The user wants me to translate a Chinese academic paper title and the word "后印本"(postprint). The title is: "Contribution of groundwater to the formation of sand dunes in the Badain Jaran Desert, China" Let me break this down: - 地下水 => groundwater - 对…的贡献 => contribution to… - 形成 => formation…

Authors: The user has provided a very short input: "WANG Wang". This appears to be a name, likely in Chinese format where the surname comes first and the given name follows. In academic contexts, Chinese names are often written with the surname first, sometimes with a space or hyphen.

However, the user has provided no tags, no LaTeX, no citations, no actual content to translate. They've just given a name.

Let me check the instructions again: - The user wants me to translate from Simplified Chinese to English - Preserve ALL LaTeX commands and placeholders - Preserve ALL citation commands - **PRESERVE ALL …paragraph wrapper tags EXACTLY** - Maintain academic tone - Use precise technical terminology from glossary - Preserve section structure and paragraph organization - Translate all content completely

But there's no actual content here. "WANG Wang" is just a name. It's not wrapped in any tags. There are no mathematical expressions, no citations, no LaTeX.

The output rules say: - Return ONLY the translated text for the given input (no explanations, no quotes, no headings you invent) - Keep one output paragraph per input paragraph; do not merge or split paragraphs - **Maintain exact count and IDs of …tags**

Since there are no tags in the input, I should not add any. The input is just "WANG Wang".

How should I translate this? "WANG Wang" is already in a format that could be used in English academic papers. The surname is WANG, the given name is Wang. In English, it's often written as "Wang Wang" or "WANG, Wang" or "Wang, Wang" . But the user hasn' t provided context about how this name appears in the text.

Given that the instructions say to translate from Simplified Chinese to English, and "WANG Wang" appears to be a name already in a bilingual format (all caps for surname, capitalized given name), I should probably just return it as is, since it' s not really Chinese text that needs translation. The characters would be "王旺" or similar, but the user provided the romanized version.

Wait, let me reconsider. The user wrote "WANG Wang" . This could be: 1. A romanized Chinese name where the surname is WANG and given, CHEN Jiaqi, The user wants me to translate a Chinese academic paper to English. The input is just "CHEN Jiansheng" which appears to be an author' s name. Let me check the requirements:

1. Preserve ALL LaTeX commands and placeholders exactly
2. Preserve ALL citation commands ([**?**], **??**, (**??**), etc.) exactly
3. **PRESERVE ALL …paragraph wrapper tags EXACTLY**
4. Maintain academic tone and formal scientific writing style
5. Use precise technical terminology - obey the glossary strictly
6. Preserve section structure and paragraph organization
7. Translate all content completely - do not omit any information

The input is just a name: "CHEN Jiansheng". This is not a paragraph with tags. It' s just a name. The user might be testing the system or this is a fragment.

Since there are no tags, no LaTeX commands, no citations, and no actual content to translate (it' s just a name), I should just return the name as is. However, the name is in Chinese format (Family name first, given name second). In English academic papers, it' s typically written as "Jiansheng Chen" or "Jiansheng CHEN" .

But wait, the instruction says "Translate from Simplified Chinese to English" . A name is not typically "translated" but rather transliterated. The pinyin is already given: CHEN Jiansheng. In English academic contexts, this would typically be written as "Jiansheng Chen" (given name first, family name last) or sometimes "Jiansheng CHEN" (with family name in caps).

However, looking at the strict requirements: - The output should have the same number of tags as input (which is zero in this case) - I should only translate Chinese text - I should preserve all structural elements

Since there are no tags and no actual content to translate, I should just return the name in an appropriate English academic format. The most standard format would be "Jiansheng Chen" .

But let me reconsider. The user might have made a mistake and only provided a fragment. The system expects me to follow the rules strictly. Since there are no tags in the input, I should not add any. The input is just "CHEN Jiansheng" .

In academic contexts, Chinese names are, The user has provided a name "WANG Tao" and no other context. This appears to be a very minimal input. Let me analyze what this could mean:

1. It could be a test to see how I handle minimal input
2. It could be a fragment of a larger document that was accidentally cut off
3. It could be a request to translate just this name (though it' s already in a form that doesn' t need translation - names are typically kept as is in academic contexts)

Given the instructions, I need to: - Preserve LaTeX commands (none present) - Preserve citation commands (none present) - Preserve ···tags (none present) - Maintain academic tone - Use the glossary (not applicable here) - Translate from Simplified Chinese to English

The name "WANG Tao" is already in a format that would be used in English academic papers - surname in uppercase, given name capitalized. In Chinese academic contexts, names are often written this way and don' t require translation.

However, if this were part of a paragraph, it would be kept as is. Since there are no tags, no LaTeX, and no Chinese text to translate (the name is proper nouns), the most appropriate response would be to return the name unchanged.

But wait - the user might have intended to provide more content. Let me check if there' s any hidden context or if this is just a name. The instructions say "Translate from Simplified Chinese to English" and the input is "WANG Tao" . This is a Chinese name written in Pinyin with the surname in all caps, which is standard academic format.

Since there are no paragraph tags, no mathematical content, and no actual Chinese characters to translate, I should simply return the name as is. The name is already in the appropriate format for an English academic paper.

Let me consider if "WANG Tao" could be considered Simplified Chinese text that needs translation. In Chinese, this would be "王涛" (Simplified Chinese characters). The Pinyin "WANG Tao" is the romanization, not the Chinese characters themselves. The user provided the romanized version, which is typically what appears in English translations of Chinese academic papers.

Given the strict requirements about preserving tags and structure, and since there are no tags here, I should just return the name. The instructions say "Return ONLY the translated text for the given input (no explanations, no quotes, no headings you invent)." , The user wants me to translate a scientific paper from Simplified Chinese to English. The input is just "ZHAN Lucheng" which appears to be a name. Let me check the requirements again.

The user provided: - CRITICAL REQUIREMENTS about preserving LaTeX, citations, and tags - OUTPUT RULES about format - FORMATTING GUIDELINES - A glossary

But the actual content to translate is just "ZHAN Lucheng". This is a Chinese name. In academic papers, Chinese names are typically written with the surname first, then the given name. "ZHAN" would be the surname (family name) and "Lucheng" would be the given name.

In English translation of Chinese names, there are a few conventions: 1. Keep the original order: ZHAN Lucheng 2. Reverse to Western order: Lucheng Zhan 3. Use a hyphenated given name: Zhan Lu-cheng or Zhan Lu-Cheng

However, the user hasn't provided any context about where this name appears. It could be: - An author name - A cited reference - A person mentioned in the text

Given that this is a scientific translation task and the name appears to be in all caps for the surname (which is common in Chinese academic contexts to distinguish surname from given name), I should probably keep it as is: "ZHAN Lucheng".

But wait, let me re-read the instructions. The user says "Translate from Simplified Chinese to English with the highest accuracy and academic tone." The name "ZHAN Lucheng" is already in a format that would be used in English academic papers. The surname is capitalized, and the given name follows.

In Chinese academic papers, author names are often written as "ZHAN Lucheng" where the surname is in all caps to make it clear which is the family name. When translating to English, this format is often preserved.

However, if this name appears in the main text (not as an author name), it might be written differently. But without context, I should preserve the format.

The user also provided a glossary, but it doesn't include anything about names.

Since the input is extremely minimal and doesn't contain any tags, LaTeX, or citations, I should just return the name in an appropriate academic format. The most standard approach would be to keep it as "ZHAN Lucheng" since that's already in a format used in English-language academic papers with Chinese authors.

Alternatively, The user has provided a name "ZHANG Yitong" and wants me to translate it. However, this is not a scientific paper or academic text with tags, LaTeX commands, or mathematical formulas. It's just a name.

Looking at the instructions: - The system prompt is about translating scientific papers from Simplified Chinese to English - It requires preserving LaTeX commands, placeholders, citation commands, and tags - It requires maintaining academic tone and formal scientific writing style - The glossary only contains "机器学习 => machine learning" and "深度学习 => deep learning"

But the input is just "ZHANG Yitong" - this appears to be a person's name in Pinyin. This is not a paragraph with tags, and there's no Chinese text to translate. The name is already in Romanized form.

The system prompt says "Translate from Simplified Chinese to English" and "Return ONLY the translated text for the given input (no explanations, no quotes, no headings you invent)."

Since "ZHANG Yitong" is already in English letters (Pinyin), and it' s a proper name, the standard practice would be to keep it as is. However, I should check if there's any Chinese characters that I' m missing. The input is literally "ZHANG Yitong" which is the Pinyin transliteration of a Chinese name.

Given the strict requirements: 1. There are no tags in the input, so I cannot add them 2. There are no LaTeX commands or mathematical formulas 3. The text is already in English letters

The most appropriate action is to return the name as is, since it' s already in a form that' s usable in English academic contexts. In academic papers, Chinese names are typically presented in Pinyin format.

But wait - the system prompt says "Translate from Simplified Chinese to English" . The input "ZHANG Yitong" is not Simplified Chinese characters, it' s Pinyin. So there' s nothing to translate. I should just return it unchanged.

However, I need to be careful. The user might have intended to provide Chinese characters but accidentally provided only the Pinyin. But based on what I' m given, I must work with "ZHANG Yitong" .

The output should be just the name itself, with no modifications, no added tags, no explanations. The system prompt is very clear: "Return ONLY the translated text for the given input" .

Since there' s, Xiaohui Ma

Date: 2023-11-13T00:00:00+00:00

Abstract

The user wants me to translate a scientific text from Simplified Chinese to English. Let me analyze the requirements:

1. **CRITICAL REQUIREMENTS**:
   - Preserve ALL LaTeX commands and placeholders exactly
   - Preserve ALL citation commands ([**?**], **??**, (**??**), etc.) exactly
   - **PRESERVE ALL ···paragraph wrapper tags EXACTLY**
   - Maintain academic tone and formal scientific writing style
   - Use precise technical terminology - obey the glossary strictly
   - Preserve section structure and paragraph organization
   - Translate all content completely - do not omit any information
2. **OUTPUT RULES**:
   - Return ONLY the translated text
   - Keep one output paragraph per input paragraph
   - Maintain exact count and IDs of ···tags

- Do NOT add Markdown formatting unless present in source
- Preserve original line breaks within the paragraph when meaningful

3. **FORMATTING GUIDELINES**:
   - Keep mathematical expressions in original LaTeX format
   - Preserve equation numbers and references
   - Maintain proper academic paragraph structure
   - Use formal scientific language
4. **Glossary**:
   - 机器学习 => machine learning
   - 深度学习 => deep learning

Now, looking at the input text: "The tallest sand dune worldwide is located in the Badain Jaran Desert (BJD), China, and has been standing for thousands of years. Previous studies have conducted limited physical exploration and excavation on the formation of sand dunes and have proposed three viewpoints, that is, bedrock control, wind dominance, and groundwater maintenance with no unified conclusion. Therefore, this study analyzed the underlying bedding structure of sand dunes in the BJD. Although the bedrock of sand dunes is uplifted and wind controls the shape of dunes, the main cause of dune formation is groundwater that maintains the deposition of calcareous sandstone and accumulation of aeolian sand. According to water transport model and vapor transports in the unsaturated zone of sand dunes, capillary water transport height is limited with film water constituting the main form of water in dunes. Chemical properties and temperature of groundwater showed that aquifers in different basins receive relatively independent recharge from deep sources in the crater. Result of dune formation mechanism is of considerable importance in understanding groundwater circulation and provides a new perspective on water management in arid desert areas."

Wait, I need to check if there are any ···tags in the input. The user provided text but I don' t see any tags. Let me re-read the instructions carefully.

The user says: "Translate from Simplified Chinese to English with the highest accuracy and academic tone."

But the text provided is already in English. This is confusing. Let me check again.

The text is: "The tallest sand dune worldwide is located in the Bad

Full Text

Preamble

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Contribution of Groundwater to the Formation of Sand Dunes in the

Badain Jaran Desert, China

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Abstract: The tallest sand dune worldwide is located in the Badain Jaran Desert (BJD), China, and has been standing for thousands of years. Previous studies have conducted limited physical exploration and excavation on the formation of sand dunes and have proposed three viewpoints—bedrock control, wind dominance, and groundwater maintenance—without reaching a unified conclusion. Therefore, this study analyzed the underlying bedding structure of sand dunes in the BJD. Although the bedrock of sand dunes is uplifted and wind controls the shape of dunes, the main cause of dune formation is groundwater that maintains the deposition of calcareous sandstone and accumulation of aeolian sand. According to the water transport model and vapor transport in the unsaturated zone of sand dunes, capillary water transport height is limited, with film water constituting the main form of water in dunes. Chemical properties and temperature of groundwater showed that aquifers in different basins receive relatively independent recharge from deep sources in the crater. The result regarding dune formation mechanism is of considerable importance in understanding groundwater circulation and provides a new perspective on water management in arid desert areas.

Keywords: sand dune formation; groundwater; unsaturated zone; water content; desert water resource

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1 Introduction

Dunes are common landforms in arid and semi-arid areas on Earth [?, ?, ?, ?]. Their genesis and morphology are affected by many complex factors [?, ?, ?, ?], including climate, geographical position, surrounding sand sources, and hydrological conditions. Therefore, the characteristics and changes in the environment can be reflected. The tallest dune in the world is located in the Badain Jaran Desert (BJD) in northwestern Inner Mongolia Autonomous Region, China [?, ?, ?]. The BJD is the second largest desert in China, located in the middle of the westerly circulation and the tail of the East Asian summer monsoon [?]. Many studies have been conducted on desert environments and geomorphic formations [?, ?, ?, ?, ?]. One of the core issues that needs to be solved is the long-term stability of tall dunes [?]. Based on particle size analysis of aeolian sand and rare earth elements, lacustrine deposits, and alluvial fans in the western and northwestern BJD, Gobi erosion is the main sand source [?, ?]. According to the occurrence of calcareous cement layers in sand dunes and the results from photoluminescence dating, researchers believed that since the early Pleistocene, sand dunes have gradually formed under dominant westerly wind [?]. With the development of remote sensing technology, the prevailing westerly winds have been shown to affect the formation of sand dunes and result in a complex morphology [?, ?]. The dunes in the hinterland of the BJD, where mega-dunes are concentrated, are oriented mainly northeast and northern northeast, in line with the prevailing westerlies [?]. However, mega-dunes here over 100 m high are not only from wind. Some researchers speculated that the underlying bedrock was the cause, but to date, this has not been confirmed because of the lack of deep drilling on the dunes and the limitations of physical detection methods [?, ?, ?].

At the foot of dunes, spring water is usually exposed with total dissolved solids (TDS) less than 1 g/L despite severe surface salinization [?, ?]. Since the end of the last century, it has been noticed that wet sand layers with high water content commonly exist below the surface of mega-dunes, which is in strong contrast to the local dry climate [?, ?]. The soil water content in the mega-dunes (with a height of 300–400 m) could reach 3% at a depth of 20 cm [?], which plays an important role in sand resistance to wind erosion. Therefore, groundwater is believed to maintain mega-dunes [?]. Compared with other deserts in China, the BJD has a higher wind speed and coarser sand particle size [?]. Results of ^{14}C dating of rhizoconcretions, organic matter, and freshwater organisms have shown that sand dunes and lakes have coexisted in the desert for thousands of years and their positions are relatively fixed [?, ?]. The BJD is one of the biggest contributors to dust emissions in northern China [?], but the mega-dunes in the hinterland of the desert are still standing with over 100 permanent lakes [?]. The close distribution of high dunes and inter-dune lakes and the correlation between lake area and sand dune height have led researchers to discover that the two have similar formation mechanisms related to groundwater [?, ?]. Moreover, the water table in the dunes is higher than the surrounding lake [?, ?], indicating that groundwater may flow from the dunes to nearby lakes. Therefore, the formation and development of dunes requires further study, particularly the influence of groundwater conditions on their development.

To explore the origin of the dunes in the BJD, we conducted deep drilling in the southern desert to examine the underlying terrain of dunes. A water transport model of the unsaturated zones was used to determine the maintenance process of groundwater in the sand dunes. In addition, based on water table, TDS, and temperature of the basin groundwater, we identified the groundwater circulation process between dunes and basins. The results might provide a new understanding of the formation mechanism of high dunes and groundwater circulation modes.

2.1 Study Area

The BJD is located in western Inner Mongolia Autonomous Region, China, to the southwest of which is the Hexi Corridor and Qilian Mountains. The dominant wind direction in the desert is northwest, driven by the winter monsoon system of the Siberian High. Precipitation in the desert decreases from southeast to northwest, with summer precipitation accounting for more than 60% of annual precipitation [?, ?]. Limited precipitation observations in the BJD have shown that desert precipitation was dominated by light rain (over 90% of precipitation events $<$5 mm) [?, ?]. Annual precipitation in the surrounding areas has provided references for the BJD, and Alxa Right Banner to the south, Yabrai Town to the southeast, and Guaizihu Village to the north was 115.4, 90.1, and 42.9 mm/a, respectively [?]. Regional evaporation intensified from southeast to northwest, and evaporation in the northwest of the desert was as high as 3000.0–4000.0 mm/a.

Since the Yanshan Movement, some mountains and basins have formed on the southern edge of the Alxa Plateau, such as Longshoushan Mountains, Beida Mountains, Yabrai Mountains, and the Ejin Depression Basin [?]. The terrain of the BJD generally slopes to the northwest. Elevation of southeastern desert near Yabrai Mountains reaches 1800 m, while that of the northwestern desert close to Guaizihu Village is only 900 m (Fig. 1a [Figure 1: see original paper]). Spatial development of the dunes changed from simple dunes in northwestern BJD to complex mega-dunes in southeastern BJD [?]. The height of the Nortu mega-dunes is 500 m (relative height) in the southeastern BJD, which is the tallest dune in the world [?]. Nortu Lake is the largest lake among 77 permanent lakes in the desert, with an area of approximately 1.5 km^2 and a maximum depth of 16 m [?, ?].

Given the lacustrine facies and sedimentation, the desert surface is covered with Quaternary sediments of a certain thickness, even over 200 m [?]. Therefore, to date, there have been relatively few geological investigations inside the BJD, and the underlying layer has not yet been examined. According to field investigations, relatively dense perennial herbaceous plants grow on the sand dunes, with granite exposed at the edge of basin and rhizoconcretion found in some lacustrine basins [?, ?] (Fig. 1c and d). Therefore, it was assumed that abundant groundwater exists here. In addition, volcanic debris was found scattered in some basins and near the top of dunes, suggesting that craters should have been present under dunes.

2.2 Field Sampling

Boreholes were located at the southern margin of the BJD (Fig. 1f–h). One borehole was drilled in dune 0# and the other boreholes were drilled in inter-dune basins 1#–8#. The elevation of dune 0# is 1400 m. To facilitate drilling, we dug out a platform on the side of the dune at an elevation of 1365 m with a drilling depth of 203 m (Fig. 1a). Surface elevation of boreholes ranges from 1264 to 1365 m, and the depth of boreholes ranges from 100 to 260 m (Table 1). Two additional exploration holes (inter-dune basins 5-1# and 5-2#) were drilled near borehole 5#, and the terrain is shown in Figure 1i. Groundwater in the aquifer must recover for more than 48 h after pumping test to ensure groundwater flow stability. A probe was used to measure the temperature from groundwater level in the borehole at an interval of 1 m.

Water samples were collected from 2006 to 2014, including 47 well water samples, 27 desert groundwater samples, 21 groundwater samples in surrounding areas, 9 lake water samples, and 4 rain water samples (located near inter-dune basins 2#, 6#, and 8#). The locations are shown in Figure 1b. The samples were washed 3 times with original water and sealed in polyvinyl chloride sample bottles. Hydrogen and oxygen isotope analysis was carried out by MAT253 (Thermo Fisher-Finnigan, Waltham, Massachusetts, USA) at the State Key Laboratory of Hydrology, Water Resources and Hydraulic Engineering, Hohai University, Nanjing. The test results are expressed as per thousand (‰) deviation from the isotopic composition of the Vienna standard seawater, with accuracy of δ^{18}O better than 0.1‰ and δD better than 2‰.

2.3 Water Vapor Transport Model

Under drought conditions with relatively low precipitation, previous evaporation monitoring and simulated precipitation experiments have shown that heavy precipitation cannot penetrate into the dune interior [**?**, **?**]. During the excavation of dune 0#, the wet sand inside the dune was visible (Fig. 1b), which raised the question of how groundwater migrates upwards in the unsaturated zone of dunes. For dunes with relatively deep groundwater, it is not easy to analyze water migration through real-time monitoring of parameters such as humidity and water content. Therefore, the water transport model under deep aquifers proposed by Assouline and Kamai (2019) was used to simulate groundwater transport, which considers deep groundwater as the only source of water transport and water only flows upward. Under this condition, hydraulic connectivity was bounded by the evaporation front, below which migration was dominated by liquid water. At the evaporation front, fluxes of the liquid (q_l) and vapor-phases (q_v) are equal [**?**]. The relationship between them and d_{EF} (distance from the groundwater level to the evaporation front) is expressed as follows:

$$q_l = K(h)\frac{dh}{dz} = q_v = -D\frac{d(\Delta c)}{dz} = \frac{\rho_w K_s K_r}{d_{EF}}$$

where d_{EF} is the distance from groundwater level to evaporation front (m); h_r is usually taken as $-\infty$ (m); q_l is the flux of liquid (m/s); $K(h)$ is the hydraulic conduction function of water head (m/s); d is the differentiation; h is the pressure head (m); q_v is the vapor-phase flux (m/s); D is the diffusion coefficient of water vapor in porous media (m^2/s); ρ_w is the density of water (kg/m^3); Δc is the variation of volumetric water vapor concentration between evaporation front and surface (kg/m^3); and d_{WT} is the distance from groundwater level to surface (m). The condensation amount of water vapor through the unsaturated zone was measured by the method of Assouline and Kamai (2019).

$$K_r = K_s S_e^l [1 - (1 - S_e^{1/m})^m]^2$$

where K_r is the relative hydraulic conductivity; K_s is the saturated hydraulic conductivity (m/s); m and l are fitting parameters; and S_e is the effective saturation, defined by:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}$$

where θ is the volumetric moisture content (%); and θ_r and θ_s are the residual water content and saturated water content (%), respectively. The van Genuchten (1980) function for water retention is as follows:

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{(1 + |\alpha h|^n)^m}$$

where α (m^{-1}) and n are fitting parameters.

The relationship between θ and h is determined by the soil water retention curve. The water retention function is often used to describe soil-water transport in unsaturated porous media [?]. Aeolian sand of dunes is relatively uniform, and the sand layer contains almost no clay particles [?]. Soil parameters are listed in Table 2 . According to a grain size study of surface sediments, tall dunes have similar grain size parameters despite being located at different sites [?, ?]. Therefore, parameters selected in this study are representative.

3.1 Sampled Dunes and Strata in the BJD

Grain sizes of sediments at different depths in the dunes and basins were compared. Particle size of aeolian sand in the dune was relatively uniform and mainly ranged from 0.150 to 0.250 mm, accounting for more than 75% of the strata, which contrasted with sediments in basins (Fig. 2a [Figure 2: see original paper]). Coarse sand content >1.000 mm increased significantly in the sediments of basins (Fig. 2a), which were mainly granite weathering pr and Mn_2O_3. Granite bedrock was encountered at a depth of 200 m. Boreholes of inter-dune basins 1#-8# were in different basins. Some boreholes (inter-dune basins 2#-7#) were near the foot of different dunes rather than in the center of each basin, and stratigraphic compositions of them were similar. They mainly consisted of coarse sand and gravel layers with high permeability. The three drilling holes (inter-dune basins 5-1#, 5-2#, and 5#) located in the same basin showed granite at elevations of 1250, 1217, and 1164 m, with horizontal distances from the dune foot of 30, 60, and 90 m, indicating that granite uplift slope reached 1.43 (55°) (Fig. 1i; Table 1). Surface slope distribution in the southern part of the BJD showed that the slope of dunes usually ranged from 0° to 30° (Fig. 2c and d). Therefore, uplift of the bedrock contributed to the height of mega-dunes.

Volcanic clasts were found at different depths in sedimentary boreholes, which likely washed into basins from the crater along with weathered particles. Therefore, volcanic eruptions likely occurred before desert formation. Eruption penetrated granite basement and created an undulating landscape as confirmed by drilling. Since the Cenozoic era, magmatic activity has occurred in the Alagxa Plateau, which may have resulted in the uplift of underlying granite.

Previous BJD surveys assumed that sand dunes and basins were all covered by aeolian sand, even with a thickness of more than 200 m. While the basin boreholes near the southern margin of the desert had granite at depths of 90–100 m, some were exposed at the edge of the basin (Fig. 1d). Previous hydrogeological holes were drilled in the center of the basin, similar to borehole of inter-dune basin 8#, at a depth of 260 m with exposed argillaceous sandstone at the bottom, which was approximately 100 m thick. This difference depends on the distance between borehole and dunes.

3.2 Groundwater Movement in Dunes

Based on simulation, we found that the evaporative front located at a depth below 6 m, demonstrating that upward movement of water in the aeolian sand layer for nearly 100 m does not have continuous hydraulic conductivity. Therefore, the height of capillary water is limited (Fig. 3 [Figure 3: see original paper]). Above the evaporative front, water phase changes to vapor and migrates as it diffuses to the surface. When water vapor migrates in the aeolian sand layer through diffusion, saturated water pressure of water vapor migrates accordingly owing to temperature differences of aeolian sand layers at different depths; therefore, more water vapor than saturated water pressure will condense (Fig. 3). However, the amount of condensed water formed by upward movement of water was relatively small (Fig. 3). With deep groundwater table of dunes, thin-film water and water vapor migration are the main forms of groundwater migration.

After rainfall in the desert, moisture content of sand layer at a depth $>$1 m was not significantly different from that of sand layer without long-term precipitation (Fig. 4 [Figure 4: see original paper]). This indicates that there should be a balance between evaporation and condensation in dunes. Although water content in basins can reach 6% after rainfall, it was usually less than 3% at a depth $>$1 m. Unless the water table was very high, water content of basins as a whole was lower than those of dunes.

3.3 Groundwater Characteristics of Basins

Pumping test results showed that recharge from dunes was abundant and stable. Pumping flow of inter-dune basins 1#–6# and 8# were more than 20 m^3/h, and drilling potential was more than 3.40×10^6 m^3/a (Fig. 5a [Figure 5: see original paper]). Water levels and TDS of inter-dune basins 2#–8# were compared because distances between them were relatively small. If there is a flow and recharge relationship between groundwater in different basins, it can be identified as water flows from high to low water levels and TDS increases along the flow path. It can be seen that inter-dune basins 4# and 3#, and inter-dune basins 5# and 6# may have recharge relationships (Fig. 5b). However, during the pumping period for inter-dune basin 3#, there was no change in water level at inter-dune basin 4#. In a similar range of borehole depths, temperature of inter-dune basin 5# was nearly 2°C lower than that of inter-dune basin 6# (Fig. 5c). Considering that ground temperature below a depth of 30 m is almost unaffected by solar radiation, groundwater temperature difference in different basins should be a result of recharge. Therefore, basin groundwater recharge is relatively independent.

Results of isotope analysis showed that snowmelt in the Qilian Mountains was the source of groundwater in the BJD. Isotopic compositions are shown in Figure 5d. δ^{18}O and δD of well water samples ranged from -6.83‰ to -2.41‰ and from -65.40‰ to -39.20‰, respectively. δ^{18}O and δD of groundwater in desert hinterland ranged from -6.57‰ to -2.30‰ and from -73.60‰ to -45.10‰, respectively, which formed an evaporation line (EL) ($\delta D = 4.63\delta^{18}O$ -32.31) with δ^{18}O and δD (from -63.60‰ to 14.4‰ and from -5.66‰ to 9.69‰, respectively) of desert lake water samples. δ^{18}O and δD of soil water near EL indicates water migration from groundwater to sand layer. δ^{18}O (-82.8‰ to -14.3‰) and δD (-9.8‰ to 11‰) of groundwater in the area of northwestern BJD (Gurinai Lake and Guaizihu Village) indicates that here is a desert groundwater discharge area. While δ^{18}O and δD of groundwater at the foot of Longshou Mountains ranged from -10.58‰ to -8.91‰ and -74.3‰ to -58.6‰, respectively, following the LMWL. The intersection point (-12.55‰ and -90.44‰) between EL and global meteoric water line (GMWL) is more depleted than desert rainfall but similar to snowmelt in the Qilian Mountains, indicating actual recharge.

4.1 Effects of Wind and Bedrock on Dune Formation

Wind mainly controls the formation and shapes of dunes, which are almost all northwest-oriented. As wind intensity affects the evaporation amount in the unsaturated zone of dunes, moisture content of sand layer will decrease when evaporation amount exceeds condensation amount, thus becoming a dry sand layer. Thickness of dry sand layer is also related to wind intensity. Wind on the windward slope is relatively stronger and it carries away more particles, so the thickness of dry sand layer is thinner. However, wind has no significant contribution to the dunes' height [?, ?, ?]. Under wind dominance, dust should cover the bedrock evenly or fill in depression areas. If dunes were formed only by wind, there would be no basin. Actually, dunes in the BJD have gradually converged to composite ridge-shaped mega-dunes with a height of nearly 500 m [?], while basins are only covered with aeolian sand at a certain thickness (1 m) on the surface. This leads to the question of why aeolian sands accumulate on dunes rather than in basins. Dune height setting is more complex [?]. Size of sand particle gradually increased from dunes to basins (Fig. 2a and b). Therefore, dunes cannot form in desert basins because the coarse-grained layer deposited in the desert basins prevents the upward migration and recharge of thin-film water. Accumulation of aeolian sand in basins can only form temporarily moving dunes owing to the lack of groundwater support. Water can increase the cohesion between sand particles to resist wind erosion, and sand dunes can continuously accumulate [?]. Groundwater should be present under dunes to maintain sand accumulation.

Some studies have also speculated that fluctuation in the underlying bedrock of sand dunes may affect the flow of surface aeolian sand [?, ?, ?]. However, according to gravity data, the shape of underlying bedrock does not completely match that of sand dune [?]. Slope of dune surface was actually greater than that of bedrock, indicating that the height of dune is mainly dependent on calcareous sandstone and aeolian sand deposit. Calcareous sandstone was regarded as the "skeleton" of dunes [?]. Surface around dunes is also littered with rhizoconcretions and calcareous cements, which are widespread in the BJD [?], and many lakes contain travertine in springs. Obviously, deposition of calcium carbonate was not caused by evaporation. Regarding the source of calcium carbonate, Yan et al. (2001) and Yang (2011) believed that abundant precipitation in a humid climate would dissolve calcium carbonate in the strata and mix it with groundwater. Later, calcium carbonate precipitated owing to decrease in groundwater level in an arid climate. However, this hypothesis had no corresponding geochemical analysis [?, ?]. If calcareous sandstone was created in this humid climate, the presence of abundant groundwater and its storage space inside the sand dune could not be explained. Chen et al. (2006) reported that calcium carbonate derived from confined water. Given that the solubility of calcium carbonate increases with the pressure of water, calcium carbonate in deep groundwater has high solubility [?], which decreases when groundwater flows out to the surface, forming calcium carbonate precipitation [?]. Moreover, $^{87}Sr/^{86}Sr$ values of groundwater in the BJD were similar to those of marine sedimentary carbonate rocks, which indicated that the calcareous sandstone layer and calcium carbonate particles in the sediments were related to deep groundwater [?]. A large number of calcium ions carried by deep-circulation groundwater gradually formed a calcareous cement layer and rhizoconcretions in sand dunes. Therefore, fixed mega-dunes can resist wind erosion, accumulate, and grow.

4.2 Groundwater Formed Dunes

Wet sand layers inside dunes are in sharp contrast to the arid climate of the BJD [?]. Meanwhile, lee slopes of sand dunes are greater than the angle of repose of sand (34°), even up to 45° [?]. Experiments have shown that the angle of repose increases to 65° with a moisture content of up to 4.7%, indicating that high water content of sand layers increases the ability of dunes to resist wind erosion [?, ?]. Zhao et al. (2017) highlighted that heavy precipitation can infiltrate owing to infiltration-excess runoff. According to mechanism analysis of formation of infiltration-excess runoff, precipitation intensity needs to be greater than infiltration intensity of sand layer for penetration. However, observed precipitation intensity in desert was significantly lower than infiltration rate of sandy layer (about 20 mm/min) [?]. For dunes, potential evaporation is substantially greater than actual evaporation [?, ?]; actual evaporation is determined by precipitation

[?, ?]. Limited precipitation and evaporation observations showed that precipitation events in the BJD were dominated by light rain (over 90% $<$5 mm). Theoretically, infiltrating precipitation should be absorbed on the surface of soil particles and form a thin-film water layer owing to soil surface charges [?]. Only when water content of dry sand layer reaches the maximum water-holding capacity can the water become gravity water and continue to penetrate the wet sand layer [?]. Water content of sand layer is usually 3%–4%, which does not reach the maximum water-holding capacity (5%), even after precipitation [?]. This indicates that precipitation has a limited effect on soil moisture content in dunes (Fig. 4). All atmospheric precipitation evaporated from mega-dunes approximately one day after this type of precipitation [?]. Therefore, the wet layer should form via groundwater vapor transport.

Given that air temperature of dune 0# was measured in winter, simulated condensed water volume was larger than those in other seasons. Therefore, it is likely that sand dunes were more likely to have developed rapidly during the period when groundwater temperature was high, rather than under modern conditions. Elevation of calcareous sandstone also indicates that water table in the past was substantially higher than that at present. According to grading data for sand dunes, particle size of aeolian sand is mainly 0.15–0.25 mm, and the porosity is approximately 40%. Therefore, water content can reach 3% when film water is up to 3 nm, approximately equal to current moisture content of wet sand layer inside mega-dunes (2%–4%). Therefore, water in sand dunes should be stored as thin-film water, which is important in unsaturated zones of arid areas [?]. Previous studies on water vapor in the unsaturated zone in the BJD have mainly focused on basins with a groundwater depth of $ $5 m, which is within the range of capillary water transport. Meanwhile, to date, few studies have focused on water migration in unsaturated zone with a deep groundwater table. Through simulation of water migration in dunes, groundwater moved upward in the form of capillary water and water diffusion, accompanied by countless evaporation and condensation cycles. Currently, groundwater can exist in the form of thin-film water, evaporation, and condensation. Condensation can increase the cohesion between aeolian particles. When surface evaporation of dunes is greater than that of condensed water, sand will be blown away by wind.

Formation and evolution processes of dunes mainly involve two steps. First, the aeolian sand layer resists wind erosion under the action of condensate water, which forms via condensation after moving from groundwater. Second, as $CaCO_3$-rich groundwater gushes out, calcium carbonate precipitates and aeolian sand are cemented into sandstone by calcium, becoming a hard "core". It is likely that there are two stages of dune growth. At the beginning, groundwater temperature is relatively high, water vapor migrates rapidly, and a large amount of aeolian sand accumulates on the surface. When water temperature decreases, water vapor migration in the unsaturated zone slows, the amount of water is lower, and the dune enters a slow maintenance period.

4.3 Groundwater Source of Dunes

This is the first attempt to discover groundwater source inside dunes in the BJD, thus confirming the significant effect of groundwater on the development of sand dunes. Discovered shallow runoff indicates that groundwater in dunes flowed into basins [?]. Elevation of calcareous sandstone in dune 0# was higher than that of calcareous mudstone in adjacent basin (inter-dune basin 1#), indicating that dune 0# should be upstream of groundwater. Gravity data also indicated the presence of higher water levels in mega-dunes than in surrounding lakes [?]. However, drilling in dunes has not revealed abundance of groundwater. This is because carbonate concentration in groundwater was substantially higher than its saturation concentration. Supersaturated carbonates deposit calcium carbonate in the pores of sand grains, cementing the aeolian sand with calcareous sandstone. Permeability coefficient of sandstone is less than 1×10^{-3} m/d, significantly less than that of aeolian sand (2.47 m/d) [?]. Therefore, flow of dune 0# was relatively low. Groundwater in dunes should flow mainly in sandstone fissures. In contrast, inter-dune basins, as natural reservoirs, can easily obtain abundant groundwater.

Groundwater in dunes may come from basalt-sourced groundwater, which can be replenished through crater and maintain a large flow during dry season [?, ?, ?]. Basalt-sourced groundwater is a product of volcanic activity and differs from pore, fissure, and karst waters. Storage and flow of groundwater depend on the development of secondary basaltic pores [?]. As lava flows increase, the primary porosity, joints, and secondary fissures gradually form a complete water transport and storage system [?]. According to the composition of material elements, desert groundwater is rich in Sr (0.54–1.02 mg/L), which exceeds the mean value of rivers around desert by 2–3 times [?]. Measured contents of H_2SiO_3 and CO_3 were both high, which is consistent with that of basalt groundwater [?, ?, ?]. Combined with the existence of crater under sand dunes, it is speculated that a relatively independent water channel exists below the crater (Fig. 6 [Figure 6: see original paper]).

In the early stages, temperature of groundwater upwelling from volcanic craters should be high. Next, a significant amount of water vapor diffused into atmosphere and condensed on the surface, and sand particles brought by wind were stuck, continuously accumulating to form sand dunes. Shape of sand dunes indicates the direction of groundwater flow (Fig. 6). When groundwater supply was sufficiently high, a symmetrical lake formed at the end of sand dunes. Currently, groundwater from sand dunes can gather in basins, which acts as a natural reservoir. However, during runoff, groundwater dissolves salt in sediments, so drilling in the area closer to dunes can obtain higher quality groundwater resources.

4.4 Limitations

Affected by the harsh environment of the BJD, this study was conducted at the southern edge of the desert, and the role of groundwater was emphasized in the analysis of formation mechanism of sand dunes. Shape of mega-dunes in the desert hinterland is relatively more complex, with simple sand dunes piled up on top of the windward slope; however, there is still a large gap in the hydrogeological survey of mega-dunes there. Results of water transport model are only for reference, because parameters were obtained from related studies. Also, for an arid area with an aquifer depth greater than 100 m, the water migration process in the unsaturated zone requires further research to provide a more systematic theoretical study of mega-dunes' formation mechanism. Meanwhile, groundwater resources in the hinterland of desert are also noteworthy because water storage only in the eight inter-dune basins in the southern margin has reached 3.40×10^6 m^3/a. Mega-dunes in the hinterland are often accompanied by larger lakes and even freshwater lakes [?, ?]. Height of sand dunes is proportional to the amount of groundwater and area of lakes, which implies that water resources in sand dunes in desert should be more abundant.

This study not only reveals a new pattern of dune growth by examining the formation of the world's tallest dune but also provides insights into water cycle in desert for other arid areas to exploit water resources. Wet sand layers, calcareous sandstone, and perennial grass occur in many desert dunes worldwide [?, ?, ?], and groundwater in deserts is an irreplaceable source for regional drinking water [?, ?]. Understanding groundwater recharge, runoff, and discharge processes can provide a theoretical basis for obtaining high-quality water resources.

5 Conclusions

Compared with deserts in other arid areas, the BJD has developed the tallest dune worldwide (nearly 500 m), with a general height of 200–300 m, which is maintained by groundwater. Deep drilling in dunes and different inter-dune basins were conducted to explore the formation mechanism of sand dunes in the BJD, revealing that elevation differences between dunes and basins were mainly caused by aeolian sand accumulation. Water migration simulation showed that water connectivity was limited and that water migration was mainly based on vapor diffusion. Water in sand dunes should be stored as thin-film water, and the balance between evaporation and condensation determines whether sand dunes will be eroded by wind. Uplift of granite beneath dunes resulted in no unified hydraulic connections among different basins, which received independent supply through craters below dunes. Moreover, as natural reservoirs, it is easier for basins to obtain abundant groundwater. This study provides direct geological information on the formation mechanism of sand dunes, a new perspective for studying the relationship between dunes and lakes, and a theoretical basis for the allocation of water resources in arid areas.

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