



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

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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 CO₂ with Ca²⁺ and Mg²⁺ 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 Gulbantonggut Desert of northwestern China [27] and the Mojave Desert of western USA [26], were both observed to be soaking up the surrounding CO₂ 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/m² 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, NH₄, K, Mg, Ca) and major anions (F, Cl, Br, NO₂, NO₃, H₂PO₄, SO₄ and HCO₃+CO₃). Major ionic concentrations were measured using ion chromatography (IC, Dionex 600) following the manufacturer's manual. An AS11 analytical column, Na₂CO₃ and NaHCO₃ 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 $TDS = 0.6452 \times EC_T / (1 + 0.02 \times \Delta t)$ ($r^2 = 0.99$), where $\Delta t = T - 25^\circ C$. 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 0.25φ 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.

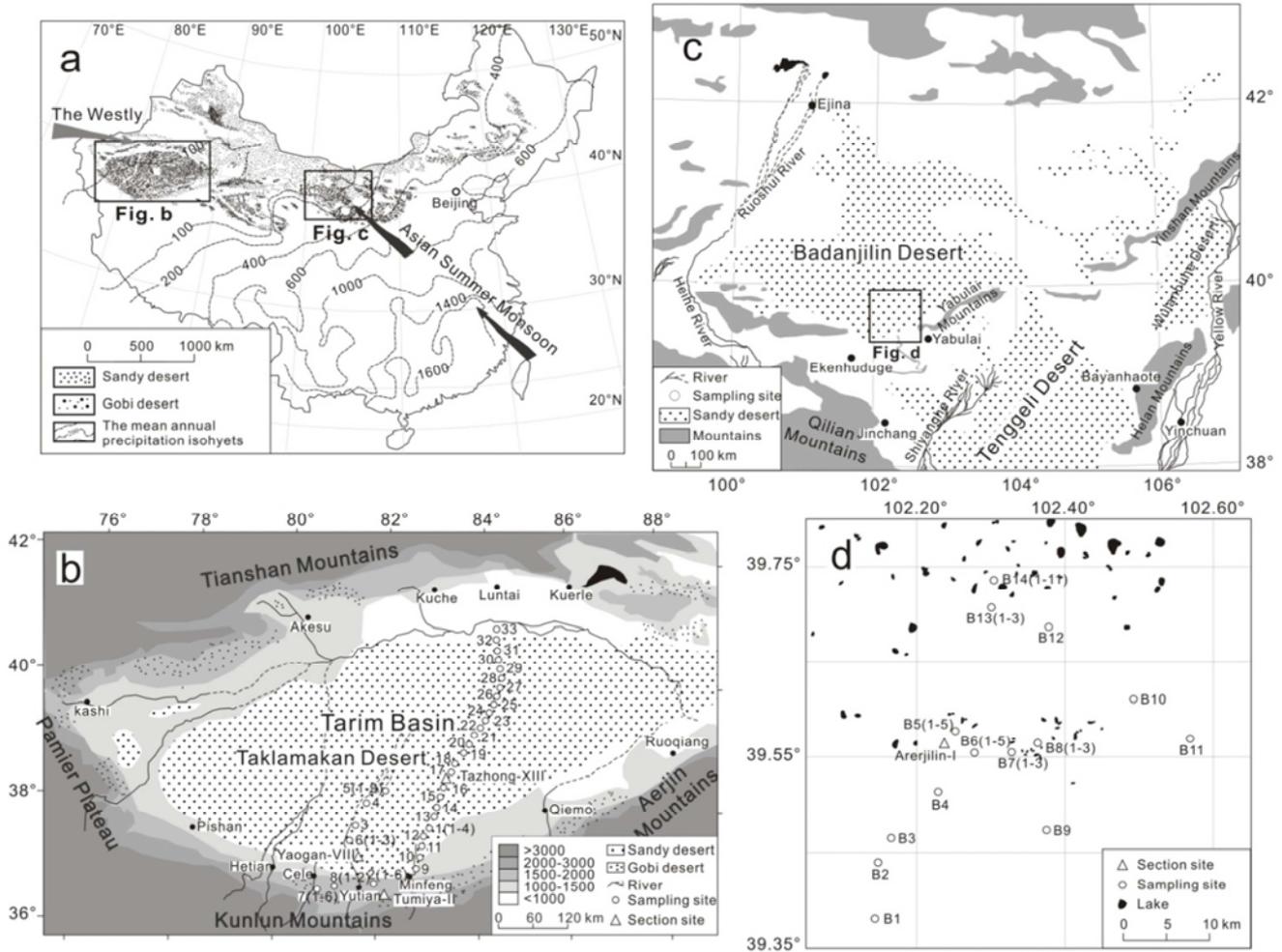


Figure 1. Locations of the study areas and sampling sites in this study. (a) The distributions of deserts and the mean annual precipitation isohyets in China, (b) the Taklamakan Desert, (c) and (d) the Badanjilin Desert.

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

Sample name	pH	Eh (mV)	EC (µS/cm)	TDS (mg/L)	Salinity (‰)	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
T2-5	9.21	-151	255	135	0.682	T3	9.14	-148	643	342	1.712
T4	9.37	-159	406	216	1.090	T5-1	9.33	-158	826	439	2.214
T5-2	9.38	-160	160	85	0.429	T5-3	9.17	-149	950	500	2.531
T6-1	9.47	-166	699	372	1.864	T9	9.47	-164	326	173	0.868
T10	9.51	-160	151	80	0.400	T11	9.26	-152	290	154	0.775
T12	9.33	-158	192	103	0.519	T13	8.77	-125	645	347	1.754
T14	9.25	-153	257	136	0.681	T15	9.29	-154	259	138	0.695
T16	9.22	-151	409	218	1.094	T17	9.10	-148	318	169	0.846
T18	9.23	-144	554	295	1.474	T19	8.99	-141	307	163	0.815
T20	9.01	-143	237	126	0.631	T21	9.25	-153	398	212	1.063
T22	9.07	-143	403	214	1.074	T23	9.16	-150	186	99	0.497
T24	9.24	-152	351	189	0.948	T25	8.91	-137	311	165	0.831
T26	8.87	-135	323	174	0.877	T27	8.89	-135	223	119	0.598
T28	8.66	-108	310	163	0.826	T29	9.11	-149	385	205	1.024
T30	9.32	-160	172	91	0.455	T31	9.33	-161	210	112	0.562
T32	9.38	-160	127	67	0.339	T33	9.54	-170	164	87	0.437
The buried sand (palaeo-sand) samples in the Taklamakan Desert											
T1-3	9.53	-168	150	80	0.400	T1-4	9.55	-170	333	176	0.880
T2-6	9.33	-158	406	216	1.086	T5-4	9.19	-150	667	355	1.779
T5-5	9.04	-142	1130	600	3.019	T5-6	9.24	-150	581	309	1.563
T5-7	9.61	-173	112	59	0.297	T5-8	8.97	-137	1210	640	3.215
T5-9	9.02	-139	1010	540	2.721	T6-2	9.21	-151	2290	1230	6.171
T6-3	8.75	-124	1240	660	3.317	T8-1	8.82	-128	1390	740	3.737
T8-2	8.65	-118	2800	1500	7.542	T7-1	8.54	-112	6300	3420	17.15
T7-2	8.50	-109	75300	49000	403.5	T7-3	8.19	-92	94400	63100	383.6
T7-4	8.52	-109	6840	3710	18.63	T7-5	8.70	-121	4120	2240	11.29
T7-6	8.74	-122	4580	2500	12.62						
the Arerjilin-I section in the Badanjinlin Desert											
Ar1	9.09	-135	428	228	1.156	Ar2	9.73	-174	492	262	1.313
Ar3	9.83	-180	267	142	0.711	Ar4	9.64	-169	526	280	1.410
Ar5	9.46	-157	678	361	1.811	Ar6	9.31	-149	684	364	1.827
Ar7	7.62	-53	833	443	2.213	Ar8	7.68	-55	496	264	1.321
Ar9	7.42	-41	1780	950	4.788	Ar10	8.84	-124	900	480	2.396
Ar11	7.60	-51	264	140	0.699	Ar12	7.74	-60	291	155	0.772
Ar13	8.24	-88	137	73.0	0.365						
the Tazhong-XIII section in the Taklamakan Desert											
Ta1	9.14	-151	217	115	0.577	Ta2	8.21	-92	5550	3010	15.09
Ta3	8.47	-111	906	482	2.424	Ta4	8.04	-84	5340	2890	14.58
Ta5	9.02	-141	523	278	1.392	Ta6	8.75	-123	980	520	2.609
the Yaogan-VIII section in the Taklamakan Desert											
Ya1	8.28	-96	16200	9100	46.29	Ya2	8.68	-119	4350	2350	11.71
Ya3	8.77	-126	2840	1520	7.576	Ya4	8.83	-128	4080	2200	11.14
Ya5	9.07	-141	2070	1110	5.617	Ya6	8.58	-114	6830	3700	18.67
Ya7	8.24	-94	41200	25000	125.27	Ya8	8.71	-121	29200	17100	86.53
Ya9	8.30	-97	59800	37900	191.01	Ya10	8.49	-109	6390	3460	17.39
Ya11	8.80	-127	6270	3400	17.19	Ya12	9.06	-141	768	409	2.062
Ya13	9.39	-161	294	156	0.786						
the Tumiya-II section in the Taklamakan Desert											
Tu1	8.64	-117	2860	1540	7.754	Tu2	9.18	-148	1010	530	2.669
Tu3	8.63	-118	2880	1540	7.747	Tu4	8.71	-122	3920	2110	10.64
Tu5	8.77	-125	4250	2310	11.87	Tu6	8.51	-109	1080	590	2.963
Tu7	9.56	-170	1410	750	3.797	Tu8	9.53	-170	2000	1070	5.422
Tu9	9.18	-149	8490	4640	23.23	Tu10	9.35	-157	3250	1750	8.740
Tu11	9.45	-165	3570	1920	9.911	Tu12	9.52	-168	1330	710	3.562
Tu13	9.48	-164	1410	750	3.836	Tu14	9.52	-169	1740	930	4.670
Tu15	9.62	-174	723	384	1.947	Tu16	9.50	-168	805	428	2.154
Tu17	9.72	-180	446	238	1.207	Tu18	9.66	-176	413	220	1.108
Tu19	9.66	-175	842	447	2.245	Tu20	9.94	-192	221	117	0.591
Tu21	9.65	-174	960	510	2.573	Tu22	9.46	-166	663	353	1.786
Tu23	8.64	-116	1570	840	4.225	Tu24	9.68	-178	608	322	1.628
Tu25	9.18	-149	1440	770	3.866	Tu26	9.12	-145	2010	1080	5.401
Tu27	9.73	-180	573	305	1.535	Tu28	8.69	-119	2380	1270	6.471
Tu29	9.66	-175	840	447	2.261						

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)	Mg ²⁺ (mg/l)	Ca ²⁺ (mg/l)	Cl ⁻ (mg/l)	SO ₄ ²⁻ (mg/l)	HCO ₃ ⁻ (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 alkalinities of these aeolian salts are mainly determined by the

carbon-bearing salts, particularly bicarbonate.

The major anions of aeolian salts are HCO₃⁻ and Cl⁻, and the SO₄²⁻ concentrations are very low in all samples (Fig. 2d). The first major cation is Na⁺, followed by Ca²⁺, while the concentrations of K⁺ and Mg²⁺ are low (Fig. 2e-f). The concentrations of the carbon-bearing ions in dune-surface sediments are positively correlated with the pH values (Fig. 2c). According to the major ion concentrations, 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.

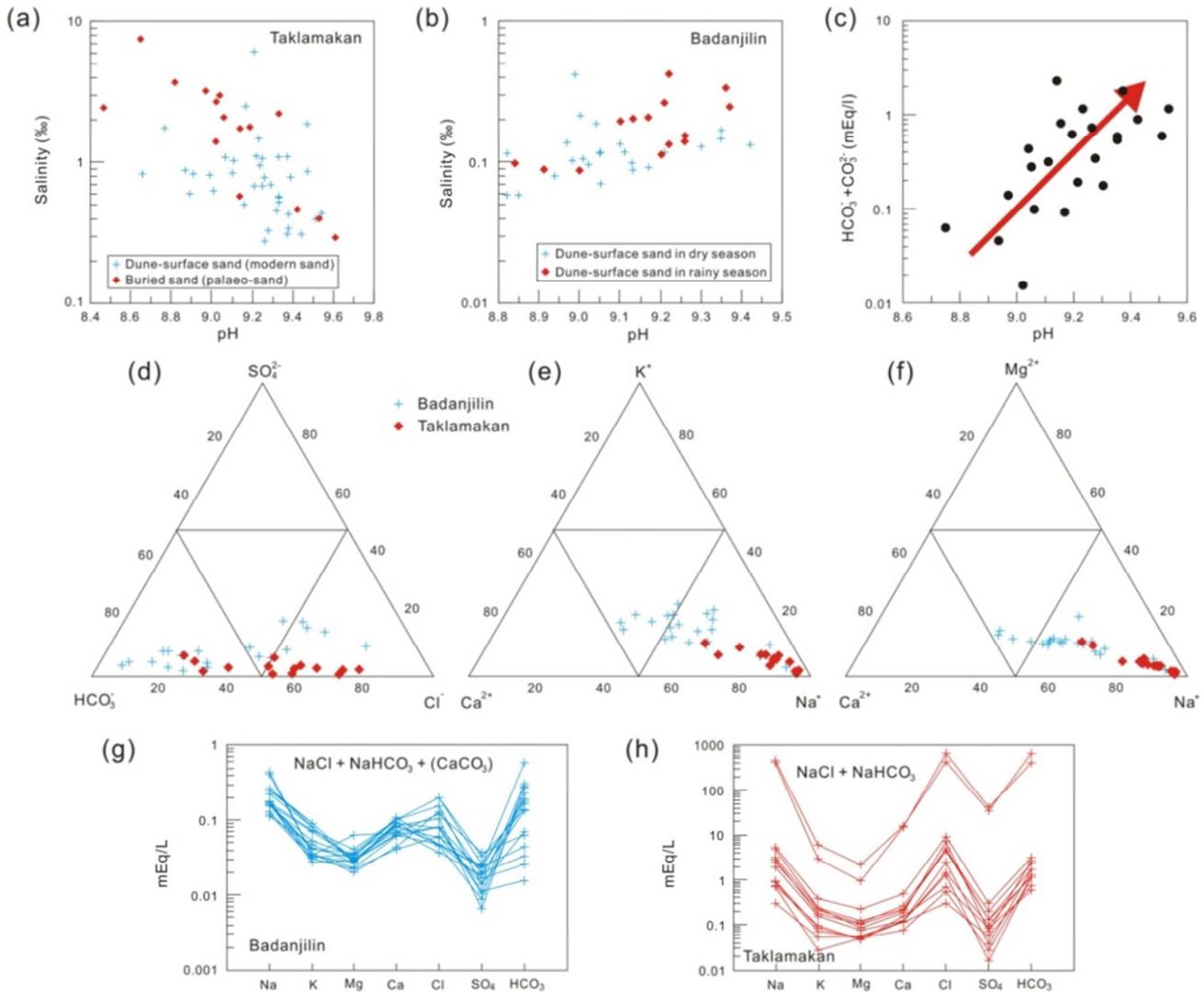


Figure 2. Salinities and major compositions of sediment solutions, (a) dune-surface sediments (modern sediment) and buried-dune sediments (palaeo-sediment) in the Taklamakan Desert, (b) dune-surface sand samples collected in different climatic seasons (dry and wet) in the Badanjinlin Desert. (c) Carbon-bearing ions vs. pH. Triangular plots of major anions (d) and cations (e and f) of the soluble salts in mEq/l unit. Distribution patterns of the major ions of the soluble salts in the aeolian sediments from (g) the Badanjinlin Desert and from (h) the Taklamakan Desert.

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 $\delta^{13}\text{C}$, 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 $\delta^{13}\text{C}$ 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, $\text{NaHCO}_3 + \text{CaCO}_3$ 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 ($\text{NaHCO}_3 + \text{CaCO}_3$) 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 $\delta^{13}\text{C}$ 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 alkalinities 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 km², 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 Gulbantonggut 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 Badanjin 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 alkalinities, 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.

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