



HAL
open science

Outcrop distribution and formation of carbonate rhizoliths in Badain Jaran Desert, NW China

Qingfeng Sun, Arnaud Huguet, Kazem Zamanian

► **To cite this version:**

Qingfeng Sun, Arnaud Huguet, Kazem Zamanian. Outcrop distribution and formation of carbonate rhizoliths in Badain Jaran Desert, NW China. CATENA, 2021, 197, pp.104975. 10.1016/j.catena.2020.104975 . hal-03004076

HAL Id: hal-03004076

<https://hal.science/hal-03004076>

Submitted on 13 Nov 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 **Outcrop distribution and formation of carbonate rhizoliths** 2 **in Badain Jaran Desert, NW China**

3 Qingfeng Sun^{a,*}, Arnaud Huguet^b, Kazem Zamanian^c

4 ^a Faculty of Geography, Northwest Normal University, Lanzhou 730070, China

5 ^b Sorbonne Université, CNRS, EPHE, PSL, UMR METIS, F-75005 Paris, France

6 ^c Department of Soil Science of Temperate Ecosystems, Georg-August University of Goettingen, Buesgenweg 2,
7 37077 Goettingen, Germany

8 *Corresponding author. Email address: sqf@nwnu.edu.cn

9 **Abstract**

10 Carbonate rhizoliths and related features are environmental and ecological
11 indicators of not only palaeosols, but also modern soils. They designate subaerial
12 vadose and pedogenic diagenesis environments. Rhizoliths are commonly used as a
13 tool for paleoenvironmental reconstructions, but uncertainty remains regarding their
14 formation mechanisms. Field characteristics of the dune rhizoliths in the Badain Jaran
15 Desert, NW China were analyzed to investigate formation mechanisms and interpret
16 paleoenvironmental significance. Systematic field sampling and intensive
17 examination showed that the tube-like rhizoliths without morphological structures of
18 plant roots have been placed at the dune soil surface following erosion and weathering
19 but the underground rhizoliths are still connected to the dead *Artemisia* roots.
20 Rhizoliths occurred only along the windward, long gentle slopes of mega-dunes. Their
21 distribution patterns of both types in connection with plant distribution and landscapes
22 have been studied. Their petrological and mineralogical characters were performed in
23 detail using microscopic and spectroscopic techniques (cathodoluminescence,
24 scanning electronic microscopy and energy dispersive X-ray spectroscopy) in
25 laboratory. Altogether, field and laboratory analyses showed that rhizolith cement is
26 calcium carbonate and despite the high porosity of soil and high aridness of climate,

27 soil moisture plays an important role in sustaining *Artemisia* growth and rhizolith
28 formation. Desert rhizoliths can therefore be used as a proxy to infer local soil
29 moisture and plant communities. Moreover, as soil moisture content is related to
30 climate and landscape position, rhizoliths could indirectly be indicators of
31 aboveground environmental conditions, e.g. annual precipitation or humidity.

32

33 **Keywords**

34 Rhizoliths; Dune soil; Deflation and weathering; Formation factors; Soil environment

35

36 **1. Introduction**

37 Rhizolith, an umbrella term, has been used widely and includes many sub-terms,
38 such as root tubules, root casts, root moulds, rhizcretions, root petrifications,
39 rhizolites, rhizomorphs, hypocoatings, rhizohalo, calcified root cells, and
40 *Microcodium* (e.g. Klappa, 1980; Košir, 2004; Kraus and Hasiotis, 2006; Barta, 2011).
41 All these sub-terms are somewhat defined by the morphological features associated
42 with their strata, sediments, or soils where they were persevered. Hence,
43 morphological features of rhizoliths provide important evidence for rhizolith research.
44 The cementing minerals of rhizoliths can be carbonate, silica, clay, jarosite and
45 rhodochrosite-siderite (e.g., Kraus and Hasiotis, 2006; Owen et al., 2008; Bojanowski
46 et al., 2016). Carbonate is the most common one among them (e.g. Sun et al., 2019a).
47 Carbonate rhizoliths occur frequently in Quaternary terrestrial aeolianites of coastal
48 regions (e.g., Klappa, 1980), dunes (e.g., Cramer and Hawkins, 2009; Golubtsov et al.,
49 2019), loess-palaeosol sequences (e.g. Wang et al., 2004; Gocke et al., 2010, 2011,
50 2014; Barta, 2011; Huguet et al., 2012, 2013.), eolian rocks and eolian sand bodies
51 (e.g. Loope, 1988), as well as lake margins (e.g., Owen et al., 2008; Sun et al., 2019a).

52 The texture and composition of Quaternary calcareous dune soils and the climatic
53 settings in desert especially provide optimal conditions for the development of
54 rhizoliths (e.g., [Loope, 1988](#); [Golubtsov et al., 2019](#)), which are abundant and of large
55 size in such environments (e.g., [Klappa, 1980](#); [Rao and Thamban, 1997](#);
56 [Alonso-Zarza et al., 2008](#); [Roberts et al., 2008](#); [Cramer and Hawkins, 2009](#)).

57 Rhizolith architecture and geometry is highly dependent on root type as well as
58 diagenetic and pedogenic parameters. Even though most rhizoliths do not retain the
59 morphological structures of their source plants ([Sarjeant, 1975](#)), they can still be used
60 to make some qualitative and quantitative inferences about the densities, sizes and
61 types of former vegetation ecosystem ([Pfefferkorn and Fuchs, 1991](#); [Rinehart et al.,](#)
62 [2015](#)). Moreover, rhizoliths and the related features are also indicators of paleosols
63 and hence of subaerial vadose environments in ancient successions and are widely
64 used as a tool for paleoenvironmental reconstructions (e.g., [Klappa, 1980](#); [Golubtsov](#)
65 [et al., 2019](#); [Nascimento et al, 2019](#); [Sun et al., 2019a](#)). Yet, the paleoecological and
66 paleoenvironmental studies based on rhizoliths often came across difficulties in
67 interpretation of ^{14}C ages and the stable isotope composition of carbonate cement
68 ([Sun et al., 2019](#)). This is mostly due to the inclusion of lithogenic carbonates from
69 the enclosing deposits and recrystallization of deposited carbonates as rhizolith
70 cement (e.g. [Gocke et al., 2011](#); [Sun et al., 2019b](#); [Golubtsov et al., 2019](#)).
71 Furthermore, the formation mechanisms of rhizoliths in sedimentary environment,
72 especially deserts, still remain highly uncertain ([Sun et al., 2019a](#)).

73 Carbonate rhizoliths ([Sun et al., 2019b](#)) or carbonate root tubes ([Li et al., 2017](#))
74 have been previously investigated in the dunes of the deserts of the Alashan Plateau,
75 especially in the Badain Jaran Desert, Northwest China, ([Gao et al., 1993](#); [Yang, 2000](#);
76 [Yang et al., 2003](#); [Chen et al., 2004](#); [Li et al., 2015a, b](#); [Li et al., 2017](#); [Zhu et al., 2019](#);

77 [Sun et al., 2019b](#)). However, it is still unclear whether the rhizolith records can be
78 effectively used to reconstruct the paleovegetation. Much remains unknown about the
79 impact of fossilization processes, even though these may introduce biases into
80 palaeobiological interpretations. Systemic studies of rhizolith features are still scarce
81 and rudimentary in this area ([Li et al., 2017](#); [Sun et al., 2019b](#)), despite usually large
82 numbers of rhizoliths can be found, especially, on a vast area, which provides good
83 data for rhizoliths study. Most importantly and firstly, rhizoliths study relies on the
84 field description of fossil morphologies to understand the evolutionary history of plant
85 and the fossilization mechanism. Fossil morphologies under field conditions remain
86 poorly understood. Therefore, this project focuses on the intensive analyzing
87 topographical distributions and architectural patterns of rhizoliths in the field. We
88 further examined the macro- and micromorphological characteristics of the cementing
89 minerals of the collected rhizoliths from the desert in laboratory. Altogether, these
90 characterizations aim to achieve a better understanding of rhizoliths formation
91 mechanisms and help in ascertaining the paleoenvironmental interpretations ([Li et al.,](#)
92 [2015a, b](#); [Li et al., 2017](#) ; [Zhu et al., 2019](#)) and ^{14}C dating previously made by using
93 these objects ([Sun et al., 2019b](#)) .

94

95 **2. Geographical setting of Badain Jaran Desert**

96 The Badain Jaran Desert (39°04'15"N to 42°12'23"N, 99°23'18"E to 104°34'02"E)
97 is located in northwestern China ([Fig. 1](#)). This desert comprises the tallest mega-dunes
98 in the world, with interdunal lakes frequently occurring between the dunes. The
99 mega-dunes are especially dense and high in the southeastern part, where they can
100 reach up to 500 m a.s.l ([Wang et al., 2005](#); [Zhu et al., 2010](#); [Yang et al., 2011](#); [Wang et](#)
101 [al., 2015](#)).

102 This desert is an arid desert climate according to the Köppen climate classification
103 (Kottek et al., 2006). The annual precipitation is currently 40–120 mm, falling mainly
104 in summer, and the annual potential evaporation is over 2500 mm. The conventional
105 precipitation (below 5 mm) accounts for approximately 90% of rainfall events (Wang
106 et al., 2013). The mean annual air temperature ranges between 9.8 and 10.2°C. The
107 prevailing cold-arid winter wind direction is northwest and the strongest winds occur
108 in spring and the mean annual wind speed ranges between 2.8 and 4.6 m/s (Fig. 1,
109 Dong et al., 2004; Hu et al., 2015; Zhang et al., 2017).

110 The vegetation of this desert is dominated by shrubs and subshrubs, including
111 *Haloxylon*, *Nitraria*, *Tamarix*, and *Reaumuria* species (Wang et al., 2015a). Perennial
112 woody *Artemisia scoparia* and herbaceous *Psammochloa villosa* and *Phragmites*
113 *australis* grow on the mega-dunes due to the existence of moist sand layers.

114 The grain size of surface sand layers is dominated by well-sorted, rounded,
115 pinky-grey, middle to fine sand, containing only a slight amount of melanocratic
116 minerals (such as hornblende, pyroxene and magnetite), with carbonates minerals
117 being less abundant in the silicate desert sands (Gates et al., 2008; Bai, 2011). The
118 average carbonate content in soils was reported as 4.6 % by Wang et al. (2004) and
119 6.5 % by Sun et al. (2019b). The thickness of the upper dry soil of the mega-dune is
120 only about 20 cm, with a conspicuous moist soil under it. The water content (by
121 weight) is usually 1-5% between 0.2-1.5 m depths (Gu et al., 2004; Zhao et al., 2011;
122 Wang et al., 2019) and is up to 10% at 90 cm depth with well-preserved sand bedding
123 (Liu et al., 2016). At 2.0-8.3 m depth, water contents vary between 2-5.0% (Zhao et
124 al., 2011). The high moisture is in low-lying and flat land, which is benefited from the
125 precipitation infiltration (Zhao et al., 2011).

126 Mega-dunes feature that small transverse dunes superimposed on the larger

127 transverse dunes can be classified into three hierarchical orders (Fig. 2, Dong et al.,
128 2009). Order III corresponds to an erosion belt, next to the shore of lakes; Order II is a
129 belt of both erosion and deposition above Order III; and Order I is a deposition belt.
130 Order III and II are situated on the windward gentle slopes and Order I dunes
131 correspond to the leeward slopes (slipface), which are steep and even.

132 **3. Field survey, examination and sampling**

133 Owing to the vast sand sea area, poor accessibility and the dominance of an
134 extremely arid climate, field explorations are only conducted in zones located in the
135 southeastern part next to the desert margin (Fig. 1). Along the exploration route of
136 about 400 km in the hinterland of the desert, rhizoliths were only found at four sites
137 (Fig. 1, red points A-D), which form a profile from the central part to the margin of
138 the desert (Sites A-B-C-D, Fig. 1). Detailed survey and examinations of landscape,
139 vegetation, modern root, sediment/soil, rhizolith exposure and morphology were
140 carried out around the four sites. At each site the most representative samples of
141 carbonate rhizoliths and their typical features were intensively described and
142 photographed. Typical rhizoliths were delicately handled for field photographing and
143 transported to the laboratory.

144

145 **4. Laboratory analyses**

146 Eight rhizolith samples (two from each site) were analyzed in the laboratory. The
147 applied analytical methods were microscopy, cathodoluminescence, staining,
148 scanning electronic microscopy - energy dispersive X-ray spectroscopy, which are all
149 performed at the Institute of Northwest Petroleum Geology, Lanzhou, China. Zeiss
150 Scope A1 microscope was used to examine mineral crystal morphology. A staining
151 method (a mixture of Alizarin red S and potassium ferricyanide) was used to analyze

152 the carbonate minerals in the cement under the microscope (Dickson 1965, 1966);
153 CITL CL8200 MK5 cathodoluminescence (CL) instrument was used to investigate the
154 luminescence color of cement. The micro-scale morphology and chemical
155 compositions of the rhizolith cement were determined by scanning electron
156 microscopy (SEM; FEI Quanta 450) coupled with Energy dispersive X-ray
157 spectroscopy (EDS). Each rhizolith specimen was first impregnated with and without
158 resin cover respectively, cut and polished to 4.8 cm×2.8 cm slices made from
159 transverse sections, and then described by polarizing microscopy and
160 cathodoluminescence. Fragments of the rhizoliths were gold coated, and then analyzed
161 by SEM coupled with EDS.

162

163 **5. Results**

164 ***5.1. Field features of rhizoliths***

165 ***5.1.1 Geomorphological distributions of rhizolith outcrops***

166 In Site A (Sumujilin Lake, 39°48'N, 102°26'E), the rhizolith outcrops were
167 found at the foot of the windward gentle slope of the mega-dune, located east of the
168 Sumujilin Lake (Fig. 3a). This site is on the eroded area of Order III, which is flatter
169 than the upper zone along the windward slope (Figs. 2a; 3a).

170 In Site B (Nuoertu Lake, 39°46'N, 102°27'E), rhizolith outcrops were found
171 along the upper gentle slope (Order II) of the mega-dune on the east side of the
172 Nuoertu Lake (Fig. 4a).

173 In Site C (Baoritaolegai Lakes, 39°35'N, 102°28'E), rhizoliths occur along the
174 whole windward gentle slope (Order III,II) of a mega-dune, south of Baoritaolegai
175 Lake(Fig. 5a).

176 Site D (39°27'N, 102°26'E) is near to (6 km to the east) the Gate of the Badain

177 Jaran Desert National Geological Park, which is located at the southern-eastern
178 margin of the desert, where small low dunes dominate (Figs. 1; 6a). Rhizolith
179 outcrops occur within the swales between the dunes. In addition to *Psammochloa*,
180 *Artemisia* is the dominant vegetation in the area, usually growing in the gentle
181 windward slopes of the swales (Fig.6a).

182 **5.1.2 Field characteristics of rhizolith specimen**

183 In Site A, rhizolith fragments are eroded out of the sand, together with caliche
184 fragments (sand soil cemented by carbonates) (Fig. 3b). This slope of the mega-dune
185 covered by fragments of the rhizolith and caliche is purple-brown, obviously different
186 from the beige color of the above dune sand along the whole slope (Fig. 3a). The
187 fragments of typical rhizoliths are hard and varnished brightly. Their centers are
188 tubular cavities (Fig. 3c). Except sparse *Psammochloa villosa*, no other vegetation
189 grows in the area of the rhizolith outcrops.

190 In Site B, at low altitude, rhizoliths occurred mostly as enormous coarse brown
191 fragments, similar to Site A. At high altitude, the rhizolith tubes are long and white,
192 branchy or separated (Fig. 4b) in some places. Relicts of fine root hairs were observed.
193 (Fig. 4c).

194 In Site C, besides usual fragments of straight short tubes, thin tubes with many
195 lateral fine root hairs and thick tubes with hemp rope-like striations were found (Fig.
196 5b). Primary rhizoliths were found under semi-arid/moist sandy soil (depth ~ 10 cm)
197 at locations where *Artemisia* was rooted. They are softer and thicker than those eroded
198 out of soil (Fig. 5c). The eroded-out tubes were constituted of either double cemented
199 layers or often a singular layer (Fig. 5d). In addition, the walls of the rhizoliths
200 containing plant relicts were thicker than those without root relicts (Fig. 5e).

201 In Site D (39°27'N, 102°26'E), rhizolith fragments are present on the sand

202 surface (Fig. 6b) and a few of them are in situ vertically within the sand (Fig. 6b). The
203 vertical rhizoliths below ground correspond to pristine rhizoliths, without any signs of
204 erosion and insolation, and are much thicker than those found aboveground (Fig. 6c).
205 Once broken, the root remains within the tubes of the pristine rhizoliths appear as
206 surrounded by white haloes of cement (Fig. 6d).

207 ***5.2. Laboratory results***

208 Two rhizoliths from each site were chosen randomly for laboratory analyses.
209 Staining and cathodoluminescence analyses confirmed that the cementing minerals of
210 the rhizoliths are carbonate, and the clastic particles are quartz and feldspars (Fig. 7a,
211 b). Cathodoluminescence observations indicated that calcium ions for carbonate
212 cement should come from the chemical weathering of feldspars (Fig. 7b). SEM and
213 EDS analyses showed that the carbonate cement was mainly calcite and
214 low-magnesium calcite, with only a slight amount of NaCl (Figs. 7c, d). The bulk
215 characteristics of the rhizoliths from the four sites were generally similar, with
216 carbonate minerals being the cement of hard rhizoliths formed in the dune sands.

217

218 **6. Discussion**

219 ***6.1. Classification and environmental implications of rhizoliths***

220 The rhizoliths from the four investigated sites were classified as tubules, or tubes
221 (Li et al., 2015a, b) based on their field features. Only a few of dead root remains
222 were found in the tubes, which indicate no root petrification or body fossilization took
223 place through diagenesis. The central voids were occasionally filled with loose
224 aeolian sand after weathering. Hypocoating occurred through pedogenesis forming
225 secondary carbonates as hard tube walls, as confirmed by SEM-EDS analyses (calcite

226 and low-Mg calcite being predominant; [Fig. 7d](#)).

227 According to the rhizoliths formation locations, two types of rhizoliths, present in
228 different zones of the soil, were observed: (i) primary ones and (ii)
229 eroded-out-weathered ones. Primary rhizoliths are in situ in the soil, which allowed
230 the preservation of their primary state - vertical but also rarely horizontal, soft and
231 thick ([Figs. 5c; 6b, c, d](#)). In contrast, the eroded-out-weathered rhizoliths were
232 apparent out of the soil, weathered and eroded at the surface, being hard and thin. This
233 indicates that strong wind deflation eroded the surface soil around the sampling site,
234 likely removing former luxurious vegetation.

235 The eroded-out-weathered rhizoliths were further sub-classified into two types
236 based on their field features: (i) those with brown-grey colors, hard and varnished
237 ([Figs. 3c; 5d](#)); (ii) those with white-grey colors, fragile, and presenting fissures ([Figs.](#)
238 [4b, c; 5e; 6b](#)). The two subtypes of rhizoliths were formed and subjected to diagenesis
239 in the same type of environment (mega-dunes) and share similar mineralogical
240 characteristics based on SEM-EDS analyses. Nevertheless, the varnish observed on
241 the first subtype of rhizoliths, hard in nature, indicates that they were formed earlier
242 than the second, more fragile subtype. Indeed varnish formation takes a long time,
243 with a stable geomorphic surface subjected to sunlight radiation ([Watchman, 2000;](#)
244 [Liu & Broecker, 2000, 2007; Xu et al., 2019](#)). Of course, varnish might also depend
245 on the type and mineralogy of the sediment and oxidation conditions. The laboratory
246 results confirmed that all rhizoliths are constituted of calcium carbonate. Therefore,
247 the first subtype of rhizoliths were eroded and weathered for a longer time than the
248 second one, consistent with geomorphological processes, i.e. the fact that hard,
249 varnished rhizoliths occurred predominantly in Order III belts.

250 These different features suggest that the rhizoliths were first formed at shallow

251 soil depth and later eroded out, with concomitant or subsequent modification of the
252 root structure. The double layer walls (Fig. 5d) and the relicts (Figs. 5c,e) of the
253 former roots further suggest that rhizoliths were likely formed around *Artemisia spp.*
254 based on comparison with the characteristics of modern desert *Artemisia spp.* roots (cf.
255 section 6.3).

256 **6.2. Rhizolith distribution pattern**

257 In the inner parts (Site A, B, C, Fig. 1) of the desert, rhizolith outcrops occur only
258 in the windward gentle slopes of mega-dunes (Figs. 3a; 4a; 5a), on Orders II and III
259 belts as the main outcrop areas. On Order I belts, rhizoliths were not found in the
260 leeward slopes of the mega-dunes, which are steep and subjected to higher
261 sedimentation rates than the windward slopes, with vegetation being quickly buried.
262 Therefore, slipping sands in the leeward slopes do not provide a stable soil
263 environment for vegetation and thus rhizolith formation.

264 In the southeastern margin of the desert (Fig. 1), rhizolith outcrops also occur, but
265 only in the low dune areas and in the windward slopes of the swales where erosion
266 takes place (Fig. 6a). No vegetation and rhizoliths were also observed in the leeward
267 slopes.

268 Therefore, wind deflation and landforms are key parameters influencing the
269 formation of rhizolith outcrops in the desert. The outcrops occur only in the windward
270 slopes of dunes or in the swale beds and depressions, where deflation and erosion are
271 transporting surface soil away, resulting in the exposure of the buried rhizoliths at the
272 surface.

273 **6.3. Vegetation**

274 Rhizolith outcrops generally occur in the same area as living/dead *Artemisia*
275 bushes rather than any other plants, or alternatively in bare zones without any plants.

276 The morphologies of the rhizoliths and their texture as well as their surface and inner
277 structures (Figs. 4b, c; 5b, c, e) are identical or similar to those of modern living
278 *Artemisia* roots, which are woody roots with cortex, stele, xylem but without a central
279 hollow. Other kinds of vegetation such as *Psammochloa* and *Phragmites* also grow at
280 or near the sampling sites, but the latter have herbaceous roots with a central hollow,
281 in contrast with the collected rhizoliths.

282 The present results suggest that the decomposition of the dead *Artemisia* roots
283 have triggered the rhizolith formation, where carbonate crystallization took place.
284 *Artemisia* root decay or rhizosphere fungi may have provided oxalic acid and calcium
285 oxalate crystals, with the microbial transformation of oxalate into carbonates leading
286 to an increase in soil pH (Verrecchia et al., 2006; Dupraz et al., 2009; Huang et al.,
287 2015). Alternatively, *Artemisia* dead roots might have provided a stable channel for
288 continuously evaporation from the subsoil and so, calcification along the roots.

289 **6.4. Soil and related environmental conditions**

290 The field investigation suggested that soil moisture and the high porosity of
291 sand provided the water and air required to sustain plant live and rhizolith formation,
292 with in turn redox conditions favoring slow root decomposition and yielding enough
293 CO₂ gas for HCO₃⁻ production.

294 Plants are growing in the dunes, which should not be considered as classical
295 soils, but rather as aeolian sediments as defined in sedimentology and petrology.
296 During their formation, the desert sediments are strongly affected by deflation due to
297 their light texture and low density. The high dust accumulation rates do not let enough
298 time for complete soil development (Sycheva, 2006). Consequently, quick denudation,
299 erosion and deposition in the mega-dunes of the Badain Jaran desert prevent soil
300 formation in this area.

301 The surface soils of the desert are aeolian loose sands with high porosity.
302 Normally, below ca. 20-40 cm depth, the soils are wet (water content ~10%) (Wen et
303 al., 2014; Wang et al., 2015a; Liu et al., 2016). Unfortunately, no systematic soil
304 moisture measurement was performed in the desert, as it is too vast. Nevertheless,
305 previous studies (Wen et al., 2014; Wang et al., 2015b; Liu et al., 2016) confirmed
306 that the soil moisture in some swales and depressions is sufficient to allow *Artemisia*
307 growth and rhizolith formation in windward slopes. It should be noted that soil
308 moisture of the lower swales and depressions was likely higher than in the higher
309 dunes based on vegetation distribution. The origin of soil and lake water remains
310 controversial, whether from precipitation, condensation of atmospheric water, or
311 groundwater (Ma & Edmunds., 2006; Wen et al., 2014; Jiao et al, 2015; Zhang et al.,
312 2017; Yue et al., 2019).

313 Vegetation often grows in small patches or bands which are defined by the dune
314 landforms. The regional landscape is characterized by mobile dunes and interdune
315 lowlands. Stable and semi-stable eolian sandy soils are the dominant form. Previous
316 results suggested that the effect of soil factors on vegetation characteristics was
317 relatively weak and it is not possible to determine whether climate (e.g., the
318 precipitation or temperature during the growing season) or geomorphology (e.g.,
319 parent materials) controls the vegetation communities in the desert (Wang et al.,
320 2015b).

321 **6.5. Climate**

322 Modern climate of the desert is characterized by very low precipitation and
323 high evaporation with strong northwestern wind. Comparatively, the sub-landscapes
324 (mega-dunes), soil and vegetation on the vast desert are similar and even; but, the
325 rhizolith outcrops are not evenly distributed everywhere in the desert. This shows that

326 local factors play a crucial role in rhizolith formation under arid climate. Rhizoliths
327 are formed in loess sequences, under a more humid climate (e.g. Gocke et al., 2010)
328 than in deserts, but also in the waterlogged soils of lake environments (Sun et al.,
329 2019a). That implies that rhizoliths do not need specific aboveground climatic
330 conditions. In the Badain Jaran Desert, the arid climate and intensive evaporation may
331 favor carbonate precipitation and crystallization around dead roots in the highly
332 porous sandy soils. This would explain the vast amount of rhizolith outcrops observed
333 in the desert dunes.

334 ***6.6. Diagenesis and pedogenesis of rhizoliths in the sand-sedimentary*** 335 ***environment***

336 The above mentioned field features of rhizoliths from the Badain Jaran desert
337 suggest that they were formed through diagenesis and pedogenesis in loose
338 windblown sand sediments, at shallow depth and with open redox environmental
339 conditions. The root relicts or hollows within the rhizoliths (Figs. 4c; 5b, c, e; 6d)
340 indicate that the deceased roots served as an organic nucleus for carbonate
341 precipitation within the rhizosphere, leading to the preservation of the root structure.

342 Based on the theory proposed by Dupraz et al. (2009), it can postulated that the
343 organic carbon of the deceased roots was oxidized under optimal oxygen and soil
344 moisture (i.e. weak redox) conditions at suitable depths, leading to the production of
345 CO₂ used for CaCO₃ formation. Free Ca²⁺ ions could be derived from authigenic
346 carbonates after *in situ* chemical weathering of soil primary silicate minerals such as
347 feldspar, mica, amphibole and pyroxene (Dupraz, et al., 2005; Liu et al., 2011; Jin et
348 al., 2015) due to low pH caused by organic matter decomposition and
349 force-of-crystallization (Durand et al., 2010; Monger, 2014) and from the dissolution
350 of *in situ* primary lithogenic carbonate rocks debris such as limestone and dolomite

351 (Sun et al., 2019b). The presence of free Ca^{2+} and local alkaline conditions through
352 seasonal upwelling of alkaline water followed by evaporation (Arp et al., 2003) could
353 lead to the nucleation of calcium carbonate on the root organic matrix (Arp et al.,
354 1999a, b). The initiation of this process depends on the initial chemical composition
355 of the root organic matter, as some organic functional groups have a high metal
356 binding potential, inhibiting calcium carbonate mineral formation, whereas some
357 others are more prompt to biotic and abiotic degradation, favoring calcium carbonate
358 precipitation (Dupraz and Visscher, 2005).

359 Previous studies in the desert suggested that rhizoliths could be used as an
360 indicator of precipitation intensity (Gao et al., 1993; Yang, 2000; Yang et al., 2003;
361 Chen et al., 2004; Li et al., 2015a, b; Li et al., 2017; Zhu et al., 2019). Therefore, this
362 work combined with previous research (Sun et al., 2019b) confirmed that such
363 application is still uncertain. Rhizolith formation is strongly dependent on local
364 conditions. Rhizolith formation is not a single function of climate but rather multiple
365 environmental factors, e.g., geomorphology of dunefields, vegetation type, strength of
366 pedogenesis, and existence of diagenesis. They could only be used as a local proxy of
367 soil moisture and vegetation coverage, but cannot be applied to reconstruct past
368 environmental conditions in such vast areas.

369

370 **7. Conclusions and outlook**

371 The formation mechanisms of rhizolith in desert remain poorly investigated,
372 despite the large abundance of these objects in such settings and their importance for
373 paleoenvironmental reconstructions. This study combined field and laboratory
374 observations to better characterize the different types of rhizoliths in the Badain Jaran
375 desert and constrain their formation conditions. Primary rhizoliths were shown to be

376 formed underground in soil of Badain Jaran desert before being brought out at the
377 surface of the dunes where they are deflated and weathered due to the loose nature of
378 the sandy soil and strong winds. Most of the rhizoliths presented a tube shape and
379 occurred only in some parts of the desert, along the windward gentle slopes of
380 mega-dunes. In contrast, the environmental conditions along the leeward steep slopes
381 of the mega-dunes do not favor rhizoliths formation. Rhizoliths were formed only
382 around dead roots of *Artemisia*. Rhizoliths and *Artemisia* bushes were indeed found to
383 systematically co-exist in the swales and depressions between sub-dunes. Soil
384 moisture plays an important role in *Artemisia* growth as well as rhizolith formation,
385 taking into account the high porosity of sand soil and aridness of the climate. The
386 results of the present study suggest that rhizoliths can only be used as a proxy for
387 local soil moisture and vegetation cover, but are not able to indicate climate
388 conditions directly above ground in a vast area, although the desert climate and the
389 windward gentle slopes of mega-dunes are homogeneous or similar.

390 Further work is required to better understand the formation mechanism of the
391 rhizoliths in deserts, taking into account the interrelations between vegetation type,
392 environmental and climatic parameters.

393

394 **Acknowledgements**

395 We express special gratitude to the anonymous reviewers and the Editor-in-Chief,
396 Professor Karl Stahr for their constructive and valuable comments to improve the
397 paper. We would like to thank Wenhui Xue and Wentao Pei for their assistance during
398 field exploration; Pu Wang for lab work; Professor Lijun Ling for photographing;
399 Professor Hong Wang and Doctor Hanan Badawy for their detail revisions; Professor
400 Viktor Golubtsov, and Doctor Eron Raines for their comments. Funding for this work

401 was provided by National Natural Science Foundation of China [No. 41561046 and
402 M-0069 (Sino-German Mobility)].

403

404 **References**

405 [Alonso-Zarza, A.M., Genise, J.F., Cabrera, M.C., Mangas, J., Martín-Pérez, A.,
406 Valdeolmillos, A., Dorado-Valiño, M., 2008. Mega-rhizoliths in Pleistocene
407 aeolian deposits on Gran Canaria \(Spain\): ichnological and palaeoenvironmental
408 significance. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 265, 39-61.](#)

409 [Arp, G., Reimer, A., Reitner, J., 1999a. Calcification in cyanobacterial biofilms of
410 alkaline salt lakes. *European J. Phycol.* 34, 393-403.](#)

411 [Arp, G., Thiel, V., Reimer, A., Michaelis, W., Reitner, J., 1999b. Biofilm
412 exopolymers control microbialite formation at thermal springs discharging into
413 the alkaline Pyramid Lake, Nevada, USA. *Sediment. Geol.* 126, 159-176.](#)

414 [Arp, G., Reimer, A., Reitner, J., 2003. Microbialite formation in seawater of increased
415 alkalinity, Satonda Crater Lake, Indonesia. *J. Sediment. Res.* 73, 105-127.](#)

416 [Bai, Y., 2011. Internal Structure and Formation Process of Mega-Dunes in the Badain
417 Jaran Desert \(in Chinese with English abstract\). Doctoral dissertation. Lanzhou
418 University.](#)

419 [Barta, G., 2011. Secondary carbonates in loess-paleosoil sequences: A general review.
420 *Centr. European J. Geosci.* 3\(2\), 129-146.](#)

421 [Bojanowski, M.J., Jaroszewicz, E., Kosir, A., Lozinski, M., Marynowski, L.,
422 Wysocka, A., Derkiwski, A., 2016. Root-related rhodochrosite and concretionary
423 siderite formation in oxygen-deficient conditions induced by a ground-water table
424 rise. *Sedimentol.* 63 \(3\), 523–551.](#)

425 [Chen, J.S., Li, L., Wang, J.Y., Barry, D.A., Sheng, X.F., Gu, W.Z., Zhao, X., Chen, L.,](#)

- 426 2004. Groundwater maintains dune landscape. *Nature* 432 (7016), 459-460.
- 427 Cramer, M.D., Hawkins, H. J., 2009. A physiological mechanism for the formation of
428 root casts. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 274(3-4), 125-133.
- 429 Dickson, J. D. D., 1965. A modified staining technique for carbonate in thin section.
430 *Nature* 205, 587
- 431 Dickson, J.D.D., 1966. Carbonate identification and diagenesis as revealed by staining.
432 *J. Sediment. Petrol.* 61, 626-505.
- 433 Dong, Z.B., Qian, G.Q., Luo, W.Y., Zhang, Z.C., Xiao, S.C., Zhao, A.G., 2009.
434 Geomorphological hierarchies for complex mega-dunes and their implications for
435 mega-dune evolution in the Badain Jaran Desert. *Geomorphol.* 106, 180-185.
- 436 Dong, Z.B., Wang, T., Wang, X.M., 2004. Geomorphology of the megadunes in the
437 Badain Jaran Desert. *Geomorphol.* 60, 191-203.
- 438 Dupraz, C. , Reid, R. P. , Braissant, O. , Decho, A. W. , Norman, R. S. , & Visscher, P.
439 T., 2009. Processes of carbonate precipitation in modern microbial mats. *Earth*
440 *Sci. Rev.* 96(3), 141-162.
- 441 Dupraz, C., Visscher, P.T., 2005. Microbial lithification in marine stromatolites and
442 hypersaline mats. *Trends Microbiol.* 13, 429-438.
- 443 Durand, N., Monger, H.C., Canti, M.G., 2010. 9-Calcium carbonate features. In:
444 Stoops, G., Marcelino, V., Mees, F. (Eds.), *Interpretation of*
445 *Micromorphological Features of Soils & Regoliths.* Elsevier, pp. 149-194.
- 446 Gao, S., Chen, W., Jin, H., Dong, G., Li, B., Yang, G., Liu, L., Guan, Y., Sun, Z., Jin,
447 J.,1993. Preliminary study on the Holocene desert evolution in the NW boundary
448 of the Asia monsoon (in Chinese with English abstract). *Ch. Sci. Ser. D* 23,
449 202-208.
- 450 Gates, J., Edmunds, M., Darling, G., Ma, J., Pang, Z., Young, A., 2008. Conceptual

- 451 model of recharge to southeastern Badain Jaran Desert groundwater and lakes
452 from environmental tracers. *Appl. Geochem.* 23, 3519-3534.
- 453 Gocke, M., Kuzyakov, Y., Wiesenberg, G.L.B., 2010. Rhizoliths in loess – evidence
454 for postsedimentary incorporation of root-derived organic matter in terrestrial
455 sediments as assessed from molecular proxies. *Org. Geochem.* 41, 1198-1206.
- 456 Gocke, M., Pustovoytov, K., Kühn, P., Wiesenberg, G.L.B., Löscher, M., Kuzyakov,
457 Y., 2011. Carbonate rhizoliths in loess and their implications for
458 paleoenvironmental reconstruction revealed by isotopic composition: $\delta^{13}\text{C}$, ^{14}C .
459 *Chem. Geol.* 283, 251-260.
- 460 Gocke, M., Peth, S., Wiesenberg, G.L.B., 2014. Lateral and depth variation of loess
461 organic matter overprint related to rhizoliths — revealed by lipidmolecular
462 proxies and X-ray tomography. *Catena* 112, 72-85.
- 463 Golubtsov, V. A., Khokhlova, O. S., & Cherkashina, A. A., 2019. Carbonate
464 Rhizoliths in Dune Sands of the Belaya River Valley (Upper Angara Region).
465 *Eurasian Soil Sci.* 52(1), 83-93.
- 466 Gu, W.Z., Chen, J.S., Wang, J.Y., Zhao, X., Xie, M., Lu, J., Seiler, K. P., 2004.
467 Challenge from the appearance of vadose water within the surface layer of
468 megadunes, Badain Jaran dune desert, Inner Mongolia (in Chinese with English
469 abstract). *Adv. Water Sci.* 15(6), 695–699
- 470 Hu, W., Wang, N., Zhao, L., Ning, K., Zhang, X., Sun, J., 2015. Surface energy and
471 water vapor fluxes observed on a megadune in the Badain Jaran Desert, *Ch. J.*
472 *Arid Land* 7, 579-589.
- 473 Huang, J., Huang, C., Liebman, M., 2015. *J. Tradi. Ch. Med.* 35(5), 594-599.
- 474 Huguet, A., Gocke, M., Derenne, S., Fosse, C., & Wiesenberg, G. L., 2013.
475 Root-associated branched tetraether source microorganisms may reduce estimated

- 476 paleotemperatures in subsoil. *Chem. Geol.* 356, 1-10.
- 477 Huguet, A., Wiesenberg, G. L., Gocke, M., Fosse, C., & Derenne, S., 2012. Branched
478 tetraether membrane lipids associated with rhizoliths in loess: Rhizomicrobial
479 overprinting of initial biomarker record. *Org. Geochem.* 43, 12-19.
- 480 Jiao, J. J., Zhang, X., & Wang, X., 2015. Satellite-based estimates of groundwater
481 depletion in the Badain Jaran Desert, *Ch. Sci. Rep.* 5(1), 8960
- 482 Jin, L., Edmunds, W. M., Lu, Z., & Ma, J., 2015. Geochemistry of sediment moisture
483 in the Badain Jaran desert: Implications of recent environmental changes and
484 water-rock interaction. *Appl. Geochem.* 63, 235-247.
- 485 Klappa, C.F., 1980. Rhizoliths in terrestrial carbonates: classification, recognition,
486 genesis and significance. *Sedimentol.* 26, 613-629.
- 487 Kottek, M., J. Grieser, C. Beck, B. Rudolf, and F. Rubel, 2006: World Map of the
488 Köppen-Geiger climate classification updated. *Meteorol. Z.* 15, 259-263. DOI:
489 10.1127/0941-2948/2006/0130.
- 490 Košir, A., 2004. *Microcodium* revisited: root calcification products of terrestrial plants
491 on carbonate-rich substrates. *J. Sediment. Res.* 74 (6), 845-857.
- 492 Kraus, M.J. and Hasiotis, S.T., 2006. Significance of different modes of rhizolith
493 preservation to interpreting paleoenvironmental and paleohydrological setting:
494 Examples from paleogene paleosols, Bighorn Basin, Wyoming, U.S.A. *J.*
495 *Sediment. Res.* 76, 633-646.
- 496 Li, Z., Wang, N., Cheng, H., Ning, K., Zhao, L., Li, R., 2015a. Formation and
497 environmental significance of late Quaternary calcareous root tubes in the deserts
498 of the Alashan Plateau, northwest China. *Quat. Int.* 372, 167-174.
- 499 Li, Z., Wang, N., Li, R., Ning, K., Cheng, H., & Zhao, L. 2015b. Indication of
500 millennial-scale moisture changes by the temporal distribution of Holocene

-
- 501 calcareous root tubes in the deserts of the Alashan Plateau, Northwest China.
502 *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 440, 496-505.
- 503 Li, Z., Gao, Y., & Han, L., 2017. Holocene vegetation signals in the Alashan Desert of
504 northwest China revealed by lipid molecular proxies from calcareous root tubes.
505 *Quat. Res.* 88(1), 60-70.
- 506 Liu, T., & Broecker, W.S., 2000. How fast does rock varnish grow? *Geol.* 28 (2),
507 183-186.
- 508 Liu, T., & Broecker, W.S., 2007. Holocene rock varnish microstratigraphy and its
509 chronometric application in the drylands of western USA. *Geomorpho.* 84, 1-21.
- 510 Liu, Z.H., Dreybrodt, W., Liu, H., 2011. Atmospheric CO₂ sink: silicate weathering or
511 carbonate weathering? *Appl. Geochem.* 26, 292-294.
- 512 Liu, S., Lai, Z., Wang, Y., Fan, X., Wang, L., Tian, M., Jang, Y., & Zhao, H., 2016.
513 Growing pattern of mega-dunes in the Badain Jaran Desert in China revealed by
514 luminescence ages. *Quat. Int.* 410, 111-118.
- 515 Loope, D. B., 1988. Rhizoliths in ancient eolianites. *Sed. Geol.* 56, 301-314.
- 516 Ma, J., & Edmunds, W. M., 2006. Groundwater and lake evolution in the Badain
517 Jaran Desert ecosystem, Inner Mongolia. *Hydrogeol. J.* 14, 1231-1243.
- 518 Monger, H. C., 2014. Soils as generators and sinks of inorganic carbon in geologic
519 time. In: A.E. Hartemink and K. McSweeney (eds.), *Soil Carbon. Prog. Soil*
520 *Sci.*, 27-36.
- 521 Nascimento, D. L., Batezelli, A., & Ladeira, F. S., 2019. The paleoecological and
522 paleoenvironmental importance of root traces: Plant distribution and topographic
523 significance of root patterns in Upper Cretaceous paleosols. *Catena* 172, 789-806.
- 524 Owen, R.A., Owen, R. B., Renaut, R. W., Scott, J. J., Jones, B., Ashley, G. M., 2008.
525 Mineralogy and origin of rhizoliths on the margins of saline, alkaline Lake

- 526 Bogoria, Kenya Rift Valley. *Sed. Geol.* 203, 143-163.
- 527 Pfefferkorn, H.W., Fuchs, K., 1991. A field classification of fossil plant substrate
528 interactions. In: *Neues Jahrbuch für Geologie und Paläontologie,*
529 *Abhandlungen* 183, 17-36.
- 530 Rao, V. P. and Thamban, M., 1997. Dune associated calcrete, rhizoliths and paleosols
531 from the Western Continental Shelf of India. *J. Geo. Soc. Ind.* 49, 297-306.
- 532 Rinehart, L.F., Lucas, S.G., Tanner, L., Nelson, W.J., Elrick, S.D., Chaney, D.S.,
533 DiMichele, W.A., 2015. Plant architecture and spatial structure of an early
534 Permian woodland buried by flood waters, Sangre de Cristo Formation, New
535 Mexico. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 424, 91-110.
- 536 Roberts, D. L. , Bateman, M. D. , Murray-Wallace, C. V. , Carr, A. S. , & Holmes, P.
537 J., 2008. Last interglacial fossil elephant trackways dated by OSL/AAR in coastal
538 aeolianites, Still Bay, South Africa. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*
539 *257(3)*, 261-279.
- 540 Sarjeant, W.A.S., 1975. Plant trace fossils. In: Frey, R.W. (Ed.), *The Study of Trace*
541 *Fossils. A Synthesis of Principles, Problems, and Procedures in Ichnology.*
542 Springer-Verlag, New York, pp. 51-69.
- 543 Sun, Q., Xue, W., Zamanian, K., Colin, C., Duchampalphonse, S., & Pei, W. 2019a.
544 Formation and paleoenvironment of rhizoliths of Shiyang River Basin, Tengeri
545 Desert, NW China. *Quat. Int.* 502, 246-257.
- 546 Sun, Q.F., Wang, H., Zamanian, K., 2019b. Radiocarbon age discrepancies between
547 the carbonate cement and the root relics of rhizoliths from the Badain Jaran and
548 the Tengeri deserts, Northwest China. *Catena* 180, 263-270.
- 549 Sycheva S.A., 2006. Long-term pedolithogenic rhythms in the Holocene. *Quat. Int.* 152,
550 181-191.

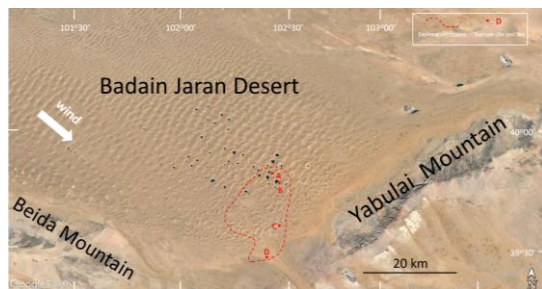
-
- 551 Verrecchia EP, Braissant O, Cailleau G., 2006. The oxalate–carbonate pathway in soil
552 carbon storage: the role of fungi and oxalotrophic bacteria. In book: *Fungi in*
553 *Biogeochemical Cycles*. Editor: G.M.Gadd. Chapter: 12. Cambridge University
554 Press. Cambridge. DOI: 10.1017/CBO9780511550522.013
- 555 Wang, X., Zhao, H., Yang, H., & Wang, K. 2019. Optical dating reveals that the
556 height of Earth’s tallest megadunes in the Badain Jaran Desert of NW China is
557 increasing. *J. Asian Earth Sci.* 185, 104025
- 558 Wang, F., Sun, D., Chen, F., Bloemendal, J., Guo, F., Li, Z., Zhang, Y., Li, B., &
559 Wang, X., 2015. Formation and evolution of the Badain Jaran Desert, North
560 China, as revealed by a drill core from the desert centre and by geological
561 survey. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 426, 139-158.
- 562 Wang, M., Dong, Z., Luo, W., Lu, J., & Li, J., 2015a. Spatial variability of vegetation
563 characteristics, soil properties and their relationships in and around China’s
564 Badain Jaran Desert. *Env. Earth Sci.* 74(9), 6847-6858.
- 565 Wang, M., Dong, Z., Lu, J., Li, J., Luo, W., Cui, X., Zhang, Y., Liu, Z., Jiao, Y.,
566 Yang, L., 2015b. Vegetation characteristics and species diversity around the
567 Badain Jaran Desert (In Chinese with English abstract). *J. Desert Res.* 35,
568 1226-1233.
- 569 Wang N A, Ma N, Chen H B, et al. 2013. A preliminary study of precipitation
570 characteristics in the hinterland of Badain Jaran Desert. *Adv. Water Sci.* 24(2),
571 153-160.
- 572 Wang, P., Clemens, S., Beaufort, L., Braconnot, P., Ganssen, G., Jian, Z., Kershaw, P.,
573 Sarnthein, M., 2005. Evolution and variability of the Asian monsoon system:
574 state of the art and outstanding issues. *Quat. Sci. Rev.* 24, 595-629.
- 575 Wang, Y., Cao, J., Zhang, X., Shen, Z., Mei, F., 2004. Carbonate content and carbon

- 576 and oxygen isotopic composition of surface soil in the dust source regions of
577 China (In Chinese with English abstract). *Mar. Geol. Quat. Geol.* 24, 113-117.
- 578 Wang, H., Ambrose, S.H., Fouke, B.W., 2004. Evidence of long-term seasonal climate
579 forcing in rhizolith isotopes during the last glaciation. *Geophys. Res. Lett.* 31(13),
580 718-730.
- 581 Watchman, A., 2000. A review of the history of dating rock varnishes. *Earth Sci. Rev.*
582 49(1-4), 261-277.
- 583 Xu, X., Li, Y., Li, Y., Lu, A., Qiao, R., Liu, K., Ding, H., & Wang, C., 2019.
584 Characteristics of desert varnish from nanometer to micrometer scale: A
585 photo-oxidation model on its formation. *Chem. Geol.* 522, 55-70.
- 586 Wen, J., Su, Z., Zhang, T., Tian, H., Zeng, Y., Liu, R., Kang, Y., & Der Velde, R. V.,
587 2014. New evidence for the links between the local water cycle and the
588 underground wet sand layer of a mega-dune in the Badain Jaran Desert, Ch. *J.*
589 *Arid Land* 6(4), 371-377.
- 590 Yang, X., Scuderi, L., Paillou, P., Liu, Z., Li, H., Ren, X., 2011. Quaternary
591 environmental changes in the drylands of China – A critical review. *Quat. Sci.*
592 *Rev.* 30, 3219-3233.
- 593 Yang, X., Liu, T., & Xiao, H., 2003. Evolution of megadunes and lakes in the Badain
594 Jaran Desert, Inner Mongolia, China during the last 31,000 years. *Quat. Int.*
595 104(1), 99-112.
- 596 Yang, X., 2000. Landscape evolution and precipitation changes in the Badain Jaran
597 Desert during the last 30,000 years. *Ch. Sci. Bull.* 45, 1042-1047.
- 598 Yue, D.P., Zhao, J.B., Ma, Y.D., Huang, X.G., Shao, T.J., Luo, X.Q., Ma, A.H., 2019.
599 Relationship between landform development and lake water recharge in the
600 Badain Jaran Desert, China. *Water* 11, 1999.

- 601 <https://www.mdpi.com/2073-4441/11/10/1999>
- 602 Zhang, K., Cai, D., Ao, Y., An, Z., & Guo, Z., 2017. Local circulation maintains the
603 coexistence of lake-dune pattern in the Badain Jaran desert. *Sci. Rep.* 7, 40238.
- 604 Zhao, J., Shao, T., Hou, Y., 2011. Moisture content of sand layer and its origin in a
605 mega-dune area in the Badain Jaran Desert (in Chinese with English abstract). *J.*
606 *Nat. Resour.* 26,694–702
- 607 Zhu, R., Li, Z., Gao, Y., Chen, Q., & Yu, Q., 2019. Variations in chemical element
608 compositions in different types of Holocene calcareous root tubes in the Tengger
609 Desert, NW China, and their palaeoenvironmental significance. *Boreas* 48(3),
610 800-809.
- 611 Zhu, J., Wang, N., Chen, H., Dong, C., & Zhang, H., 2010. Study on the boundary and
612 the area of Badain Jaran Desert based on the remote sensing imagery (in
613 Chinese with English abstract). *Prog. Geogr.* 29, 1087-1094.
- 614
- 615
- 616
- 617
- 618
- 619
- 620
- 621
- 622
- 623
- 624
- 625

626 **Figures and Captions**

627

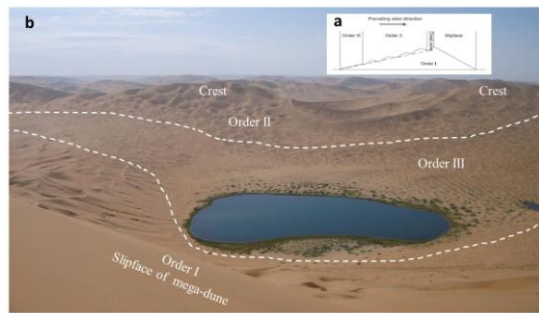


628

629 Fig. 1 Exploration route and sample sites in Badain Jaran Desert. Megadunes—ridges; Lakes—
 630 black dots; Exploration route—red dashed line; Sampling sites—A,B,C,D. A-Sumujilin Lake;
 631 B-Nuoertu Lake; C-Baoritaolegai Lakes; D-The Gate of National Geological Park of Badain Jaran
 632 Desert.

633

634

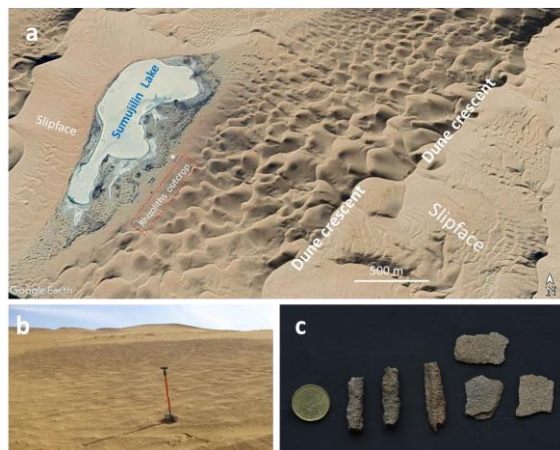


635

636 Fig.2 Conceptual typical (a, Dong et al., 2009) and field real (b) hierarchical orders in a
 637 compound megadune-lake system.

638

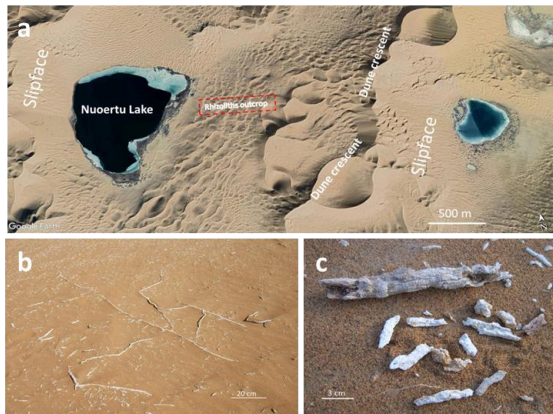
639



640

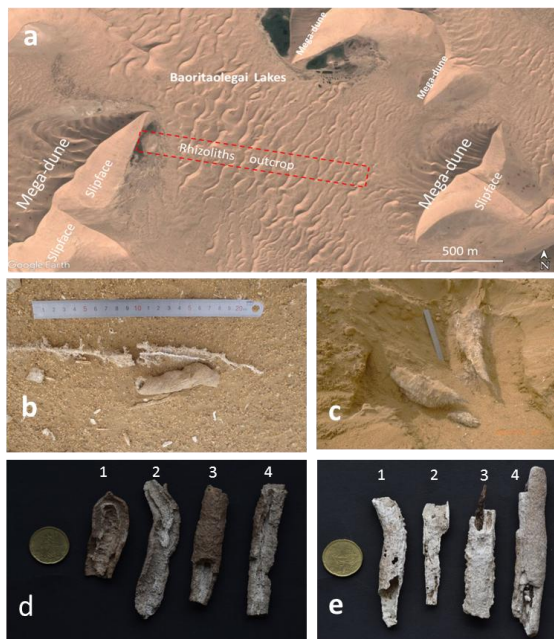
641 Fig. 3. Rhizoliths of Sumujinlin Lake. **a**-Rhizolith outcrops on the southeast side of the lake.
 642 **b**-Brown purple fragments of caliche and rhizoliths on the slope (the spade length is ~ 60 cm).
 643 **c**-Typical hard varnished rhizoliths and thick caliche fragments (the diameter of the coin is
 644 20mm).

645



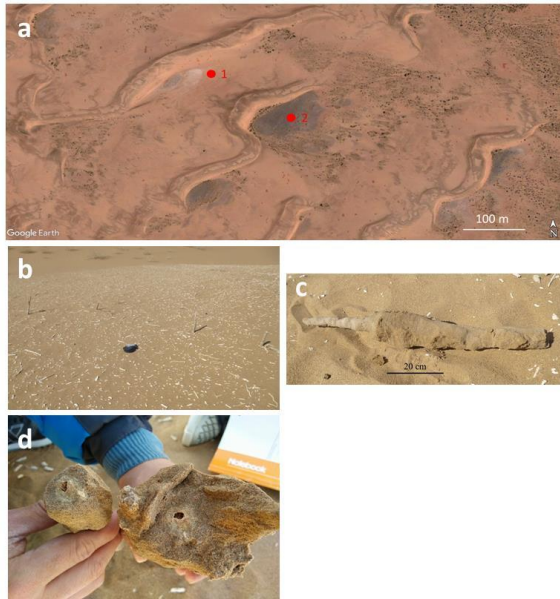
646
647
648
649
650

Fig. 4. Rhizoliths of Nuoertu Lake. **a**-Location of rhizolith outcrop, east side of Nuoertu Lake. **b**-White long branchy tubes of rhizoliths. **c**-Relicts of fine root hairs within a rhizolith tube.



651
652
653
654
655
656
657
658
659
660
661
662
663
664
665

Fig.5. Rhizolith outcrops of Baoritaolegai Lakes. **a**-Location of rhizolith outcrops, south of Baoritaolegai lakes. **b**-Small and thin rhizolith tubes with lateral fine hair-like tubes and thick rhizolith tube with hemp rope-like striations. **c**-Loose sand particles are being cemented by carbonate around the deceased *Artemisia* roots within wet sand (the length of the ruler in the above photos is 20 cm). **d**-Double cemented layers (#1&2) and singular layer (#3&4) of the rhizolith walls. **e**-Plant relicts within rhizolith tubes and different thickness of tube walls. #1-2 have thin walls without plant relicts. #3-4 have thick walls containing plant relicts (the coin diameter in the above photos is 20 mm.).

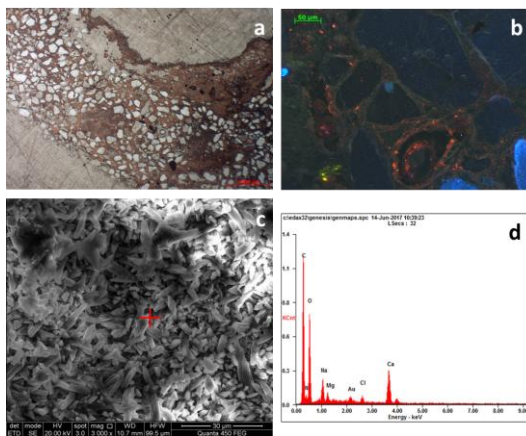


666

667 Fig. 6. Rhizoliths near to the Gate of National Geopark, Badain Jaran Desert. **a**-Rhizolith outcrops
 668 occur within the swales between the low dunes. #1 swale bed is white for enormous weathered
 669 fragments of rhizoliths and #2 swale bed is black due to pebbles from weathering of parent rocks
 670 underlying. The black dots are mainly *Artemisia* bushes. Singular barchan dune, barchan dune
 671 chains and erosional depressions can be observed at this site. **b**-Vertical rhizoliths and lying
 672 fragments of rhizoliths (the length of the camera bag is 12 cm). **c**-Primary rhizoliths dug out of
 673 soil in Fig **b**. **d**-Root relicts with central cavity and beige peripheral part of the primary rhizoliths.

674

675



676

677 Fig.7. Micro-texture and composition of rhizoliths. **a**-Microscopy image of rhizolith cross-sections
 678 stained by Alizarin red S and potassium ferricyanide. The cement among particles was stained in
 679 dark purple red whereas the particles were not stained and remained bright in color
 680 (plane-polarized light, Baoritaolegai). **b**-Clastic particles and cement of rhizolith cross-section
 681 under cathodoluminescence. The light blue and green grains are feldspars; the deep dark grains are
 682 quartz. The small red orange dots are carbonates. Un-cathodoluminescence lighted cement may be
 683 clay minerals distributed in carbonate minerals, or may be caused by addition of Fe^{2+} and Mn^{2+}
 684 cations during the formation of the cement. In the bottom part of the picture, the dotted orange
 685 loop-like halos may be calcite derived from weathered feldspar grains (plane-polarized light, The
 686 Gate). **c**-SEM images of cement. **d**-EDS spectrum (of **c**) of the cement (The Gate).