

Dear Editor,

We appreciate greatly the valuable comments from you and the reviewers. We have carefully considered these comments and revised the manuscript accordingly. The details of the revisions and a marked-up version of the revised manuscript are attached to this letter.

Thank you for your consideration of our paper.

Yours sincerely,
Lucheng Zhan
On behalf of the co-authors

Detailed change list

Please refer to the marked-up version of the revised manuscript when checking the revisions.

Referee #1

- A key role in both papers is the data set from the WMO/IAEA on stable isotopes in precipitation – station Zhangye (1986 – 2003, n=86). I recommend, that more information on GNIP station Zhangye and in addition to the mean monthly isotope data set (Fig. 1a) the long-term isotope set is implemented in the work to clarify seasonality and trends of the 17 years data set.

Changes: Figure 1 has been modified (Lines 253-258) with addition of more information about the seasonality and trends of precipitation isotope in the study area; and related discussions were added in the text (Lines 52-56).

- Wu et al. were describing their data point as annual average from ‘monthly weighted average’ values. Therefore I would recommend that the authors include their weighing formula into the text. Were mean monthly values weighed or monthly values to yearly precipitation?

Changes: The detailed descriptions of the methods used to calculate the weighted isotopic compositions of precipitation have been added. (Lines 62-71)

- The authors do not comment on earlier an earlier hypotheses, that groundwater might contribute fossil water (Line 30), which potentially was recharged during cooler periods and therefore with more depleted d2H, d18O values. If this would be the case, elevations would not need to be as high as 3914 m a.s.l. (Line 88).

Changes: For clarity, more analysis and discussion on the groundwater age and residence time have be added in the revised manuscript to further support our hypothesis. (Lines 35-37, 154-166)

- Line 82: (Figure 2b, c) instead of (Figure 2b&c)

Changes: This has been revised as suggested. (Line 98)

- Line 105: Wu et al. 2017 instead of 2016

Changes: This mistake has been corrected. (Line 126)

- Line 144: ...isotope data of the Zhangye station to determine....

Changes: This sentence has been revised. (Line 178)

- Line 217: ...monthly precipitation of the GNIP station Zhanye (a). ...

Changes: This sentence has been revised following the suggestion. (Line 254)

- Line 220: delete: Further details are provided in the text.

Changes: This sentence has been deleted. (Line 258)

- Line 222: dD vs. d18O ...

Changes: This sentence has been changed to “ δD vs. $\delta^{18}O$ plot of water related to...” (Line 260)

- Line 223: ... (b, c) ... instead of (b & c)

Changes: It has been revised. (Line 261)

Referee #2

1. Precisely describe methods used to calculate both the weighted and unweighted average isotopic compositions of precipitation.

Changes: More details about the calculation processes have been added in the text. (Lines 62-71)

2. The two disputed components of groundwater – recent infiltration and water recharging in distant mountain chain - should be easily distinguishable by the concentrations or concentration ratios of dissolved components. Are there any data that could be used to identify their chemical signatures?

Changes: We have added some discussions based on existing studies related to groundwater chemical compositions to further support our hypothesis. (Lines 148-153)

3. Page 2/line 32. Distance between Qilian Mountains and the desert shown on the map (Fig. 3) seems to be smaller than 500 km.

Changes: This sentence has been revised. (Line 32)

4. Page 2/lines 35 - 38. The reasoning presented in the last two sentences of page 2 is logically flawed. Incorrect calculation of the averaged isotopic composition of precipitation does not invalidate the meaning and significance of tritium results.

Changes: This paragraph has been revised following the comment to improve its logic. (Lines 34-43)

5. Page 5/lines 113 - 117. Are the surface water bodies mentioned here known to recharge groundwater or do hydrogeological conditions allow for infiltration from them?

Changes: Large deep fault systems in this area may act as an important pathway for the groundwater recharge. More discussions related to the fault systems and the possible recharge processes have been added in the revised manuscript to address the concerns. (Lines 157-171)

6. Page 5-6/lines 122 - 127. Recharge in Qilian Mountains cannot be a source of detectable tritium in the desert or we have to assume that groundwater flows over hundreds of kilometers in tens of years. As with point 3, tritium data are not well integrated in the discussion.

Changes: More discussions about the tritium data and how groundwater transports from the Qilian Mountains to BJD over decades have been added in the text. (Lines 157-166)

Fig. 1. What are standard deviations (due to averaging) of the monthly and annual averages presented here? They should be shown on the plots if significant.

Changes: The standard deviations of the values have been added in this figure. (Lines 253-258)

Fig. 2. There is a considerable spread in groundwater isotopic data used to derive EL2 evaporation line, which might lead to a biased identification of the line itself and of its interception with GMWL. These data are pooled results of several studies, do all of them represent locations on the presumed groundwater flow lines between the recharge area and BJD lakes? Perhaps not all of them are representative for derivation of the evaporation line.

Changes: Some statements have been added or revised to address the concerns. (Lines 87-89, 173-176)

X. Wu

1. This comment make some good theoretic analysis of the altitude effect on the stable isotopes of precipitation, however, I did not see more isotopic data from the Qilian Mountain. Considering they questioned the representability of the samples from Shiyang River (Li et al., 2016), I think more data from the Qilian Mountain would make this comparison more clearly.

Changes: More data for Qilian sourced water (some rivers on the northern slope) and related discussions have been added in the revised manuscript. (Lines 119-125, 259)

2. In my opinion, the more specific description of the hydrogeological processes and the evolution of water isotopes is necessary to support the remote Qilian Mountain as the major recharge area.

Changes: More descriptions of the hydrogeological conditions and discussions on the recharge and discharge processes of groundwater have been added. (Lines 157-171)

1 **Comment on “Origin of water in the Badain Jaran Desert, China:**
2 **new insight from isotopes” by Wu et al. (2017)**

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12 **Abstract**

13 Precipitation isotope data were used to determine the origin of groundwater in the Badain Jaran
14 Desert (BJD) in the study of Wu et al. (2017). Both precipitation and its isotope composition
15 vary seasonally, so arithmetic averages of precipitation isotope values poorly represent the
16 isotope composition of meteoric water. Their finding that the BJD groundwater is recharged by
17 modern meteoric water from local areas including the southeastern adjacent mountains was
18 based on arithmetic averaging. However, this conclusion is not supported by the corrected mean
19 precipitation isotope values, which are weighted by the precipitation rate. Indeed, the available
20 isotopic evidence shows that modern precipitation on the Qilian Mountains is more likely to be
21 the main source of the groundwater and lake water in the BJD, as found by Chen et al. (2004).

22 **1 Introduction**

23 The Badain Jaran Desert (BJD) is characterized by a unique landscape that contains a large
24 number of lakes and the world's largest stationary sand dunes maintained by groundwater.
25 However, the origin of the groundwater remains uncertain (Dong et al., 2013). Using stable and
26 radioactive environmental isotopes, Wu et al. (2017) investigated the connection between lakes
27 and groundwater, and the origin of groundwater in the southeastern desert area. They suggested
28 that the BJD groundwater is derived primarily from modern meteoric water from local areas,
29 including the southeastern adjacent small mountains. Based on isotopic evidence, the authors
30 ruled out other hypotheses on the groundwater source, including fossil groundwater (Gates et
31 al., 2008; Ma and Edmunds, 2006; Wang et al., 2015; Yang et al., 2010) and snowmelt from the
32 Qilian Mountains, 500 km (center-to-center distance) southwest of the desert (Chen et al., 2004;
33 2006).

34 The authors argued that the ^{14}C dating over-estimated the age (~10 ka) of the BJD
35 groundwater due to interference by additional dead carbon input from ancient carbonates. **We**
36 **have conducted work related to the ^{14}C dating and found the same problem with overestimation**
37 **of the groundwater age (Chen et al., 2014; Wang and Chen, 2018).** They reasoned that the
38 average age of groundwater in the BJD should be much younger, since it includes modern
39 meteoric water as indicated by tritium levels (Gates et al., 2008; Wu et al., 2017). **They**

40 presented many evidences and discussions for their conclusion of groundwater recharged by
41 modern precipitation from local areas. However, their averaging of the precipitation isotope
42 data did not account for seasonality of precipitation amount, which led to a misconception of
43 the real groundwater origin.

44 **2 Source water identification based on weighted mean precipitation isotope values**

45 The determination of mean precipitation isotope values is of great significance for assessing the
46 contribution of precipitation as a water source to regional hydrological systems and for
47 assessing interactions among different hydrological components. To examine the relationship
48 between the BJD groundwater and local precipitation, the historical precipitation isotope data
49 from a nearby GNIP (Global Network of Isotopes in Precipitation,
50 <https://nucleus.iaea.org/wiser/index.aspx>) station in Zhangye (1986–2003) were used by Wu et
51 al. (2017). The GNIP database provides data on monthly precipitation isotopes as well as
52 monthly rainfall for the Zhangye station. As shown in Figure 1a and Figure 1b, the monthly δD
53 and $\delta^{18}O$ values in the study area exhibit large seasonal variations, which are mainly controlled
54 by temperature (Zhan et al., 2017). The isotopic seasonality pattern of precipitation is similar
55 in different years. During the summer half year when temperature is higher, the rainfall is more
56 enriched in heavier isotopes.

57 According to the GNIP data, the mean annual precipitation is about 130 mm, with more
58 than 60% of the total annual rainfall occurring from June to August during which the isotope
59 values are the highest (Figure 1b). Since the annual precipitation is seasonal, the monthly
60 precipitation isotope data should be weighted by the monthly precipitation amount to calculate
61 the annual mean for representing the isotope composition of local precipitation as a potential
62 source of the BJD groundwater. The weighted mean isotopic values $\overline{\delta}_w$ can be calculated
63 using the following equation:

$$\overline{\delta}_w = \frac{\sum_{j=Jan}^{Dec} \overline{\delta}_j \cdot \overline{P}_j}{\sum_{j=Jan}^{Dec} \overline{P}_j} \quad (1)$$

65 where $\overline{\delta_j}$ and $\overline{P_j}$ are the averaged isotopic values and averaged rainfall amount of month j
66 during the GNIP observation years, respectively. $\overline{\delta_j}$ and $\overline{P_j}$ can be calculated as follows:

$$67 \quad \overline{\delta_j} = \frac{\sum_i \delta_{i,j}}{n} \quad (2)$$

$$68 \quad \overline{P_j} = \frac{\sum_i P_{i,j}}{n} \quad (3)$$

69 where $\delta_{i,j}$ and $P_{i,j}$ are the isotopic value (δD or $\delta^{18}\text{O}$) and rainfall amount of month j in
70 year i from the available dataset of GNIP database, respectively; and n is the corresponding
71 number of data available years.

72 Based on the dataset from the GNIP database, the calculated weighted mean values for δD
73 and $\delta^{18}\text{O}$ of Zhangye's precipitation are -40.9‰ and -5.50‰, respectively (Figure 1c). Using
74 arithmetic average values, Wu et al. (2017) determined δD and $\delta^{18}\text{O}$ values around -74‰ and -
75 10.5‰, respectively. When plotted on the $\delta^{18}\text{O}$ - δD graph (Figure 1c), the arithmetic average
76 values are close to the intersection of the evaporation line EL1 (for groundwater and lake water
77 in the desert) and the GMWL (Global Meteoric Water Line), which led Wu et al. (2017) to
78 conclude that groundwater and lake water in the BJD originates from modern meteoric
79 precipitation in local areas including the adjacent small mountains. However, if the weighted
80 mean values are used, this conclusion no longer holds. The source water recharging the BJD
81 groundwater and lakes is much more depleted in D and ^{18}O , compared with the isotope
82 composition of local precipitation.

83 **3 Reanalysis on the origin of groundwater in the BJD**

84 Using available data from literature, we reanalyzed the possible origin of groundwater in the
85 BJD. We focus on the BJD southern margin area where the desert lakes are mostly concentrated.
86 The isotope data of the groundwater and lake water (Figure 2a) lie on the evaporation line EL2
87 ($\delta\text{D} = 4.6\delta^{18}\text{O} - 29.8$, $r^2 = 0.94$), which is reasonably similar to EL1 in Wu et al. (2017). Here
88 only data from groundwater and lake water samples within the BJD area were used for

89 **determining the EL2.** The weighted mean isotope values of precipitation in the regions close to
90 the BJD (blue circles) show a decreasing trend with increasing elevation from 1382 to 2569 m
91 a.s.l., reflecting the effect of elevation on isotope fractionation (Poage and Chamberlain, 2001).
92 The intersection of EL2 and GMWL ($\delta D = -83.6\text{‰}$, $\delta^{18}O = -11.7\text{‰}$), which represents the mean
93 isotope composition of the recharge source for BJD groundwater, is clearly outside the range
94 of precipitation in the local and adjacent regions, indicating another different source water with
95 more depleted isotope composition.

96 Together with the statistical isotopic values of precipitation in the BJD and the Qilian
97 Mountains (rainfall and snowmelt) from literature data, a significant inverse correlation of δD
98 and $\delta^{18}O$ values with elevations of the precipitation can be established (Figure 2b, c). The
99 altitude gradients for δD and $\delta^{18}O$ are $-2.0\text{‰}/100\text{m}$ and $-0.26\text{‰}/100\text{m}$, respectively, which are
100 close to the global mean levels (Poage and Chamberlain, 2001). Based on these gradients, the
101 location of water associated with the intersection of EL2 and GMWL corresponds to an average
102 elevation of 3914 m a.s.l. (3920 m estimated by δD and 3908 m by $\delta^{18}O$). Therefore, the
103 recharge region for groundwater and lake water in the BJD is likely to include areas of
104 elevations higher than 3914 m a.s.l. to produce source water of more depleted isotope
105 composition.

106 The closest region that could meet this elevation requirement is the Qilian Mountains
107 (average elevation between 4000 and 5000 m a.s.l.), northeast of the Qinghai-Tibet Plateau
108 (Figure 3a). Nineteen snowmelt and rainfall water samples from 3540 to 5010 m a.s.l. in the
109 glacier zone of the Qilian Mountains were collected by Ren (1999). The statistical isotope
110 compositions of these samples are close to that given by the GMWL-EL2 intersection (Figure
111 2a). Therefore, the isotope evidence points to the Qilian Mountains as a main source region for
112 groundwater and lake water in the BJD, as observed previously (Chen et al., 2004).

113 In the study of Wu et al. (2017), they ruled out the Qilian Mountains as a recharge area for
114 groundwater in the BJD based on the large isotopic difference between the GMWL-EL2
115 intersection and data of water samples mainly collected from the Shiyang River watershed (Li
116 et al., 2016), which is located in the eastern lower area of the Qilian Mountains. The mean
117 elevation of the Shiyang River watershed is only 2487 m a.s.l. (Bourque and Hassan, 2009),

118 lower than even the mean level of the entire mountain. Therefore, their argument for excluding
119 the Qilian Mountains as a recharge region is questionable. Water samples collected from rivers
120 on the northern slope of the Qilian Mountains are characterized by large variations of isotope
121 compositions (Figure 2a), with the lowest isotopic values found by Ren (1999) from a river in
122 the upstream glacier zone. Scattered data between the plots of snowmelt on the mountain and
123 rainfall in lower regions indicated that most of these river samples are likely to be mixtures of
124 snowmelt water and piedmont precipitation. Isotope signatures show little connection between
125 these rivers on the northern slope and the groundwater in the BJD.

126 The relationship between d-excess and $\delta^{18}\text{O}$ was also discussed in Wu et al. (2017). The
127 d-excess value ($\text{d-excess} = \delta\text{D} - 8\delta^{18}\text{O} < 0$) indicates the deviation from the GMWL, reflecting
128 the degree of evaporation, to which the water has been subjected to. Wu et al. (2017) noted the
129 difference in the d-excess value between the Qilian-sourced water (sampled from the northern
130 slope rivers of the Qilian Mountains region) and BJD groundwater, and argued that the Qilian
131 Mountains cannot be the origin of the latter because no evaporation could occur to water
132 underground. Located in the northeastern margin of the Qinghai-Tibet Plateau, the Qilian
133 Mountains area consists of many northwest–southeast parallel mountain ranges and valleys
134 (Qiu et al., 2016). Although little evidence of evaporation was found in sampled river water
135 from the northern slope area, water in other near-surface water systems (like lakes, wetlands,
136 and soil water reservoir) of longer residence time within the wide Qilian Mountains region
137 would have been subjected to more intense evaporation and produced isotopic signature similar
138 to that of the BJD groundwater. The d-excess results cannot exclude the Qilian Mountains as a
139 recharge region either.

140 Groundwater in the BJD has also been postulated to be sourced from the Yabulai Mountain
141 region (Figure 3a). The highest mountain there is 1938 m a.s.l., which is unlikely to provide
142 rainfall input with depleted heavy isotopes as shown in Figure 2. In a recent groundwater
143 resource development project, eight wells were drilled (depths of 135 to 260 m) in the
144 southeastern part of the BJD. The static groundwater levels in these wells show a decreasing
145 trend from southwest to northeast (Figure 3b), indicating an overall movement of groundwater
146 along this direction. The groundwater flow direction is consistent with our opinion of

147 groundwater originating from Qilian Mountains, which is located to the southwest of the BJD.
148 Researchers have also examined the chemistry of lake water and groundwater in the study area
149 and surrounding areas. For example, Yang and Williams (2003) investigated the ion chemistry
150 of lake water and groundwater from the BJD and its periphery, and ruled out the possibility of
151 recharge from recent local rainfall to the lakes and groundwater. In a previous study (Chen et
152 al., 2012), the hydrochemical and isotopic results also supported our remote recharge
153 hypothesis.

154 We agree with the concern of Wu et al. (2017) about the accuracy of ^{14}C dating for the
155 BJD groundwater, which provided estimates of very old ages. In a recently published paper
156 (Wang and Chen, 2018), we found considerable overestimation of the groundwater age by the
157 ^{14}C dating method due to neglect of dead carbon brought by deep CO_2 emission. In contrast to
158 the fossil groundwater hypothesis, the detectable tritium activities as shown in their study and
159 many others (Chen et al., 2006; Gates et al., 2008; Yang and Williams, 2003) indicate a modern
160 precipitation source of the BJD groundwater. This suggests that the groundwater flows through
161 hundreds of kilometers over only tens of years. Due to geological activities, various southwest–
162 northeast deep fault systems have developed between the Qilian Mountains and the desert
163 (Chen et al., 2006). Based on the geological conditions and geochemical evidences (helium
164 results), these large deep fault systems are hypothesized to act as a quick passage for the
165 groundwater (Chen et al., 2006, 2004, 2012), which explains the detectable tritium in the
166 groundwater.

167 The reanalysis above suggests that groundwater in the BJD mainly originates from the
168 modern precipitation of Qilian Mountains. We hypothesize that near-surface water in the Qilian
169 Mountains, subjected to evaporation, infiltrates and recharges groundwater, which is then
170 delivered to the BJD through the deep interconnected faults. This hypothesis of course still
171 needs to be further verified and studied. It should also be noted that, the higher average elevation
172 (4000 to 5000 m a.s.l.) of the Qilian Mountains than the mean recharge elevation (3914 m a.s.l.)
173 estimated in this study, as well as the large variation of isotope composition of groundwater in
174 the BJD, may imply a mixture of the Qilian-sourced water (of more depleted isotope
175 compositions from 4000 to 5000 m a.s.l) with precipitation from other lower areas. Groundwater

176 might have mixed with rainwater from low-elevation areas on its pathway.

177 **4 Concluding remarks**

178 We reanalyzed the precipitation isotope data of the Zhangye station to determine the original
179 source of the groundwater in the Badain Jaran Desert. These data were averaged arithmetically
180 in the recent study of Wu et al. (2017), whereas weighted averaging is more appropriate. The
181 reanalysis does not support the conclusion of Wu et al. (2017) that the BJD groundwater is
182 sourced from local meteoric water. Indeed, the reanalysis suggests a mean recharge elevation
183 of about 3914 m a.s.l. for the BJD groundwater, which indicates that the precipitation in the
184 Qilian Mountains region is more likely to be a main source of the BJD groundwater, as initially
185 hypothesized by Chen et al. (2004).

186 **References**

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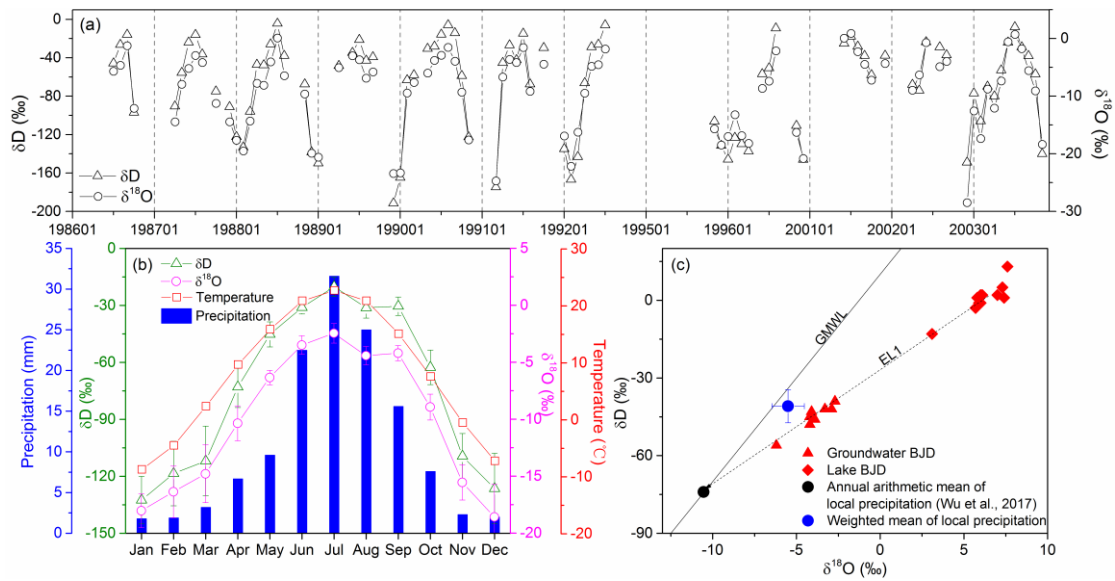
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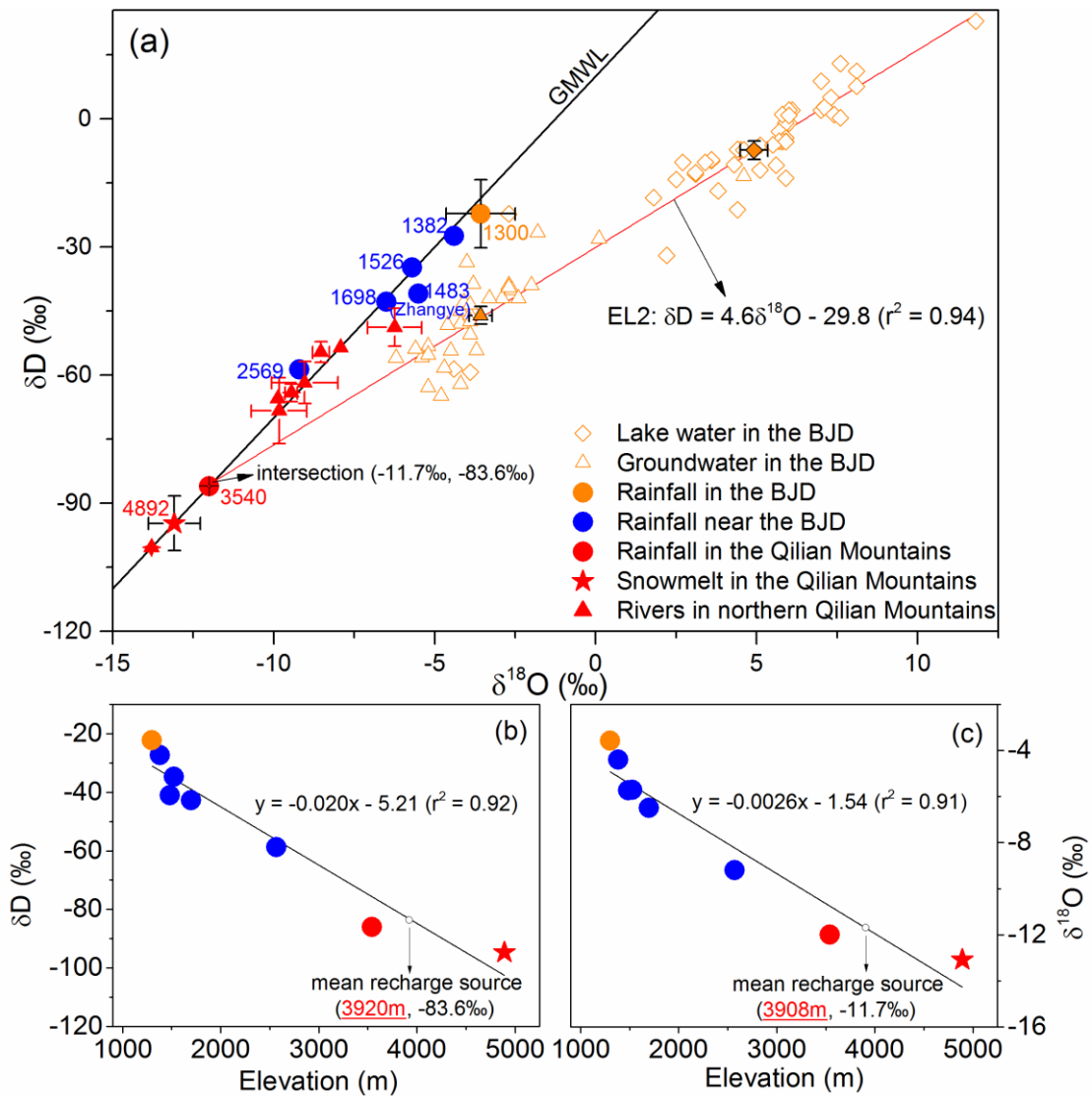
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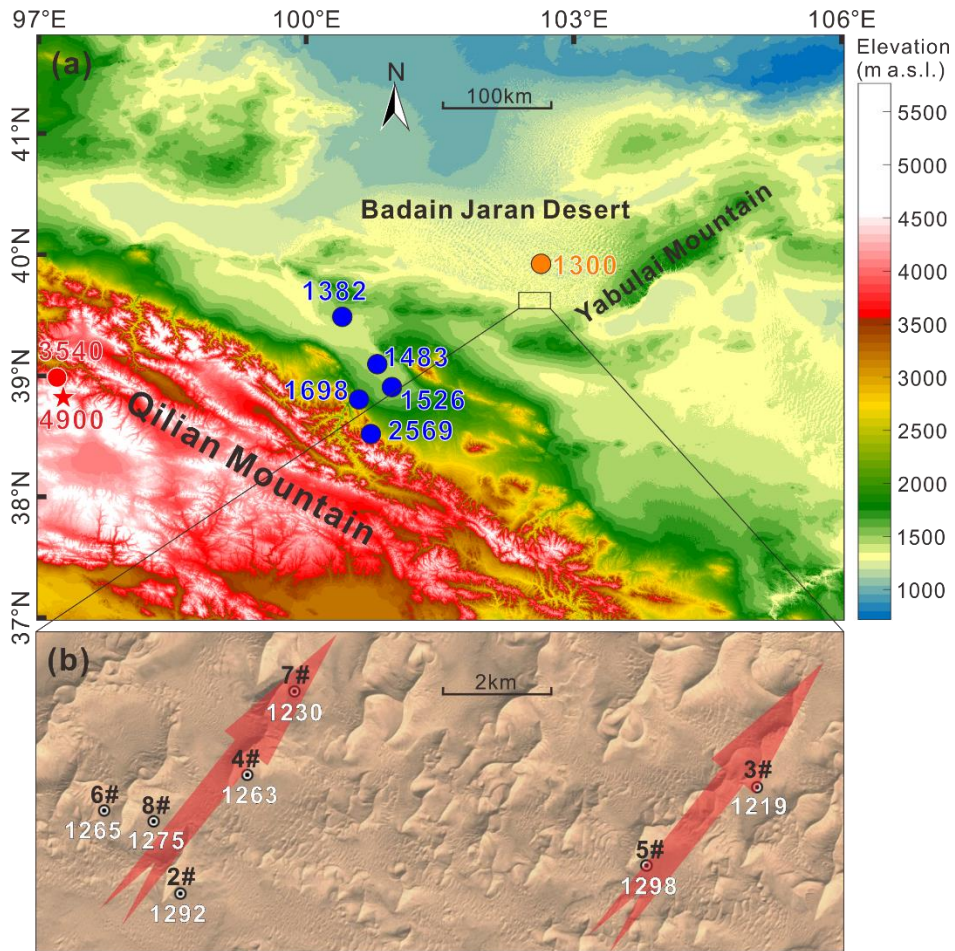
253

254 **Figure 1.** Isotope composition of monthly precipitation of the GNIP station Zhangye (all
 255 available dataset (a) and monthly mean values (b)), and δD-δ¹⁸O plots of groundwater, lake
 256 water and annual precipitation in the study area (based on data from Zhangye station) (c). Data
 257 in (a) and (b) are sourced from the GNIP database while plot (c) is modified from Wu et al.
 258 (2017). Statistical mean values are shown together with standard errors where feasible.



259

260 **Figure 2.** δD vs. $\delta^{18}O$ plot of water related to the BJD groundwater origin (a), and altitude
 261 gradients of related precipitation isotopes (b, c). For precipitation (rainfall and snowmelt), the
 262 corresponding sampling elevations (m a.s.l.) are also shown. Statistical mean values are shown
 263 together with standard errors where feasible. The weighted means of local rainfall (blue circles)
 264 are from Wu et al. (2010) and the GNIP database. Rainfall (yellow circle), lake water (yellow
 265 square; 47 samples) and groundwater (yellow triangle; 31 samples) in within the BJD area are
 266 based on data from Wu et al. (2017), Ma and Edmunds (2006), Zhao et al. (2012), Gates et al.
 267 (2008), Chen et al. (2012) and Yang et al. (2010). Summer rainfall (red circle; 4 samples) and
 268 snowmelt (red pentagram; 15 samples) in the Qilian Mountains are based on data from Ren
 269 (1999). Isotopic data for various rivers (red triangles) on the northern slope of the Qilian
 270 Mountain are collected from Chen et al. (2012), Li et al. (2016), Zhu, Su, and Feng (2008) and
 271 Ren (1999).



272

273 **Figure 3.** Elevation map of the study area (a) and groundwater wells drilled in the BJD (b).

274 Locations for precipitation sampling in different areas are also shown in (a), as well as the

275 elevation (m a.s.l.). The elevations of static groundwater levels in seven of the extraction wells

276 (well #1 is far away from these wells and hence not shown) are indicated by white text in (b).

277 Arrows in (b) show the estimated groundwater flow direction (based on groundwater elevation).