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Atmospheric significance of aeolian salts in the sandy deserts of northwestern China

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Abstract: Large sandy deserts in the middle latitudes of northwestern China were investigated for soluble salt variations in modern and ancient aeolian sediments, aiming to explore the environmental significance of “aeolian salts”. Results revealed that aeolian salt variations have a clear relationship with the changing meridional and zonal gradients of the desert locations and the aeolian differentiation effect, but are weakly linked to local geological conditions. It suggests that the natural system of aeolian salts is hydrologically open and the chemistry of the parent brines are different from that predicted for hydrologically closed systems. Atmospheric depositions of water-soluble chemical species are an important process/source contributing to aeolian salt. Sequential variations of soluble salts in sedimentary profiles interbedded with aeolian and non-aeolian deposits and their palaeoenvironmental implications in the hinterland areas of these deserts were further evaluated, based on the constraints of OSL dating and radiocarbon dating data. The results indicate that the inorganic salts may be a latent geoproxy in revealing regional palaeoclimatic changes in desert areas for the sediments deposited under onefold depositional environment, but the interpretation should be more careful for the sediments deposited under diverse depositional conditions. This study presents the evidence of atmospheric origin of aeolian salt in sandy deserts, with limited climatic significance in paleoenvironmental reconstruction.

Keywords: aeolian salt archive; environmental geoproxy; atmospheric deposition; palaeoclimate change; middle-latitude sandy desert; northwestern China

1. Introduction

Salt deposits (evaporites) are found in locations as diverse as Antarctica to the equatorial latitudes, and in depositional settings ranging from intracontinental to marginal marine (Handford, 1991). Much of what we know about ancient sedimentary facies and their depositional environments was derived from the study of modern sedimentary environments. Formation of soluble/inorganic salts in many types of deposits (e.g., soils, playa and lake sediments) is supposed to be governed mainly by climate factors including annual precipitation inputs, soil moisture changes, evapotranspiration losses, and solar radiation (Borchert and Muir, 1964; Sinha and Raymahashay, 2004; Warren, 2006; Singer, 2007). Thus salt archives in sediments are critical to understanding a number of geochemical processes in the supergene environment of the hydrogeologic and hydroclimatic systems. For instance, the soluble salt mineral assemblages embody significant signals indicating the processes of the solutes origin and transportation after their deposition (Warren, 2006; Zhu and Yang, 2010). Because soluble salts in soil/sediments response sensitively to

48 regional-scale climate and hydrology changes (Borchert and Muir, 1964; Smoot and
49 Lowenstein, 1991), they have been used as a key environmental proxy indicator in
50 sedimentary records of oceans, lakes, sandy deserts and loess-paleosol sediments
51 (Borchert and Muir, 1964; Sinha and Raymahashay, 2004; Hay et al., 2006; Warren,
52 2006; Sun et al. 2006; Liu et al., 2008; Sun et al. 2008). In these case studies, vertical
53 variations of salt solutes in sediment strata are used as a geoproxy to indicate past
54 salinity conditions and climatic changes in many parts of the world (Wasson et al.,
55 1984; Last, 1990; Dean and Schwalb, 2000; Schutt, 2000; Last and Vance, 2002; Sinha
56 and Raymahashay, 2004).

57 In arid conditions the desert landscape is globally distributed. For these areas,
58 non-marine salt deposits are common features of modern arid closed basins.
59 Researches on salt deposits under arid climate have been documented over a long
60 time, however, the environmental implications of inorganic salt formation in desert
61 areas are still not clear, to a certain extent because of the diverse compositions of
62 salt solutes with complicated formation mechanisms in different geomorphologic
63 units. Researches about salt formation have been performed worldwide in different
64 arid conditions, with the main purpose to identify the relationship between salt
65 regime and environmental factors, for instance, salt formation in different clay type
66 (Rengasamy et al., 1984), hydrological distribution (Borchert and Muir, 1964; Warren,
67 2006), fire ashes (Lasanta and Cerda, 2005; Bodi et al., 2012, 2014), soil erosion
68 (Lasanta and Cerda, 2005; Cerda et al., 2013; Agata et al., 2015), hydrological
69 distribution (Borchert and Muir, 1964; Warren, 2006; Bodi et al., 2012),
70 geomorphologic setting and dust source (Wang et al., 2008), volcanism and
71 atmospheric fixation (Oyarzun and Oyarzun, 2007), rainfall patterns (Ahuja, 1990;
72 Dragovich and Dominis, 2008) and mean annual climatic conditions (Dan and Yaalon,
73 1982; Lavee et al., 1991; Pariente, 2001), but relatively few have been recognized in
74 the aeolian sediments. Until now, few investigations have been involved into the
75 environmental implications of salt deposits from the sandy deserts in northern China
76 (Zhu and Yang, 2010; Zhu et al., 2012), although these deserts comprise of the
77 majority of middle-latitude deserts in the temperate zone of the Northern
78 Hemisphere (NH).

79 In this work we present a physical and geochemical exploration into inorganic
80 solutes filtrated from aeolian sediments collected from the inland sandy deserts in
81 northwestern China, representing a cross-section of different environments (from
82 westerly to monsoon climate control) in the NH middle latitudes. The objective of the
83 paper is to explore the atmospheric significance of inorganic salts in aeolian
84 sediments and their possible climatic implications.

85 86 **2. Methodology**

87
88 The study areas and sampling sites were chosen from famous sandy deserts in
89 China (Fig. 1a), i.e., the Taklamakan Desert in the Tarim Basin (the westerly climate
90 control) and the Badain JaranBadanjilin Desert in the Alexashan Plateau (the
91 monsoon climate control). Both the modern and ancient aeolian sediments were
92 designed to be sampled in the field. For modern aeolian sediment, thirty-three dunes
93 in the Taklamakan Desert and fourteen dunes in the Badain JaranBadanjilin Desert
94 were sampled in the field. The modern sands were sampled from the active dune

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95 surface. The geographical locations of these sample sites are mainly situated in
96 dune fields from the center and southern edges of the Taklamakan Desert (Fig. 1b)
97 and the southern inland area in the [Badain JaranBadanjilin](#) Desert (Fig. 1c-d).

98 In the Inner part of the Taklamakan and the [Badain JaranBadanjilin](#) Deserts,
99 aeolian and lacustrine (or fluvial in Taklamakan) deposits (palaeosediments) are
100 frequently found interbedded (Fig. 2). For instance, lacustrine/fluvial sediment strata
101 widely occur in the hinterland dune fields of the Taklamakan Desert along the N-S
102 oil-transporting highway (Fig. 2a-b). Four sedimentary sequences with clearly
103 stratigraphical layers were selected from hinterland areas of the two deserts in this
104 study (Fig. 1). It is about 4 m in depth for the Arerjilin-I section from the [Badain](#)
105 [JaranBadanjilin](#) Desert (Fig. 1d). Lacustrine sediments in this section were
106 interbedded by aeolian sand layers (Fig. 3a). For the Tazhong-XIII section in the
107 Taklamakan Desert (Fig. 3b), it is general a lacustrine sequence interlayered with
108 dune sediments. The Yaogan-VIII section is situated at the lower reaches of the Keriya
109 River (Fig. 1b) close to the south margin of the Taklamakan Desert. The top of this
110 section is buried by a 30-m active dune (Fig. 3c). The Tumiya-II section is located at
111 the low reaches of the Tumiya palaeochannel close to the south edge of the
112 Taklamakan Desert (Fig. 1b). This section is general a silty sand or sandy silt sequence
113 interlayered by cemented calcium-carbonate layers (Fig. 3d). In general, lithologies of
114 the lacustrine sediments are greatly different from those of the aeolian sediments in
115 all sedimentary sequences from the Taklamakan Desert. These sequences were
116 chronologically analyzed based on optically stimulated luminescence (OSL) dating
117 and radiocarbon (^{14}C) dating methods.

118 The analytical methods for soluble salt geochemistry of aeolian sediment
119 samples can be seen from [Zhu and Yang \(2010\)](#), and the OSL and radiocarbon dating
120 methods can be seen from [Yang et al. \(2006, 2010\)](#). The physical and chemical
121 analytical data of the soluble salt compositions of sediments are shown in On-line
122 Supplementary Table 1 and Table 2, respectively. The resulting OSL and radiocarbon
123 dating ages are summarized in On-line Supplementary Table 3 and Table 4,
124 respectively. Note that the partial characteristics of aeolian salts from the
125 Taklamakan and [Badain JaranBadanjilin](#) Deserts were previously reported in our early
126 works ([Zhu and Yang, 2010](#); [Zhu et al., 2012](#)) with preliminary descriptions of their
127 composition and distribution and related influencing factors, but their complete
128 stratigraphies and chronologic results are presented here along with other new
129 palaeoenvironmental estimations.

130 131 **3. Results**

132
133 Salinity values for all samples are mathematically calculated based on TDS
134 values of the filtrates and their water-sediment mass ratios. The pH and the
135 calculated salinity values for the dune sediments from the Taklamakan Desert range
136 between 8.66 and 9.54 (mean 9.22) and 0.27‰ and 1.86‰ (mean 0.78‰),
137 respectively. For the dune sediments in the [Badain JaranBadanjilin](#) Desert, the pH
138 and the salinity values lie between 8.82 and 9.42 (mean 9.12) and 0.05 and 0.42‰
139 (mean 0.15‰), respectively. The range of pH values between the aeolian sediments
140 is narrow (8.6-9.5). It indicates that the soil conditions and acid buffer capacities for
141 these deserts are similar, generally in alkaline nature. Studies have proved that pH

142 values in soil between 6.4-12.2 are mainly caused by bicarbonate (6.4-10.3) and
143 carbonate (10.3-12.2) (Wetzel and Likens, 2000). It thus means that the alkalinities of
144 aeolian salts in Chinese deserts are mainly controlled by the carbon-bearing salts,
145 particularly bicarbonate.

146 For the 15 palaeo-aeolian sediment samples buried beneath modern dunes in
147 the Taklamakan Desert with OSL ages ranging between 40-2 ka B.P. (On-line
148 Supplementary Table 4), The salinities and pH values are slightly higher in salinity and
149 lower in pH than those of modern dune sand samples (Fig. 4a). The modern dune
150 samples collected from the identical months in different climatic year (such as the
151 autumns in the arid 2006 and in the wet 2008) in the [Badain JaranBadanjilin](#) Desert
152 are quite similar to each other (Fig. 4b).

153 The major anions of aeolian salts are Cl^- and HCO_3^- in all samples. The SO_4^{2-}
154 concentrations are relatively low (Fig. 4d). Na^+ is the first major cation and Ca^{2+} is the
155 second. The concentrations of K^+ and Mg^{2+} are relatively low (Fig. 4e-f). It should be
156 noted that the carbon-bearing ion concentrations in these sediments are highly
157 correlated with pH (Fig. 4c). Based on charge balances and mass matches between
158 major cations and anions, the potential salt mineralogy of these aeolian sediments
159 can be categorized as: $\text{NaHCO}_3 + \text{NaCl} + (\text{CaCO}_3)$ in the [Badain JaranBadanjilin](#) Desert
160 (Fig. 4g), and $\text{NaCl} + \text{NaHCO}_3$ in the Taklamakan Desert (Fig. 4h). It indicates that the
161 assemblage of sodium carbonate and chloride is widely distributed in aeolian
162 sediments within the Chinese sandy deserts.

163 The fingerprint diagrams of the ion distribution patterns for aeolian sediment
164 solutes, local groundwaters and surface waters are shown in Fig. 5 a-b. The
165 distribution patterns for dune surface sediments from the [Badain JaranBadanjilin](#)
166 Desert are different from the local groundwaters and the local lake waters (Fig. 5a).
167 The chemical differences between aeolian salts and natural waters are also evident in
168 the Taklamakan Desert (Fig. 5b), particularly in the patterns of magnesium and
169 sulfate. These factors reflect a weaker influence of local waters on aeolian salts both
170 in the [Badain JaranBadanjilin](#) and Taklamakan Deserts.

171 For the Taklamakan Desert, the salt salinities of aeolian sediments have a strong
172 positive correlation with the median grain sizes of the corresponding samples (Mz in
173 phi unit, Fig. 5c), indicating an enrichment of soluble salts towards the finer particles
174 of aeolian sediments. A same trend is also observed in the [Badain JaranBadanjilin](#)
175 Desert, as the salt concentrations in different grain size fractions increasing when
176 particle fractions become finer (Fig. 5d).

177 In dune surface sediments from the two deserts along the longitude (E) and
178 latitude (N) lines of sampling sites, the salt salinities show regularly varied trends,
179 with an increasing salinity together with the decreases of the longitude and latitude
180 degrees, respectively (Fig. 5e-h). Because the mean annual precipitation in northern
181 China increases gradually along the same meridional direction, and the temperature
182 or mean solar radiation decreases along the same latitudinal gradients, this indicates
183 that enrichment of aeolian salt contents have a clearly relationship with the changing
184 meridional and zonal gradients of the sample locations, which correspond to the
185 regional climatic gradient, as well as the aeolian effects of granularity differentiation
186 caused by wind/atmospheric dynamics, but are weakly linked with local hydrological
187 conditions.

188 For the Arerjilin-I section in the [Badain JaranBadanjilin](#) Desert, black carbon from

189 the highest shorelines of Arerjilin Lake (+10 m) were dated to 5628±221 cal yr BP
190 (CNR-185, Fig. 3a and On-line Supplementary Table 3). Calcareous gyttja (+6 m) and
191 black carbon (+5.5 m) from deposits above the lake surface was dated to 4757±315
192 cal yr BP (CNR-173) and 7144±200 cal yr BP (CNR-186), respectively (Fig. 3a and
193 On-line Supplementary Table 3). Normally, deposits are younger at locations below
194 the highest lake level. However, in this case it is believed that younger sediments
195 were removed by wind erosion. Consequently, the older lacustrine sediments are
196 now exposed to the surface.

197 The Tazhong-XIII section contains three lacustrine layers interbedded by aeolian
198 sand sediments (Fig. 3b). The OSL age of the bottom aeolian layer is 39,800±2900 a
199 (On-line Supplementary Table 4). Aeolian layers underlying the top two lacustrine
200 layers are dated to 28,000±2300 a and 29,200±2600 a. The age limits of the lower
201 lacustrine layer range between ca 40,000 and 30,000 a ago (Fig. 3b).

202 Lacustrine strata in the Yaogan-VIII section are intercalated with two aeolian
203 sand layers (Fig. 3c). The aeolian sands underlying the lacustrine section is dated to
204 14,500±1100 a (On-line Supplementary Table 4), and the aeolian sands overlying the
205 lacustrine section is dated to 2320±180 a. The age constraints of aeolian sand layers
206 indicate that the paleolake was dried between ca 14,000 and 2000 a (Fig. 3c).

207 In the Tumiya-II section that deposited on the palaeoterrace of the Tumiya River
208 near the south margin of the Taklamakan Desert, The OSL chronology is dated to
209 between 23,700±1800 a and 8700±800 a (On-line Supplementary Table 4). The
210 accumulation of sandy loess at this section indicates that southern margin of the
211 Taklamakan Desert at the time between 23,700±1800 and 8700±800 a was wet.

212 The above chronological data show that the OSL data hold great uncertainty. It
213 may be necessary to discuss the uncertainty in different locations in this study. As
214 previously reported, textures such as grain size and shape are important parameters
215 influencing the OSL dating of sediment (Aitken, 1985; Fain et al., 1999; Brennan,
216 2003; Guerin et al., 2012; Duval et al., 2015), since they have a direct impact on
217 several correction factors that are used for evaluating the dose rate. The aeolian sand
218 layers for OSL dating in the Tazhong-XIII section have a mean particle sizes of 3.3-3.5
219 phi (sieving result), which is much coarser than the interbedded lacustrine deposits
220 (mean particle size 5.8-6.7 phi). The aeolian sand layers in the Yaogan-VIII section
221 have a mean grain size of 3.8 phi, also coarser than the intercalated lacustrine
222 deposits (mean particle size 4.6-6.2 phi). Aeolian silt or sandy loess deposits in the
223 Tumiya-II section have a mean grain size of 3.6-4.0 phi. These data show a large
224 variability in term of size of grains between the samples for OSL dating in the
225 Taklamakan Desert. Because there is a distinction between the sieve aperture size, or
226 sieve opening, and the diameter of a particle, consequently, the main dimension
227 controlling the sorting of the grains for non-spherical particles is the so-called
228 intermediate diameter. For example, for standard mesh of 50, 100, 200 and 300 mm,
229 grains passing through may have an intermediate dimension in the range of from 50
230 to 71 mm, 100-141 mm, 200-283 mm, 300-424 mm, respectively (Duval et al., 2015).
231 Besides, the grain size distribution of the raw sediment may have also an impact on
232 the dating results, like in the case of a bimodal distribution (Duval et al., 2015). So
233 the principal sources of uncertainty in OSL dating data of this study may potentially
234 be derived from the grain size of aeolian sediments. On the other hand, the
235 difference in ¹⁴C ages between the uppermost and lowermost organic carbon layers

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236 | of a sediment profile usually underestimates the time of sediment deposition, and
237 | the difference in OSL ages taken from sediment units overlying and underlying a
238 | buried soil most likely overestimates it (Miao et al., 2016). For example, the
239 | comparison of OSL and ¹⁴C ages suggests that the radiocarbon dating technique may
240 | significantly underestimate the age of sediments for samples older than 30 cal ka BP
241 | (corresponding to ~25 ¹⁴CkaBP) (Long et al., 2015). This factor could also lead to a
242 | certain uncertainty in the chronological data of this study.

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243 | **4. Discussion**

244 | **4. 1. Primary or secondary salt in origin?**

245 |
246 |
247 |
248 | Firstly, it is necessary to understand whether the nature of soluble salt in aeolian
249 | sediment is primary or secondary in origin. As defined by Warren (2006), an original
250 | salt deposit (evaporite) is hydrologically driven by solar evaporation and is sourced
251 | from saturated brine on ground surface or nearsurface. In order to emphasize the
252 | highly reactive nature of soluble salts in the sedimentary realm, such salts that is
253 | precipitated from surface brine and retaining crystallographic evidence of the
254 | depositional process are regarded as primary salt. According to this definition and
255 | the related two limiting factors, almost every subsurface salt texture is secondary,
256 | because it is diagenetically altered, frequently with fabrics indicating pervasive early
257 | recrystallization. Secondary salts can be formed in surface/subsurface settings
258 | equivalent to the eogenetic, mesogenetic and telogenetic realms (Choquette and
259 | Pray, 1970). Under this definition of a primary versus secondary salt, we can say that,
260 | outside of a few Neogene examples (Riding et al., 1998; Valero-Garces et al., 1999,
261 | 2001; Pedley et al., 2003), there are few salt deposit with textures that are wholly
262 | and completely “primary”. Without exception, soluble salts in aeolian sediments
263 | should be secondary salt originated in the eogenetic realm.

264 | According to the salt category defined by Warren (2006), salt minerals can be
265 | simply subdivided into evaporitic alkaline earth carbonates and evaporite salts. In a
266 | view of depositional process, evaporitic alkaline earth carbonates are the
267 | firstly-precipitated salt minerals that sourced from concentrating hypersaline water.
268 | Compared with the evaporite salts, they are tend to be formed during the early
269 | stages of surface brine concentration-crystallization, while the evaporite salts are
270 | formed during the more saline stages of concentration-crystallization process (Smoot
271 | and Lowenstein, 1991). As analyzed above, NaHCO₃ + CaCO₃ are the identical
272 | components in dune sediments from both the Taklamakan and the Badain
273 | JaranBadanjilin Deserts. It indicates that evaporitic alkaline earth carbonates are
274 | major component of these aeolian salts.

275 | Although texture of most of the subsurface salts is secondary, the earliest
276 | secondary salts are often syndepositional precipitates (Warren, 2006), with
277 | formation of cements and replacement even as the primary matrix accumulates
278 | around them. For example, nodular anhydrite and aragonite were recognized in
279 | Permian mudflats by Kerr and Thomson (1963), they interpreted it as a subaqueous
280 | saline pan indicator. Works by Gerdes et al. (1994, 2000) have shown that carbonate
281 | grains, such as ooids and peloids, typically thought of as indicators of marine
282 | conditions and mechanical agitation, can precipitate in situ in CaCO₃-saturated

283 evaporitic settings. For aeolian sediments in arid environment, we image that much
284 of surface salts are deposited in multiple episodes of early diagenetic
285 (syndepositional) cementation. This syndepositional salt may be formed in multiple
286 dissolution-precipitation events in the sand particle surface and are precipitated
287 between successive depositional episodes of salt crust formation.

288 Besides alkaline earth carbonates ($\text{NaHCO}_3 + \text{CaCO}_3$), NaCl is another major
289 component of aeolian salts in the deserts studied. This salt, dominantly halite, is
290 evaporite salts according to the classification by Warren (2006) that precipitated
291 from concentrated brine after the brine has crystallized the alkaline earth carbonates.
292 Both the evaporitic alkaline earth carbonates and evaporite salts coexist in the
293 aeolian sediments of the deserts, indicating that aeolian salts are complex salt
294 mixture formed by multiple evaporation and precipitation processes in the eogenetic
295 realm.

296

297 **4. 2. Possible mechanism of aeolian salt formation**

298

299 All evaporite salts are ionic salts. The definition of a salt deposit (evaporite)
300 proposed by Warren (2006), as mentioned above, has no assumption as to the origin
301 of the parent brine. It may be marine, nonmarine or a hybrid (Smoot and Lowenstein,
302 1991). By definition, there is a need for aridity and for water loss to exceed inflow
303 (Borchert and Muir, 1964). This means deposition and diagenesis in evaporites is
304 more dependent on climate than in either siliciclastic or carbonate sediments.
305 Therefore, modern continental evaporites typically accumulate in semi-arid to
306 hyperarid deserts. Suites of precipitated salts follow the geochemical make-up of the
307 parent brine (Braitsch, 1971). It means that the mineralogy and order of precipitates
308 in any brine pool are controlled by the ionic make-up of the parent brine. This
309 provides a clue to reveal the possible source and mechanism of salt formation under
310 particular environment.

311 Generally speaking, eight mechanisms or processes precipitate most salt
312 minerals and crusts worldwide: 1) in-situ pedogenic weathering and eluviation
313 processes of existing salty or volcanogenic (ash) parent materials; 2) eolian or fluvial
314 input of salt or salt-rich sediment; 3) upward movement of salt via capillary flow
315 from a shallow salty groundwater, 4) an oceanic aerosol source, creating in
316 salt-enriched rainfall that evaporatively concentrates within the regolith, 5) intrusion
317 and flooding by seawater, 6) decomposition of vegetation, 7) in-situ oxidation of
318 sulphide minerals, 8) anthropogenic pollutants (Petrov, 1976; Smoot and Lowenstein,
319 1991; Warren, 2006; Singer, 2007). The first two sources are direct evaporite
320 associations, while the third is typically associated with salt lakes, sabkhas and playas
321 in semi-arid or desert settings within 500-1000 km of the coast. Many salt soil
322 horizons are combinations of both pedogenically precipitated and detrital
323 wind-reworked salt (Warren, 2006; Singer, 2007). Based on the eight views, we can
324 get clues into the possible mechanism of aeolian salt formation in Chinese deserts.

325 To the weathering mechanism in view (1), our previous study has shown that the
326 degree of weathering of aeolian sand in the Taklamakan is very low ($\text{CIA} \approx 50$) (Zhu
327 and Yang, 2009), which is similar to that of the un-weathered Upper Continental
328 Crust. This observation suggests that salt contributions directly from bedrock
329 weathering are of minor significance. For the eluviations process in view (1), studies

330 have demonstrated that in a region with a mean annual precipitation less than 500
331 mm, the export of erosible elements by eluviation processes in the soil will be less
332 significant than their preservation by evaporation-crystallization processes (Birkeland,
333 1999; Kraimer et al., 2005). Since the mean annual precipitation in desert regions of
334 northern China is lower than 400 mm (Fig. 1a), the degree of eluviation exerted on
335 soluble salts in the two sandy seas is lower than that of preservation. The salt
336 concentrations of samples buried in dune subsurface layers in this study are equal to
337 or only slightly higher than those of the surface samples (Fig. 4a), indicating only a
338 little downward movement of these salts is taking place. Case studies on salt
339 movement in desert soil have also shown that only 1.64% of the rainfall-leached salt
340 can reach 1.0 m depths, and only 0.02% of the rainfall-leached salt can penetrate 2.0
341 m below the ground surface (Marion et al., 2008). This means that salt contributions
342 from eluviation processes of parent salts are also minor.

343 To the view (3), dunes in both the Taklamakan and [Badain JaranBadanjilin](#)
344 Deserts are generally higher than 20~50 m (Zhu et al., 1985), particularly being
345 higher than 200 m in the [Badain JaranBadanjilin](#) Desert, so it is impossible for
346 groundwater to contribute salt to aeolian sediments by drawing upward to the dune
347 surface via capillarity.

348 To the view (4) and (5), both the two sandy deserts studied are geographically far
349 away from any ocean and have been under the control of terrestrial processes since
350 at least the Cenozoic (Zhu et al., 1980). Salt contributions from present or ancient
351 seawater and aerosol can, therefore, be neglected. However, contributions from
352 oceanic-sourced rainfall precipitation (atmospheric wet deposition) will discuss
353 below.

354 To the view (6), although the decomposition of vegetation may contribute to the
355 salts of some desert areas (Petrov, 1976), but plants in/around the sampling sites of
356 the deserts in this study are scarce, so any influence of vegetation is minimal.

357 To the view (7), Petrov (1975) suggested that the salt chemistry in the world
358 deserts can be classified into four types: chloride, sulfate, carbonate and mixed.
359 Many desert soils in arid to semi-arid environment are sulphate-rich in areas
360 surrounding the perennial saline lakes, the brine pan depressions and their dune
361 margins (Petrov, 1976; Smoot and Lowenstein, 1991; Warren, 2006). For example,
362 gypsum crusts have been reported from all the continents, including Antarctic
363 (El-Sayed, 1993). Studies have shown that chloride–sulfate salts but not bicarbonate
364 salts are dominated in the Kalahari Desert (Wang et al., 2009). This is also the case
365 for wide-distributed aeolian loess deposits in the Loess Plateau of northern China
366 (Zhu et al., 2012), which are mainly composed of $\text{Na}_2\text{SO}_4+\text{NaHCO}_3$ for loess and of
367 $\text{Na}_2\text{SO}_4+\text{NaCl}+\text{NaHCO}_3$ for paleosol (Sun et al., 2006). While, the analysis of this
368 study shows that aeolian salts in the Taklamakan and [Badain JaranBadanjilin](#)
369 Deserts are mixture of sodium bicarbonate and chloride. This is different from both the
370 Chinese loess deposits and the global tropical/subtropical deserts. Although sodium
371 sulphate (Na_2SO_4) is an important salt existed in loess-paleosol sequences, but less
372 common in the dune sediments from the sandy deserts in this study. So mechanism
373 of in-situ oxidation of sulphide minerals can be excluded for the aeolian salts in this
374 study.

375 To the view (8), anthropogenic pollutants, generated by human activities, are
376 usually inorganic ions such as NH_4^+ , NO_3^- , H_2PO_4^- and SO_4^{2-} and some organic anions.

377 The contents of all samples studied, however, have roughly equivalent numbers of
378 cations and anions with low/none above-mentioned ions ([On-line Supplementary](#)
379 [Table 2](#)), suggesting that human impact on salt concentrations across the two sandy
380 deserts is negligible.

381 On the basis of all above results, only the view (2) is unexplained. Actually the
382 mechanism in view (2) involves the hydrological and atmospheric processes of salt
383 origin and transportation. We discuss it below.

384

385 **4. 3. Atmospheric origin?**

386

387 There are wide similarities but partial differences existing in the salt chemistry
388 and ion distribution patterns of aeolian salts between the Taklamakan and [Badain](#)
389 [JaranBadanjinlin](#) deserts ([Fig. 4g-h](#)). Besides, they are weakly correlated with the
390 chemical compositions of the nearby ground waters under local hydrological setting
391 ([Zhu and Yang, 2010](#)) ([Fig. 5a-b](#)), but are strongly associated with the regional
392 climatic and wind regime ([Zhu et al., 2012](#)) ([Fig. 5c-h](#)). All these evidences indicate
393 that the natural system of aeolian salts is hydrologically open and the chemistry of
394 the parent brines and the associated salt deposits may be significantly different from
395 that predicted for hydrologically closed systems. It means that the sources of aeolian
396 salts in the deserts are strongly controlled by earth surface processes at a regional or
397 large scale, but not at a local scale. Seen from this point, only an atmospheric origin
398 but not hydrological origin can be responsible for this pattern.

399 It has been recognized that atmospheric chemical species is a significant source
400 contributing acidic and eutrophic elements to both the terrestrial and ocean
401 ecosystems (e.g., [Sehmel, 1980](#); [Wesely and Hicks, 2000](#); [Inomata et al., 2009](#)). For
402 example, soil salts in many desert areas have been implicated to be originated from
403 the atmospheric sources ([Amit and Yaalon, 1996](#); [Bohlke et al., 1997](#); [Oyarzun and](#)
404 [Oyarzun, 2007](#)). Generally, there are two forms for atmospheric deposition, wet and
405 dry deposition. Wet deposits contain salts derived from rainwater and snow. Studies
406 have shown that chloride and carbonate are major species in rainfall in central Asia
407 and north China ([Fujita et al., 2000](#); [Li et al., 2007](#); [Zhao et al., 2008](#)). It indicates that
408 the chemical compositions between wet depositions and aeolian salts are similar.

409 Besides rainfall, aerosol and dust, known as atmospheric dry deposition, is
410 another global phenomenon of salt transportation ([Goudie and Middleton, 2006](#)). At
411 present there are few data being available for understanding the salt compositions of
412 dust in the study areas. However, wide studies have proved that salt transportation
413 and redeposition via dust are one of the important patterns for biogeochemical
414 cycles in arid areas ([Logan, 1974](#); [Yaalon and Ginzboung, 1966](#); [Reheis and Kihl, 1995](#);
415 [Al-Momani et al., 1995](#); [Kiefert, 1997](#); [Blank et al., 1999](#); [Kulshrestha et al., 2003](#);
416 [Zheng et al., 2005](#); [Abuduwaili et al., 2009](#)). It should be a similar case for the
417 hinterlands of northwestern China.

418

419 **4. 4. Climatic implications**

420

421 The coexistences of palaeo-lacustrine sediments (playa) and aeolian sediments
422 are commonly seen in desert regions globally. These are clear evidences for past
423 environmental changes in desert conditions ([Smith, 1971](#); [Yechieli and Wood, 2002](#);

424 [Alonso-Zarza, 2003](#); [Yang et al., 2006](#); [Tripaldi et al., 2011](#); [Dong et al., 2012](#)),
425 Therefore, the large number of playa deposits in the inter-dune depressions of these
426 deserts offers an exceptional opportunity to study regional paleohydrological and
427 paleoclimatic change. Over the past decade, there have been significant advances in
428 our understanding of the late Quaternary history of the desert regions of
429 northwestern China. OSL and ^{14}C chronologies of aeolian sediments from various
430 locations in these deserts provide important archives to understand the timing of
431 lacustrine/fluvial and aeolian processes related to environmental and climate
432 changes. However, despite this increased interest, paleolimnological and
433 palaeoaeolian research is limited by a paucity of potential geoproxy and the study
434 sites with relatively long, uninterrupted stratigraphic sequences. Sequential
435 variations of inorganic salts have been tentatively applied to reconstruct the
436 palaeoenvironmental history in desert areas. For instance, taking the soluble salts
437 variations in thick Cenozoic deposits as one of the indicators of paleoenvironmental
438 change, [Sun et al. \(2008\)](#) reconstructed the aridity history of the Tarim Basin and
439 argued that hyperarid climate had been prevailed within the basin since 5.3 Ma ago.

440 The variations in soluble salts content for the four sections collected from the
441 Taklamakan and ~~Badain Jaran~~[Badanjilin](#) deserts are examined in this study, as shown
442 in [Figs. 6-9](#). The OSL and ^{14}C age constraints of these sequences are also shown in
443 these figures. The data indicates that all of these playa deposits had experienced
444 fluctuations in high moisture conditions during the period from late Pleistocene to
445 mid-Holocene.

446 For the Arerjilin-1 section, there are an increase-decline pattern in salinity
447 variation and a decline-increase-decline pattern in pH variation during the
448 early-middle Holocene ([Fig. 6](#)). For the Tazhong-XIII section, there is a clear serrate
449 shape ([Fig. 7](#)) in the pattern of salinity variation. It indicates that there are at least
450 three times of humid environmental fluctuations during the past 40 to 28 ka B.P.. In
451 the Yaogan-VIII section, the sequence salinities are relatively high ([Fig. 8](#)). It suggests
452 that a saline lacustrine environment has occurred this area and the local hydrological
453 settings have been retained the saline conditions for a long time from the end of the
454 last glacial to late Holocene. In the Tumiya-II section, variations of the sequence
455 salinities were unstable during the LGM (24 ka B.P.). There are two stages of salinity
456 increase during the end of the LGM (about 10-11 ka) and the early Holocene (after
457 8.7 ka B.P.), respectively ([Fig. 9](#)). Taken the four sections as a whole into
458 consideration, there are evident differences between the aeolian sediments and
459 fluvial sediments in salt content. In general, salinities in aeolian sediments are
460 evidently lower than those of lacustrine sediments. It suggests that a great salt
461 depositional discrepancy exists between the aeolian and the lacustrine sedimentary
462 systems, which could be owing to the differential mechanisms of salt formation and
463 origin in wind and water regimes. The results suggest that the inorganic salt is a
464 latent proxy indicator for single depositional-environment sequence in revealing local
465 hydrological variations and climate changes in desert areas during the late
466 Quaternary.

467 However, the interpretation based on salt archives should be careful for the
468 sedimentary sequences with dual/multiple depositional end-members. Researcher
469 have reported that in a sediment strata formed by an identical geological process like
470 lacustrine or aeolian dynamics, the increase of sequence salinity commonly reflects a

471 stepped-up environmental aridity (Sinha and Taymahashay, 2004; Warren, 2006; Liu
472 et al., 2008). Because whatever under the aeolian and lacustrine depositional
473 settings, the increase in salt content is a reflection of the enhanced evaporation
474 potential. However, in a sediment profile controlled by multiple geological processes
475 like combined aeolian and lacustrine dynamics, the increase in salt content could be
476 not a reflection of the enhanced aridity, just like the case in this study. It is generally
477 higher in salinity for the lacustrine sediments than for the aeolian sediments. In this
478 study, the salinity increases in sections of the Arerjilin-I, Tazhong-XIII and Yaogan-VIII
479 are general a representation of the enhanced wetter conditions (Figs. 6-8), because
480 the higher salinities are always located in the lacustrine/fluvial layers. In general,
481 lacustrine/fluvial strata in aeolian sequences always reflect enhanced humid periods
482 than that of the aeolian period (Yang et al. 2006). However, this is not the similar
483 conditions for the Tumiya-II section, as the salt increases in this sequence should be
484 attributed to enhance aridity (Fig. 9), because the sedimentary structure of this
485 section is uniformly dominated by aeolian process. Thus it can be confirmed that
486 once the coexistence of aeolian and fluvial/lacustrine sediments occurs in a
487 sedimentary structure in desert regions, the single use of salt archives should be
488 cautious in reconstructing the regional environmental changes. A combined use of
489 salt archives and sedimentary proxies is recommended under this situation.

490 Besides, land surface processes such as chemical, physical and mechanical
491 processes can weld younger to older sediment profiles and affect the accumulation,
492 dissolution, and reprecipitation of mineral materials in sediments, as illustrated by
493 Olson and Nettleton (1998). Sediment properties most affected include texture and
494 the content and distribution of soluble salts. Processes such as erosion and
495 deposition can truncate profiles or bury them either rapidly or extremely slowly.
496 Effects of these and other processes on sediment properties must be examined with
497 care in paleosols that have been buried even for short interval. The above-mentioned
498 analogies of fluvial/lacustrine-aeolian profiles in the Taklamakan and [Badain](#)
499 [JaranBadanjilin](#) deserts should be evaluated carefully in future studies and possible
500 avoided as single indicators in paleoenvironmental reconstruction in the desert
501 environment.

502 **5. Conclusion**

505 Formations of inorganic salt in aeolian sediments in the desert environment are
506 significant to understanding the interrelationships between aeolian dynamics and
507 regional hydrological and climate regimes. Geological information related to the
508 inorganic salt composition and distribution and their environmental significance in
509 aeolian sediments in the middle-latitudes deserts are still rare. Geochemistry of
510 soluble salts in modern and ancient dune sediments from the sandy deserts in
511 northwestern China was surveyed in this work. Variations of the salt composition
512 around these sandy deserts are closely related to regional climatic parameters, such
513 as the precipitation, temperature and wind agent. The aeolian salts are proposed to
514 be sourced from the atmospheric depositions that are strongly associated with the
515 local-scale and regional-scale dry and wet depositions, such as rainfall and dustfall
516 precipitation. Single salt archive in sedimentary deposits interlayered by aeolian and
517 lacustrine facies should be carefully used as geoproxy to reconstruct

518 palaeoenvironmental histories in arid conditions.

519

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527 **References:**

528

529 Abuduwaili, J., Gabchenko, M. V., and Xu, J.: Eolian transport of salts – a case study in
530 the area of Lake Abinur (Xinjiang, Northwest China), *J. Arid Environ.*, 72, 1843–
531 1852, 2009.

532 Agata, N., Cerda, A., Carmelo, D., Giuseppe, LP, Antonino, S., and Luciano, G.:
533 Effectiveness of carbon isotopic signature for estimating soil erosion and
534 deposition rates in Sicilian vineyards. *Soil and Tillage Research*, 152, 1-7, 2015.

535

536 Ahuja, L. R.: Modeling soluble chemical transfer to runoff with rainfall impact as a
537 diffusion process, *Soil Sci. Soc. Am. J.*, 54, 312–321, 1990.

538 Aitken, M.J. *Thermoluminescence Dating*. Academic Press, London, 1985.

539

540 Al-Momani, I. F., Tuncel, S., Eler, U., Ortel, E., Sirin, G., and Tuncel, G.: Major ion
541 composition of wet and dry deposition in the eastern Mediterranean basin, *Sci.*
542 *Total Environ.*, 164, 75–85, 1995.

543 Alonso-Zarza, A. M.: Palaeoenvironmental significance of palustrine carbonates and
544 calcretes in the geological record, *Earth-Sci. Rev.*, 60, 261–298, 2003.

545 Amit, R. and Yaalon, D. H.: The micromorphology of gypsum and halite in reg soils –
546 the Negev Desert, Israel, *Earth Surf. Proc. Land.*, 21, 1127–1143, 1996.

547 Birkeland, P. W.: *Soils and Geomorphology*, Oxford University Press, New York, 1999.

548 Blank, R. R., Young, J. A., and Allen, F. L.: Aeolian dust in a saline playa environment,
549 Nevada, USA, *J. Arid Environ.*, 41, 365–381, 1999.

550

551 Brennan, B. J.: *Beta doses to spherical grains. *Radiation Measurements* 37, 299-303,*
552 *2003.*

553 Bodi, M.B., Doerr, S.H., Cerda, A., and Mataix-Solera, J.: *Hydrological effects of a layer*
554 *of vegetation ash on underlying wetttable and water repellent soil. *Geoderma,**
555 *191, 14-23, 2012.*

556 Bohlke, J. K., Ericksen, G. E., and Revesz, K.: Stable isotope evidence for an
557 atmospheric origin of desert nitrate deposits in northern Chile and southern
558 California, USA, *Chem. Geol.*, 136, 135–152, 1997.

559 Borchert, H. and Muir, R. O.: *Salt Deposits: The Origin, Metamorphism and*
560 *Deformation of Evaporites*, Van Nostrand Company, London, 1964.

561 Braitsch, O.: *Salt Deposits: Their Origin and Composition*, Springer-Verlag, Berlin,
562 1971.

563

564 Cerda, A., Brazier, R., Nearing, M., and de Vente, J.: *Scales and erosion. *Catena*, 102,*

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带格式的: 缩进: 左侧: 0 厘米,
悬挂缩进: 2.57 字符

- 565 | [1-2, 2013.](#)
- 566 | Choquette, P. W. and Pray, L. C.: Geological nomenclature and classification of
567 | porosity in sedimentary carbonates, AAPG Bull., 54, 207–250, 1970.
- 568 | Dan, J. and Yaalon, D. H.: Automorphic saline soils in Israel, Catena, 1, 103–115,
569 | Supplementary, 1982.
- 570 | Dean, W. E. and Schwalb, A.: Holocene environmental and climatic change in the
571 | Northern Great Plains as recorded in the geochemistry of sediments in Pickerel
572 | Lake, South Dakota, Quatern. Int., 67, 5–20, 2000.
- 573 | Dragovich, D. and Dominis, M.: Dryland salinity and rainfall patterns: a preliminary
574 | investigation in central 5 west New South Wales (Australia), Land Degrad. Dev.,
575 | 19, 564–573, 2008.
- 576 | Dong, Z., Lv, P., Qian, G., Xia, X., Zhao, Y., and Mu, G.: Research progress in China's Lop
577 | Nur, Earth-Sci. Rev., 111, 142–153, 2012.
- 578 |
- 579 | [Duval, M., Campana, I., Guilarte, V., Miguens, L., Iglesias, J., and Sierra, S.G.:](#)
580 | [Assessing the uncertainty on particle size and shape: Implications for ESR and](#)
581 | [OSL dating of quartz and feldspar grains. Radiat. Meas., 81, 116-122, 2015.](#)
- 582 | El-Sayed, M. I.: Gypcrete of Kuwait: field investigation, petrography and genesis, J.
583 | Arid Environ., 25, 199–203, 1993.
- 584 |
- 585 | [Fain, J., Soumana, S., Montret, M., Miallier, D., Pilleyre, T., and Sanzelle, S.:](#)
586 | [Luminescence and ESR dating beta-dose attenuation for various grain shapes](#)
587 | [calculated by a Monte-Carlo method. Quat. Sci. Rev., 18, 231-234, 1999.](#)
- 588 | Fujita, S., Takahashi, A., Weng, J., Huang, L., Kim, H., Li, C., Huang, F. T. C., and Jeng, F.:
589 | Precipitation chemistry in East Asia, Atmos. Environ., 34, 525–537, 2000.
- 590 | Gerdes, G., Dunajtschik-Piewak, K., Riege, H., Taher, A. G., Krumbein, W. E., and
591 | Reineck, H. E.: Structural diversity of biogenic carbonate particles in microbial
592 | mats, Sedimentology, 41, 1273–1294, 1994.
- 593 | 15 Gerdes, G., Krumbein, W. E., and Noke, N.: Evaporite microbial sediment. in:
594 | Microbial Sediments, edited by: Riding, R. E. and Awramik, S. M.,
595 | Springer-Verlag, Berlin, Heidelberg, 196–208, 2000.
- 596 | Goudie, A. S. and Middleton, N. J.: Desert Dust in the Global System, Springer, Berlin,
597 | 2006.
- 598 |
- 599 | [Guerin, G., Mercier, N., Nathan, R., Adamiec, G., and Lefrais, Y.: On the use of the](#)
600 | [infinite matrix assumption and associated concepts: a critical review. Radiat.](#)
601 | [Meas., 47, 778-785, 2012.](#)
- 602 | Handford, C. R.: Marginal marine halite: sabkhas and salinas, in: Evaporites,
603 | Petroleum and Mineral Resources, edited by: Melvin, J. L., Elsevier, Amsterdam,
604 | 1–66, 1991.
- 605 | Hay, W. W., Migdisov, A., Balukhovskiy, A. N., Wold, C. N., Flogel, S., and Soding, E.:
606 | Evaporites and the salinity of the ocean during the phanerozoic: implications
607 | for climate, ocean circulation and life, Palaeogeogr. Palaeoclimatol., 240, 3–46, 2006.
- 608 | Inomata, Y., Igarashi, Y., Chiba, M., Shinoda, Y., and Takahashi, H.: Dry and wet
609 | deposition of water-insoluble and water-soluble chemical species during spring
610 | 2007 in Tsukuba, Japan, Atmos. Environ., 43, 4503–4512, 2009.
- 611 | Kerr, S. D. J. and Thomson, A.: Origin of nodular and bedded anhydrite in Permian

- 612 shelf sediments, Texas and New Mexico, AAPG Bull., 47, 1726–1732, 1963.
- 613 Kiefert, L.: Characteristics of wind transported dust in eastern Australia, Dissertation,
614 Griffith University, Brisbane, Australia, 1997.
- 615 Kraimer, R. A., Monger, H. C., and Steiner, R. L.: Mineralogical distinctions of
616 carbonates in desert soils, Soil Sci. Soc. Am. J., 69, 1773–1781, 2005.
- 617 Kulshrestha, M. J., Kulshrestha, U. C., Parashar, D. C., and Vairamani, M.: Estimation
618 of SO₄ contribution by dry deposition of SO₂ onto the dust particles in India,
619 Atmos. Environ., 37, 3057–3063, 2003.
- 620
- 621 Lasanta, T. and Cerda, A.: Long-term erosional responses after fire in the Central
622 Spanish Pyrenees: 2. Solute release. Catena, 60, 81-100, 2005.
- 623 Last, W. M.: Paleochemistry and paleohydrology of Ceylon Lake, a salt-dominated
624 playa basin in the Northern great plains, Canada, J. Paleolimnol., 4, 219–238,
625 1990.
- 626 Last, W. M. and Vance, R. E.: The Holocene history of Oro Lake, one of the western
627 Canada's longest continuous lacustrine records, Sediment. Geol., 148, 161–184,
628 2002.
- 629 Lavee, H., Imeson, A. C., Pariente, S., and Benyamini, Y.: The response of soils to
630 simulated rainfall along a climatological gradient in an arid and semi-arid
631 region, Catena, 19, 19–37, 1991.
- 632 Li, C., Kang, S., Zhang, Q., and Kaspari, S.: Major ionic composition of precipitation in
633 the Nam Co region, Central Tibetan Plateau, Atmos. Res., 85, 351–360, 2007.
- 634 Liu, X., Dong, H., Rech, J. A., Matsumoto, R., Yang, B., and Wang, Y.: Evolution of
635 Chaka Salt Lake in NW China in response to climatic change during the latest
636 pleistocene-holocene, Quaternary Sci. Rev., 27, 867–879, 2008.
- 637 Logan, J.: African dusts as a source of solutes in Gran Canaria ground waters,
638 Geological Society of America, 6, 849, Abstracts with Programs, 1974.
- 639 Long, H., Shen, J., Wang, Y., Gao, L., and Frechen, M.: High-resolution OSL dating of a
640 late Quaternary sequence from Xingkai Lake (NE Asia): chronological challenge
641 of the "MIS3a Mega-paleolake" hypothesis in China, Earth and Planetary
642 Science Letters, 428, 281-292, 2015.
- 643 Marion, G. M., Verberg, P. S. J, McDonald, E. V., and Arnone, J. A.: Modeling salt
644 movement through a Mojave Desert soil, J. Arid Environ., 72, 1012–1033,
645 2008.
- 646 Miao, X., Wang, H., Hanson, P. R., Mason, J. A., and Liu, X.: A new method to
647 constrain soil development time using both OSL and radiocarbon dating,
648 Geoderma, 261, 93-100, 2016.
- 649 Olson, C. G. and Nettleton, W. D.: Paleosols and the effects of alteration, Quatern. Int.,
650 51/52, 185–194, 1998.
- 651 Oyarzun, J. and Oyarzun, R.: Massive volcanism in the Altiplano-Puna Volcanic
652 Plateau and formation of the huge Atacama Desert nitrate deposits: a case for
653 thermal and electric fixation of atmospheric nitrogen, Int. Geol. Rev., 49, 962–
654 968, 2007.
- 655 Pariente, S.: Soluble salts dynamics in the soil under different climatic conditions,
656 Catena, 43, 307–321, 2001.
- 657 Pedley, M., Martin, J. A. G, Delgado, S. O., and Del Cura, D.: Sedimentology of
658 Quaternary perched springline and paludal tufas: criteria for recognition, with

带格式的: 字体: (默认) Calibri,
(中文) 黑体, 小四

带格式的: 缩进: 左侧: 0 厘米,
悬挂缩进: 2.57 字符

- 659 examples from Guadalajara Province, Spain, *Sedimentology*, 50, 23–44, 2003.
- 660 Petrov, M. P.: *Deserts of the World*, John Wiley & Sons, New York, 1976.
- 661 Reheis, M. C. and Kihl, R.: Dust deposition in southern Nevada and California, 1984–
662 1989: relations to climate, source area and source lithology, *J. Geophys. Res.*,
663 100, 8893–8918, 1995.
- 664 Rengasamy, P., Greene, R. S. B., and Ford, G. W.: The role of clay fraction in the
665 particle arrangement and stability of soil aggregates – a review, *Clay Research*,
666 3, 53–67, 1984.
- 667 Riding, R., Braga, J. C., Martin, J. M., and Sanchezalmazo, I. M.: Mediterranean
668 Messinian salinity crisis – constraints from a coeval marginal basin, Sorbas,
669 southeastern Spain, *Mar. Geol.*, 146, 1–20, 1998.
- 670 Schutt, B.: Holocene paleohydrology of playa-lake systems in central Spain: a
671 reconstruction based on mineral composition of the lacustrine sediments,
672 *Quatern. Int.*, 73/74, 7–27, 2000.
- 673 Sehmel, G. A.: Particle and gas dry deposition: a review, *Atmos. Environ.*, 14, 983–
674 1101, 1980.
- 675 Singer, A.: Introduction on arid zone soil: salt accumulation and distribution – saline
676 soils. in: *Biogeochemistry of Trace Elements in Arid Environments*, edited by:
677 Han, F. X., Springer, Dordrecht, 3–44, 2007.
- 678 Sinha, R. and Raymahashay, B. C.: Evaporite mineralogy and geochemical evolution of
679 the Sambhar Salt Lake, Rajasthan, India, *Sediment. Geol.*, 166, 59–71, 2004.
- 680 Smith, H. T. U.: Desert sedimentary environments, *Earth-Sci. Rev.*, 7, A125–A126,
681 1971.
- 682 Smoot, J. P. and Lowenstein, T. K.: Depositional environments of non-marine
683 evaporites. in: *Evaporites, Petroleum and Mineral Resources*, edited by: Melvin,
684 J. L., Elsevier, Amsterdam, 189–347, 1991.
- 685 Sun, B., Guo, Z., Yin, Q., and Hao, Q.: Soluble salts in a Quaternary loess-soil sequence
686 near Xining and their environmental implications, *Quaternary Sciences*, 26,
687 649–656, 2006 (in Chinese).
- 688 Sun, J., Zhang, L., Deng, C., and Zhu, R.: Evidence for enhanced aridity in the Tarim
689 Basin of China since 5.3 Ma, *Quaternary Sci. Rev.*, 27, 1012–1023, 2008.
- 690 Tripaldi, A., Zarate, M. A., Brook, G. A., and Li, G. Q.: Late quaternary
691 paleoenvironments and paleoclimatic conditions in the distal Andean
692 piedmont, southern Mendoza, Argentina, *Quaternary Res.*, 76, 253–263, 2011.
- 693 Valero-Garcés, B. L., Delgado-Huertas, A., Ratto, N., and Navas, A.: Large C-13
694 enrichment in primary carbonates from Andean Altiplano lakes, northwestern
695 Argentina, *Earth Planet. Sc. Lett.*, 171, 253–266, 1999.
- 696 Valero-Garcés, B. L., Arenas, C., and Delgado-Huertas, A.: Depositional environments
697 of Quaternary lacustrine travertines and stromatolites from high-altitude
698 Andean lakes, northwestern Argentina, *Can. J. Earth Sci.*, 38, 1263–1283, 2001.
- 699 Wang, L., D’Odorico, P., Okin, G., and Macko, S.: Isotope composition and anion
700 chemistry of soil profiles along the Kalahari Transect, *J. Arid Environ.*, 73, 480–
701 486, 2009.
- 702 Wang, X., Xia, D., Wang, T., Xue, X., and Li, J.: Dust sources in arid and semiarid China
703 and southern Mongolia: impacts of geomorphological setting and surface
704 materials, *Geomorphology*, 97, 583–600, 2008.
- 705 Warren, J. K.: *Evaporites: Sediments, Resources and Hydrocarbons*, Springer, Berlin,

2006. Wasson, R. J., Smith, G. S., and Agrawal, D.P.: Late quaternary sediments, minerals, and inferred geochemical history of Didwana lake, Thar Desert, India, *Palaeogeogr. Palaeoclimatol.*, 46, 345–372, 1984.
- Wesely, M. L. and Hicks, B. B.: A review of the current status of knowledge on dry deposition, *Atmos. Environ.*, 34, 2261–2282, 2000.
- Wetzel, R. G. and Likens, G. E.: *Limnological Analyses*, 3rd edn., Springer, New York, 2000.
- Yaalon, D. H. and Ginzburg, D.: Sedimentary characteristics and climatic analysis of easterly dust storms in the Negev (Israel), *Sedimentology*, 6, 315–322, 1966.
- Yang, X. and Williams, M. A. J.: The ion chemistry of lakes and late Holocene desiccation in the Badain Jaran Desert, Inner Mongolia, China, *Catena*, 51, 45–60, 2003.
- Yang, X., Preusser, F., and Radtke, U.: Late Quaternary environmental changes in the Taklamakan Desert, western China, inferred from OSL-dated lacustrine and aeolian deposits, *Quaternary Sci. Rev.*, 25, 923–932, 2006.
- Yang, X., Ma, N., Dong, J., Zhu, B., Xu, B., Ma, Z., and Liu, J.: Recharge to the inter-dune lakes and Holocene climatic changes in the Badain Jaran Desert, western China, *Quaternary Res.*, 73, 10–19, 2010.
- Yecheili, Y. and Wood, W. W.: Hydrogeologic processes in saline systems: playas, sabkhas, and saline lakes, *Earth-Sci. Rev.*, 58, 343–365, 2002.
- Zhao, Z., Tian, L., Fischer, E., Li, Z., and Jiao, K.: Study of chemical composition of precipitation at an alpine site and a rural site in the Urumqi River Valley, Eastern Tien Shan, China, *Atmos. Environ.*, 42, 8934–8942, 2008.
- Zheng, M., Guo, Z., Fang, M., Rahn, K. A., and Kester, D. R.: Dry and wet deposition of elements in Hong Kong, *Mar. Chem.*, 97, 124–139, 2005.
- Zhu, B. and Yang, X.: The ion chemistry of surface and ground waters in the Taklamakan Desert of Tarim Basin, western China, *Chinese Sci. Bull.*, 52, 2123–2129, 2007.
- Zhu, B. and Yang, X.: Chemical weathering of detrital sediments in the Taklamakan Desert, Northwestern China, *Geogr. Res.*, 47, 57–70, 2009.
- Zhu, B. and Yang, X.: The origin and distribution of soluble salts in the sand seas of northern China, *Geomorphology*, 123, 232–242, 2010.
- Zhu, B., Yang, X., Liu, Z., Rioual, P., Li, C., and Xiong, H.: Geochemical compositions of soluble salts in aeolian sands from the Taklamakan and Badanjilin deserts in northern China, and their influencing factors and environmental implications, *Environmental Earth Sciences*, 66, 337–353, 2012.
- Zhu, Z., Wu, Z., Liu, S., and Di, X.: *An Outline of Chinese Sandy Deserts*, Science Press, Beijing, 1980 (in Chinese).

Figure Captions

Figure 1 Locations of the study areas and sampling sites in this study. (a) The distributions of deserts and the mean annual precipitation isohyets in China, (b) the Taklamakan Desert, (c) and (d) the [Badain Jaran](#) ~~Badanjilin~~ Desert.

Figure 2 Photograph views of Quaternary and modern sediments of aeolian and

753 lacustrine/fluvial facies that consisted of clay and sand/silt sand alternations in the
754 Taklamakan and [Badain JaranBadanjilin](#) Deserts. (a) and (b) the Taklamakan Desert,
755 (c) and (d) the [Badain JaranBadanjilin](#) Desert.

756

757 **Figure 3** Sketch maps of the sedimentary profiles studied in this study. (a) Lacustrine
758 sediments interbedded by aeolian sand layers with ^{14}C ages at the Arerjilin-I section
759 in the [Badain JaranBadanjilin](#) Desert, (b) interbedding of aeolian and lacustrine
760 deposits and their OSL ages at the Tazhong-XIII section in the Taklamakan Desert, (c)
761 lacustrine deposits buried under a 30 m high dune at the Yaogan-VIII section in
762 southern Taklamakan, and (d) sandy loess deposits with OSL dating results at the
763 Tumiya-II section on southern margin of the Taklamakan Desert.

764

765 **Figure 4** Salinities vs. pH of sediment solutions, (a) dune-surface sediments (modern
766 sediment) and buried-dune sediments (palaeo-sediment) in the Taklamakan Desert,
767 (b) dune-surface sand samples collected in different climatic seasons (dry and wet) in
768 the [Badain JaranBadanjilin](#) Desert. (c) Carbon-bearing ions vs. pH. Triangular plots of
769 major anions (d) and cations (e and f) of the soluble salts in mEq/l unit. Distribution
770 patterns of the major ions of the soluble salts in the aeolian sediments from (g) the
771 [Badain JaranBadanjilin](#) Desert and from (h) the Taklamakan Desert.

772

773 **Figure 5** Distribution patterns of the major ions of aeolian salts, groundwaters and
774 lake waters in (a) the [Badain JaranBadanjilin](#) Desert and (b) the Taklamakan Desert.
775 The data of local lake water and groundwater bodies in the [Badain JaranBadanjilin](#)
776 are cited from [Yang and Williams \(2003\)](#), and the river water and groundwater bodies
777 in the Taklamakan from [Zhu and Yang \(2007\)](#). The relationship between salinities and
778 grain size compositions of the aeolian sediments: (c) salinity vs. median particle
779 diameter (Mz, in phi unit) of dune-surface sediment from the Taklamakan Desert,
780 and (d) salinity vs. grain size compositions of randomly-selected dune sediments
781 from the [Badain JaranBadanjilin](#) Desert. Spatial distributions of the salinities of the
782 aeolian sediments along the longitudinal and latitudinal degrees in the Taklamakan
783 Desert (e and g) and in the [Badain JaranBadanjilin](#) Desert (f and h), respectively.

784

785 **Figure 6** Sequential variations in soluble salts contents (salinity and pH) of the
786 Arerjilin-I section in the [Badain JaranBadanjilin](#) Desert.

787

788 **Figure 7** Sequential variations in soluble salts contents (salinity and pH) of the
789 Tazhong-XIII section in the Taklamakan Desert.

790

791 **Figure 8** Sequential variations in soluble salts contents (salinity and pH) of the
792 Yaogan-VIII section in the Taklamakan Desert.

793

794 **Figure 9** Sequential variations in soluble salts contents (salinity and pH) of the
795 Tumiya-II section in the Taklamakan Desert.

796

797

798 **On-line Supplementary Table Captions**

799

800 **On-line Supplementary Table 1** Physical parameters of the soil-water extraction of
801 the modern and ancient aeolian sediments from the Taklamakan and [Badain](#)
802 [JaranBadanjilin](#) deserts in northwestern China.

803

804 **On-line Supplementary Table 2** The analytical data of major ionic compositions for
805 the soil-water extraction of the aeolian sediments from the Taklamakan and [Badain](#)
806 [JaranBadanjilin](#) deserts

807

808 **On-line Supplementary Table 3** Conventional radiocarbon ages for section samples
809 from the [Badain JaranBadanjilin](#) Desert (cited from [Yang et al., 2010](#))

810

811 **On-line Supplementary Table 4** Summary data for OSL ages of section samples from
812 the Taklamakan Deserts (cited from [Yang et al., 2006](#)).

The revised manuscript (clearcopy)

Atmospheric significance of aeolian salts in the sandy deserts of northwestern China

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Abstract: Large sandy deserts in the middle latitudes of northwestern China were investigated for soluble salt variations in modern and ancient aeolian sediments, aiming to explore the environmental significance of “aeolian salts”. Results revealed that aeolian salt variations have a clear relationship with the changing meridional and zonal gradients of the desert locations and the aeolian differentiation effect, but are weakly linked to local geological conditions. It suggests that the natural system of aeolian salts is hydrologically open and the chemistry of the parent brines are different from that predicted for hydrologically closed systems. Atmospheric depositions of water-soluble chemical species are an important process/source contributing to aeolian salt. Sequential variations of soluble salts in sedimentary profiles interbedded with aeolian and non-aeolian deposits and their palaeoenvironmental implications in the hinterland areas of these deserts were further evaluated, based on the constraints of OSL dating and radiocarbon dating data. The results indicate that the inorganic salts may be a latent geoproxy in revealing regional palaeoclimatic changes in desert areas for the sediments deposited under onefold depositional environment, but the interpretation should be more careful for the sediments deposited under diverse depositional conditions. This study presents the evidence of atmospheric origin of aeolian salt in sandy deserts, with limited climatic significance in palaeoenvironmental reconstruction.

Keywords: aeolian salt archive; environmental geoproxy; atmospheric deposition; palaeoclimate change; middle-latitude sandy desert; northwestern China

1. Introduction

Salt deposits (evaporites) are found in locations as diverse as Antarctica to the equatorial latitudes, and in depositional settings ranging from intracontinental to marginal marine (Handford, 1991). Much of what we know about ancient sedimentary facies and their depositional environments was derived from the study of modern sedimentary environments. Formation of soluble/inorganic salts in many types of deposits (e.g., soils, playa and lake sediments) is supposed to be governed mainly by climate factors including annual precipitation inputs, soil moisture changes, evapotranspiration losses, and solar radiation (Borchert and Muir, 1964; Sinha and Raymahashay, 2004; Warren, 2006; Singer, 2007). Thus salt archives in sediments are critical to understanding a number of geochemical processes in the supergene environment of the hydrogeologic and hydroclimatic systems. For instance, the soluble salt mineral assemblages embody significant signals indicating the processes of the solutes origin and transportation after their deposition (Warren, 2006; Zhu and Yang, 2010). Because soluble salts in soil/sediments response sensitively to

48 regional-scale climate and hydrology changes (Borchert and Muir, 1964; Smoot and
49 Lowenstein, 1991), they have been used as a key environmental proxy indicator in
50 sedimentary records of oceans, lakes, sandy deserts and loess-paleosol sediments
51 (Borchert and Muir, 1964; Sinha and Raymahashay, 2004; Hay et al., 2006; Warren,
52 2006; Sun et al. 2006; Liu et al., 2008; Sun et al. 2008). In these case studies, vertical
53 variations of salt solutes in sediment strata are used as a geoproxy to indicate past
54 salinity conditions and climatic changes in many parts of the world (Wasson et al.,
55 1984; Last, 1990; Dean and Schwalb, 2000; Schutt, 2000; Last and Vance, 2002; Sinha
56 and Raymahashay, 2004).

57 In arid conditions the desert landscape is globally distributed. For these areas,
58 non-marine salt deposits are common features of modern arid closed basins.
59 Researches on salt deposits under arid climate have been documented over a long
60 time, however, the environmental implications of inorganic salt formation in desert
61 areas are still not clear, to a certain extent because of the diverse compositions of
62 salt solutes with complicated formation mechanisms in different geomorphologic
63 units. Researches about salt formation have been performed worldwide in different
64 arid conditions, with the main purpose to identify the relationship between salt
65 regime and environmental factors, for instance, salt formation in different clay type
66 (Rengasamy et al., 1984), hydrological distribution (Borchert and Muir, 1964; Warren,
67 2006), fire ashes (Lasanta and Cerda, 2005; Bodi et al., 2012, 2014), soil erosion
68 (Lasanta and Cerda, 2005; Cerda et al., 2013; Agata et al., 2015), hydrological
69 distribution (Borchert and Muir, 1964; Warren, 2006; Bodi et al., 2012),
70 geomorphologic setting and dust source (Wang et al., 2008), volcanism and
71 atmospheric fixation (Oyarzun and Oyarzun, 2007), rainfall patterns (Ahuja, 1990;
72 Dragovich and Dominis, 2008) and mean annual climatic conditions (Dan and Yaalon,
73 1982; Lavee et al., 1991; Pariente, 2001), but relatively few have been recognized in
74 the aeolian sediments. Until now, few investigations have been involved into the
75 environmental implications of salt deposits from the sandy deserts in northern China
76 (Zhu and Yang, 2010; Zhu et al., 2012), although these deserts comprise of the
77 majority of middle-latitude deserts in the temperate zone of the Northern
78 Hemisphere (NH).

79 In this work we present a physical and geochemical exploration into inorganic
80 solutes filtrated from aeolian sediments collected from the inland sandy deserts in
81 northwestern China, representing a cross-section of different environments (from
82 westerly to monsoon climate control) in the NH middle latitudes. The objective of the
83 paper is to explore the atmospheric significance of inorganic salts in aeolian
84 sediments and their possible climatic implications.

85

86 **2. Methodology**

87

88 The study areas and sampling sites were chosen from famous sandy deserts in
89 China (Fig. 1a), i.e., the Taklamakan Desert in the Tarim Basin (the westerly climate
90 control) and the Badain Jaran Desert in the Alex Plateau (the monsoon climate
91 control). Both the modern and ancient aeolian sediments were designed to be
92 sampled in the field. For modern aeolian sediment, thirty-three dunes in the
93 Taklamakan Desert and fourteen dunes in the Badain Jaran Desert were sampled in
94 the field. The modern sands were sampled from the active dune surface. The

95 geographical locations of these sample sites are mainly situated in dune fields from
96 the center and southern edges of the Taklamakan Desert (Fig. 1b) and the southern
97 inland area in the Badain Jaran Desert (Fig. 1c-d).

98 In the Inner part of the Taklamakan and the Badain Jaran Deserts, aeolian and
99 lacustrine (or fluvial in Taklamakan) deposits (palaeosediments) are frequently found
100 interbedded (Fig. 2). For instance, lacustrine/fluvial sediment strata widely occur in
101 the hinterland dune fields of the Taklamakan Desert along the N-S oil-transporting
102 highway (Fig. 2a-b). Four sedimentary sequences with clearly stratigraphical layers
103 were selected from hinterland areas of the two deserts in this study (Fig. 1). It is
104 about 4 m in depth for the Arerjilin-I section from the Badain Jaran Desert (Fig. 1d).
105 Lacustrine sediments in this section were interbedded by aeolian sand layers (Fig. 3a).
106 For the Tazhong-XIII section in the Taklamakan Desert (Fig. 3b), it is general a
107 lacustrine sequence interlayered with dune sediments. The Yaogan-VIII section is
108 situated at the lower reaches of the Keriya River (Fig. 1b) close to the south margin of
109 the Taklamakan Desert. The top of this section is buried by a 30-m active dune (Fig.
110 3c). The Tumiya-II section is located at the low reaches of the Tumiya palaeochannel
111 close to the south edge of the Taklamakan Desert (Fig. 1b). This section is general a
112 silty sand or sandy silt sequence interlayered by cemented calcium-carbonate layers
113 (Fig. 3d). In general, lithologies of the lacustrine sediments are greatly different from
114 those of the aeolian sediments in all sedimentary sequences from the Taklamakan
115 Desert. These sequences were chronologically analyzed based on optically stimulated
116 luminescence (OSL) dating and radiocarbon (^{14}C) dating methods.

117 The analytical methods for soluble salt geochemistry of aeolian sediment
118 samples can be seen from Zhu and Yang (2010), and the OSL and radiocarbon dating
119 methods can be seen from Yang et al. (2006, 2010). The physical and chemical
120 analytical data of the soluble salt compositions of sediments are shown in On-line
121 Supplementary Table 1 and Table 2, respectively. The resulting OSL and radiocarbon
122 dating ages are summarized in On-line Supplementary Table 3 and Table 4,
123 respectively. Note that the partial characteristics of aeolian salts from the
124 Taklamakan and Badain Jaran Deserts were previously reported in our early works
125 (Zhu and Yang, 2010; Zhu et al., 2012) with preliminary descriptions of their
126 composition and distribution and related influencing factors, but their complete
127 stratigraphies and chronologic results are presented here along with other new
128 palaeoenvironmental estimations.

129 130 **3. Results**

131
132 Salinity values for all samples are mathematically calculated based on TDS
133 values of the filtrates and their water-sediment mass ratios. The pH and the
134 calculated salinity values for the dune sediments from the Taklamakan Desert range
135 between 8.66 and 9.54 (mean 9.22) and 0.27‰ and 1.86‰ (mean 0.78‰),
136 respectively. For the dune sediments in the Badain Jaran Desert, the pH and the
137 salinity values lie between 8.82 and 9.42 (mean 9.12) and 0.05 and 0.42‰ (mean
138 0.15‰) , respectively. The range of pH values between the aeolian sediments is
139 narrow (8.6-9.5). It indicates that the soil conditions and acid buffer capacities for
140 these deserts are similar, generally in alkaline nature. Studies have proved that pH
141 values in soil between 6.4-12.2 are mainly caused by bicarbonate (6.4-10.3) and

142 carbonate (10.3-12.2) (Wetzel and Likens, 2000). It thus means that the alkalinities of
143 aeolian salts in Chinese deserts are mainly controlled by the carbon-bearing salts,
144 particularly bicarbonate.

145 For the 15 palaeo-aeolian sediment samples buried beneath modern dunes in
146 the Taklamakan Desert with OSL ages ranging between 40-2 ka B.P. (On-line
147 Supplementary Table 4), The salinities and pH values are slightly higher in salinity and
148 lower in pH than those of modern dune sand samples (Fig. 4a). The modern dune
149 samples collected from the identical months in different climatic year (such as the
150 autumns in the arid 2006 and in the wet 2008) in the Badain Jaran Desert are quite
151 similar to each other (Fig. 4b).

152 The major anions of aeolian salts are Cl^- and HCO_3^- in all samples. The SO_4^{2-}
153 concentrations are relatively low (Fig. 4d). Na^+ is the first major cation and Ca^{2+} is the
154 second. The concentrations of K^+ and Mg^{2+} are relatively low (Fig. 4e-f). It should be
155 noted that the carbon-bearing ion concentrations in these sediments are highly
156 correlated with pH (Fig. 4c). Based on charge balances and mass matches between
157 major cations and anions, the potential salt mineralogy of these aeolian sediments
158 can be categorized as: $\text{NaHCO}_3 + \text{NaCl} + (\text{CaCO}_3)$ in the Badain Jaran Desert (Fig. 4g),
159 and $\text{NaCl} + \text{NaHCO}_3$ in the Taklamakan Desert (Fig. 4h). It indicates that the
160 assemblage of sodium carbonate and chloride is widely distributed in aeolian
161 sediments within the Chinese sandy deserts.

162 The fingerprint diagrams of the ion distribution patterns for aeolian sediment
163 solutes, local groundwaters and surface waters are shown in Fig. 5 a-b. The
164 distribution patterns for dune surface sediments from the Badain Jaran Desert are
165 different from the local groundwaters and the local lake waters (Fig. 5a). The
166 chemical differences between aeolian salts and natural waters are also evident in the
167 Taklamakan Desert (Fig. 5b), particularly in the patterns of magnesium and sulfate.
168 These factors reflect a weaker influence of local waters on aeolian salts both in the
169 Badain Jaran and Taklamakan Deserts.

170 For the Taklamakan Desert, the salt salinities of aeolian sediments have a strong
171 positive correlation with the median grain sizes of the corresponding samples (Mz in
172 phi unit, Fig. 5c), indicating an enrichment of soluble salts towards the finer particles
173 of aeolian sediments. A same trend is also observed in the Badain Jaran Desert, as
174 the salt concentrations in different grain size fractions increasing when particle
175 fractions become finer (Fig. 5d).

176 In dune surface sediments from the two deserts along the longitude (E) and
177 latitude (N) lines of sampling sites, the salt salinities show regularly varied trends,
178 with an increasing salinity together with the decreases of the longitude and latitude
179 degrees, respectively (Fig. 5e-h). Because the mean annual precipitation in northern
180 China increases gradually along the same meridional direction, and the temperature
181 or mean solar radiation decreases along the same latitudinal gradients, this indicates
182 that enrichment of aeolian salt contents have a clearly relationship with the changing
183 meridional and zonal gradients of the sample locations, which correspond to the
184 regional climatic gradient, as well as the aeolian effects of granularity differentiation
185 caused by wind/atmospheric dynamics, but are weakly linked with local hydrological
186 conditions.

187 For the Arerjilin-I section in the Badain Jaran Desert, black carbon from the
188 highest shorelines of Arerjilin Lake (+10 m) were dated to 5628 ± 221 cal yr BP

189 (CNR-185, Fig. 3a and On-line Supplementary Table 3). Calcareous gyttja (+6 m) and
190 black carbon (+5.5 m) from deposits above the lake surface was dated to 4757 ± 315
191 cal yr BP (CNR-173) and 7144 ± 200 cal yr BP (CNR-186), respectively (Fig. 3a and
192 On-line Supplementary Table 3). Normally, deposits are younger at locations below
193 the highest lake level. However, in this case it is believed that younger sediments
194 were removed by wind erosion. Consequently, the older lacustrine sediments are
195 now exposed to the surface.

196 The Tazhong-XIII section contains three lacustrine layers interbedded by aeolian
197 sand sediments (Fig. 3b). The OSL age of the bottom aeolian layer is $39,800\pm2900$ a
198 (On-line Supplementary Table 4). Aeolian layers underlying the top two lacustrine
199 layers are dated to $28,000\pm2300$ a and $29,200\pm2600$ a. The age limits of the lower
200 lacustrine layer range between ca 40,000 and 30,000 a ago (Fig. 3b).

201 Lacustrine strata in the Yaogan-VIII section are intercalated with two aeolian
202 sand layers (Fig. 3c). The aeolian sands underlying the lacustrine section is dated to
203 $14,500\pm1100$ a (On-line Supplementary Table 4), and the aeolian sands overlying the
204 lacustrine section is dated to 2320 ± 180 a. The age constraints of aeolian sand layers
205 indicate that the paleolake was dried between ca 14,000 and 2000 a (Fig. 3c).

206 In the Tumiya-II section that deposited on the palaeoterrace of the Tumiya River
207 near the south margin of the Taklamakan Desert, The OSL chronology is dated to
208 between $23,700\pm1800$ a and 8700 ± 800 a (On-line Supplementary Table 4). The
209 accumulation of sandy loess at this section indicates that southern margin of the
210 Taklamakan Desert at the time between $23,700\pm1800$ and 8700 ± 800 a was wet.

211 The above chronological data show that the OSL data hold great uncertainty. It
212 may be necessary to discuss the uncertainty in different locations in this study. As
213 previously reported, textures such as grain size and shape are important parameters
214 influencing the OSL dating of sediment (Aitken, 1985; Fain et al., 1999; Brennan,
215 2003; Guerin et al., 2012; Duval et al., 2015), since they have a direct impact on
216 several correction factors that are used for evaluating the dose rate. The aeolian sand
217 layers for OSL dating in the Tazhong-XIII section have a mean particle sizes of 3.3-3.5
218 phi (sieving result), which is much coarser than the interbedded lacustrine deposits
219 (mean particle size 5.8-6.7 phi). The aeolian sand layers in the Yaogan-VIII section
220 have a mean grain size of 3.8 phi, also coarser than the intercalated lacustrine
221 deposits (mean particle size 4.6-6.2 phi). Aeolian silt or sandy loess deposits in the
222 Tumiya-II section have a mean grain size of 3.6-4.0 phi. These data show a large
223 variability in term of size of grains between the samples for OSL dating in the
224 Taklamakan Desert. Because there is a distinction between the sieve aperture size, or
225 sieve opening, and the diameter of a particle, consequently, the main dimension
226 controlling the sorting of the grains for non-spherical particles is the so-called
227 intermediate diameter. For example, for standard mesh of 50, 100, 200 and 300 mm,
228 grains passing through may have an intermediate dimension in the range of from 50
229 to 71 mm, 100-141 mm, 200-283 mm, 300-424 mm, respectively (Duval et al., 2015).
230 Besides, the grain size distribution of the raw sediment may have also an impact on
231 the dating results, like in the case of a bimodal distribution (Duval et al., 2015). So
232 the principal sources of uncertainty in OSL dating data of this study may potentially
233 be derived from the grain size of aeolian sediments. On the other hand, the
234 difference in ^{14}C ages between the uppermost and lowermost organic carbon layers
235 of a sediment profile usually underestimates the time of sediment deposition, and

236 the difference in OSL ages taken from sediment units overlying and underlying a
237 buried soil most likely overestimates it (Miao et al., 2016). For example, the
238 comparison of OSL and ¹⁴C ages suggests that the radiocarbon dating technique may
239 significantly underestimate the age of sediments for samples older than 30 cal ka BP
240 (corresponding to ~25 ¹⁴CkaBP) (Long et al., 2015). This factor could also lead to a
241 certain uncertainty in the chronological data of this study.

242 **4. Discussion**

243 **4. 1. Primary or secondary salt in origin?**

244
245
246
247 Firstly, it is necessary to understand whether the nature of soluble salt in aeolian
248 sediment is primary or secondary in origin. As defined by Warren (2006), an original
249 salt deposit (evaporite) is hydrologically driven by solar evaporation and is sourced
250 from saturated brine on ground surface or nearsurface. In order to emphasize the
251 highly reactive nature of soluble salts in the sedimentary realm, such salts that is
252 precipitated from surface brine and retaining crystallographic evidence of the
253 depositional process are regarded as primary salt. According to this definition and
254 the related two limiting factors, almost every subsurface salt texture is secondary,
255 because it is diagenetically altered, frequently with fabrics indicating pervasive early
256 recrystallization. Secondary salts can be formed in surface/subsurface settings
257 equivalent to the eogenetic, mesogenetic and telogenetic realms (Choquette and
258 Pray, 1970). Under this definition of a primary versus secondary salt, we can say that,
259 outside of a few Neogene examples (Riding et al., 1998; Valero-Garces et al., 1999,
260 2001; Pedley et al., 2003), there are few salt deposit with textures that are wholly
261 and completely “primary”. Without exception, soluble salts in aeolian sediments
262 should be secondary salt originated in the eogenetic realm.

263 According to the salt category defined by Warren (2006), salt minerals can be
264 simply subdivided into evaporitic alkaline earth carbonates and evaporite salts. In a
265 view of depositional process, evaporitic alkaline earth carbonates are the
266 firstly-precipitated salt minerals that sourced from concentrating hypersaline water.
267 Compared with the evaporite salts, they are tend to be formed during the early
268 stages of surface brine concentration-crystallization, while the evaporite salts are
269 formed during the more saline stages of concentration-crystallization process (Smoot
270 and Lowenstein, 1991). As analyzed above, NaHCO₃ + CaCO₃ are the identical
271 components in dune sediments from both the Taklamakan and the Badain Jaran
272 Deserts. It indicates that evaporitic alkaline earth carbonates are major component
273 of these aeolian salts.

274 Although texture of most of the subsurface salts is secondary, the earliest
275 secondary salts are often syndepositional precipitates (Warren, 2006), with
276 formation of cements and replacement even as the primary matrix accumulates
277 around them. For example, nodular anhydrite and aragonite were recognized in
278 Permian mudflats by Kerr and Thomson (1963), they interpreted it as a subaqueous
279 saline pan indicator. Works by Gerdes et al. (1994, 2000) have shown that carbonate
280 grains, such as ooids and peloids, typically thought of as indicators of marine
281 conditions and mechanical agitation, can precipitate in situ in CaCO₃-saturated
282 evaporitic settings. For aeolian sediments in arid environment, we image that much

283 of surface salts are deposited in multiple episodes of early diagenetic
284 (syndepositional) cementation. This syndepositional salt may be formed in multiple
285 dissolution-precipitation events in the sand particle surface and are precipitated
286 between successive depositional episodes of salt crust formation.

287 Besides alkaline earth carbonates ($\text{NaHCO}_3 + \text{CaCO}_3$), NaCl is another major
288 component of aeolian salts in the deserts studied. This salt, dominantly halite, is
289 evaporite salts according to the classification by Warren (2006) that precipitated
290 from concentrated brine after the brine has crystallized the alkaline earth carbonates.
291 Both the evaporitic alkaline earth carbonates and evaporite salts coexist in the
292 aeolian sediments of the deserts, indicating that aeolian salts are complex salt
293 mixture formed by multiple evaporation and precipitation processes in the eogenetic
294 realm.

295

296 **4. 2. Possible mechanism of aeolian salt formation**

297

298 All evaporite salts are ionic salts. The definition of a salt deposit (evaporite)
299 proposed by Warren (2006), as mentioned above, has no assumption as to the origin
300 of the parent brine. It may be marine, nonmarine or a hybrid (Smoot and Lowenstein,
301 1991). By definition, there is a need for aridity and for water loss to exceed inflow
302 (Borchert and Muir, 1964). This means deposition and diagenesis in evaporites is
303 more dependent on climate than in either siliciclastic or carbonate sediments.
304 Therefore, modern continental evaporites typically accumulate in semi-arid to
305 hyperarid deserts. Suites of precipitated salts follow the geochemical make-up of the
306 parent brine (Braitsch, 1971). It means that the mineralogy and order of precipitates
307 in any brine pool are controlled by the ionic make-up of the parent brine. This
308 provides a clue to reveal the possible source and mechanism of salt formation under
309 particular environment.

310 Generally speaking, eight mechanisms or processes precipitate most salt
311 minerals and crusts worldwide: 1) in-situ pedogenic weathering and eluviation
312 processes of existing salty or volcanogenic (ash) parent materials; 2) eolian or fluvial
313 input of salt or salt-rich sediment; 3) upward movement of salt via capillary flow
314 from a shallow salty groundwater, 4) an oceanic aerosol source, creating in
315 salt-enriched rainfall that evaporatively concentrates within the regolith, 5) intrusion
316 and flooding by seawater, 6) decomposition of vegetation, 7) in-situ oxidation of
317 sulphide minerals, 8) anthropogenic pollutants (Petrov, 1976; Smoot and Lowenstein,
318 1991; Warren, 2006; Singer, 2007). The first two sources are direct evaporite
319 associations, while the third is typically associated with salt lakes, sabkhas and playas
320 in semi-arid or desert settings within 500-1000 km of the coast. Many salt soil
321 horizons are combinations of both pedogenically precipitated and detrital
322 wind-reworked salt (Warren, 2006; Singer, 2007). Based on the eight views, we can
323 get clues into the possible mechanism of aeolian salt formation in Chinese deserts.

324 To the weathering mechanism in view (1), our previous study has shown that the
325 degree of weathering of aeolian sand in the Taklamakan is very low ($\text{CIA} \approx 50$) (Zhu
326 and Yang, 2009), which is similar to that of the un-weathered Upper Continental
327 Crust. This observation suggests that salt contributions directly from bedrock
328 weathering are of minor significance. For the eluviations process in view (1), studies
329 have demonstrated that in a region with a mean annual precipitation less than 500

330 mm, the export of erosible elements by eluviation processes in the soil will be less
331 significant than their preservation by evaporation-crystallization processes (Birkeland,
332 1999; Kraimer et al., 2005). Since the mean annual precipitation in desert regions of
333 northern China is lower than 400 mm (Fig. 1a), the degree of eluviation exerted on
334 soluble salts in the two sandy seas is lower than that of preservation. The salt
335 concentrations of samples buried in dune subsurface layers in this study are equal to
336 or only slightly higher than those of the surface samples (Fig. 4a), indicating only a
337 little downward movement of these salts is taking place. Case studies on salt
338 movement in desert soil have also shown that only 1.64% of the rainfall-leached salt
339 can reach 1.0 m depths, and only 0.02% of the rainfall-leached salt can penetrate 2.0
340 m below the ground surface (Marion et al., 2008). This means that salt contributions
341 from eluviation processes of parent salts are also minor.

342 To the view (3), dunes in both the Taklamakan and Badain Jaran Deserts are
343 generally higher than 20~50 m (Zhu et al., 1985), particularly being higher than 200
344 m in the Badain Jaran Desert, so it is impossible for groundwater to contribute salt to
345 aeolian sediments by drawing upward to the dune surface via capillarity.

346 To the view (4) and (5), both the two sandy deserts studied are geographically far
347 away from any ocean and have been under the control of terrestrial processes since
348 at least the Cenozoic (Zhu et al., 1980). Salt contributions from present or ancient
349 seawater and aerosol can, therefore, be neglected. However, contributions from
350 oceanic-sourced rainfall precipitation (atmospheric wet deposition) will discuss
351 below.

352 To the view (6), although the decomposition of vegetation may contribute to the
353 salts of some desert areas (Petrov, 1976), but plants in/around the sampling sites of
354 the deserts in this study are scarce, so any influence of vegetation is minimal.

355 To the view (7), Petrov (1975) suggested that the salt chemistry in the world
356 deserts can be classified into four types: chloride, sulfate, carbonate and mixed.
357 Many desert soils in arid to semi-arid environment are sulphate-rich in areas
358 surrounding the perennial saline lakes, the brine pan depressions and their dune
359 margins (Petrov, 1976; Smoot and Lowenstein, 1991; Warren, 2006). For example,
360 gypsum crusts have been reported from all the continents, including Antarctic
361 (El-Sayed, 1993). Studies have shown that chloride-sulfate salts but not bicarbonate
362 salts are dominated in the Kalahari Desert (Wang et al., 2009). This is also the case
363 for wide-distributed aeolian loess deposits in the Loess Plateau of northern China
364 (Zhu et al., 2012), which are mainly composed of $\text{Na}_2\text{SO}_4 + \text{NaHCO}_3$ for loess and of
365 $\text{Na}_2\text{SO}_4 + \text{NaCl} + \text{NaHCO}_3$ for paleosol (Sun et al., 2006). While, the analysis of this
366 study shows that aeolian salts in the Taklamakan and Badain Jaran Deserts are
367 mixture of sodium bicarbonate and chloride. This is different from both the Chinese
368 loess deposits and the global tropical/subtropical deserts. Although sodium sulphate
369 (Na_2SO_4) is an important salt existed in loess-paleosol sequences, but less common
370 in the dune sediments from the sandy deserts in this study. So mechanism of in-situ
371 oxidation of sulphide minerals can be excluded for the aeolian salts in this study.

372 To the view (8), anthropogenic pollutants, generated by human activities, are
373 usually inorganic ions such as NH_4^+ , NO_3^- , H_2PO_4^- and SO_4^{2-} and some organic anions.
374 The contents of all samples studied, however, have roughly equivalent numbers of
375 cations and anions with low/none above-mentioned ions (On-line Supplementary
376 Table 2), suggesting that human impact on salt concentrations across the two sandy

377 deserts is negligible.

378 On the basis of all above results, only the view (2) is unexplained. Actually the
379 mechanism in view (2) involves the hydrological and atmospheric processes of salt
380 origin and transportation. We discuss it below.

381

382 **4. 3. Atmospheric origin?**

383

384 There are wide similarities but partial differences existing in the salt chemistry
385 and ion distribution patterns of aeolian salts between the Taklamakan and Badain
386 Jaran deserts (Fig. 4g-h). Besides, they are weakly correlated with the chemical
387 compositions of the nearby ground waters under local hydrological setting (Zhu and
388 Yang, 2010) (Fig. 5a-b), but are strongly associated with the regional climatic and
389 wind regime (Zhu et al., 2012) (Fig. 5c-h). All these evidences indicate that the
390 natural system of aeolian salts is hydrologically open and the chemistry of the parent
391 brines and the associated salt deposits may be significantly different from that
392 predicted for hydrologically closed systems. It means that the sources of aeolian salts
393 in the deserts are strongly controlled by earth surface processes at a regional or large
394 scale, but not at a local scale. Seen from this point, only an atmospheric origin but
395 not hydrological origin can be responsible for this pattern.

396 It has been recognized that atmospheric chemical species is a significant source
397 contributing acidic and eutrophic elements to both the terrestrial and ocean
398 ecosystems (e.g., Sehmel, 1980; Wesely and Hicks, 2000; Inomata et al., 2009). For
399 example, soil salts in many desert areas have been implicated to be originated from
400 the atmospheric sources (Amit and Yaalon, 1996; Bohlke et al., 1997; Oyarzun and
401 Oyarzun, 2007). Generally, there are two forms for atmospheric deposition, wet and
402 dry deposition. Wet deposits contain salts derived from rainwater and snow. Studies
403 have shown that chloride and carbonate are major species in rainfall in central Asia
404 and north China (Fujita et al., 2000; Li et al., 2007; Zhao et al., 2008). It indicates that
405 the chemical compositions between wet depositions and aeolian salts are similar.

406 Besides rainfall, aerosol and dust, known as atmospheric dry deposition, is
407 another global phenomenon of salt transportation (Goudie and Middleton, 2006). At
408 present there are few data being available for understanding the salt compositions of
409 dust in the study areas. However, wide studies have proved that salt transportation
410 and redeposition via dust are one of the important patterns for biogeochemical
411 cycles in arid areas (Logan, 1974; Yaalon and Ginzbourg, 1966; Reheis and Kihl, 1995;
412 Al-Momani et al., 1995; Kiefert, 1997; Blank et al., 1999; Kulshrestha et al., 2003;
413 Zheng et al., 2005; Abuduwaili et al., 2009). It should be a similar case for the
414 hinterlands of northwestern China.

415

416 **4. 4. Climatic implications**

417

418 The coexistences of palaeo-lacustrine sediments (playa) and aeolian sediments
419 are commonly seen in desert regions globally. These are clear evidences for past
420 environmental changes in desert conditions (Smith, 1971; Yechieli and Wood, 2002;
421 Alonso-Zarza, 2003; Yang et al., 2006; Tripaldi et al., 2011; Dong et al., 2012),
422 Therefore, the large number of playa deposits in the inter-dune depressions of these
423 deserts offers an exceptional opportunity to study regional paleohydrological and

424 paleoclimatic change. Over the past decade, there have been significant advances in
425 our understanding of the late Quaternary history of the desert regions of
426 northwestern China. OSL and ¹⁴C chronologies of aeolian sediments from various
427 locations in these deserts provide important archives to understand the timing of
428 lacustrine/fluvial and aeolian processes related to environmental and climate
429 changes. However, despite this increased interest, paleolimnological and
430 palaeoaeolian research is limited by a paucity of potential geoproxy and the study
431 sites with relatively long, uninterrupted stratigraphic sequences. Sequential
432 variations of inorganic salts have been tentatively applied to reconstruct the
433 palaeoenvironmental history in desert areas. For instance, taking the soluble salts
434 variations in thick Cenozoic deposits as one of the indicators of paleoenvironmental
435 change, Sun et al. (2008) reconstructed the aridity history of the Tarim Basin and
436 argued that hyperarid climate had been prevailed within the basin since 5.3 Ma ago.

437 The variations in soluble salts content for the four sections collected from the
438 Taklamakan and Badain Jaran deserts are examined in this study, as shown in Figs.
439 6-9. The OSL and ¹⁴C age constraints of these sequences are also shown in these
440 figures. The data indicates that all of these playa deposits had experienced
441 fluctuations in high moisture conditions during the period from late Pleistocene to
442 mid-Holocene.

443 For the Arerjilin-1 section, there are an increase-decline pattern in salinity
444 variation and a decline-increase-decline pattern in pH variation during the
445 early-middle Holocene (Fig. 6). For the Tazhong-XIII section, there is a clear serrate
446 shape (Fig. 7) in the pattern of salinity variation. It indicates that there are at least
447 three times of humid environmental fluctuations during the past 40 to 28 ka B.P.. In
448 the Yaogan-VIII section, the sequence salinities are relatively high (Fig. 8). It suggests
449 that a saline lacustrine environment has occurred this area and the local hydrological
450 settings have been retained the saline conditions for a long time from the end of the
451 last glacial to late Holocene. In the Tumiya-II section, variations of the sequence
452 salinities were unstable during the LGM (24 ka B.P.). There are two stages of salinity
453 increase during the end of the LGM (about 10-11 ka) and the early Holocene (after
454 8.7 ka B.P.), respectively (Fig. 9). Taken the four sections as a whole into
455 consideration, there are evident differences between the aeolian sediments and
456 fluvial sediments in salt content. In general, salinities in aeolian sediments are
457 evidently lower than those of lacustrine sediments. It suggests that a great salt
458 depositional discrepancy exists between the aeolian and the lacustrine sedimentary
459 systems, which could be owing to the differential mechanisms of salt formation and
460 origin in wind and water regimes. The results suggest that the inorganic salt is a
461 latent proxy indicator for single depositional-environment sequence in revealing local
462 hydrological variations and climate changes in desert areas during the late
463 Quaternary.

464 However, the interpretation based on salt archives should be careful for the
465 sedimentary sequences with dual/multiple depositional end-members. Researchers
466 have reported that in a sediment strata formed by an identical geological process like
467 lacustrine or aeolian dynamics, the increase of sequence salinity commonly reflects a
468 stepped-up environmental aridity (Sinha and Taymashay, 2004; Warren, 2006; Liu
469 et al., 2008). Because whatever under the aeolian and lacustrine depositional
470 settings, the increase in salt content is a reflection of the enhanced evaporation

471 potential. However, in a sediment profile controlled by multiple geological processes
472 like combined aeolian and lacustrine dynamics, the increase in salt content could be
473 not a reflection of the enhanced aridity, just like the case in this study. It is generally
474 higher in salinity for the lacustrine sediments than for the aeolian sediments. In this
475 study, the salinity increases in sections of the Arerjilin-I, Tazhong-XIII and Yaogan-VIII
476 are general a representation of the enhanced wetter conditions (Figs. 6-8), because
477 the higher salinities are always located in the lacustrine/fluvial layers. In general,
478 lacustrine/fluvial strata in aeolian sequences always reflect enhanced humid periods
479 than that of the aeolian period (Yang et al. 2006). However, this is not the similar
480 conditions for the Tumiya-II section, as the salt increases in this sequence should be
481 attributed to enhance aridity (Fig. 9), because the sedimentary structure of this
482 section is uniformly dominated by aeolian process. Thus it can be confirmed that
483 once the coexistence of aeolian and fluvial/lacustrine sediments occurs in a
484 sedimentary structure in desert regions, the single use of salt archives should be
485 cautious in reconstructing the regional environmental changes. A combined use of
486 salt archives and sedimentary proxies is recommended under this situation.

487 Besides, land surface processes such as chemical, physical and mechanical
488 processes can weld younger to older sediment profiles and affect the accumulation,
489 dissolution, and reprecipitation of mineral materials in sediments, as illustrated by
490 Olson and Nettleton (1998). Sediment properties most affected include texture and
491 the content and distribution of soluble salts. Processes such as erosion and
492 deposition can truncate profiles or bury them either rapidly or extremely slowly.
493 Effects of these and other processes on sediment properties must be examined with
494 care in paleosols that have been buried even for short interval. The above-mentioned
495 analogies of fluvial/lacustrine-aeolian profiles in the Taklamakan and Badain Jaran
496 deserts should be evaluated carefully in future studies and possible avoided as single
497 indicators in paleoenvironmental reconstruction in the desert environment.

498 499 **5. Conclusion**

500
501 Formations of inorganic salt in aeolian sediments in the desert environment are
502 significant to understanding the interrelationships between aeolian dynamics and
503 regional hydrological and climate regimes. Geological information related to the
504 inorganic salt composition and distribution and their environmental significance in
505 aeolian sediments in the middle-latitudes deserts are still rare. Geochemistry of
506 soluble salts in modern and ancient dune sediments from the sandy deserts in
507 northwestern China was surveyed in this work. Variations of the salt composition
508 around these sandy deserts are closely related to regional climatic parameters, such
509 as the precipitation, temperature and wind agent. The aeolian salts are proposed to
510 be sourced from the atmospheric depositions that are strongly associated with the
511 local-scale and regional-scale dry and wet depositions, such as rainfall and dustfall
512 precipitation. Single salt archive in sedimentary deposits interlayered by aeolian and
513 lacustrine facies should be carefully used as geoproxy to reconstruct
514 palaeoenvironmental histories in arid conditions.

515
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522

523 **References:**

524

525 Abuduwaili, J., Gabchenko, M. V., and Xu, J.: Eolian transport of salts – a case study in
526 the area of Lake Abinur (Xinjiang, Northwest China), *J. Arid Environ.*, 72, 1843–
527 1852, 2009.

528 Agata, N., Cerda, A., Carmelo, D., Giuseppe, LP., Antonino, S., and Luciano, G.:
529 Effectiveness of carbon isotopic signature for estimating soil erosion and
530 deposition rates in Sicilian vineyards. *Soil and Tillage Research*, 152, 1-7, 2015.

531

532 Ahuja, L. R.: Modeling soluble chemical transfer to runoff with rainfall impact as a
533 diffusion process, *Soil Sci. Soc. Am. J.*, 54, 312–321, 1990.

534 Aitken, M.J. *Thermoluminescence Dating*. Academic Press, London, 1985.

535 Al-Momani, I. F., Tuncel, S., Eler, U., Ortel, E., Sirin, G., and Tuncel, G.: Major ion
536 composition of wet and dry deposition in the eastern Mediterranean basin, *Sci.*
537 *Total Environ.*, 164, 75–85, 1995.

538 Alonso-Zarza, A. M.: Palaeoenvironmental significance of palustrine carbonates and
539 calcretes in the geological record, *Earth-Sci. Rev.*, 60, 261–298, 2003.

540 Amit, R. and Yaalon, D. H.: The micromorphology of gypsum and halite in reg soils –
541 the Negev Desert, Israel, *Earth Surf. Proc. Land.*, 21, 1127–1143, 1996.

542 Birkeland, P. W.: *Soils and Geomorphology*, Oxford University Press, New York, 1999.

543 Blank, R. R., Young, J. A., and Allen, F. L.: Aeolian dust in a saline playa environment,
544 Nevada, USA, *J. Arid Environ.*, 41, 365–381, 1999.

545 Brennan, B. J.: Beta doses to spherical grains. *Radiation Measurements* 37, 299-303,
546 2003.

547 Bodi, M.B., Doerr, S.H., Cerda, A., and Mataix-Solera, J.: Hydrological effects of a layer
548 of vegetation ash on underlying wettable and water repellent soil. *Geoderma*,
549 191, 14-23, 2012.

550 Bohlke, J. K., Ericksen, G. E., and Revesz, K.: Stable isotope evidence for an
551 atmospheric origin of desert nitrate deposits in northern Chile and southern
552 California, USA, *Chem. Geol.*, 136, 135–152, 1997.

553 Borchert, H. and Muir, R. O.: *Salt Deposits: The Origin, Metamorphism and*
554 *Deformation of Evaporites*, Van Nostrand Company, London, 1964.

555 Braitsch, O.: *Salt Deposits: Their Origin and Composition*, Springer-Verlag, Berlin,
556 1971.

557 Cerda, A., Brazier, R., Nearing, M., and de Vente, J.: Scales and erosion. *Catena*, 102,
558 1-2, 2013.

559 Choquette, P. W. and Pray, L. C.: Geological nomenclature and classification of
560 porosity in sedimentary carbonates, *AAPG Bull.*, 54, 207–250, 1970.

561 Dan, J. and Yaalon, D. H.: Automorphic saline soils in Israel, *Catena*, 1, 103–115,
562 Supplementary, 1982.

563 Dean, W. E. and Schwalb, A.: Holocene environmental and climatic change in the
564 Northern Great Plains as recorded in the geochemistry of sediments in Pickerel

565 Lake, South Dakota, *Quatern. Int.*, 67, 5–20, 2000.

566 Dragovich, D. and Dominis, M.: Dryland salinity and rainfall patterns: a preliminary
567 investigation in central 5 west New South Wales (Australia), *Land Degrad. Dev.*,
568 19, 564–573, 2008.

569 Dong, Z., Lv, P., Qian, G., Xia, X., Zhao, Y., and Mu, G.: Research progress in China's Lop
570 Nur, *Earth-Sci. Rev.*, 111, 142–153, 2012.

571 Duval, M., Campana, I., Guilarte, V., Miguens, L., Iglesias, J., and Sierra, S.G.:
572 Assessing the uncertainty on particle size and shape: Implications for ESR and
573 OSL dating of quartz and feldspar grains. *Radiat. Meas.*, 81, 116-122, 2015.

574 El-Sayed, M. I.: Gypcrete of Kuwait: field investigation, petrography and genesis, *J.*
575 *Arid Environ.*, 25, 199–203, 1993.

576 Fain, J., Soumana, S., Montret, M., Miallier, D., Pilleyre, T., and Sanzelle, S.:
577 Luminescence and ESR dating beta-dose attenuation for various grain shapes
578 calculated by a Monte-Carlo method. *Quat. Sci. Rev.*, 18, 231-234, 1999.

579 Fujita, S., Takahashi, A., Weng, J., Huang, L., Kim, H., Li, C., Huang, F. T. C, and Jeng, F.:
580 Precipitation chemistry in East Asia, *Atmos. Environ.*, 34, 525–537, 2000.

581 Gerdes, G., Dunajtschik-Piewak, K., Riege, H., Taher, A. G., Krumbein, W. E., and
582 Reineck, H. E.: Structural diversity of biogenic carbonate particles in microbial
583 mats, *Sedimentology*, 41, 1273–1294, 1994.

584 15 Gerdes, G., Krumbein, W. E., and Noke, N.: Evaporite microbial sediment. in:
585 *Microbial Sediments*, edited by: Riding, R. E. and Awramik, S. M.,
586 Springer-Verlag, Berlin, Heidelberg, 196–208, 2000.

587 Goudie, A. S. and Middleton, N. J.: *Desert Dust in the Global System*, Springer, Berlin,
588 2006.

589 Guerin, G., Mercier, N., Nathan, R., Adamiec, G., and Lefrais, Y.: On the use of the
590 infinite matrix assumption and associated concepts: a critical review. *Radiat.*
591 *Meas.*, 47, 778-785, 2012.

592 Handford, C. R.: Marginal marine halite: sabkhas and salinas, in: *Evaporites,*
593 *Petroleum and Mineral Resources*, edited by: Melvin, J. L., Elsevier, Amsterdam,
594 1–66, 1991.

595 Hay, W. W., Migdisov, A., Balukhovsky, A. N, Wold, C. N., Flogel, S., and Soding, E.:
596 Evaporites and the salinity of the ocean during the phanerozoic: implications
597 for climate, ocean circulation and life, *Palaeogeogr. Palaeocl.*, 240, 3–46, 2006.

598 Inomata, Y., Igarashi, Y., Chiba, M., Shinoda, Y., and Takahashi, H.: Dry and wet
599 deposition of water-insoluble and water-soluble chemical species during spring
600 2007 in Tsukuba, Japan, *Atmos. Environ.*, 43, 4503–4512, 2009.

601 Kerr, S. D. J. and Thomson, A.: Origin of nodular and bedded anhydrite in Permian
602 shelf sediments, Texas and New Mexico, *AAPG Bull.*, 47, 1726–1732, 1963.

603 Kiefert, L.: Characteristics of wind transported dust in eastern Australia, Dissertation,
604 Griffith University, Brisbane, Australia, 1997.

605 Kraimer, R. A., Monger, H. C., and Steiner, R. L.: Mineralogical distinctions of
606 carbonates in desert soils, *Soil Sci. Soc. Am. J.*, 69, 1773–1781, 2005.

607 Kulshrestha, M. J., Kulshrestha, U. C., Parashar, D. C., and Vairamani, M.: Estimation
608 of SO₄ contribution by dry deposition of SO₂ onto the dust particles in India,
609 *Atmos. Environ.*, 37, 3057–3063, 2003.

610 Lasanta, T. and Cerda, A.: Long-term erosional responses after fire in the Central
611 Spanish Pyrenees: 2. Solute release. *Catena*, 60, 81-100, 2005.

- 612 Last, W. M.: Paleochemistry and paleohydrology of Ceylon Lake, a salt-dominated
613 playa basin in the Northern great plains, Canada, *J. Paleolimnol.*, 4, 219–238,
614 1990.
- 615 Last, W. M. and Vance, R. E.: The Holocene history of Oro Lake, one of the western
616 Canada's longest continuous lacustrine records, *Sediment. Geol.*, 148, 161–184,
617 2002.
- 618 Lavee, H., Imeson, A. C., Pariente, S., and Benyamini, Y.: The response of soils to
619 simulated rainfall along a climatological gradient in an arid and semi-arid
620 region, *Catena*, 19, 19–37, 1991.
- 621 Li, C., Kang, S., Zhang, Q., and Kaspari, S.: Major ionic composition of precipitation in
622 the Nam Co region, Central Tibetan Plateau, *Atmos. Res.*, 85, 351–360, 2007.
- 623 Liu, X., Dong, H., Rech, J. A., Matsumoto, R., Yang, B., and Wang, Y.: Evolution of
624 Chaka Salt Lake in NW China in response to climatic change during the latest
625 pleistocene-holocene, *Quaternary Sci. Rev.*, 27, 867–879, 2008.
- 626 Logan, J.: African dusts as a source of solutes in Gran Canaria ground waters,
627 *Geological Society of America*, 6, 849, Abstracts with Programs, 1974.
- 628 Long, H., Shen, J., Wang, Y., Gao, L., and Frechen, M.: High-resolution OSL dating of a
629 late Quaternary sequence from Xingkai Lake (NE Asia): chronological challenge
630 of the "MIS3a Mega-paleolake" hypothesis in China, *Earth and Planetary
631 Science Letters*, 428, 281-292, 2015.
- 632 Marion, G. M., Verberg, P. S. J, McDonald, E. V., and Arnone, J. A.: Modeling salt
633 movement through a Mojave Desert soil, *J. Arid Environ.*, 72, 1012–1033,
634 2008.
- 635 Miao, X., Wang, H., Hanson, P. R., Mason, J. A., and Liu, X.: A new method to
636 constrain soil development time using both OSL and radiocarbon dating,
637 *Geoderma*, 261, 93-100, 2016.
- 638 Olson, C. G. and Nettleton, W. D.: Paleosols and the effects of alteration, *Quatern. Int.*,
639 51/52, 185–194, 1998.
- 640 Oyarzun, J. and Oyarzun, R.: Massive volcanism in the Altiplano-Puna Volcanic
641 Plateau and formation of the huge Atacama Desert nitrate deposits: a case for
642 thermal and electric fixation of atmospheric nitrogen, *Int. Geol. Rev.*, 49, 962–
643 968, 2007.
- 644 Pariente, S.: Soluble salts dynamics in the soil under different climatic conditions,
645 *Catena*, 43, 307–321, 2001.
- 646 Pedley, M., Martin, J. A. G, Delgado, S. O., and Del Cura, D.: Sedimentology of
647 Quaternary perched springline and paludal tufas: criteria for recognition, with
648 examples from Guadalajara Province, Spain, *Sedimentology*, 50, 23–44, 2003.
- 649 Petrov, M. P.: *Deserts of the World*, John Wiley & Sons, New York, 1976.
- 650 Reheis, M. C. and Kihl, R.: Dust deposition in southern Nevada and California, 1984–
651 1989: relations to climate, source area and source lithology, *J. Geophys. Res.*,
652 100, 8893–8918, 1995.
- 653 Rengasamy, P., Greene, R. S. B, and Ford, G. W.: The role of clay fraction in the
654 particle arrangement and stability of soil aggregates – a review, *Clay Research*,
655 3, 53–67, 1984.
- 656 Riding, R., Braga, J. C., Martin, J. M., and Sanchezalmazo, I. M.: Mediterranean
657 Messinian salinity crisis – constraints from a coeval marginal basin, Sorbas,
658 southeastern Spain, *Mar. Geol.*, 146, 1–20, 1998.

- 659 Schutt, B.: Holocene paleohydrology of playa-lake systems in central Spain: a
660 reconstruction based on mineral composition of the lacustrine sediments,
661 *Quatern. Int.*, 73/74, 7–27, 2000.
- 662 Sehmel, G. A.: Particle and gas dry deposition: a review, *Atmos. Environ.*, 14, 983–
663 1101, 1980.
- 664 Singer, A.: Introduction on arid zone soil: salt accumulation and distribution – saline
665 soils. in: *Biogeochemistry of Trace Elements in Arid Environments*, edited by:
666 Han, F. X., Springer, Dordrecht, 3–44, 2007.
- 667 Sinha, R. and Raymahashay, B. C.: Evaporite mineralogy and geochemical evolution of
668 the Sambhar Salt Lake, Rajasthan, India, *Sediment. Geol.*, 166, 59–71, 2004.
- 669 Smith, H. T. U: Desert sedimentary environments, *Earth-Sci. Rev.*, 7, A125–A126,
670 1971.
- 671 Smoot, J. P. and Lowenstein, T. K.: Depositional environments of non-marine
672 evaporites. in: *Evaporites, Petroleum and Mineral Resources*, edited by: Melvin,
673 J. L., Elsevier, Amsterdam, 189–347, 1991.
- 674 Sun, B., Guo, Z., Yin, Q., and Hao, Q.: Soluble salts in a Quaternary loess-soil sequence
675 near Xining and their environmental implications, *Quaternary Sciences*, 26,
676 649–656, 2006 (in Chinese).
- 677 Sun, J., Zhang, L., Deng, C., and Zhu, R.: Evidence for enhanced aridity in the Tarim
678 Basin of China since 5.3 Ma, *Quaternary Sci. Rev.*, 27, 1012–1023, 2008.
- 679 Tripaldi, A., Zarate, M. A., Brook, G. A., and Li, G. Q.: Late quaternary
680 paleoenvironments and paleoclimatic conditions in the distal Andean
681 piedmont, southern Mendoza, Argentina, *Quaternary Res.*, 76, 253–263, 2011.
- 682 Valero-Garces, B. L., Delgado-Huertas, A., Ratto, N., and Navas, A.: Large C-13
683 enrichment in primary carbonates from Andean Altiplano lakes, northwestern
684 Argentina, *Earth Planet. Sc. Lett.*, 171, 253–266, 1999.
- 685 Valero-Garces, B. L., Arenas, C., and Delgado-Huertas, A.: Depositional environments
686 of Quaternary lacustrine travertines and stromatolites from high-altitude
687 Andean lakes, northwestern Argentina, *Can. J. Earth Sci.*, 38, 1263–1283, 2001.
- 688 Wang, L., D’Odorico, P., Okin, G., and Macko, S.: Isotope composition and anion
689 chemistry of soil profiles along the Kalahari Transect, *J. Arid Environ.*, 73, 480–
690 486, 2009.
- 691 Wang, X., Xia, D., Wang, T., Xue, X., and Li, J.: Dust sources in arid and semiarid China
692 and southern Mongolia: impacts of geomorphological setting and surface
693 materials, *Geomorphology*, 97, 583–600, 2008.
- 694 Warren, J. K.: *Evaporites: Sediments, Resources and Hydrocarbons*, Springer, Berlin,
695 2006. Wasson, R. J., Smith, G. S., and Agrawal, D.P: Late quaternary sediments,
696 minerals, and inferred geochemical history of Didwana lake, Thar Desert, India,
697 *Palaeogeogr. Palaeocl.*, 46, 345–372, 1984.
- 698 Wesely, M. L. and Hicks, B. B.: A review of the current status of knowledge on dry
699 deposition, *Atmos. Environ.*, 34, 2261–2282, 2000.
- 700 Wetzel, R. G. and Likens, G. E.: *Limnological Analyses*, 3rd edn., Springer, New York,
701 2000. Yaalon, D. H. and Ginzbourg, D.: Sedimentary characteristics and climatic
702 analysis of easterly dust storms in the Negev (Israel), *Sedimentology*, 6, 315–
703 322, 1966.
- 704 Yang, X. and Williams, M. A. J: The ion chemistry of lakes and late Holocene
705 desiccation in the Badain Jaran Desert, Inner Mongolia, China, *Catena*, 51, 45–

706 60, 2003.

707 Yang, X., Preusser, F., and Radtke, U.: Late Quaternary environmental changes in the
708 Taklamakan Desert, western China, inferred from OSL-dated lacustrine and
709 aeolian deposits, *Quaternary Sci. Rev.*, 25, 923–932, 2006.

710 Yang, X., Ma, N., Dong, J., Zhu, B., Xu, B., Ma, Z., and Liu, J.: Recharge to the
711 inter-dune lakes and Holocene climatic changes in the Badain Jaran Desert,
712 western China, *Quaternary Res.*, 73, 10–19, 2010.

713 Yechieli, Y. and Wood, W. W.: Hydrogeologic processes in saline systems: playas,
714 sabkhas, and saline lakes, *Earth-Sci. Rev.*, 58, 343–365, 2002.

715 Zhao, Z., Tian, L., Fischer, E., Li, Z., and Jiao, K.: Study of chemical composition of
716 precipitation at an alpine site and a rural site in the Urumqi River Valley,
717 Eastern Tien Shan, China, *Atmos. Environ.*, 42, 8934–8942, 2008.

718 Zheng, M., Guo, Z., Fang, M., Rahn, K. A., and Kester, D. R.: Dry and wet deposition of
719 elements in Hong Kong, *Mar. Chem.*, 97, 124–139, 2005.

720 Zhu, B. and Yang, X.: The ion chemistry of surface and ground waters in the
721 Taklimakan Desert of Tarim Basin, western China, *Chinese Sci. Bull.*, 52, 2123–
722 2129, 2007.

723 Zhu, B. and Yang, X.: Chemical weathering of detrital sediments in the Taklamakan
724 Desert, Northwestern China, *Geogr. Res.*, 47, 57–70, 2009.

725 Zhu, B. and Yang, X.: The origin and distribution of soluble salts in the sand seas of
726 northern China, *Geomorphology*, 123, 232–242, 2010.

727 Zhu, B., Yang, X., Liu, Z., Rioual, P., Li, C., and Xiong, H.: Geochemical compositions of
728 soluble salts in aeolian sands from the Taklamakan and Badanjin deserts in
729 northern China, and their influencing factors and environmental implications,
730 *Environmental Earth Sciences*, 66, 337–353, 2012.

731 Zhu, Z., Wu, Z., Liu, S., and Di, X.: *An Outline of Chinese Sandy Deserts*, Science
732 Press, Beijing, 1980 (in Chinese).

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734

735 **Figure Captions**

736

737 **Figure 1** Locations of the study areas and sampling sites in this study. (a) The
738 distributions of deserts and the mean annual precipitation isohyets in China, (b) the
739 Taklamakan Desert, (c) and (d) the Badain Jaran Desert.

740

741 **Figure 2** Photograph views of Quaternary and modern sediments of aeolian and
742 lacustrine/fluvial facies that consisted of clay and sand/silt sand alternations in the
743 Taklamakan and Badain Jaran Deserts. (a) and (b) the Taklamakan Desert, (c) and (d)
744 the Badain Jaran Desert.

745

746 **Figure 3** Sketch maps of the sedimentary profiles studied in this study. (a) Lacustrine
747 sediments interbedded by aeolian sand layers with ^{14}C ages at the Arerjilin-I section
748 in the Badain Jaran Desert, (b) interbedding of aeolian and lacustrine deposits and
749 their OSL ages at the Tazhong-XIII section in the Taklamakan Desert, (c) lacustrine
750 deposits buried under a 30 m high dune at the Yaogan-VIII section in southern
751 Taklamakan, and (d) sandy loess deposits with OSL dating results at the Tumiya-II
752 section on southern margin of the Taklamakan Desert.

753

754 **Figure 4** Salinities vs. pH of sediment solutions, (a) dune-surface sediments (modern
755 sediment) and buried-dune sediments (palaeo-sediment) in the Taklamakan Desert,
756 (b) dune-surface sand samples collected in different climatic seasons (dry and wet) in
757 the Badain Jaran Desert. (c) Carbon-bearing ions vs. pH. Triangular plots of major
758 anions (d) and cations (e and f) of the soluble salts in mEq/l unit. Distribution
759 patterns of the major ions of the soluble salts in the aeolian sediments from (g) the
760 Badain Jaran Desert and from (h) the Taklamakan Desert.

761

762 **Figure 5** Distribution patterns of the major ions of aeolian salts, groundwaters and
763 lake waters in (a) the Badain Jaran Desert and (b) the Taklamakan Desert. The data of
764 local lake water and groundwater bodies in the Badain Jaran are cited from [Yang and](#)
765 [Williams \(2003\)](#), and the river water and groundwater bodies in the Taklamakan from
766 [Zhu and Yang \(2007\)](#). The relationship between salinities and grain size compositions
767 of the aeolian sediments: (c) salinity vs. median particle diameter (Mz, in phi unit) of
768 dune-surface sediment from the Taklamakan Desert, and (d) salinity vs. grain size
769 compositions of randomly-selected dune sediments from the Badain Jaran Desert.
770 Spatial distributions of the salinities of the aeolian sediments along the longitudinal
771 and latitudinal degrees in the Taklamakan Desert (e and g) and in the Badain Jaran
772 Desert (f and h), respectively.

773

774 **Figure 6** Sequential variations in soluble salts contents (salinity and pH) of the
775 Arerjilin-I section in the Badain Jaran Desert.

776

777 **Figure 7** Sequential variations in soluble salts contents (salinity and pH) of the
778 Tazhong-XIII section in the Taklamakan Desert.

779

780 **Figure 8** Sequential variations in soluble salts contents (salinity and pH) of the
781 Yaogan-VIII section in the Taklamakan Desert.

782

783 **Figure 9** Sequential variations in soluble salts contents (salinity and pH) of the
784 Tumiya-II section in the Taklamakan Desert.

785

786

787 **On-line Supplementary Table Captions**

788

789 **On-line Supplementary Table 1** Physical parameters of the soil-water extraction of
790 the modern and ancient aeolian sediments from the Taklamakan and Badain Jaran
791 deserts in northwestern China.

792

793 **On-line Supplementary Table 2** The analytical data of major ionic compositions for
794 the soil-water extraction of the aeolian sediments from the Taklamakan and Badain
795 Jaran deserts

796

797 **On-line Supplementary Table 3** Conventional radiocarbon ages for section samples
798 from the Badain Jaran Desert (cited from [Yang et al., 2010](#))

799

800 **On-line Supplementary Table 4** Summary data for OSL ages of section samples from
801 the Taklamakan Deserts (cited from [Yang et al., 2006](#)).