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The origin and distribution of soluble salts in the sand seas of northern China

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A R T I C L E I N F O

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A B S T R A C T

Based on samples taken from four large sand seas of northern China, this paper first provides basic data about the concentrations and chemistries of soluble salts in deserts of northern China and then discusses the origins and parameters triggering geographical variations. The total concentration of soluble salts in the aeolian sands of four large sand seas in northern China ranges between 0.14‰ and 1.32‰, with the pH of the soluble salts solution (mixing ratio of sand and water 1:5) changing between 8.4 and 9.6, confirming alkaline soil conditions in these regions. Sodium chloride and bicarbonate are the dominant salts occurring as soluble salts in the aeolian deposits of these sand seas. The geographical changes of soluble salts' concentration display a clear correlation with regional climatic parameters, i.e., precipitation and temperature. The domination of sedimentation of soluble salts in the aeolian sands deposited via atmospheric processes is discussed, which are heavily associated with dry deposition. The mean percentages of Na and Cl, derived from dry depositions, are estimated to be >90% in both Badain Jaran and Taklamakan deserts.

1. Introduction

All soils on earth contain salts, and the mineralogical compositions of the salts contain important information of their origins and geochemical signals during their transportation and after deposition. Salts, including secondary carbonates, are easily dissolved and transported in wet conditions and readily crystallized and precipitated in arid environments. Consequently, they are often used to estimate the degree of eluviation and the pedogenetic intensity imposed on soils (Liu, 1985; Felix-Henningsen et al., 2008) as well as understand regional weathering processes (Petrov, 1976; Goudie and Viles, 1997; Zhu and Yang, 2009). Terrestrial carbon-salt precipitation/dissolution can play significant roles as either sinks or sources of global carbon (Marion et al., 2008) and desert inorganic salts may have greatly influenced the break-even balance of the global carbon cycle (Stone, 2008). Due to a sensitive response to variations of local, regional or global environmental conditions such as climate and hydrology (Borchert and Muir, 1964; Smoot and Lowenstein, 1991), soluble salts in sedimentary sequences often serve as one of the environmental proxies used in evaluating the palaeoclimatic records of ocean (Krijgsman et al., 2001; Hay et al., 2006), lake (Li et al, 2000; Sinha and Raymahashay, 2004; Liu et al., 2008), sandy deserts (Jin and Li, 1992; Sun et al., 2008) and loess-paleosol sequences (Guo and Fedoroff, 1992; Sun et al., 2006).

Salt compositions and distributions in modern land surface are critical to understanding the abovementioned scientific issues, especially the interactions between earth surface processes and geologic and climatic systems. Although studies about salt deposits in arid areas have long histories, due partly to the multiple types of inorganic salts in different geomorphologic units, the mechanisms behind salt origin and distribution in desert environments remain unclear, and most researches have focused their efforts on the low-latitude deserts (Petrov, 1976; Smettan and Blume, 1987; Berger and Cooke, 1997; Eckardt and Spiro, 1999; Peck and Hatton, 2003; Smith and Compton, 2004; Dragovich and Dominis, 2008). Detailed investigations about salts in the middle- and high-latitude deserts are still rare. Desert landscapes in northern China, covering over 1.3 million km^2, among which the area of sand seas accounts for 45%, are important portions of the mid-latitude arid zone in the North Hemisphere. The sand seas of northern China contain abundant information about the interactions among the hydrosphere, atmosphere and lithosphere and are latent laboratories offering the opportunity to explore the relationship between salt distribution and its environmental factors. Based on our recent studies about soluble salts in sands from four large sand seas in northern China, this paper aims to provide a basic database about ion chemistries of soluble salts in the sand seas of China and analyze the spatio-temporal variations of soluble salts in the middle-latitude deserts and their triggering factors. Finally, this paper will discuss the origins of these salts.

2. Materials and methodology

2.1. Study area and sampling sites

The extensive arid regions of northern China are isolated from moisture sources by their extreme distances from surrounding oceans and by the topographic barrier of the Himalayas and the Tibetan Plateau and are characterized by an extensive distribution of various sand seas

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and sandy lands (Zhu et al., 1980; Yang et al., 2008). The climate is dry with scanty and sporadic rainfall that decreases from east to west as the distance from the sea increases. For this study, our sampling sites are located in four large sand seas in northern China (Fig. 1), i.e., the Taklamakan Desert, the Badain Jaran Desert, the Tenggeli Desert and the Kumutage Desert. All of them are characterized by active dunes as the major landforms in each desert (Yang et al., 2004).

The Taklamakan Desert (337,000 km^2) in the central Tarim Basin (Fig. 1a) is the largest sand sea in China with annual precipitation as low as 10 mm in its driest parts and with dunes reaching about 20–100 m in height (Zhu et al., 1980). The Tarim Basin is encircled by high mountains ranging 4500–6000 m and is one of the largest closed basins on the earth. Alluvial fans and gravel aprons produced by the Kunlun and Tianshan ranges (Fig. 1a) are generally fed to the basin with thick sediments, making the Taklamakan the sand sea with the most positive sediment budget in the world. Moisture trapped in the surrounding mountains provides a steady recharge to many rivers, which enter the basin and then mostly disappear in the Taklamakan. Local groundwater in the Taklamakan is chemically and hydrologically related to rivers with headwaters in the mountains (Zhu and Yang, 2007).

The Kumutage Desert, located in eastern Xinjiang, is bordered by the Lop Nor Depression to its west and the piedmonts of the Aerjin to the south, which stretches eastward toward Dunhuang (Fig. 1c). It is the sixth biggest sand sea in China with an area of 29,000 km^2. Mean annual precipitation ranges between 10 and 30 mm. The morphology is characterized by interlaced landforms of dunes, desert pavements, wind-deflated fields, denudated hills and saline-soil plains (Zhu et al., 1980; Dong et al., 2008). A great salt plain exists in the Lop Nor Depression at the lowest part of the basin.

The Badain Jaran Desert is located in the western Alashan Plateau and is bounded by mountains (maximum elevation about 2000 m) to the south and southeast and by palaeo-lake basins (about 900 m) to the west and north (Fig. 1d). It is the third largest desert in China with an area of 49,000 km^2. Surface morphology consists primarily of sand dunes that attain average heights of 200–300 m and rise to 460 m in the southeast. No surface river flows into the desert, but there are many permanent lakes in the inter-dune depressions. Most of these lakes are saline (Yang and Williams, 2003; Yang et al., 2010) and are concentrated in the southeast part of the desert (Fig. 1b).

The Tenggeli Desert, located in the western foreland of the Helan Mountains (Fig. 1d), is the fourth largest desert in China with an area of 42,700 km^2. The landforms of this desert consist of dunes, vegetated lake beds and basement hills. About 93% of the dunes are mobile and normally 10–20 m in height. The dune fields are separated by lake basins and rock hills. The main dunes are net-shaped, with

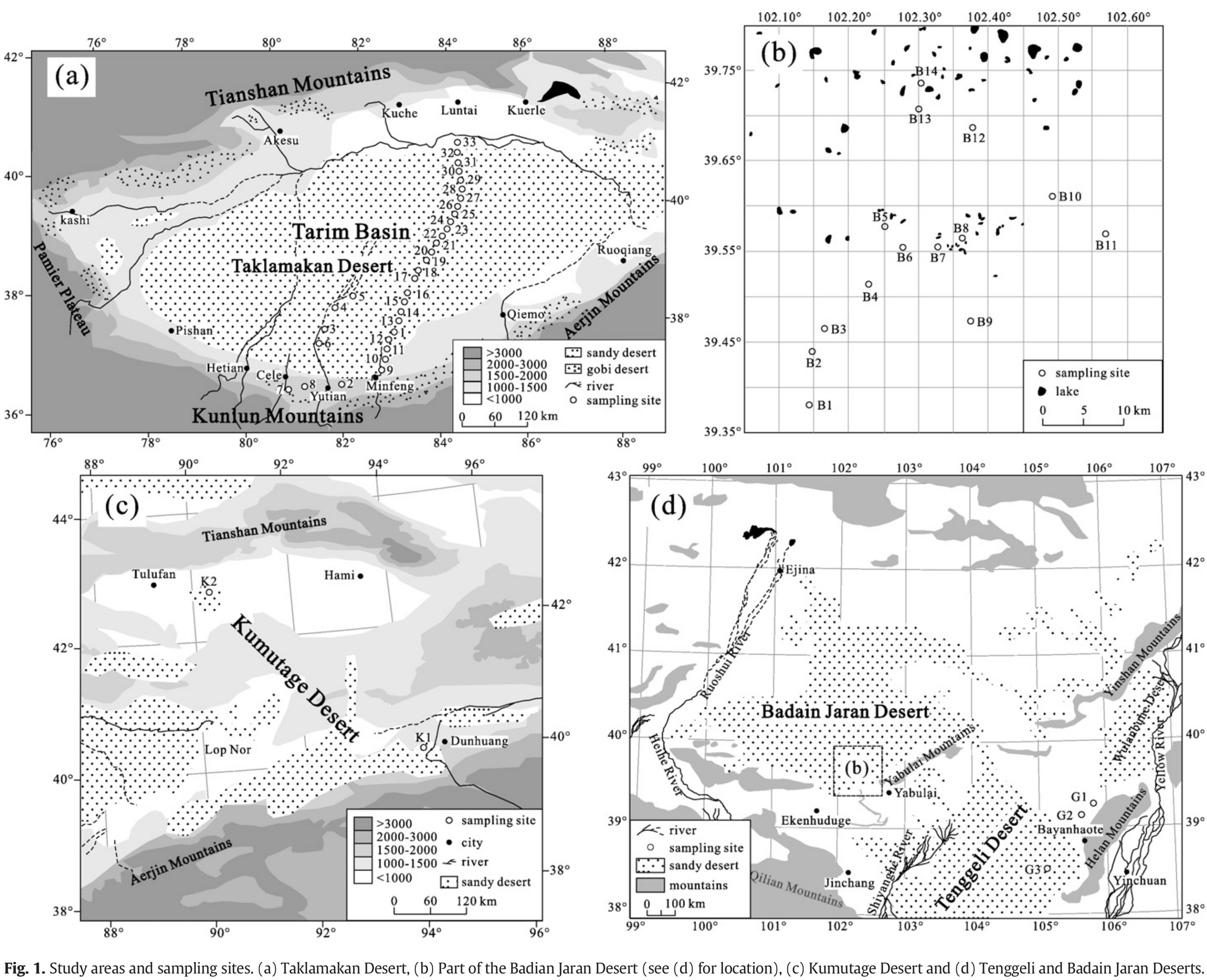

Fig. 1. Study areas and sampling sites. (a) Taklamakan Desert, (b) Part of the Badian Jaran Desert (see (d) for location), (c) Kumutage Desert and (d) Tenggeli and Badain Jaran Deserts.

dune chains on the margins. There are about 422 lake basins in the desert with various areas, most of which are dry or contain only shallow water with dense vegetation including *Ephedra* and *Artemisia* at the water margins (Zhu et al., 1980).

Samples for this study were mainly collected from the surface of active dunes, geographically located in the center and south edge of the Taklamakan (Fig. 1a), the south part of the Badain Jaran (Fig. 1b), the eastern and northern Kumutage (Fig. 1c) and the eastern Tenggeli (Fig. 1d). For the Taklamakan, Kumutage and Tenggeli deserts, samples were mainly taken from the ridges of dunes reaching a height of 20–30 m. For the Badain Jaran Desert, samples were from the ridges and the slopes of megadunes about 200–300 m in height as well as from the ridges of small dunes on the margins. In addition, sands buried under lacustrine layers and interdune playa sediments were also sampled for the Taklamakan and Badain Jaran. Aeolian sands on the Pingtan Island of southern China, characterized by subtropical humid climate and termed as "Old Red Sands", were sampled for comparison. Each dune sample consisted of 500–600 g of sand collected over a sampling area of about 10×10 cm and a depth of 0–10 cm.

2.2. Analytical methods

Fifteen grams of sediment from each sample (stripped of vegetation remains and plant fragments before analyzing) was mixed in the laboratory with 75 g deionized water to produce a water–soil solution. The solutions were left statically for 24 hours and then vibrated for 5 minutes in an ultrasonic-wave oscillator at room temperature to leach the water-soluble salt from the solid sample. After oscillation, the leachate was extracted and filtered through a PTFE membrane of syringe Millipore filter (with a pore size of 0.45 μm) to filter out the suspension of particles and macromolecular colloid in the solution.

The analytical items employed in this analysis include temperature (*T*), pH, electrical conductivity (EC), electrical potential (EP), total dissolved solid (TDS), major cations (Li^+, Na^+, NH_4^+, K^+, Mg^{2+} and Ca^{2+}) and major anions (F^-, Cl^-, NO_2^-, NO_3^-, $H_2PO_4^-$, SO_4^{2-} and $HCO_3^- + CO_3^{2-}$). All measurements were carried out at the Institute of Geology and Geophysics, Chinese Academy of Sciences. Major ionic concentrations were measured using Ion Chromatography (Dionex 600) following the manufacturer's manuals. The detection limit for major anions and cations is <0.1 mg l^{-1} and the error bar of the analytical procedures is $\pm 2\%$. The parameters including *T*, pH, EC, EP and TDS were measured with a Multi-Parameter Analyzers (Eijkelkamp 18.28), the bias of the analytical procedures is $<2\%$ for pH and EP, $<1\%$ for EC, TDS and *T*. Alkalinity was measured using Gran's method (Wetzel and Likens, 2000). The suitability of water–soil extraction ratio (Fig. 2a) and the qualities of data are confirmed using three indices based on the method proposed by Miles and Yost

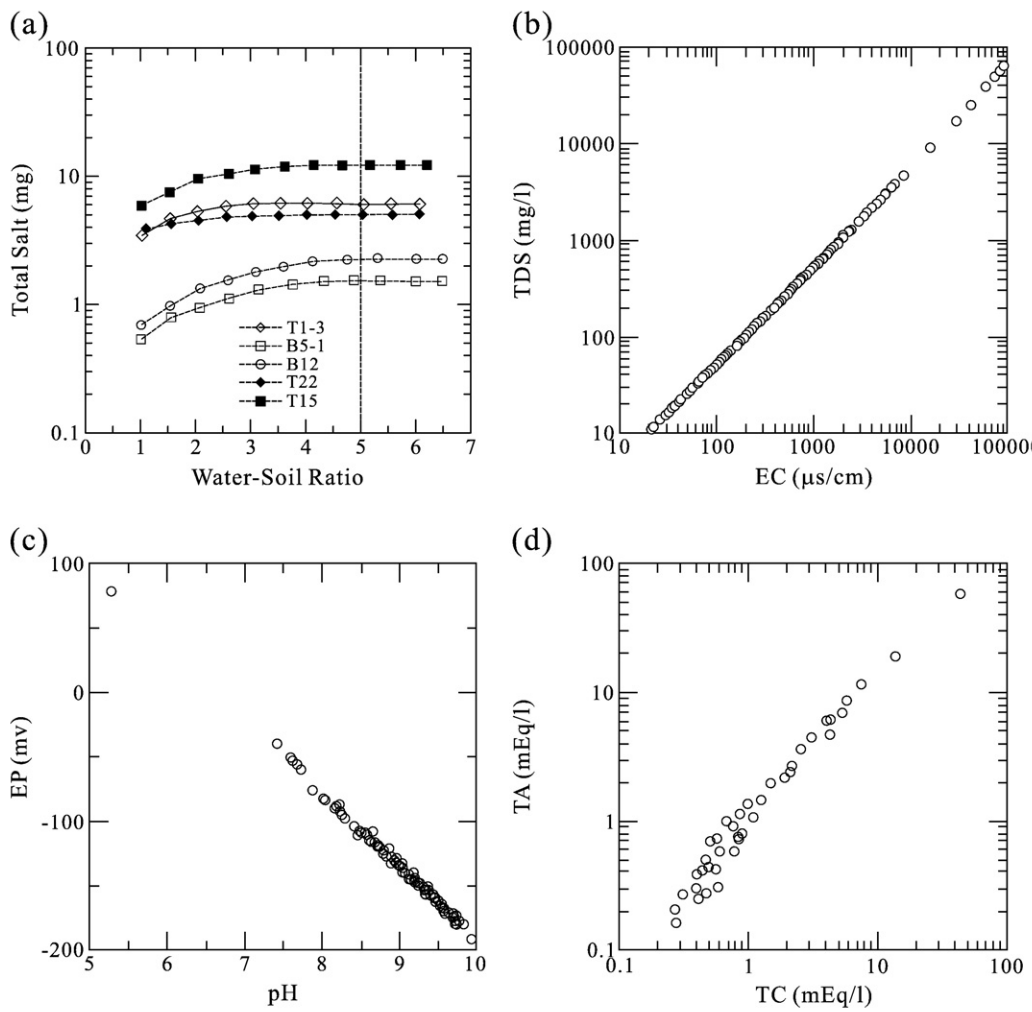

Fig. 2. Plots used for checking the correctness of the analytical methods and the quality of the data. (a) TDS value vs. the water–soil (sediment) ratio of solution of five aeolian sand samples selected randomly. The soluble salts in samples were completely dissolved into water when the water–sediment ratio reached 5:1. (b) TDS vs. EC. (c) EP vs. pH. (d) TA (total anions) vs. TC. All plots show that the data were in good quality and balanced in electric charges.

(1982) (Fig. 2b-d). Based on the TDS, the water and soil mass quantity, the total salt content to total sample mass is calculated, termed here as the “salinity” of samples. All details of measurements can be found in the on-line supplementary data (two tables) of this journal.

3. Results

3.1. Salt concentrations

To a great extent, the EC and TDS values reflect the salt concentration in the solution, while the EP and pH represent the salt compositions and soil condition. TDS of the water–soil solution of dune sand samples from the Badain Jaran Desert ranges between 11.6 and 84.0 mg l^{-1} (mean value 30.2 mg l^{-1}), while pH ranges from 8.82 to 9.42 (mean value 9.12) (Fig. 3a). The calculated salinity values are 0.05–0.42‰ (mean 0.15‰) in the sands of Badain Jaran. In the dune sand samples from the Taklamakan Desert, the TDS, pH and salinity values range between 55 and 372 mg l^{-1} (mean 155 mg l^{-1}), between 8.66 and 9.54 (mean 9.22) (Fig. 3b) and between 0.27‰ and 1.86‰ (mean 0.78‰), respectively. In the sand samples from the Tenggeli Desert, the TDS, pH and salinity values are 23.5–100 mg l^{-1} (mean 47.6 mg l^{-1}), 8.90–9.31 (mean 9.15) (Fig. 3c) and 0.12–0.50‰ (mean 0.24‰), respectively. The TDS salinity values of the Old Red Sands (O1) are similar to those of the Kumutage (K1 and K2), but its pH value is just 5.29.

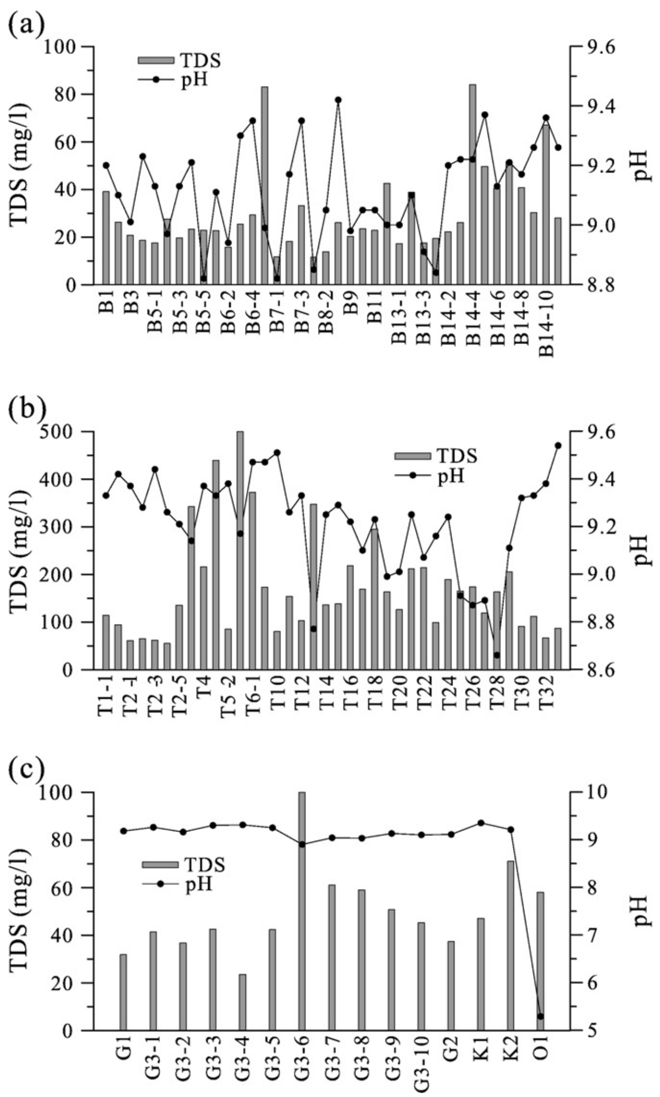

Fig. 3. TDS and pH values of the water sediments extraction (5:1). (a) Badain Jaran dune sands. (b) Taklamakan dune sands. (c) Tenggeli dune sands (sample numbers starting with G), Kumutage Desert dune sands (samples K1 and K2), and Old Red Sands in southern China (sample O1). For sampling locations see Fig. 1. To avoid confusing several samples from the same sampling site, samples are marked with an extension number such as B5-1. The samples are presented incrementally from left to right after their numbers in (a) and (b), and therefore some sample numbers are omitted due to space limitations.

3.2. Ionic compositions of the soluble salts

The major anions include Cl^- and HCO_3^-; SO_4^{2-} concentration is relatively low in all samples (Fig. 4a). The first major cation is Na^+, and the second Ca^{2+}, while the concentrations of K^+ and Mg^{2+} are low (Fig. 4b,c). The regional variations of major anions in different deserts are larger than those of the major cations. The concentrations of the carbon-bearing ions in dune-surface sand samples are positively correlated with the pH values (Fig. 4d).

The distribution curves of the major ions in different desert sands are plotted in Fig. 5. In a single desert, the ion distribution patterns are similar. According to the major ion concentrations, the mineralogy of samples can GEOMOR be classified as follows: $NaHCO_3 + NaCl + CaCO_3$ in the Badain Jaran, $NaCl + NaHCO_3$ in the Taklamakan and Kumutage and $CaCO_3 + NaHCO_3 + NaCl$ in the Tenggeli. It is clear that NaCl and $NaHCO_3$ are the most common salts in aeolian sands throughout all of the deserts studied here (Fig. 5). In contrast, the major salts are $NaHCO_3 + Na_2SO_4$ in loess and $Na_2SO_4 + NaCl + NaHCO_3$ in palaeo-soil in the Chinese Loess Plateau (Sun et al., 2006). It is apparent that while Na_2SO_4 is one of the major salts in loess-soil sequences, it infrequently occurs in desert sand. For salt chemistry and salinization, desert sands in the world can be divided into the following types: chloride, sulfate, carbonate and mixed (Petrov, 1976). The results here indicate that the soluble salt in desert sands of northern China is a mixture of sodium chloride and sodium carbonate. This is different from salts in the tropical and subtropical deserts. For instance, the Kalahari desert is dominated by the chloride-sulfate salts (Wang et al., 2009).

3.3. Salt accumulation and its spatio-temporal variations

The concentration of soluble salt in aeolian sands represents the degree of salt accumulation in its desert environment. Our data show that the total salinity of surface sands in deserts mainly ranges between 0.05‰ and 1.86‰ (mean 0.42‰), and the Taklamakan has the highest concentration of soluble salts among all sand seas studied here (Fig. 6a,b).

The pH values show a narrow range of changes in the sands of all deserts in northern China (8.6–9.4), indicating a generally similar alkaline soil condition across these deserts. An alkalinity of soil with a pH value 6.4–12.2 is mainly caused by bicarbonate (6.4–10.3) and carbonate (10.3–12.2) (Wetzel and Likens, 2000). Consequently, the alkalinities of the studied samples are mainly determined by the carbon-bearing salts, particularly bicarbonate.

The salinities and alkalinities of 15 palaeo-aeolian sands with the OSL ages 40–2 ka B.P. (Yang et al., 2006), which are buried beneath modern dunes in the Taklamakan, are quite similar to those of modern dune sand samples (Fig. 6c). The dune-surface sands, collected from the same months of different climatic years (namely, an arid 2006 and wet 2008 autumn), are quite similar to each other (Fig. 6d). Salt concentrations in dune sands are clearly lower than in the inter-dune playa sediments in each sand sea (Fig. 6e,f).

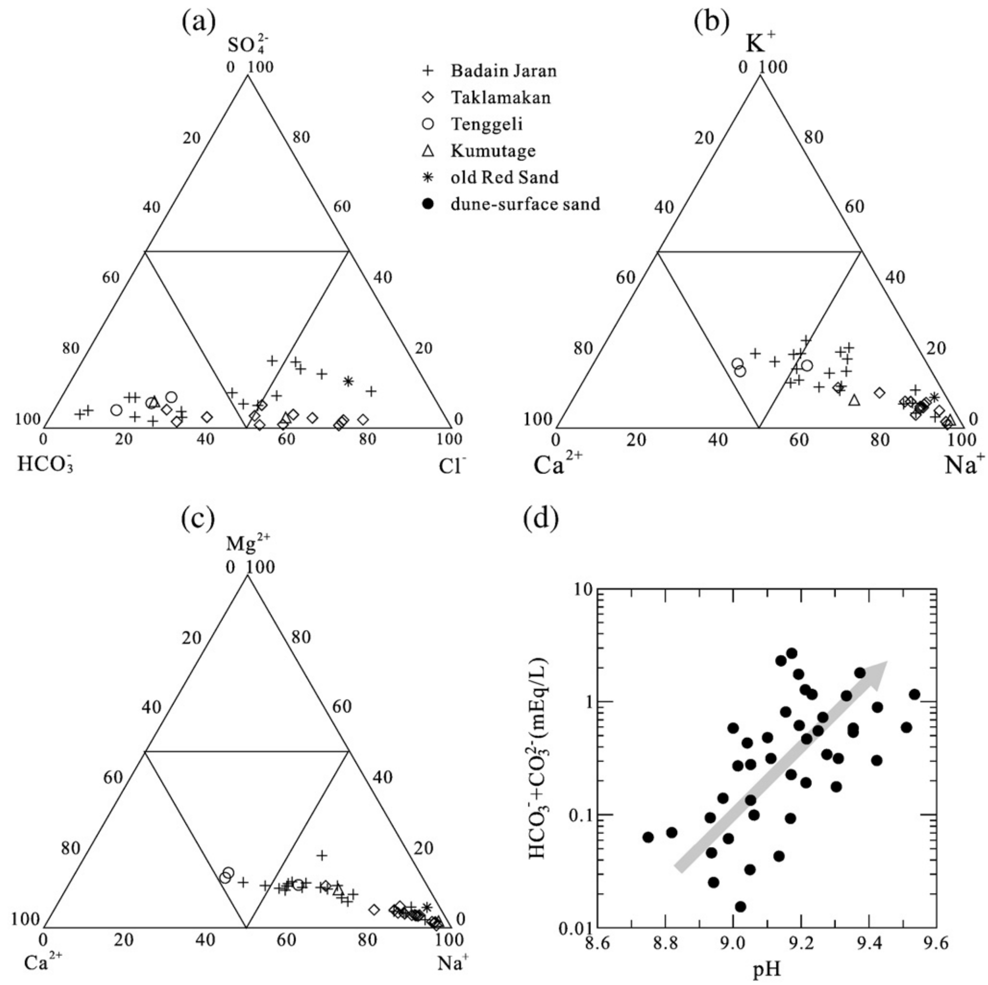

Fig. 4. Triangular plots of (a) major anions and (b and c) cations (Unit: mEq l^{-1}), and (d) carbon-bearing ions vs. pH of the soluble salts in the aeolian sand samples.

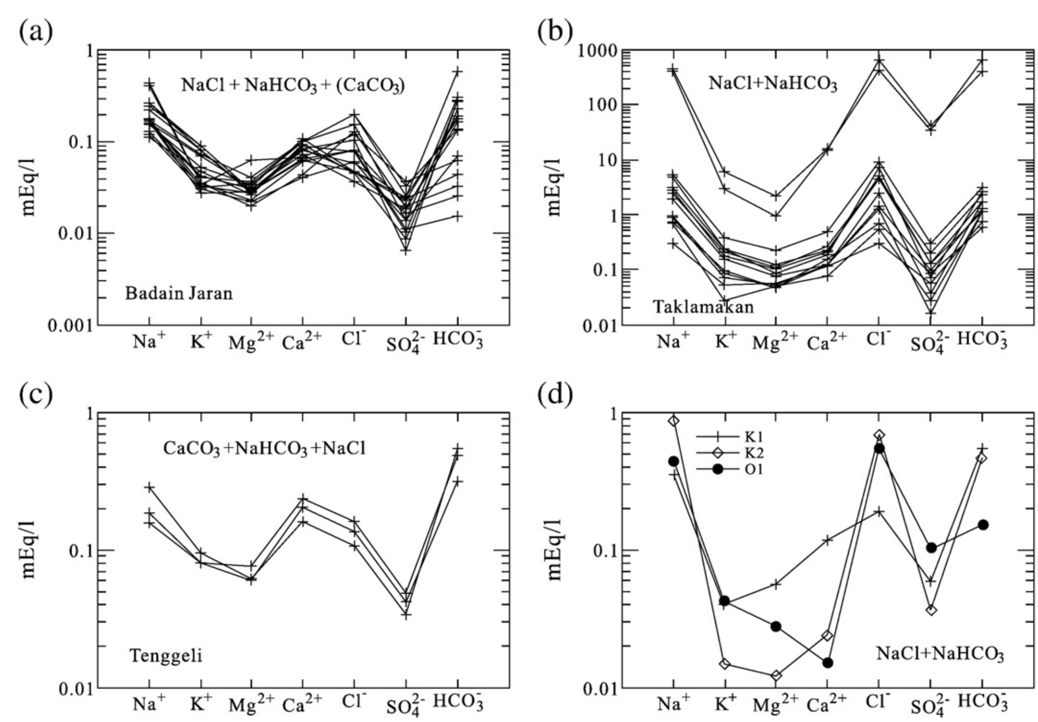

Fig. 5. Distribution patterns of the major ions of the soluble salts in the aeolian sands. (a) Badain Jaran. (b) Taklamakan. (c) Tenggeli. (d) Kumutage and Old Red Sand in southern China (O1).

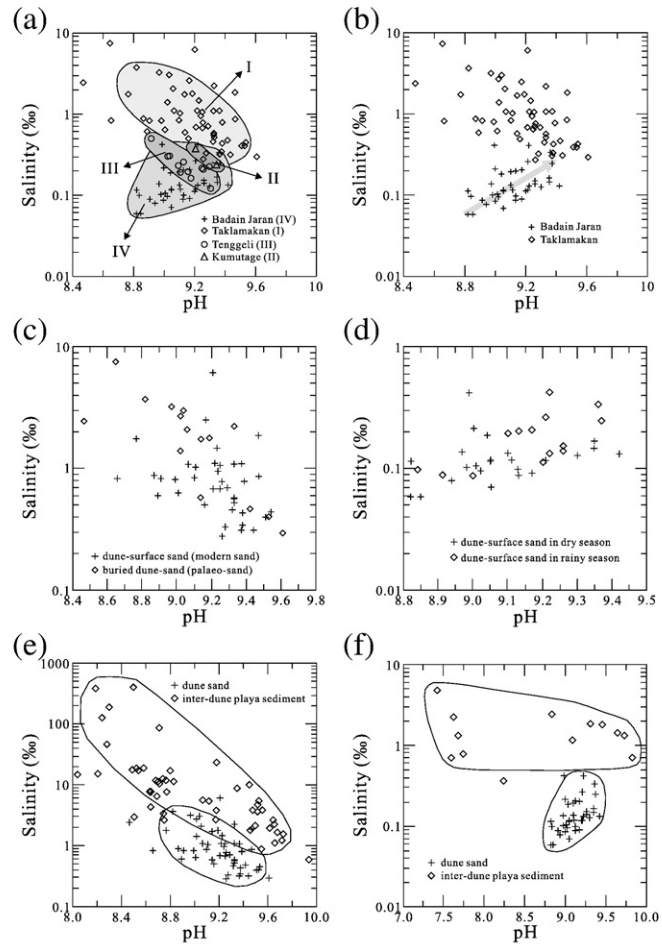

Fig. 6. Total salinities vs. pH of sediment solutions (5:1) in various samples. (a) Dune-surface sand samples only. (b) Dune-surface sand samples from the Badain Jaran and Taklamakan. (c) Dune-surface sand samples and buried-dune sand samples (palaeo-sand) in the Taklamakan. (d) Dune-surface sand samples collected in different climatic seasons in the Badain Jaran. (e) Dune-sand samples and the inter-dune playa sediments in the Taklamakan. (f) Dune-sand samples and the inter-dune playa sediments in the Badain Jaran.

4. Discussion

4.1. Parameters causing the variations of soluble salts in the sand seas

Studies have shown that salts in arid environments are influenced greatly by climate and hydrogeology (Borchert and Muir, 1964; Warren, 2006), partly by vegetation (Petrov, 1976) and by human activity (Gill, 1996; Yang, 2006; Abuduwaili et al., 2009).

4.1.1. Climatic impact

The salt concentrations in dune surface along the lines of longitude (E) and latitude (N) show two variational trends, with relatively high correlation between salinity and longitude as well as between salinity and latitude (Fig. 7). Salinities decrease gradually from west to east (Fig. 7a), whereas the mean annual precipitation increases gradually along the same direction, indicating the salt contents in northern China were probably influenced by the continentality. The decreasing salinity in desert sands from south to north (Fig. 7b) suggests the potential impact of the temperature or mean solar radiation. Climatic conditions characterized by low precipitation and high temperature lead to relatively limited leaching in the soil and high evaporation rates, so the soluble salt concentrations could be raised, as shown in Fig. 7. A similar phenomenon of soluble salt in arid soil coupled with a change in climatic gradient was also reported in regions from western Israel to the Mediterranean (Pariente, 2001).

4.1.2. Influence of grain sizes

Atmospheric circulation is a key factor influencing salt precipitation because wind affects the rate of evaporation (Borchert and Muir, 1964), and salt particles are often carried long distances by windblown aerosol and dust, giving rise to cyclic salts (Berger and Cooke, 1997; Goudie and Middleton, 2006). A significant aftereffect resulting from wind dynamics on aeolian sediments is that compositions of aeolian sediments become mineralogically and geochemically sorted according to their grain size (Liu, 1985; Zhu and Yang, 2009).

The salt concentrations of bulk samples from dune sands in the Taklamakan statistically show a strong positive correlativity with median particle diameters (*Mz*; Fig. 8a), and a negative relationship between pH and *Mz* values (Fig. 8b). The salt concentrations of different gain size fractions of sand samples in the Badain Jaran and Tenggeli Deserts also increase as their corresponding sand compositions become finer (Fig. 8c), with the opposite trend occurring between pH values and grain size (Fig. 8d). These data from different deserts demonstrate a general salt enrichment trend toward finer particles in aeolian sand. The higher salt content in the fine sands could be explained by the fact that salt grains transported by aeolian processes are generally fine sized, similar to salty dust. A so-called surface reaction mechanism was reported to have caused the increase of the percentage of evaporated Cl^- in the finer fraction of aerosol samples collected in the south coast of Finland (Pakkanen, 1996). In the soluble salt solutions, pH is dependent on the concentration of calcium carbonate. Thus, the increase of pH in the coarser fractions might be due to the potential that carbonate

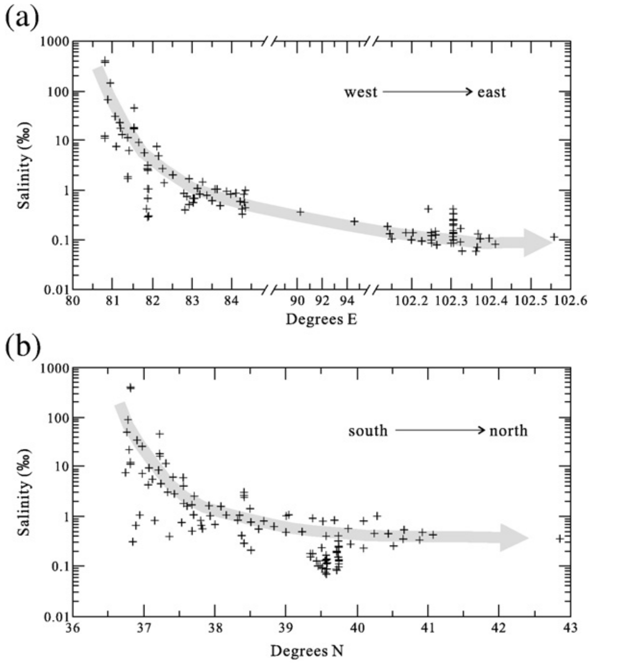

Fig. 7. Sketch map showing the relationship between the soluble salt concentrations of desert sands in China and their (a) longitude and (b) latitude degrees. The correlation coefficient reaches −0.74 between salinity and longitude values and −0.67 between salinity and latitude values.

content is relatively richer in the coarser particles, because coarser grains are often covered by secondary layers of calcium carbonate in arid environments, as is the case in the Chinese Loess Plateau (Liu, 1985).

4.1.3. Role of local hydrology

Salt deposits in the world are commonly found in past or present arid basins (Warren, 2006), and their depositional setting reflects both climatic and tectonic conditions (Smoot and Lowenstein, 1991; Warren, 2006). Geological and morphological conditions in arid areas are important for salt deposition because they determine the development of local water systems, by which all solutes are introduced (Borchert and Muir, 1964; Singer, 2007). The chemical compositions of soluble salts in aeolian sands with those of local ground and surface waters provide clues to explore the influence of local hydrology on salt accumulations (Fig. 9).

The distribution patterns of salt chemistry of dune sands in the Badain Jaran are similar to those of the region's local ground water, both of which are relative flat in shape in Fig. 9 but different from those of the region's lake waters (Fig. 9a). Fig. 9b shows that the chemical relationship between dune sand salts and natural water bodies are weak in the Taklamakan, indicating a weaker influence of local waters on sand salts. It has been reported that the chemical contributions of meteoric precipitation on local ground waters and river waters in the Takalamakan Desert are almost negligible (Zhu and Yang, 2007).

The evolutional model of soil salt controlled by ground water (Borchert and Muir, 1964) shows that from wet tropic zones to arid desert, salt types vary (in order of increasing aridity) from limonite, limestone, gypsum, glauber salt + halite and finally to more or less pure halite or sylvite. The model suggests that salt precipitates of groundwater origin are mainly carbonate, sulfate and chloride, respectively, during the early, middle and terminal stages of salt development. No mixing of asynchronous salt, such as carbonate and chloride, exists. The main compositions of soluble salt in aeolian sands studied here suggest the coexistences of chloride (NaCl) and bicarbonate ($NaHCO_3$) (Fig. 5). This discords distinctly with the rule of groundwater precipitate development, indicating that the salt in these desert sands is not, at least not directly, derived from local ground water.

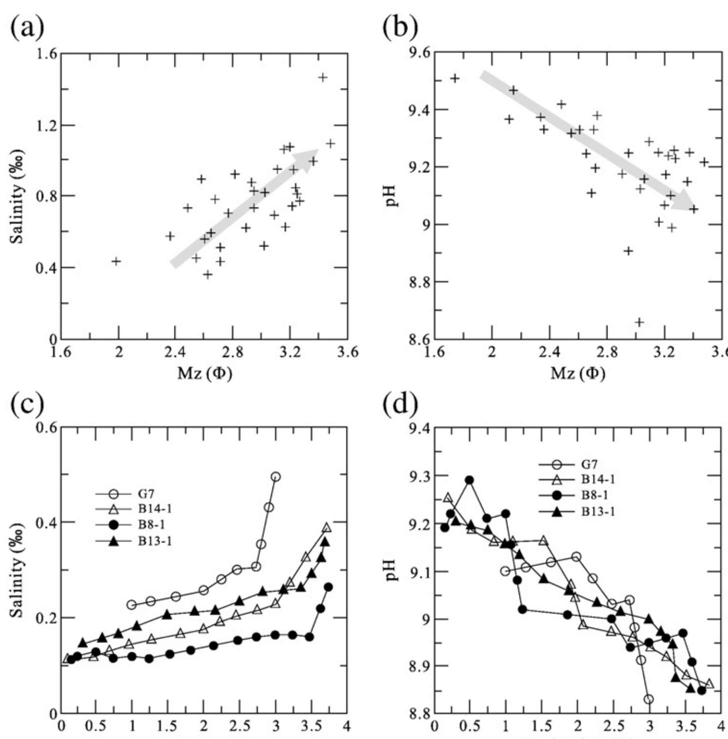

Fig. 8. Relationship between total salinities and the gain size of the sediments. (a) Salinity vs. median particle diameter (*Mz*, lower values correspond to larger diameter of the grains) of dune-surface sand samples from the Taklamakan. (b) pH vs. *Mz* of dune-surface sand samples from the Taklamakan. (c) Salinity vs. grain size composition of randomly-selected sand samples from the Badain Jaran and the Tenggeli. (d) pH vs. grain size composition of the corresponding samples shown in (c).

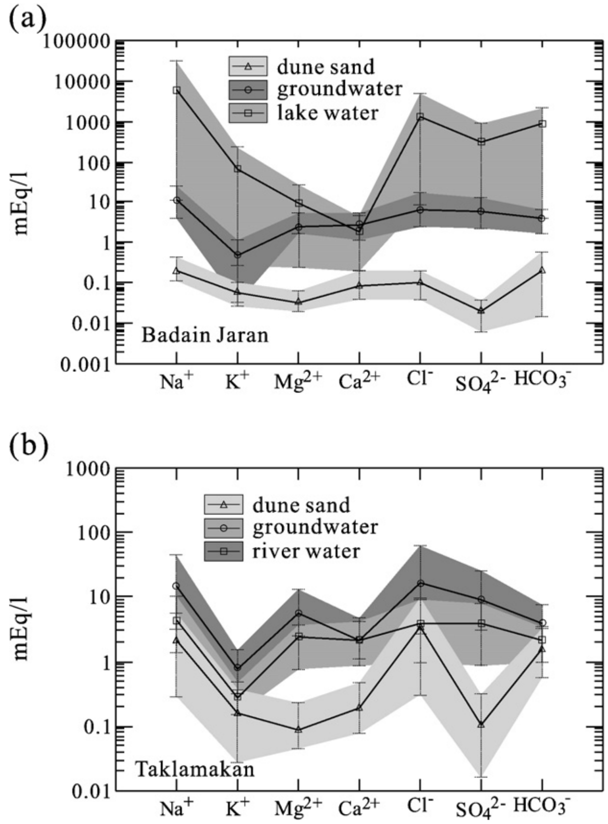

Fig. 9. Chemical compositions of the soluble salts in dune-surface sands, (a) in the local ground waters and surface waters in the Badain Jaran and (b) in the Taklamakan. The shadow area presents the variation range of the congeneric samples, and the thick solid line marks the mean value. The data of lake water and groundwater samples in the Badain Jaran are from Yang and Williams (2003), the river water and groundwater samples in the Takalamakan from Zhu and Yang (2007).

4.2. Origins of the soluble salts in the sand seas

Evaporites deposited in many desert playa depressions may be sourced from local groundwater and surface waters, or sea salt resulting from an inbreak of sea water, sea fog or sea spume (Borchert and Muir, 1964; Smoot and Lowenstein, 1991; Warren, 2006). Salts in soils may originate from one of the following three sources: (1) deposition of wind-blown salt spray, dust or anthropogenic pollutants, (2) in situ weathering of salt-containing rocks or sediments and (3) upward movement of salts with the capillary flow from a shallow salty groundwater. In deserts along the coastline, salinization may occur through intrusion and flooding by seawater (Singer, 2007).

Our analytical data show that the salt concentrations in dune surfaces are between 0.14‰ and 1.32‰. Studies have demonstrated that in a region with mean annual precipitation less than 500 mm, the export of erosible elements by eluviation processes in soil will be less significant than the preservation by evaporation–crystallization processes (Birkeland, 1999; Kraimer et al., 2005). As the mean annual precipitation in desert regions of northern China is lower than 400 mm, the effect of eluviation exerted on soluble salt in the sand seas of northern China is weaker than that of preservation. The salt concentrations of samples buried in dune subsurface layers are not higher than those of the surface samples (Fig. 6c), indicating little downward movement of these salts. Case studies about salt movement in desert soil have also shown that only 1.64% of the rainfall-leached salt can reach 1.0 m depths and that only 0.02% of the rainfall-leached salt can penetrate 2.0 m below the ground surface (Marion et al., 2008).

The sand seas of northern China are all geographically far away from any ocean and have been under terrestrial processes since at least the Cenozoic (Zhu et al., 1980). Therefore, salt contributions from present or ancient seawater can be neglected. Decomposition of vegetations may also be somewhat contributive to the salts of some desert areas (Petrov, 1976), but the plants in the sampling sites of this study are scare, so the influence of vegetation is minimal. Anthropogenic pollutants, generated by human activities, are usually inorganic ions such as NH_4^+, NO_3^-, $H_2PO_4^-$ and SO_4^{2-} and some organic anions. The contents of all samples studied here, however, have roughly equivalent numbers of cations and anions (Fig. 2d), suggesting that human impact on salt concentrations in China's sand seas is of minor importance. The degree of weathering of aeolian sand in the Taklamakan, characterized by low chemical index of alteration (*CIA*), is similar to that of the unweathered Upper Continental Crust (Zhu and Yang, 2009). This observation suggests that salt contributions originating directly from bedrock weathering is also of minor significance.

This weak correlation with the local hydrological setting and strong association with the local climatic and wind regime indicate that the soluble salts in dune sands are likely of atmospheric origin, i.e., dry and wet depositions. Case studies have also alluded to atmospheric origins (both dry and wet depositions) of soluble salts in some desert soils, such as in arid middle Asia (Amit and Yaalon, 1996) as well as in North and South American deserts (Bohlke et al., 1997).

As for atmospheric wet deposits, meteoric water contains salts that are derived from low-temperature weathering reactions between bedrock and rainwater (Smoot and Lowenstein, 1991). Chemical studies about atmospheric precipitation in Central Asia (Al-Khashman, 2009) and North China (Fujita et al., 2000; Li et al, 2007; Zhao et al., 2008) have shown chloride and carbonate are important dissolved species in terrestrial rainfall. In addition to salts related to rainfall, salt transported by atmospheric dry deposition such as aerosol and dust is another well-known global phenomenon (Goudie and Middleton, 2006). Although little data about soluble salt compositions in dust of the study areas are available, the salt-carrying capacity of dust and salt movement by dust storms are particularly important in arid regions (Goudie and Middleton, 2006). For example, the concentrations of soluble salts in dusts are as high as 1.2–3.6% in the Canaries (Logan, 1974), up to 3.1% in Negev dust (Yaalon and Ginzbourg, 1966), 4–19% in Southern Nevada and California dust samples (Reheis and Kihl, 1995) and even reach 50% in some Australian dusts (Kiefert, 1997). Salt emissions via dust from a salty playa are much higher than from any soil, reaching 14 to 27 g m^{-2} per year in Ebinur of Western Xinjiang, China (Abuduwaili et al., 2009). As salty playas around the Badain Jaran and the Taklamakan are important regions of dust sources in the world (Goudie and Middleton, 2006), we assume that the remarkable quantity of salt derived from such playas have been deposited on the dune surfaces by aeolian processes.

4.3. Relative contributions of different sources

Various studies have estimated the relative contributions of different sources on regional wet or dry depositions in arid regions (Al-Momani et al., 1995; Bohlke et al., 1997; Freydier et al., 2002; Okada and Kai, 2004; Qu et al., 2009). A key step in this process is to select a standard reference which can represent a base for the regional atmospheric setting, uninfluenced by extraordinary atmospheric events. The Waliguan weather-monitoring station (36.28°N, 100.90°E, 3810 m asl), located at Waliguan Mountain in Qinghai Province, northwestern China, is one of three base stations in China and the only one in northern China. It is also the one and only inland plateau monitoring station in the hinterland of the Euro-Asian continent among the 20 land-based Global Atmospheric Watch (GAW) base stations. It has been confirmed that the Waliguan station is minimally impacted by dust and local sources of pollution (Tang et al., 2000) and can be the representative of atmospheric "background"

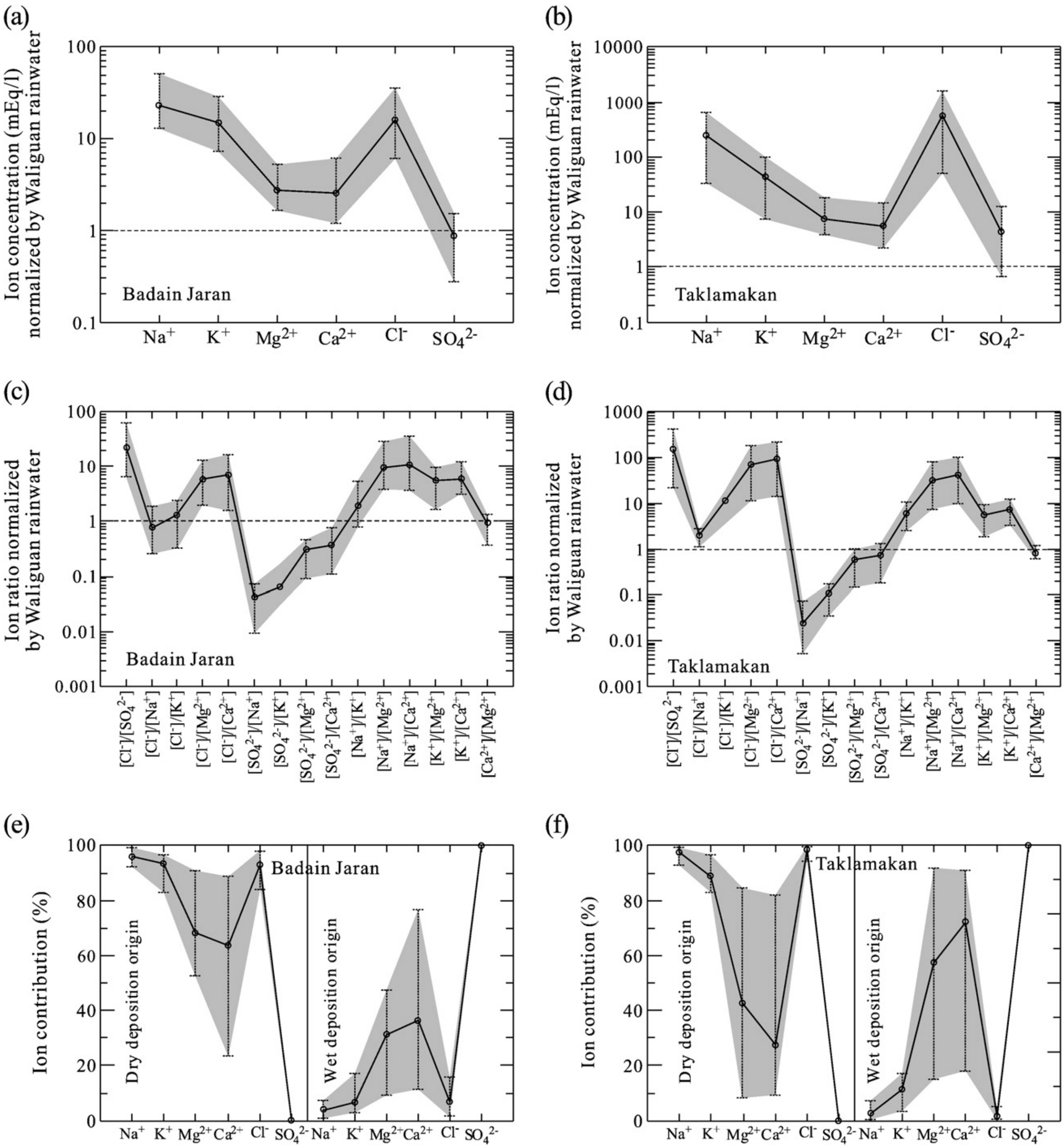

Fig. 10. Distributions of (a, b) ion concentrations and (c, d) ratios, normalized by Waliguan rainwater, of soluble salts in aeolian sands from (a, c) the Badain Jaran and (b, d) the Taklamakan, respectively, and the relative contributions of wet and dry depositions on ions in (e) the Badain Jaran and (f) the Taklamakan. The shadow area presents the variation range, and the thick solid line indicates the mean value.

conditions in northern China (Tang et al., 2000; Li et al., 2007; Zhao et al., 2008; Qu et al., 2009).

The fluctuations of the ionic distribution curves of soluble salts in aeolian sands, normalized by the mean chemistries of Waliguan rainwater (Fig. 10), indicate that the chemical compositions of soluble salt in aeolian sands are distinctly different from that of Waliguan rainwater, especially the enrichment of Cl and Na relative to other ions.

Elements derived from a special source play a key role in understanding the origin of soluble species in soil, dust and water (Negrel and Roy, 1998). They are used widely as indicators of specific sources, such as Cl in moisture-unsaturated sandy aquifer in deserts indicating atmospheric recharge for groundwater (Edmunds et al., 2006; Gates et al., 2008), Na in atmospheric wet deposition and ice core indicating a sea-salt (marine) source (Negrel and Roy, 1998; Freydier et al., 2002) and Ca and Mg (Li et al., 2007, Zhao et al., 2008) indicating terrestrial (dust) source. As the salts in the local desert water bodies are often composed of Cl or Na, we believe that these elements cannot be used directly as indicators of salt contribution from rainfall (Fig. 9). Other ions are also selectively enriched relative to the data observed in Waliguan, such as Ca and Mg (Fig. 10c,d). One can use the lowest-enriched element as a reference to estimate the enrichments of other elements and contribution from rainfall, as long as no chemical or physical loss mechanism for the element occurs in the oxidative desert environment. From Fig. 10a–d, it appears that SO_4^{2-} is a suitable choice. Based on the

Table 1
Percentages of salts in aeolian sediments deposited via atmospheric dry and wet sedimentations in the Badain Jaran and the Taklamakan.

	Ion	Badain Jaran		Taklamakan	
		Range (%)	Mean (%)	Range (%)	Mean (%)
Atmospheric precipitation (wet deposition)	Na^{+}	0.9–7.3	4.1	0.5–7.0	2.4
	K^{+}	3.2–17.2	6.5	3.5–17.5	11.3
	Mg^{2+}	9.3–47.5	31.5	15.2–99.7	57.5
	Ca^{2+}	11.1–76.7	36.5	18.2–99.8	72.2
	Cl^{-}	1.6–15.3	6.9	0.2–4.7	1.4
	SO_4^{2-}		100		100
Dry deposition (evaporites transported in dust)	Na^{+}	92.6–99.1	95.9	93.0–99.5	97.6
	K^{+}	82.8–96.8	93.5	82.5–96.4	88.7
	Mg^{2+}	52.5–90.7	68.5	0.3–84.8	42.5
	Ca^{2+}	23.3–88.8	63.5	0.2–81.7	27.8
	Cl^{-}	84.7–98.4	93.1	95.2–99.8	98.6
	SO_4^{2-}	/	0	/	0

Waliguan database (Tang et al., 2000) and SO_4^{2-} data in the Badain Jaran and Taklamakan sands, the contributions from different sources are calculated (Table 1, Fig. 10e,f) following the common approaches used by Li et al. (2007), Zhao et al. (2008) and Qu et al. (2009). Our calculations show that the mean percentages of Na, K and Cl, derived from dry deposition, account for 95.9%, 93.5% and 93.1% in the Badain Jaran and 97.6%, 88.7% and 98.6% in the Taklamakan, respectively (Table 1). Ca and Mg derived from dry deposition in sand are much lower than those of Na, K and Cl, reaching to 68.5% and 63.5% in the Badain Jaran and 42.5% and 27.8% in the Taklamakan, respectively. This demonstrates that the salts transported by dry deposition are much higher in concentration than those transferred via wet deposition in these two sand seas. The percentage of dry deposition in soluble salts in the Taklamakan is higher than that of the Badain Jaran. This hypothesis is consistent with the regional difference of aridity, since the Taklamakan is more arid than the Badain Jaran.

5. Conclusions

The total salinities of aeolian sands in the sand seas of northern China, inferred from soluble salts, range between 0.14‰ and 1.32‰, and NaCl and $NaHCO_3$ are the most common salts in the four deserts investigated in this study. The salt concentration varies across these sand seas depending on regional climate characteristics (i.e., the warmer and drier the climate is, the higher the salt concentration will be). An atmospheric origin is proposed for the salts in these sand seas, which is related with local and regional atmospheric precipitation and dust fall processes. By comparing records from the national weather monitoring station Waliguan, relative contributions of atmospheric wet and dry depositions of unique chemical ions were calculated. Our data show that the origins of each ion need to be individually examined, as they frequently change from site to site. The mean percentages of Na and Cl, derived from dry depositions, reach to over 90% in both the Badain Jaran and the Taklamakan deserts. In contrast, among the total soluble Ca, only ca. 68% in the Badain Jaran and ca. 40% in the Taklamakan are from processes of dry deposition.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at 10.1016/j.geomorph.2010.07.001.

References

Abuduwaili, J., Gabchenko, M.V., Xu, J., 2009. Eolian transport of salts—A case study in the area of Lake Abinur (Xinjiang, Northwest China). J. Arid Environ. 72, 1843–1852.
Al-Khashman, O.A., 2009. Chemical characteristics of rainwater collected at a western site of Jordan. Atmos. Res. 91, 53–61.
Al-Momani, I.F., Tuncel, S., Eler, U., Ortel, E., Sirin, G., Tuncel, G., 1995. Major ion composition of wet and dry deposition in the eastern Mediterranean basin. Sci. Total Environ. 164, 75–85.
Amit, R., Yaalon, D.H., 1996. The micromorphology of gypsum and halite in reg soils—the Negev Desert, Israel. Earth Surf. Process. Land. 21, 1127–1143.
Berger, I.A., Cooke, R.U., 1997. The origin and distribution of salts on alluvial fans in the Atacama Desert, northern Chile. Earth Surf. Process. Land. 22, 581–600.
Birkeland, P.W., 1999. Soils and Geomorphology. Oxford University Press, New York.
Bohlke, J.K., Ericksen, G.E., Revesz, K., 1997. Stable isotope evidence for an atmospheric origin of desert nitrate deposits in northern Chile and southern California, U.S.A. Chem. Geol. 136, 135–152.
Borchert, H., Muir, R.O., 1964. Salt Deposits: The Origin, Matamorphism and Deformation of Evaporites. D. Van Nostrand Company, London.
Dong, Z., Qu, J., Wang, X., Qian, G., Luo, W., Wei, Z., 2008. Pseudo-feathery dunes in the Kumtagh Desert. Geomorphology 100, 328–334.
Dragovich, D., Dominis, M., 2008. Dryland salinity and rainfall patterns: a preliminary investigation in central west New South Wales (Australia). Land Degrad. Dev. 19, 564–573.
Eckardt, F.D., Spiro, B., 1999. The origin of sulphur in gypsum and dissolved sulphate in the Central Namib Desert, Namibia. Sed. Geol. 123, 255–273.
Edmunds, W.M., Ma, J., Aeschbach-Hertig, W., Kipfer, R., Darbyshire, D.P.F., 2006. Groundwater recharge history and hydrogeochemical evolution in the Minqin Basin, North West China. Appl. Geochem. 21, 2148–2170.
Felix-Henningsen, P., Rummel, B., Blume, H.P., 2008. Soil processes and salt dynamics in dune soils. In: Breckle, S.W., Yair, A., Veste, M. (Eds.), Arid Dune Ecosystems: the Nizzana Sands in the Negev Desert. Springer, Berlin, pp. 225–238.
Freydier, R., Dupre, B., Dandurand, J., Fortune, J., Sigha-Nkamdjou, L., 2002. Trace elements and major species in precipitation at African stations: concentrations and sources. Bulletin Society Geology France 173, 129–146.
Fujita, S., Takahashi, A., Weng, J., Huang, L., Kim, H., Li, C., Huang, T.C., Jeng, F., 2000. Precipitation chemistry in East Asia. Atmos. Environ. 34, 525–537.
Gates, J.B., Edmunds, W.M., Ma, J., Scanlon, B.R., 2008. Estimating groundwater recharge in a cold desert environment in northern China using chloride. Hydrogeol. J. 16, 893–910.
Gill, T.E., 1996. Eolian sediments generated by anthropogenic disturbance of playas: human impacts on the geomorphic system and geomorphic impacts on the human system. Geomorphology 17, 207–228.
Goudie, A.S., Middleton, N.J., 2006. Desert Dust in the Global System. Springer, Berlin.
Goudie, A.S., Viles, H.A., 1997. Salt Weathering Hazards. John Wiley, Chichester.
Guo, Z., Fedoroff, N., 1992. A study on the paleoclimatic implication of the saline-alkali paleosols in Xifeng and Xi'an Loess Sections. Quaternary Sciences 2, 107–117 (in Chinese with English abstract).
Hay, W.W., Migdisov, A., Balukhovsky, A.N., Wold, C.N., Flogel, S., Soding, E., 2006. Evaporites and the salinity of the ocean during the Phanerozoic: implications for climate, ocean circulation and life. Palaeogeogr. Palaeoclimatol. Palaeoecol. 240, 3–46.
Jin, H., Li, B., 1992. Discussion on the analytical results of calcium carbonates and soluble salt in Pulu statigraphic profile in Xinjiang. Journal of Desert Research 12 (4), 29–33 (in Chinese with English abstract).
Kiefert, L., 1997. Characteristics of wind transported dust in Eastern Australia. Ph.D. thesis, Griffith University, Griffith.
Kraimer, R.A., Monger, H.C., Steiner, R.L., 2005. Mineralogical distinctions of carbonates in desert soils. Soil Sci. Soc. Am. J. 69, 1773–1781.
Krijgsman, W., Fortuin, A.R., Hilgen, F.J., Sierro, F.J., 2001. Astrochronology for the Messinian Sorbas basin (SE Spain) and orbital (precessional) forcing for evaporite cyclicity. Sed. Geol. 140, 43–60.
Li, R., Qiao, J., Qiu, W., Zai, Q., Li, Y., 2000. Soluble salt deposit in the Nihewan beds and its environmental significance. Science in China Series D 43, 464–479.
Li, C., Kang, S., Zhang, Q., Kaspari, S., 2007. Major ionic composition of precipitation in the Nam Co region, Central Tibetan Plateau. Atmos. Res. 85, 351–360.
Liu, T., 1985. Loess and Environment. China Ocean Press, Beijing.
Liu, X., Dong, H., Rech, J.A., Matsumoto, R., Yang, B., Wang, Y., 2008. Evolution of Chaka Salt Lake in NW China in response to climatic change during the Latest Pleistocene-Holocene. Quatern. Sci. Rev. 27, 867–879.
Logan, J., 1974. African dusts as a source of solutes in Gran Canaria ground waters. Geological Society of America 6 (7), 849 Abstracts with Programs.
Marion, G.M., Verberg, P.S.J., McDonald, E.V., Arnone, J.A., 2008. Modeling salt movement through a Mojave Desert soil. J. Arid Environ. 72, 1012–1033.
Miles, L.M., Yost, K.L., 1982. Quality analysis of USGS precipitation chemistry data for New York. Atmos. Environ. 18, 2889–2898.
Negrel, P., Roy, S., 1998. Chemistry of rainwater in the Massif Central (France): a strontium isotope and major element study. Appl. Geochem. 13, 941–952.
Okada, K., Kai, K., 2004. Atmospheric mineral particles collected at Qira in the Taklamakan Desert, China. Atmos. Environ. 38, 6927–6935.

Pakkanen, T.A., 1996. Study of formation of coarse particle nitrate aerosol. Atmos. Environ. 30, 2475–2482.
Pariente, S., 2001. Soluble salts dynamics in the soil under different climatic conditions. Catena 43, 307–321.
Peck, A.J., Hatton, T., 2003. Salinity and the discharge of salts from catchments in Australia. J. Hydrol. 272, 191–202.
Petrov, M.P., 1976. Deserts of the World. John Wiley & Sons, New York.
Qu, W., Zhang, X., Arimoto, R., Wang, Y., Wang, D., Sheng, L., Fu, G., 2009. Aerosol background at two remote CAWNET sites in western China. Sci. Total Environ. 407, 3518–3529.
Reheis, M.C., Kihl, R., 1995. Dust deposition in southern Nevada and California, 1984–1989: relatins to climate, source area and source lithology. J. Geophys. Res. 100 (D5), 8893–8918.
Singer, A., 2007. Introduction on arid zone soil: salt accumulation and distribution—saline soils. In: Han, F.X. (Ed.), Biogeochemistry of Trace Elements in Arid Environments. Springer, Dordrecht, pp. 3–44.
Sinha, R., Raymahashay, B.C., 2004. Evaporite mineralogy and geochemical evolution of the Sambhar Salt Lake, Rajasthan, India. Sed. Geol. 166, 59–71.
Smettan, U., Blume, H.P., 1987. Salts in sandy desert soils in South-western Egypt. Catena 14, 333–343.
Smith, M., Compton, J.S., 2004. Origin and evolution of major salts in the Darling pans, Western Cape, South Africa. Appl. Geochem. 19, 645–664.
Smoot, J.P., Lowenstein, T.K., 1991. Depositional environments of non-marine evaporites. In: Melvin, J.L. (Ed.), Evaporites, Petroleum and Mineral Resources. Elsevier, Amsterdam, pp. 189–347.
Stone, R., 2008. Have desert researchers discovered a hidden loop in the carbon cycle? Science 320, 1409–1410.
Sun, B., Guo, Z., Yin, Q., Hao, Q., 2006. Soluble salts in a Quaternary loess-soil sequence near Xining and their environmental implications. Quaternary Sciences 26, 649–656 (in Chinese with English abstract).
Sun, J., Zhang, L., Deng, C., Zhu, R., 2008. Evidence for enhanced aridity in the Tarim Basin of China since 5.3 Ma. Quatern. Sci. Rev. 27, 1012–1023.
Tang, J., Xue, H., Ding, X., Cheng, H., Xu, X., Zhang, X., Ji, J., 2000. The preliminary study on chemical characteristics of precipitation at Mt. Waliguan. Acta Scientiae Circumstantiae 20, 420–425 (in Chinese with English abstract).
Wang, L., D'Odorico, P., Okin, G., Macko, S., 2009. Isotope composition and anion chemistry of soil profiles along the Kalahari Transect. J. Arid Environ. 73, 480–486.
Warren, J.K., 2006. Evaporites: Sediments, Resources and Hydrocarbons. Springer, Berlin.
Wetzel, R.G., Likens, G.E., 2000. Limnological Analyses3rd ed. Springer, New York.
Yaalon, D.H., Ginzbourg, D., 1966. Sedimentary characteristics and climatic analysis of easterly dust storms in the Negev (Israel). Sedimentology 6, 315–322.
Yang, X., 2006. Chemistry and late Quaternary evolution of ground and surface waters in the sea of Yabulai Mountains, western Inner Mongolia, China. Catena 66, 135–144.
Yang, X., Williams, M.A.J., 2003. The ion chemistry of lakes and late Holocene desiccation in the Badain Jaran Desert, Inner Mongolia, China. Catena 51, 45–60.
Yang, X., Rost, K.T., Lehmkuhl, F., Zhu, Z., Dodson, J., 2004. The evolution of dry lands in northern China and in the Republic of Mongolia since the Last Glacial Maximum. Quatern. Int. 118–119, 69–85.
Yang, X., Preusser, F., Radtke, U., 2006. Late Quaternary environmental changes in the Taklamakan Desert, western China, inferred from OSL-dated lacustrine and aeolian deposits. Quatern. Sci. Rev. 25, 923–932.
Yang, X., Zhang, F., Fu, X., Wang, X., 2008. Oxygen isotopic compositions of quartz in the sand seas and sandy lands of northern China and their implications for understanding the provenances of aeolian sands. Geomorphology 102, 278–285.
Yang, X., Ma, N., Dong, J., Zhu, B., Xu, B., Ma, Z., Liu, J., 2010. Recharge to the inter-dune lakes and Holocene climatic changes in the Badain Jaran Desert, western China. Quatern. Res. 73, 10–19.
Zhao, Z., Tian, L., Fischer, E., Li, Z., Jiao, K., 2008. 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.
Zhu, B., Yang, X., 2007. The ion chemistry of surface and ground waters in the Taklimakan Desert of Tarim Basin, western China. Chin. Sci. Bull. 52, 2123–2129.
Zhu, B., Yang, X., 2009. Chemical weathering of detrital sediments in the Taklamakan Desert, Northwestern China. Geographical Research 47, 57–70.
Zhu, Z., Wu, Z., Liu, S., Di, X., 1980. An Outline of Chinese Deserts. Science Press, Beijing. (in Chinese).