since the late Pleistocene, basin lakes gradually dried and climate became arid and windy. Sand-sized particles preserved near dried lakes, ancient channels, and alluvial fans were then transported by northerly and northwesterly winds, eventually developing into various dune types. During this transport, typical aeolian micro-textures like crescent- and dish-shaped depressions and pockmarked pits became well developed.

Dune sands in the Qaidam Basin were successively transported by glacial, fluvial, and aeolian processes. However, overall roundness was poor (Table 2), attributable to shorter inland river flow paths (Zhang and Liu, 1985) and proximity to source regions. Despite these similarities, chemical processes acting on quartz grains showed distinct differences between terrain types. Quartz grains in alluvial fans showed fewer signs of long-term modification, suggesting recent deposition. Low-energy chemical environment features like solution grooves, scaly exfoliation, and siliceous films appeared only on some grains. In contrast, dry salt flat quartz grains showed well-developed pits, grooves, and scaly exfoliation from SiO_2 solution, plus siliceous scales and films from SiO_2 precipitation, representing a high-energy chemical environment.

Conclusions

Based on grain-size data, soluble salt contents, and quartz sand grain surface micro-textures in the Qaidam Basin, we explored underlying terrain influence on dune sands. Barchan dunes were dominated by medium sands showing unimodal frequency distributions with saltation load dominance. Linear dunes consisted mainly of fine sands with bimodal distributions representing saltation load (main peak) and modified saltation or suspension load (secondary peak). Soluble salt contents in linear dunes on salt flats were much higher than in barchan dunes on alluvial fans. Overall dune sand roundness was poor, dominated by sub-angular and angular particles, suggesting relatively short-distance transport by exogenic agents. Quartz grain surface micro-textures indicated successive transport by glacial, fluvial, and aeolian processes before deposition and dune formation. Alluvial fans represented low-energy chemical environments where chemical etching and precipitation micro-textures were poorly developed in barchan dunes. In contrast, salt flats had high-energy chemical environments where linear dune quartz grains exhibited well-developed chemical etching and precipitation micro-textures.

Acknowledgements

This study was funded by the National Natural Science Foundation of China (41601005, 41930641) and the Scientific and Technological Innovation Programs of Higher Education Institutions in Shanxi Province (2019L0797). We appreciate the constructive and insightful comments from two anonymous reviewers who greatly improved the manuscript.

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Figures

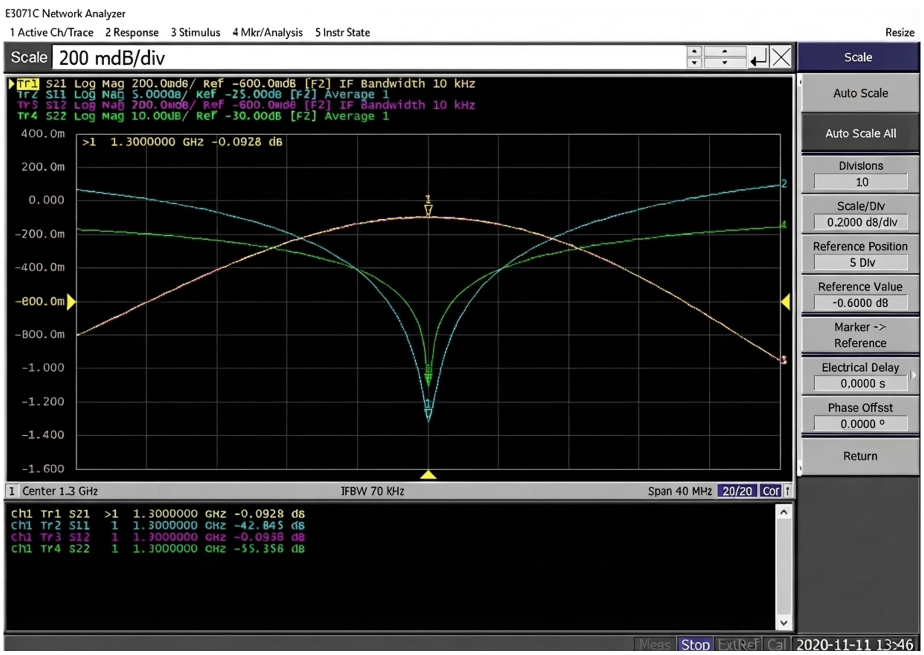

Figure 1: Figure 1

Source: ChinaXiv —Machine translation. Verify with original.

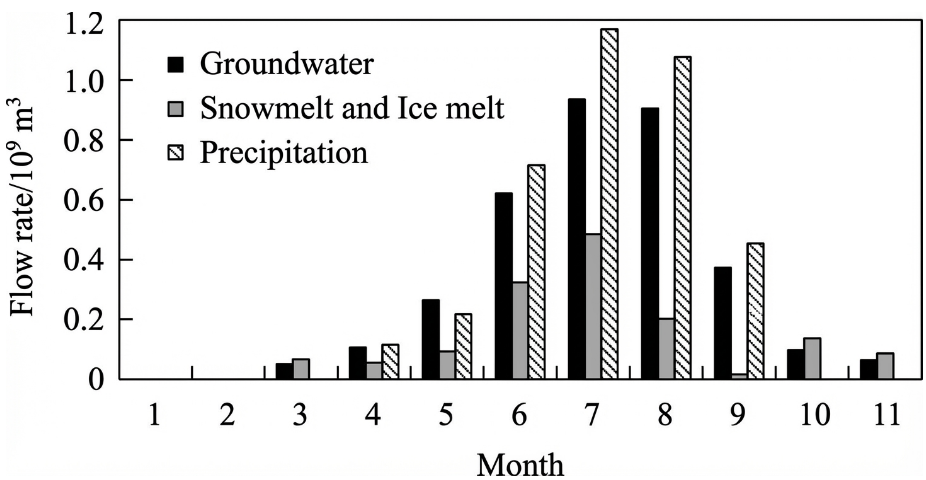

Figure 2: Figure 7

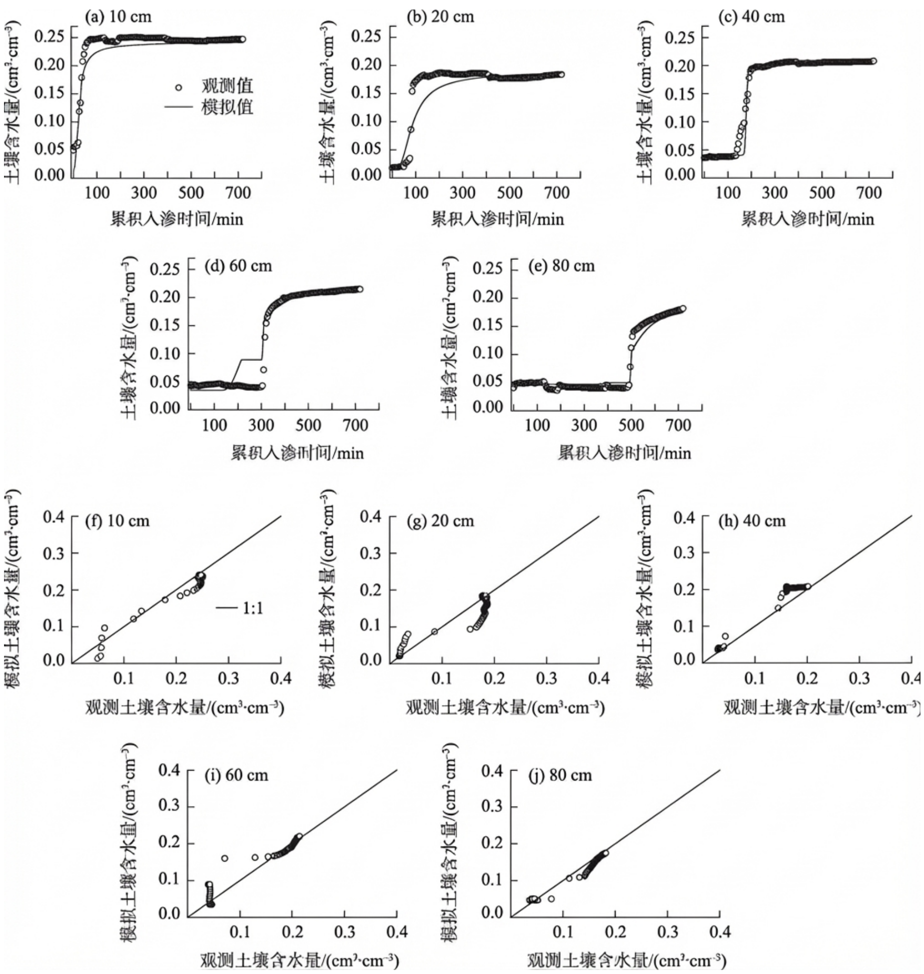

Figure 3: Figure 8

Figure 4: Figure 10

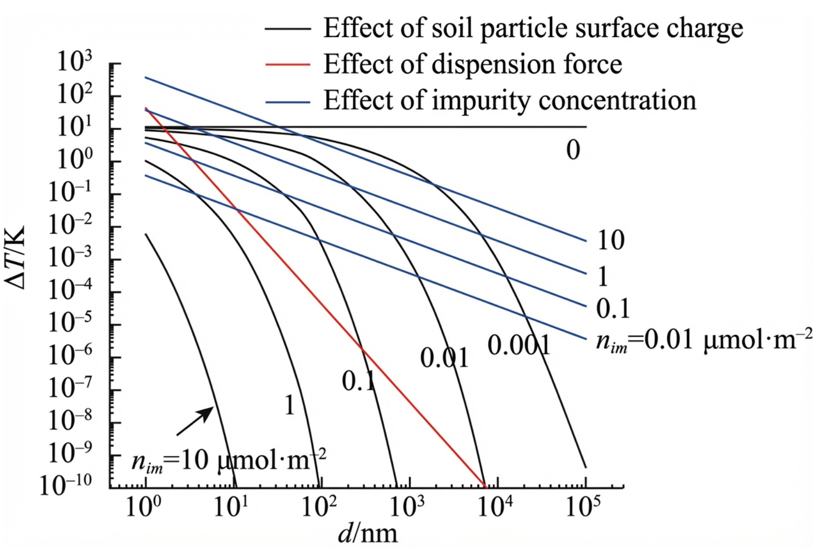

Figure 5: Figure 11

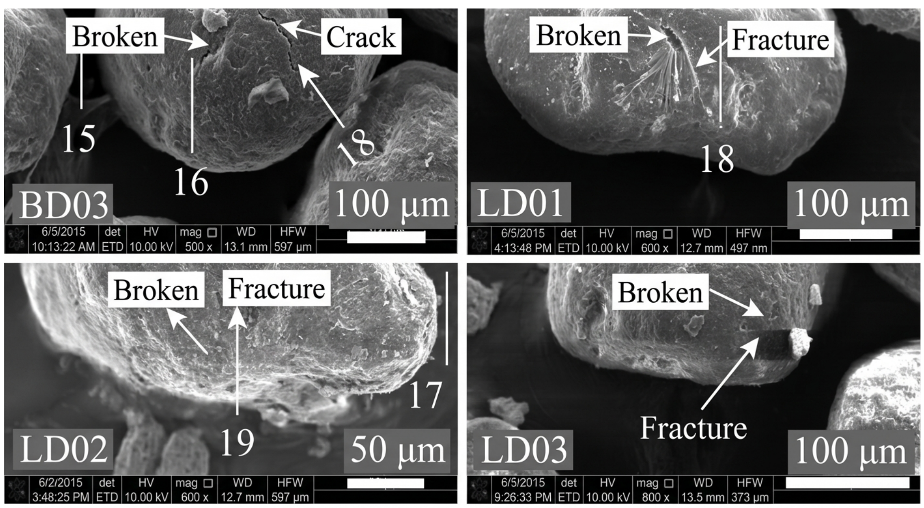

Figure 6: Figure 25