Aeolian Carbon Salts in the Taklamakan and Badanjilin Deserts in Northwestern China and Their Potential Role in Global Carbon Cycle

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To cite this article:
Bing-Qi Zhu. Aeolian Carbon Salts in the Taklamakan and Badanjilin Deserts in Northwestern China and Their Potential Role in Global Carbon Cycle. American Journal of Biological and Environmental Statistics. Vol. 3, No. 2, 2017, pp. 26-35. doi: 10.11648/j.ajbes.20170302.12

Received: January 13, 2017; Accepted: January 31, 2017; Published: November 1, 2017

Abstract: Previous studies have suggested that a significant loop in the carbon cycle may be hidden in the global desert areas (both low latitude and middle latitude). Due to the complexity of salt formation involved in atmosphere-landscape relation, there are few study involved into the pool of secondary carbonates in world desert soils, particularly in arid areas in northern China. Large sandy deserts in the middle latitudes of northwestern China were investigated in this study. The physical and geochemical examinations are carried out into soluble carbon salts in modern and ancient dune sediments from the inland deserts in northwestern China, with the aim to explore the composition of carbon salts in aeolian sediments and their possible environmental implications for global carbon cycle. The results show that the aeolian salt has high alkalinities, which are mainly determined by evaporitic alkaline earth carbonates. The carbonates are secondary salt in origin and are possibly introduced from the atmosphere into the pedosphere by a carbon-fixation process. Owing to the high capability to neutralize atmospheric carbonic acid, large desert area, and the strong potential of carbonate preservation in soil under arid climate, the middle-latitude Chinese deserts can be potentially qualified as a significant contributor to the global carbon cycle. But the low-latitude deserts in tropic areas may be not able to provide such a contribution.

Keywords: Global Carbon Cycle, Evaporitic Carbon Salt, Aeolian Sediment, Carbon-Fixation Process, Middle-Latitude Desert, Northwestern China

1. Introduction

Soil inorganic carbon (SIC), with a global reservoir of approximately 940 Pg [1], is one of the three major components (SIC, SOC and ocean reservoirs) of the global C pool. The SIC pool is primarily located in soils of the arid regions which contain several times (2 to 5) more SIC than SOC [2].

In desert areas, soil carbonate-C is the dominant type of C stored in soil [3]. The SIC pool includes lithogenic carbon (LIC) and pedogenic carbon (PIC), the latter also being termed the secondary carbonates [2]. PIC is the major component of SIC in soil under the arid environment [2]. This secondary carbonates (PIC) may be formed through the decomposition/dissolution of LIC or carbonate bearing minerals and reprecipitation of weathering products, or through precipitation of atmospheric CO$_2$ with Ca$^{2+}$ and Mg$^{2+}$ on other salts in soils [4]. Because of the complexity of these processes involved in atmosphere-landscape relation, there are few reliable estimates of the pool of secondary carbonates in world desert soils [5, 6, 7, 8, 9, 10], particularly in arid areas in northern China [11, 12, 13, 14, 15, 16, 17].

The global carbon balance includes a large terrestrial carbon sink, but that sink has not been fully identified nor its mechanisms explained [18, 19, 20, 21, 22, 23]. Recent findings that desert regions remove carbon dioxide (CO2) from the atmosphere at a magnitude of ~100 g Cm$^{-2}$ yr$^{-1}$ suggest that these systems may explain at least a portion of that terrestrial carbon sink [23, 24, 25, 26, 27, 28]. Stone (2008) [25] suggests that a significant loop in the carbon cycle may be
hidden in the global desert areas (both low latitude and middle latitude), because two of the northern middle-latitude deserts, the Gurbantonggut Desert of northwestern China [27] and the Mojave Desert of western USA [26], were both observed to be soaking up the surrounding CO\textsubscript{2} in an inorganic-salt form at a surprising rate.

Recent studies [15, 29, 30, 31, 32, 33, 35] have reported that the total SIC storage in China, approximately 55.3±10.7 Pg C with a current average content of 6.3±1.2 kg/m\textsuperscript{2} C in surface soil layers (including both organic – A horizon – and mineral horizons – B and C horizons), representing 5.8% of the global SIC pool [15], is experiencing great variation. For example, approximately 51% of total cultivated soil surfaces in China have experienced C loss where the most significant loss has been observed in the eastern part of northern China in dry farmlands as well as irrigated soils and paddy soils. On the contrary, SIC has increased (~10%) in irrigated soils in northwestern China. These evaluations, however, to a great extent are based on farmlands, irrigated lands or grassland without consideration of sandy desert areas which together account for about a fourth of China’s land mass.

In this work we present a physical and geochemical exploration into soluble carbon-bearing salts in sandy dunes from the inland deserts (such as the Taklamakan and the Badanjilin Deserts) in northwestern China, representing a cross-section of different environments (from westerly to monsoon climate control) in the middle-latitudes of the Northern Hemisphere (NH). The objectives of this paper were to explore the composition and distribution of evaporitic carbon salts in aeolian sediments and their possible environmental implications for global carbon cycle.

2. Methodology

The study areas and sampling sites were chosen from large sand seas in northwestern China (Fig. 1a), i.e., the Taklamakan Desert (the westerly climate control) and the Badanjilin Desert (the monsoon climate control). Both the modern and ancient aeolian sediments were designed to be sampled in the field. For modern aeolian sediment, thirty-three dunes in the Taklamakan Desert and fourteen dunes in the Badanjilin Desert were sampled in this study. The modern samples were mainly collected from the surface of active dunes, geographically located in the center and southern edge of the Taklamakan (Fig. 1b), and from the southern part of the Badanjilin (Fig. 1c-d).

After removing coarse plant fragments, 15 g of sediment were weighted from each bulk sample. In the laboratory, samples were mixed with 75 g of deionized water to produce water–soil solutions. The solutions were allowed to settle for 24 h and then vibrated for 5 min in an ultrasonic-wave oscillator at room temperature to leach the water-soluble salts from the solid phase of the samples. After oscillation, the leachate was extracted and filtered through a PTFE membrane using a Millipore syringe (with a pore size of 0.45 µm). The leachate extraction was then prepared for analysis. The parameters measured in this analysis include temperature (T), pH, electrical conductivity (EC), oxidation–reduction potential (Eh), total dissolved solid (TDS), major cations (Li, Na, NH\textsubscript{4}, K, Mg, Ca) and major anions (F, Cl, Br, NO\textsubscript{3}, NO\textsubscript{2}, H\textsubscript{3}PO\textsubscript{4}, SO\textsubscript{4} and HCO\textsubscript{3}+CO\textsubscript{3}). Major ionic concentrations were measured using ion chromatography (IC, Dionex 600) following the manufacturer’s manual. An AS11 analytical column, Na\textsubscript{2}CO\textsubscript{3} and NaHCO\textsubscript{3} eluent and 100 µl sample loop were employed for the determinations of anions. The cations were determined by IC with a CS12A analytical column and a 25µl sample loop, with methanesulphonic acid (MSA) as the eluent. The detection limit for major anions and cations is <0.1 mg/l and the error of the analytical procedures is ±2%. The T, pH, EC, Eh, and TDS were measured with a Multi-Parameter Analyzer (Eijkelkamp 18.28). The TDS is calculated based on electrical conductivity (EC) and temperature (T) and by a standard calculation implemented in the Eijkelkamp 18.28 analyzer. The used formula was TDS = 0.6452 × EC\textsuperscript{1/2}/(1 + 0.02 × Δt) (r\textsuperscript{2} = 0.99), where Δt = T – 25°C. The error of the analytical procedures was <2% for pH and Eh, <1% for EC and TDS. Alkalinity was measured using Gran’s method [36]. Based on the TDS and the water and soil mass quantity, the total salt content to total sample mass was calculated, and it is referred here as the “salinity” of the sample. To explore the relationship between the salt concentration and particle size distribution, some dune surface samples were selected for particle size analysis (PSA). Thirty grams of sediment from each sample was dry sieved at 0.25± intervals with measurement ranging from 38 to 2,360 µm by a three-dimensional vibration sieving machine (Retsch AS200 Grain-size Analyzers). Soil–water extractions of several selected particle-size fractions of these samples were also measured for physical data using the methods stated above. Detailed analytical methods for soluble salt geochemistry of aeolian sediment samples can also be seen from Zhu and Yang (2010) [16]. The physical and chemical analytical data of the soluble salt compositions of sediments are shown in Table 1 and Table 2, respectively. Partial characteristics of aeolian salts from the Taklamakan and Badanjilin Deserts were previously reported in our early works [16, 17] with preliminary descriptions of their composition and distribution, but the characteristics of evaporitic carbonates in aeolian sediments and their environmental significance are presented here along with the salt origin estimations.
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 Badanjilin Desert.

Table 1. Physical parameters of the soil-water extraction of the modern and ancient aeolian sediments from the Taklamakan and Badanjilin deserts in northwestern China.

| Sample name | pH   | Eh (mV) | EC (µS/cm) | TDS (mg/L) | Salinity (%) | Sample name | pH   | Eh (mV) | EC (µS/cm) | TDS (mg/L) | Salinity (%) |
|-------------|------|---------|------------|------------|-------------|-------------|------|---------|------------|------------|-------------|
| The dune-surface sand samples collected from the Badanjilin Desert
| B1         | 9.20 | -141    | 73.6       | 39.1       | 0.197       | B2         | 9.10 | -145    | 49.4       | 26.3       | 0.134       |
| B3         | 9.01 | -140    | 39.2       | 20.8       | 0.104       | B4         | 9.23 | -143    | 35.0       | 18.6       | 0.096       |
| B5-1       | 9.13 | -139    | 33.0       | 17.6       | 0.088       | B5-2       | 8.97 | -131    | 51.6       | 27.5       | 0.137       |
| B5-3       | 9.13 | -139    | 36.9       | 19.6       | 0.098       | B5-4       | 9.21 | -143    | 43.7       | 23.3       | 0.117       |
| B5-5       | 8.82 | -129    | 42.9       | 22.9       | 0.114       | B6-1       | 9.11 | -145    | 42.7       | 22.7       | 0.116       |
| B6-2       | 8.94 | -129    | 29.7       | 15.8       | 0.079       | B6-3       | 9.30 | -148    | 48.0       | 25.5       | 0.128       |
| B6-4       | 9.35 | -151    | 55.0       | 29.3       | 0.146       | B6-5       | 8.99 | -138    | 157        | 83.0       | 0.414       |
| B7-1       | 8.82 | -123    | 22.0       | 11.7       | 0.059       | B7-2       | 9.17 | -141    | 33.9       | 18.1       | 0.091       |
| B7-3       | 9.35 | -151    | 62.5       | 33.2       | 0.167       | B8-1       | 8.85 | -122    | 21.9       | 11.6       | 0.059       |
| B8-2       | 9.05 | -132    | 26.1       | 13.9       | 0.070       | B8-3       | 9.42 | -154    | 48.9       | 26.0       | 0.131       |
| B9         | 8.98 | -137    | 37.8       | 20.3       | 0.102       | B10        | 9.05 | -140    | 43.8       | 23.5       | 0.117       |
| B11        | 9.05 | -141    | 42.9       | 22.8       | 0.115       | B12        | 9.00 | -132    | 80.2       | 42.6       | 0.213       |
| B13-1      | 9.00 | -138    | 32.3       | 17.2       | 0.086       | B13-2      | 9.10 | -143    | 72.9       | 38.8       | 0.194       |
| B13-3      | 8.91 | -134    | 33.1       | 17.6       | 0.088       | B14-1      | 8.84 | -128    | 36.5       | 19.4       | 0.098       |
| B14-2      | 9.20 | -148    | 41.6       | 22.2       | 0.112       | B14-3      | 9.22 | -150    | 49.1       | 26.1       | 0.132       |
| B14-4      | 9.22 | -151    | 159        | 84.0       | 0.421       | B14-5      | 9.37 | -159    | 93.1       | 49.6       | 0.248       |
| B14-6      | 9.13 | -146    | 76.0       | 40.4       | 0.203       | B14-7      | 9.21 | -149    | 97.4       | 51.7       | 0.261       |
| B14-8      | 9.17 | -150    | 76.7       | 40.7       | 0.206       | B14-9      | 9.26 | -153    | 57.0       | 30.3       | 0.152       |
| B14-10     | 9.36 | -160    | 126        | 67.0       | 0.336       | B14-11     | 9.26 | -154    | 52.7       | 28.0       | 0.140       |
| The dune-surface sand samples collected from the Taklamakan Desert
| T1-1       | 9.33 | -157    | 215        | 114        | 0.575       | T1-2       | 9.42 | -163    | 177        | 94         | 0.472       |
| T2-1       | 9.37 | -158    | 115        | 61         | 0.311       | T2-2       | 9.28 | -155    | 122        | 65         | 0.329       |
### Table 1

| Sample name | pH  | Eh (mV) | EC (µS/cm) | TDS (mg/L) | Salinity (%) |
|-------------|-----|---------|------------|------------|--------------|
| T2-3        | 9.44 | -163    | 118        | 62         | 0.310        |
| T2-4        | 9.26 | -154    | 104        | 55         | 0.277        |
| T3          | 9.14 | -148    | 643        | 342        | 1.712        |
| T4          | 3.97 | -159    | 406        | 216        | 1.090        |
| T5          | 3.93 | -160    | 165        | 85         | 0.429        |
| T6          | 9.47 | -166    | 699        | 372        | 1.864        |
| T7          | 9.47 | -164    | 326        | 173        | 0.868        |
| T8          | 9.51 | -160    | 151        | 80         | 0.400        |
| T9          | 9.30 | -158    | 192        | 103        | 0.519        |
| T10         | 9.25 | -153    | 257        | 136        | 0.681        |
| T11         | 9.22 | -151    | 409        | 218        | 1.094        |
| T12         | 9.23 | -144    | 554        | 295        | 1.474        |
| T13         | 9.01 | -143    | 237        | 126        | 0.631        |
| T14         | 9.07 | -143    | 403        | 214        | 1.074        |
| T15         | 9.24 | -152    | 351        | 189        | 0.948        |
| T16         | 8.87 | -135    | 323        | 174        | 0.877        |
| T17         | 8.66 | -108    | 310        | 163        | 0.826        |
| T18         | 9.32 | -160    | 127        | 91         | 0.455        |
| T19         | 9.38 | -160    | 127        | 67         | 0.339        |

The buried sand (palaeo-sand) samples in the Taklamakan Desert:

- **T1-3**: pH 9.53, Eh (mV) -168, EC 150, TDS 80, Salinity (%) 0.400
- **T2-6**: pH 9.33, Eh (mV) -158, EC 406, TDS 216, Salinity (%) 1.086
- **T5-5**: pH 9.04, Eh (mV) -142, EC 1130, TDS 600, Salinity (%) 3.019
- **T5-7**: pH 9.61, Eh (mV) -173, EC 112, TDS 59, Salinity (%) 0.297
- **T6-3**: pH 9.02, Eh (mV) -139, EC 1010, TDS 540, Salinity (%) 2.721
- **T6-5**: pH 8.75, Eh (mV) -124, EC 1240, TDS 660, Salinity (%) 3.317
- **T6-8**: pH 8.65, Eh (mV) -118, EC 2800, TDS 1500, Salinity (%) 7.542
- **T7-2**: pH 8.50, Eh (mV) -109, EC 75300, TDS 490000, Salinity (%) 403.5
- **T7-4**: pH 8.52, Eh (mV) -109, EC 6840, TDS 3710, Salinity (%) 18.63
- **T7-6**: pH 8.74, Eh (mV) -122, EC 4580, TDS 2500, Salinity (%) 12.62

The Arerjilin-I section in the Badanjilin Desert:

- **Ar1**: pH 9.09, Eh (mV) -135, EC 428, TDS 228, Salinity (%) 1.156
- **Ar2**: pH 9.83, Eh (mV) -180, EC 267, TDS 142, Salinity (%) 0.711
- **Ar4**: pH 9.46, Eh (mV) -157, EC 678, TDS 361, Salinity (%) 1.811
- **Ar6**: pH 7.62, Eh (mV) -53, EC 833, TDS 443, Salinity (%) 2.213
- **Ar8**: pH 7.42, Eh (mV) -41, EC 1780, TDS 950, Salinity (%) 4.788
- **Ar10**: pH 7.60, Eh (mV) -51, EC 264, TDS 140, Salinity (%) 0.699
- **Ar12**: pH 8.24, Eh (mV) -88, EC 137, TDS 73, Salinity (%) 0.365

The Tazhong-XIII section in the Taklamakan Desert:

- **Ta1**: pH 9.14, Eh (mV) -151, EC 217, TDS 115, Salinity (%) 0.577
- **Ta2**: pH 8.47, Eh (mV) -111, EC 906, TDS 482, Salinity (%) 2.424
- **Ta4**: pH 9.02, Eh (mV) -141, EC 523, TDS 278, Salinity (%) 1.392
- **Ta6**: pH 8.47, Eh (mV) -111, EC 906, TDS 482, Salinity (%) 2.424

The Yaogan-VIII section in the Taklamakan Desert:

- **Ya1**: pH 8.28, Eh (mV) -96, EC 16200, TDS 9100, Salinity (%) 46.29
- **Ya2**: pH 8.77, Eh (mV) -125, EC 2840, TDS 1520, Salinity (%) 7.576
- **Ya4**: pH 9.07, Eh (mV) -141, EC 2070, TDS 1110, Salinity (%) 5.617
- **Ya8**: pH 8.24, Eh (mV) -94, EC 41200, TDS 25000, Salinity (%) 125.27
- **Ya9**: pH 8.30, Eh (mV) -97, EC 59800, TDS 37900, Salinity (%) 191.01
- **Ya10**: pH 8.80, Eh (mV) -127, EC 6270, TDS 3400, Salinity (%) 17.19
- **Ya12**: pH 9.39, Eh (mV) -161, EC 294, TDS 156, Salinity (%) 0.786

The Tiumi-II section in the Taklamakan Desert:

- **Tu1**: pH 8.64, Eh (mV) -117, EC 2860, TDS 1540, Salinity (%) 7.754
- **Tu3**: pH 8.63, Eh (mV) -118, EC 2880, TDS 1540, Salinity (%) 7.747
- **Tu5**: pH 8.77, Eh (mV) -125, EC 4250, TDS 2310, Salinity (%) 11.87
- **Tu7**: pH 9.56, Eh (mV) -170, EC 1410, TDS 750, Salinity (%) 3.797
- **Tu9**: pH 9.18, Eh (mV) -149, EC 8490, TDS 4640, Salinity (%) 23.23
- **Tu11**: pH 9.45, Eh (mV) -165, EC 3570, TDS 1920, Salinity (%) 9.911
- **Tu13**: pH 9.48, Eh (mV) -164, EC 1410, TDS 750, Salinity (%) 3.836
- **Tu15**: pH 9.62, Eh (mV) -174, EC 723, TDS 384, Salinity (%) 1.947
- **Tu17**: pH 9.72, Eh (mV) -180, EC 446, TDS 238, Salinity (%) 1.207
- **Tu19**: pH 9.66, Eh (mV) -175, EC 842, TDS 447, Salinity (%) 2.245
- **Tu21**: pH 9.65, Eh (mV) -174, EC 960, TDS 510, Salinity (%) 2.571
- **Tu23**: pH 9.64, Eh (mV) -116, EC 1570, TDS 840, Salinity (%) 4.225
- **Tu25**: pH 9.18, Eh (mV) -149, EC 1440, TDS 770, Salinity (%) 3.866
- **Tu27**: pH 9.73, Eh (mV) -180, EC 573, TDS 305, Salinity (%) 1.535
- **Tu29**: pH 9.66, Eh (mV) -175, EC 447, TDS 228, Salinity (%) 2.261
carbon-bearing salts, particularly bicarbonate.

Table 2. The analytical data of major ionic compositions for the soil-water extraction of the aeolian sediments from the Taklamakan and Badanjilin deserts.

| Sample name | Na⁺ (mg/l) | K⁺ (mg/l) | Mg²⁺ (mg/l) | Ca²⁺ (mg/l) | Cl⁻ (mg/l) | SO₄²⁻ (mg/l) | HCO₃⁻ (mg/l) |
|-------------|------------|-----------|-------------|-------------|-----------|-------------|-------------|
| B1          | 4.30       | 3.66      | 0.46        | 2.03        | 7.62      | 1.53        | 13.0        |
| B3          | 2.53       | 1.81      | 0.32        | 1.82        | 2.74      | 0.50        | 8.39        |
| B4          | 10.0       | 1.37      | 0.28        | 1.23        | 2.87      | 0.53        | 0.46        |
| B5-1        | 3.85       | 1.68      | 0.38        | 1.44        | 1.32      | 0.90        | 4.99        |
| B5-2        | 3.91       | 2.80      | 0.50        | 2.03        | 6.99      | 1.61        | 4.25        |
| B5-3        | 6.07       | 3.22      | 0.33        | 1.63        | 2.10      | 1.16        | 1.30        |
| B5-4        | 5.71       | 3.54      | 0.36        | 1.67        | 1.67      | 1.11        | 5.78        |
| B6-2        | 5.11       | 3.22      | 0.35        | 1.24        | 1.69      | 0.80        | 0.77        |
| B6-3        | 3.62       | 2.04      | 0.42        | 2.04        | 7.12      | 1.21        | 5.39        |
| B7-1        | 2.80       | 1.19      | 0.27        | 0.81        | 2.12      | 0.67        | 2.08        |
| B7-2        | 2.99       | 1.27      | 0.34        | 1.85        | 1.63      | 0.42        | 7.00        |
| B7-3        | 3.71       | 2.75      | 0.38        | 2.13        | 1.64      | 1.20        | 17.5        |
| B8-1        | 4.16       | 1.32      | 0.77        | 1.35        | 4.33      | 1.76        | 1.90        |
| B8-2        | 3.79       | 1.06      | 0.34        | 1.28        | 2.90      | 0.96        | 0.98        |
| B8-3        | 3.64       | 1.59      | 0.45        | 2.01        | 5.44      | 0.66        | 9.08        |
| B10         | 9.45       | 1.37      | 0.24        | 0.88        | 4.60      | 0.91        | 4.01        |
| B11         | 3.77       | 1.24      | 0.43        | 1.67        | 3.70      | 0.31        | 8.58        |
| B12         | 4.48       | 4.18      | 0.70        | 4.13        | 2.05      | 1.67        | 17.5        |
| T1-1        | 20.7       | 2.77      | 0.65        | 2.49        | 45.1      | 0.77        | 33.5        |
| T1-3        | 15.6       | 1.09      | 0.59        | 1.55        | 19.6      | 1.33        | 34.4        |
| T2-4        | 6.84       | 2.05      | 0.67        | 2.36        | 10.9      | 2.74        | 22.3        |
| T2-5        | 21.4       | 3.34      | 0.57        | 2.43        | 49.4      | 4.51        | 38.5        |
| T3          | 62.0       | 6.97      | 1.25        | 4.21        | 162       | 9.46        | 68.8        |
| T4          | 43.9       | 6.03      | 0.91        | 2.42        | 89.4      | 1.72        | 53.1        |
| T5-3        | 107        | 9.48      | 1.01        | 3.67        | 257       | 3.35        | 80.8        |
| T5-4        | 72.9       | 9.26      | 1.47        | 4.44        | 178       | 6.06        | 52.4        |
| T5-8        | 125        | 14.6      | 2.70        | 9.57        | 331       | 14.7        | 96.0        |
| T7-2        | 10375      | 234       | 26.3        | 325.4       | 15091     | 1699        | 19203       |
| T7-3        | 9255       | 117       | 11.2        | 293         | 23841     | 2013        | 12419       |
| T10         | 16.8       | 3.77      | 0.56        | 3.08        | 24.1      | 4.01        | 17.3        |
| T18         | 55.3       | 8.19      | 1.35        | 5.32        | 156       | 6.27        | 34.4        |

3. Results

The calculated salinity values are 0.27-1.86‰ (average 0.78‰) in the dune sediments of the Taklamakan Desert, with pH values ranging from 8.66 to 9.54 (average 9.22) (Fig. 2a). For the dune sediments from the Badanjilin Desert, the pH and salinity values range between 8.82 and 9.42 (average 9.12) and 0.05‰ and 0.42‰ (average 0.15‰), respectively (Fig. 2b). The range of pH values between the aeolian sediments is narrow (8.6-9.5), suggesting generally similar alkaline soil conditions and buffer capacities. Because pH values in soil between 6.4-12.2 are mainly caused by bicarbonate (6.4-10.3) and carbonate (10.3-12.2) [36], consequently, the alkalinitities of these aeolian salts are mainly determined by the mineralogy of aeolian salts can be classified as follows: NaHCO₃ + NaCl + (CaCO₃) in the Badanjilin Desert (Fig. 2g), and NaCl + NaHCO₃ in the Taklamakan Desert (Fig. 2h). It indicates that sodium carbonate and chloride are the common salts in aeolian sediments within the deserts of northwestern China.
4. Discussion

4.1. Secondary Salt

It is firstly necessary to understand whether the nature of soluble salt in aeolian sediment is primary or secondary in origin.

As defined by Warren (2006) [4], a salt deposit (evaporite) is originally precipitated from a saturated surface or nearsurface brine by hydrologies, driven by solar evaporation. It means that primary salts are precipitated from a standing body of surface brine and retaining crystallographic evidence of the depositional process. According to this definition, almost every subsurface salt texture is secondary, because it is diagenetically altered, frequently with fabrics indicating pervasive early recrystallization. Secondary salts can be formed in surface/subsurface settings equivalent to the eogenetic, mesogenetic and telogenetic realms [37].

Under this definition of a primary versus secondary salt, we can say that, outside of a few Neogene examples [38, 39, 40, 41], there are few salt deposit with textures that are wholly and completely “primary”. Without exception, soluble salts in aeolian sediments should be secondary salt originated in the eogenetic realm.

Besides, studies in Chinese deserts that focusing on sediment/soil carbonate $\delta^{13}$C, which can establish strategies for determining the provenance and formation of these carbonates, have proposed that the carbonates in the middle-latitude Chinese deserts are enriched in carbon isotope, with positive $\delta^{13}$C values around or above 0‰ [42, 43]. Because CO$_2$ absorption/degassing, in combination with evaporation and rapid microbial growth, can drive extreme carbon isotope enrichment [44], it further suggests that the carbonates in aeolian sediments from Chinese deserts are secondary salt in origin.
4.2. Evaporitic Alkaline Earth Carbonates and Syndepositional Process

Salt minerals can be simply subdivided into evaporitic alkaline earth carbonates and evaporite salts [4]. Evaporitic alkaline earth carbonates are the first salt minerals to precipitate from a concentrating hypersaline surface water and they tend to form in the initial/early stages of brine concentration, while the other evaporitic salts are precipitated in the more saline stages of concentration [45]. As analyzed above in this study, NaHCO$_3$ + CaCO$_3$ are the common salts in aeolian sediments within both the Taklamakan and the Badanjilin Deserts. It indicates that evaporitic alkaline earth carbonates are major component of these aeolian salts.

Although texture of most of the soluble salts is secondary, these secondary salts are often syndepositional precipitates, forming cements and replacement even as the primary matrix accumulates around them [4]. For aeolian sediments in arid environment, we image that much of surface salts are deposited in multiple episodes of early diagenetic (syndepositional) cementation. This syndepositional salt may be formed in multiple dissolution-precipitation events in the sand particle surface and are precipitated between successive depositional episodes of salt crust formation.

4.3. Potential Role of Aeolian Carbon Salts in PIC Pool

According to the analysis above, evaporitic alkaline earth carbonate salts (NaHCO$_3$ + CaCO$_3$) are a prominent component of aeolian salts in the Taklamakan and Badanjilin Deserts, two of the largest middle-latitude deserts where much of the Asian dust is produced [13, 43]. Because soluble salts in aeolian sediments are mainly atmospheric origin [16, 17], and conversely dust from Asian deserts can affect global atmospheric chemical processes and aerosol characteristics due to the acid neutralizing capacity of this species [46], it thus can say that aeolian carbon salts in the Chinese deserts are a potential component of global PIC pool. Evaluating the role of aeolian salts in PIC pool and its dynamics is important to understanding the global carbon cycle.

Stone (2008) [25] has suggested that a significant loop in the carbon cycle may be hidden in the global desert areas. According to the hypothesis of Stone (2008) [25], it implies that a desert region would provide a significant contribution for the global carbon cycle if it satisfies the following prerequisites: 1) it can fix the carbon in inorganic-salt form from the atmosphere, 2) the acid-buffering capacity of the soil is large, 3) its area is large enough so that the quantity of carbon fixed can be noticeable on a global scale and 4) the fixed carbon can be conserved in the soil.

There is little vegetation (herbs, shrubs, trees and lianas as C3 and C4 plants) in the Taklamakan and Badanjilin deserts due to their hyper-arid climate, and the $^{13}$C values dominated by carbonates are produced by atmospheric deposition [42, 43], thus the alkaline earth carbonate salts in aeolian sands are closely related to atmospheric CO$_2$ absorption. This means that the elemental carbon in aeolian salts is introduced from the atmosphere into the pedosphere by a carbon-fixation process.

Alkalinity is a key buffer for neutralizing the hydrogen ion (H$^+$) [36], meaning that a degree of soil alkalinity has a potential capability to neutralize atmospheric carbonic acid. The ground surface conditions of the Taklamakan and Badanjilin Deserts in northwestern China are alkaline and these alkalinites result from the presence of the carbonates. This is evidenced by the relatively high pH values (8.4-9.6) of the surface dune sands (On-line Supplementary Table 1) and the positive correlation between pH and the content of carbon-bearing salts (Fig. 2c). The increase in carbonate contents together with the increase in pH values in the aeolian sediments (Fig. 2c) indicates that the potential capacity of atmospheric carbon fixation in soil also increases. The reaction with atmospheric CO$_2$ would consume the alkalinity within a relatively short period under humid conditions. There has to be a long acting source. Calcium carbonate can rapidly precipitate during drought conditions, that is, when both soil moisture and root activity are low, and more generally, carbonate typically accumulates in soils where the mean annual precipitation is less than 1000 mm yr$^{-1}$ [47].

The summary area of the Taklamakan and the Badanjilin deserts in northwestern China, about 386,000 km$^2$, accounts for about one third (32%) of the total area of the global mid-latitudes sandy deserts, undoubtedly a noticeable body on a global scale.

In humid environments, soil carbonate is subjected to leaching, but when mean annual precipitation is limited to approximately 500 mm [48, 49], at least a portion of soil carbonate accumulates in the soil profile. In this way, carbonate in desert soils may provide a sink for atmospheric C [3, 50, 51, 52]. Regarding the balance between the eluviation and the precipitation processes for the desert environment in northwestern China, the mean annual precipitation rates in this land are less than 400 mm in most cases (Fig. 1a), namely the deserts of northwestern China are almost located in areas below the 400 mm isohyet, thus resulting a more strong precipitation process than an eluviations process. In continental scale, mean annual precipitation tends to increase from west to east in northern China. This is supported by the observation that the carbonate content of surface soils in northern China varies inversely with mean annual precipitation [53, 43]. This kind of couples between moisture and salt distribution patterns indicates that the carbon salts in the desert soil across the two Chinese deserts has the nature to be preserved in the soil. Within the past several dozen of years, desertification induced by human activities may have caused over a 40% loss of total carbon storage (including organic) in the desert lands of northwestern China [14, 54], however, our works have proved that a considerable amount of this carbon was re-deposited downwind of the desert rather than being released into the atmosphere [14]. All these mean that the fixed carbon in the desert can be finally conserved in the soil.

The analysis confirms that the aeolian sediments in the wide desert regions of northwestern China, the large middle-latitude deserts in northern Hemisphere, can fix atmospheric carbon in an inorganic-salt form with a
significant acid-buffering capacity, due to their strong alkalinity. This evidence strongly implies that the two Chinese deserts potentially qualify as significant contributors to the global carbon cycle. This is, to a great extent, similar to the Gurbantonggut Desert in northwestern China and the Mojave Desert in the USA [25], both of which are key regions for the global carbon cycle in the mid-latitudes of the Northern Hemisphere. However, the author of this paper think that the low-latitude deserts in tropic areas are not capable of providing such a contribution for the global carbon cycle as proposed by Stone (2008)[25], because the tropic deserts could not satisfy entirely the four prerequisites mentioned above in this study, since the compositions of soil inorganic salts in these deserts are sulphate- or chloride-rich (not carbonate-rich), such as chloride–sulfate salts dominated in the Kalahari Desert [55], and the degree of soil alkalinity is not high (pH 6.9–8.1, [56]).

5. Conclusion

Due to the complexity of salt formation involved in atmosphere-landscape relation, there are few study involved into the pool of secondary carbonates in world desert soils, particularly in arid areas in northern China. In this work we carried out a physical and geochemical exploration into soluble carbon salts in dune sediments from the inland deserts (the Taklamakan and the Badanjilin Deserts) in northwestern China to explore the composition and distribution of evaporitic carbon salts in aeolian sediments and their possible environmental implications for global carbon cycle. The results show that the aeolian salt has high alkalinites, which are mainly determined by evaporitic alkaline earth bicarbonates. The carbonates are secondary salt in origin and are possibly introduced from the atmosphere into the pedosphere by a carbon-fixation process. Due to the high capability to neutralize atmospheric carbonic acid, large desert area, and the strong potential of carbonate accumulation in soil under arid climate, the middle-latitude Chinese deserts can be potentially qualified as a significant contributor to the global carbon cycle. But the low-latitude deserts in tropic areas are maybe not able to provide such a contribution.

Acknowledgments

This work was supported by Foundations from China (Grant no.: NKRDP 2016YFA0601901 and 2016YFA0601904, NSFC 41371060, IGSNRR 2013RC101, NSFC 41225001 and 41671198). The author is grateful to Prof. Xiaoping Yang for his generous help in the research work.

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