

# Chemistry of Aerosols over Chukchi Sea and Bering Sea \*

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**Abstract:** The contents of elements in aerosols sampled during the First Chinese Arctic Research Expedition (CHINARE-1) show great differences from one element to another. Na, K, Ca, Mg, Al, F, and Cl are the major components in the aerosols, whose contents are larger than 30 ng/m<sup>3</sup>. The chemical elements whose contents vary between 0.1 – 30 ng/m<sup>3</sup> are Br, Sr, Cr, Ni, and Zn. The chemical elements whose contents are close to or slightly higher than 0.1 ng/m<sup>3</sup> are Rb, Ba, Zr, Th, and Pb. The contents of As, Sb, W, Mo, Au, La, Ce, Nd, Sm, Eu, Tb, Yb, Lu, Sc, Co, Hf, Ta, and Cd are less than 0.1 ng/m<sup>3</sup>. The mass concentration data for the same element, as observed during CHINARE-1, are almost accordant, but much lower than what is observed in the China's seas or the coasts of China. The enrichment factor and electron microscopic analyses and lead isotope tracing were used to distinguish their sources. Four groups of sources can be classified as follows: anthropogenic: As, Sb, W, F, Mo, Au, Cu, Pb, Cd, V; crustal: La, Ce, Nd, Sm, Eu, Tb, Yb, Lu, Fe, Sc, Cr, Co, Ba, Zr, Hf, Ta, Cs, Mn, Th, U; oceanic: Na, K, Ca, and Mg; and mixing: Rb, Sr, Ca, and Mg.

**Key words:** marine aerosol; global change; Arctic; CHINARE-1

The feedback effects between industrial pollutants in Arctic aerosols and sea ice, seawater and biome by atmospheric transport can greatly influence the biogeochemical cycle, ocean chemical characteristics, the chemical composition of ice and snow, oceanic sedimentation, atmospheric environment and climatic evolution. Since the 1980's, an increasing trend of the concentrations of pollutants in the Arctic troposphere has been observed (Barrie, 1986). Moreover, haze and acid snow in the Arctic region have been discovered (Polissar et al., 1999; Rahn, 1981). The chemical species transported to the Arctic by atmosphere can be input into snow or sea ice by dry-wet deposition (Koerner, 1986; Barrie and Vet, 1984; Davidson et al., 1989; Joranger and Semb, 1989). Most of the pollutants in the Arctic region have been found to come from circumambient industrialized countries. These pollutants have also been found to be of long-term stay in the air when a steady and dry atmosphere exists, and then they would be transported to the high-latitude Arctic region through three approaches; long-distance transportation, oceanic current or surficial flow-off (Barrie, 1992). Therefore, the Arctic is an acceptor of anthropogenic pollutants from Eurasia, especially from North America and West Europe. Variations in atmospheric environment of the Arctic will impact the Arctic ecosystem (Antonietta Ianniello et al., 2002; Thomas et al., 1992). Many studies have been conducted on the chemical composition, source, and seasonal variation of aerosols in the troposphere and their fallout in the snow of North America, Greenland, and Scandinavian, such as IGBP, WC-

RP, ACSGE and ARCSS (Barrie, 1986; Xie et al., 1999a; Xie et al., 1999b; Sturges and Barrie, 1989; Antonietta Ianniello et al., 2002). At present time, the main objectives are to clearly understand how the atmospheric pollutants in the Arctic or subarctic regions are transferred into water, ice and snow, and how they influence the climate (Xie et al., 1999a; Sturges and Barrie, 1989; Barrie, 1986; Sun Chengquan and Zhang Haihua, 1999). In this paper, we will present the results of research on aerosols sampled during a voyage of the First Chinese National Arctic Research Expedition (CHINARE-1) from July, 1999 to September, 1999.

## 1 Collection and analysis of aerosol samples

### 1.1 Sampling and analysis

**1.1.1 Sample collection** The aerosol samples were taken on board the RV XUELONG which participated in the First Chinese Arctic Research Expedition between June and August, 1999. High-volume bulk aerosol samples were collected by drawing air through 41 Whatman filters (20 × 25 cm) at volume flow rates of about 1.2 m<sup>3</sup>/min. The sampler was controlled by wind direction sensors. To minimize contamination from the ship, the

pumps operated only when the winds were blowing at 90°. Upon the termination of sampling, the filters were folded in half, stored in polyethylene bags and placed in a freezer for analysis. In the analytical procedure, sample treatment was carried out in a clean laboratory (class-100).

**1.1.2 Instrumental neutron activation analysis (INAA)** Instrumental neutron activation analysis of aerosol samples was conducted for the atmospheric concentrations of Au, Eu, Sc, La, Ce, Nd, Sm, Tb, Ho, Tm, Yb, Lu, Co, As, Sb, Cs, Hf, Ta, Th, U, Mo, W, Cr, Rb, Zn, Ba, Ni, and Zr using the research reactor and the facilities of the China Engineering Physics Institute. One eighth of each sample filter was taken using a plastic scissor. These filter sections were placed in a previously cleaned polyethylene vial. The sample vials were placed in a plastic delivery tube and irradiated for 10–20 h at a thermal neutron flux of  $1 \times 10^{18} \text{ n cm}^{-2} \text{ s}^{-1}$ . After cooling for 4–6 d, the sample was counted for 4000 s, followed by 15-d decay, and then repeatedly counted for 2000 s. The concentrations of these trace elements were obtained in terms of the gamma-ray spectral analyses using gamma spectroscopy software (Analytical Division, Chengdu University of Technology).

**1.1.3 Atomic absorption spectrometry (AAS)** For determination of the total atmospheric concentrations of Na, K, Ca, Mg, Cu, Pb, Cd, V, Al, and Mn, a portion of each sampling filter was dissolved in de-distilled HNO<sub>3</sub> and pure HF in Teflon beakers. The digests were stored in polystyrene vials. Determinations were carried out of the concentrations by graphite-furnace atomic absorption spectrometry (Perkin Elmer 3030, with HGA500).

**1.1.4 Ion chromatography (IC)** A portion of each sampling filter was placed in a 50 ml scaling flask with 10 ml of double deionized water and let to stand at room temperature for 24 h. Before a-

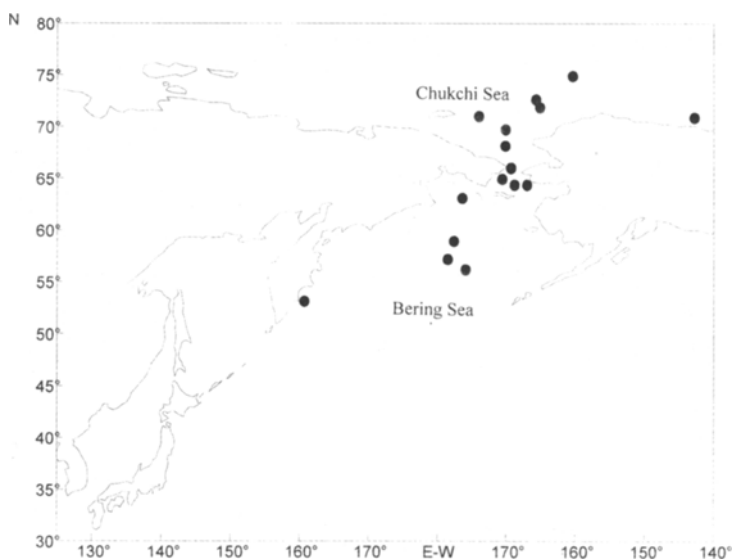


Fig. 1. The sketch map showing the distribution of aerosol sample localities along the route of Arctic expedition.

nalysis, all the extracted samples were filtered through a 0.45  $\mu\text{m}$  filter to remove particulate materials. The resulting extracts were analyzed for  $\text{F}^-$ ,  $\text{Cl}^-$ ,  $\text{NO}_3^-$ , and  $\text{SO}_4^{2-}$  on a ZIC-I ion chromatograph, equipped with an A-8-358 anion chromatographic column. The precision of each analysis was about 10%.

## 2 Results and discussion

### 2.1 The concentrations and distribution characteristics of elements in aerosols from different sea zones

The concentrations of elements in aerosols sampled during CHINARE-1 are listed in Table 1. In order to make a comparative study, the analytical results from the Chinese seas ( $120^\circ - 129^\circ\text{E}$ ,  $28^\circ - 36^\circ\text{N}$ ) (Yang Shaojun et al., 1994) and inlands (clean areas of North China) (Dong Jinquan and Yang Shaojun, 1998) and Alert, Canada ( $82.5^\circ\text{N}$ ,  $61.25^\circ\text{W}$ ), are also listed in Table 1 (Xie et al., 1999a; Xie et al., 1999b). Owing to the difference in geochemical characteristics and source of elements, their concentrations in aerosols sampled during CHINARE-1 vary greatly. Na, K, Mg, Al, F, and Cl are the main elements in aerosols with the concentrations larger than  $30 \text{ ng/m}^3$ ; the chemical elements with the concentrations varying between  $0.1 - 30 \text{ ng/m}^3$  are Br, Sr, Cr, Ni, and Zn; the chemical elements with the concentrations close to  $0.1 \text{ ng/m}^3$  are Rb, Ba, Zr, Th, and Pb. The concentrations of As, Sb, W, Mo, Au, La, Ce, Nd, Sm, Eu, Tb, Yb, Lu, Sc, Co, Hf, Ta, and Cd are less than  $0.1 \text{ ng/m}^3$ . The concentrations of the same element in aerosols taken from different sea zones are basically constant, showing the mass concentrations of marine aerosols are nearly uniform in different sea zones, but greatly lower than those of the Chinese seas and inlands. The concentrations of some elements are more than 10 – 100 orders of magnitude lower.

### 2.2 The source of elements in Arctic aerosols

Arctic aerosols are characterized by multi-source chemical composition. The chemical composition of the Arctic aerosols cannot only reflect the status of pollution in the Arctic atmospheric environment, but also reflect how much it would influence the Arctic ecosystem. In this paper, the enrichment factor method and electron microscopy were used to determine the possible origin of chemical components, in combination with the characteristic ratios of Mg/Na, K/Na, Cl/Na, Ca/Na, Th/U, Rb/Sr, Sr/Ba, Fe/Sc, La/Sm, Sm/Nd, and Eu/Sm.

In research on the pollution of atmospheric environment, the enrichment factor method is one of the common methods to differentiate the possible sources of chemical components in atmospheric fall-out materials. The enrichment factor can be calculated as follows:

$$EF_i = (X_i/X_r)_{\text{air}} / (X_i/X_r)_{\text{sou}} \quad (1)$$

where  $EF_i$  is the enrichment factor of element  $i$ ,  $r$  is the reference element,  $(X_i/X_r)_{\text{air}}$  is the concentration ratio of element  $i$  over element  $r$  in aerosols, and  $(X_i/X_r)_{\text{sou}}$  is the abundance ratio of element  $i$  over  $r$  in source materials. If  $EF$  is nearly equal to 1, it can be considered that the source of element  $r$  is the major source of element  $i$ ; if  $EF \gg 1$ , it can be considered that element  $i$  has another source, because, relative to element  $r$ , element  $i$  is greatly enriched. Na is chosen as the reference element of oceanic source, and Al as the reference element of crustal source. The results of calculation of enrichment factors for some elements are shown in Figs. 2 and 3.

**Table 1. The average chemical composition of trace elements in aerosols over Chukchi Sea and Bering Sea ( $\text{ng}/\text{m}^3$ )**

Element	Chukchi Sea	Bering Sea	Alert, Arctic	Terrestrial aerosol	Offshore waters of China
As	0.018	0.026	0.130	1.49	8.7
Br	1.991	1.416	2.600	3.82	21
Sb	0.057	0.206	0.025	-	1.1
W	0.088	0.036	-	0.340	-
Mo	0.076	0.090	-	-	-
Au	0.009	0.005	-	-	-
La	0.035	0.009	0.030	0.32	1.2
Ce	0.023	0.015	-	1.07	2.6
Nd	0.074	0.045	-	-	-
Sm	0.019	0.011	0.008	0.059	0.20
Eu	0.005	0.006	-	0.051	0.046
Tb	0.005	0.007	-	-	0.037
Yb	0.008	0.032	-	-	0.076
Lu	0.002	0.003	-	0.005	0.015
Sr	1.862	1.978	-	-	-
Fe	15.322	6.555	-	113	1300
Sc	0.004	0.003	0.020	0.05	0.36
Cr	0.834	0.574	-	-	3.2
Co	0.065	0.080	-	0.38	0.55
Ni	1.768	2.686	-	-	-
Zn	3.073	1.066	2.300	35	42
Rb	0.217	0.343	-	-	4.9
Cs	0.023	0.035	-	0.35	0.41
Ba	1.690	2.609	-	109	27
Zr	1.156	0.960	-	-	-
Hf	0.007	0.003	-	-	0.12
Ta	0.015	0.009	-	-	0.040
Th	0.111	0.112	-	0.33	0.42
U	0.165	0.178	-	0.45	0.21
F	48	76	-	-	-
Cl	1383	1585	63	-	-
Cu	3.234	1.635	-	-	-
Pb	0.687	0.395	0.6	-	-
Cd	0.088	0.075	-	-	-
V	19.017	4.860	0.28	-	-
K	1075	253	7.300	570	1400
Na	1151	650	100.00	102	2500
Ca	72	40	70	355	1200
Mg	130	75	-	-	-
Al	153.659	92.808	65	-	-
Mn	3.234	1.650	0.75	-	-

From the enrichment factor diagram of elements in Arctic aerosols relative to Na, it can be seen that (1) the elements in the Chukchi Sea, whose average enrichment factor varies between 0.5 and 10, are Br, Rb, Sr, Cl, K, Na, Ca, Mg; and those with enrichment factor >10 are As, Sb, W, Mo, Au, La, Ce, Nd, Sm, Eu, Yb, Lu, Fe, Sc, Cr, Co, Ni, Zn, Rb, Cs, Ba, Th, U, F,

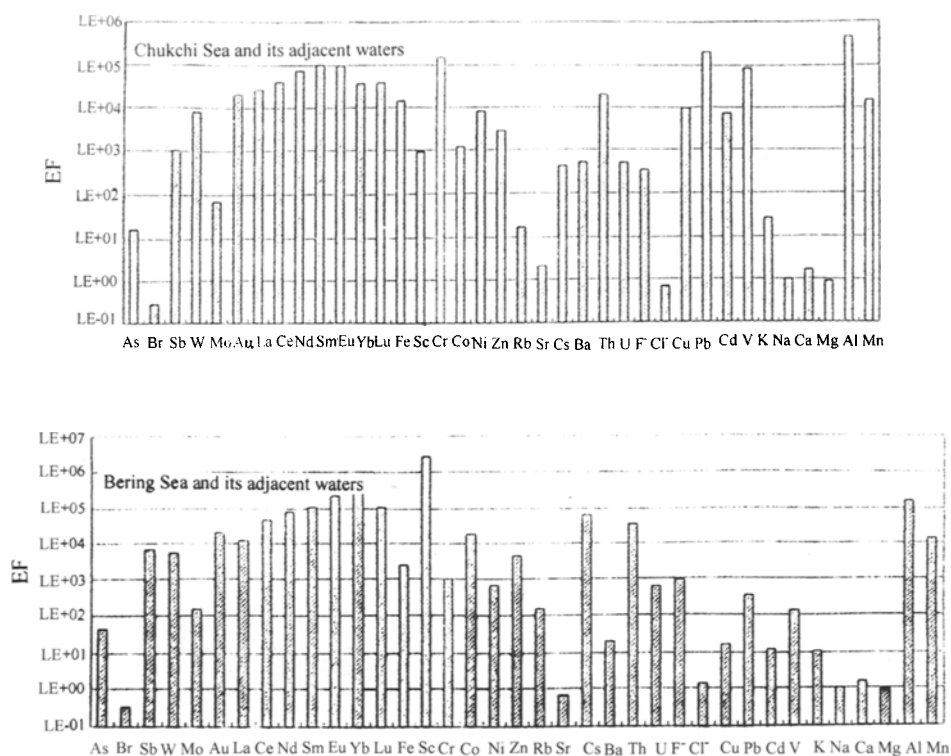


Fig. 2. Enrichment factor diagram of Na in atmospheric aerosols sampled along the route of Arctic expedition.

Cu, Pb, Cd, V, Al, and Mn; (2) the elements in the Bering Sea with enrichment factor varying between 0.5 and 10 are Br, Sr, Cl, K, Na, Ca, Mg; the elements with enrichment factor  $>10$  are As, Sb, W, Mo, Au, La, Ce, Nd, Sm, Eu, Yb, Lu, Fe, Sc, Cr, Co, Ni, Zn, Rb, Cs, Ba, Th, U, F, Cu, Pb, Cd, V, Al, and Mn. The source of elements with the enrichment factor close to 1 is similar to that of reference elements. The source of elements with the enrichment factor  $>10$  can not be explained from reference elements. The results of calculation above show that the enrichment factors of K, Na, Ca, Mg, Br, Rb, and Sr vary between 0.5 and 10, suggesting that these elements come mainly from seawater. The enrichment factors of As, Sb, W, Mo, Au, La, Ce, Nd, Sm, Eu, Yb, Lu, Fe, Sc, Cr, Co, Ni, Zn, Rb, Cs, Ba, Th, U, F, Cu, Pb, Cd, V, Al, and Mn are very large ( $>10$ ), showing that these elements do not come from seawater, but possibly from crust and industrial pollutants.

From the enrichment factor diagram of elements in Arctic aerosols relative to Al, it can be seen that (1) the elements in the Chukchi Sea with the average enrichment factor varying between 0.5 and 1 are La, Ce, Nd, Sm, Eu, Tb, Yb, W, Sr, Fe, Sc, Cr, Co, Rb, Ba, Zr, Hf, Ta, Th, Ca, Mg, Al, and Mn; the elements with the average enrichment factor  $>1$  are As, Br, Sb, W, Mo, Au, Ni, Zn, Cs, U, F, Cl, Cu, Pb, Cd, V, K, and Na; (2) the elements in the Bering Sea with the average enrichment factor  $<10$  are La, Ce, Nd, Sm, Eu, Tb, Yb, Lu, Sr, Sc, Cr, Co, Rb, Ba, Zr, Hf, Ta, Ca, Mg, Al, and Mn; the elements with the average enrichment factor  $>10$  are As, Br, Sb, W, Mo, Au, Ni, Cs, U, F, Cl, Cu, Pb, Cd, V, K, and Na. For the elements La, Ce, Nd, Sm, Eu, Tb, Yb, Lu, Sr, Sc, Cr, Co, Rb, Ba, Zr, Hf, Ta, Ca, Mg, Al, and

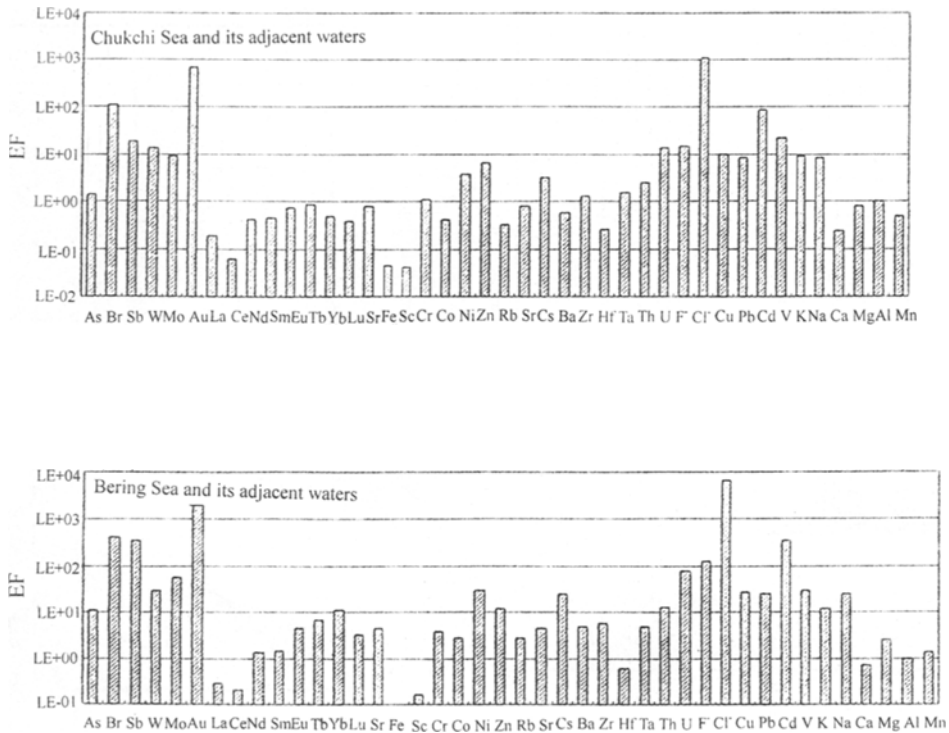


Fig. 3. Enrichment factor diagram of Al in atmospheric aerosols sampled along the route of Arctic expedition.

Mn, their average enrichment factor is less than 10, showing that these elements possibly come from the crust. For the elements As, Br, Sb, W, Mo, Au, Ni, Cs, U, F, Cl, Cu, Pb, Cd, V, K, and Na, their average enrichment factor is generally larger than 10, showing that these elements do not come dominantly from the crust.

To sum up, the results of calculation of enrichment factors relative to Na and Al show that the enrichment factor of K, Cl, Ca, Mg, and Br is close to that of Na. The major components of Arctic aerosols are Cl, Na, Mg, Ca, and K (Table 1), the same as those of seawater. Also the concentration ratios of Mg/Na, K/Na, Cl/Na, and Ca/Na are close to those of seawater, suggesting these elements would come principally from ocean. The enrichment factor of the element Br relative to Na is less than 1. It can be explained that under the action of ultraviolet rays, Br in aerosol particles can be oxidized to Br molecule, and then changed into gaseous state. Then the enrichment factor of Br in sea salt particles should be lower than 1 (Maenhaut et al., 1999). This may be the reason why the enrichment factor of Br in aerosols sampled during CHINARE-1 is less than 1. Therefore, it is suggested that the elements Cl, Na, Mg, Ca, K, and Br in Arctic aerosols come mainly from ocean. These elements can be called the "sea salt elements". This conclusion is in consistence with the results of electron microscopic observation (Electron microscopic analyses were finished using HRSTEM of JEM-2000FXII type equipped with EDX facility at the Institute of Geochemistry, Chinese Academy of Sciences.). The "sea salt elements" have been observed under SEM-EDX, with the feature that low-concentration, easily dissolved elements such as Cl, K, Ca, and Na can be seen in EDX (Figs. 4–7). These elements can be adsorbed on quartz and bauxite grains by chemical

reaction.

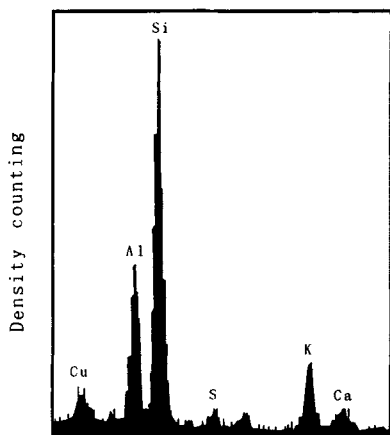


Fig. 4. EDX patterns of aluminum silicate particles.

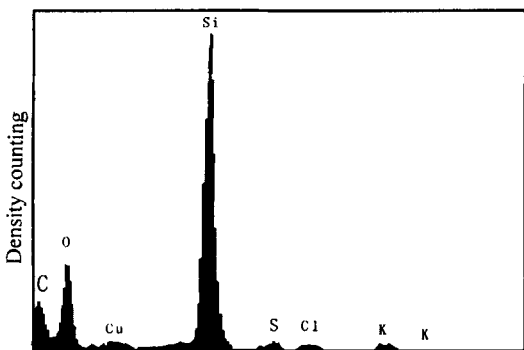


Fig. 6. EDX patterns of quartz grains.

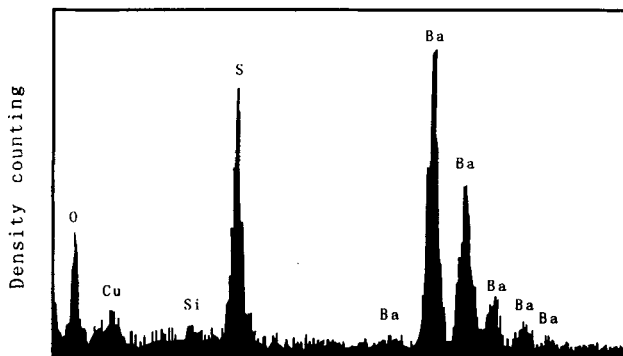


Fig. 5. DEX patterns of barium salt particles.

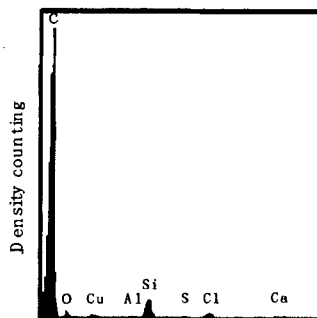


Fig. 7. DEX patterns of organic particles.

The concentrations of the elements As, Sb, W, Mo, F, Au, Cu, Pb, Cd, and V in seawater are very low, their enrichment factors are not close to those of Al and Na. But the concentrations of these elements in aerosols are high relative to crust and ocean, and their enrichment factors are larger than 10, showing that these elements come mainly from anthropogenic pollutants from inland. It is well known that, except for F, As, Sb, W, Mo, F, Au, Cu, Pb, Cd, and V are the ore elements most greatly developed and utilized by mankind. The elements As, Sb, W, Mo, F, Au, Cu, Pb, Cd, and V can be released into atmosphere and finally turn back to oceans, owing to mining and smelting activities and combustion of fossil fuels such as oil and coal. Adjacent to the Arctic are industrialized countries (Canada, America, Russia, etc.), and it is imaginable that the pollution is caused by artificial activities in these countries and the pollutants are involved in the cycle of Arctic atmosphere. In fact, the pollutants discharged by artificial activities in Eurasia and western Europe can also be retained in the dry and steady atmosphere for a long time and then transferred over long

distance to high-latitude Arctic regions (Xie et al., 1999a; Xie et al., 1999b; Sturges and Barrie, 1989; Antonietta Ianniello et al., 2002). The provenance of cyclone entering the Arctic near the Kara Sea and Laptev Sea is located in eastern Europe and Russia. The cyclone entering the Arctic via the North Pacific and the Bering Sea can carry the pollutants from western North America and the Far East of Russia (Barrie, 1986; Polissar et al., 1999; Xie et al., 1999a; Xie et al., 1999b; Sturges and Barrie, 1989; Antonietta Ianniello et al., 2002). The concentrations of the element F in Arctic aerosols are high relative to ocean and crust, showing that F in Arctic aerosols is related to the involvement of terrigenous pollutants. This conclusion is in good agreement with other studies. Wilkness, in his study of marine atmospheric aerosols, suggested that the enrichment of F would be attributed to the transfer of terrigenous pollutants (Chen Liqi et al., 1992). The enrichment of F in Arctic aerosols is more than 100 – 1000 times that of seawater, and therefore, it must be highly alert that the great enrichment of F in Arctic atmosphere and long-term accumulation effect would greatly influence marine ecosystem. It can also be further evidenced by the geochemistry of stable lead isotope tracer for atmospheric aerosols in the Chukchi Sea and adjacent seawaters that As, Sb, W, Mo, F, Au, Cu, Pb, Cd, and V come predominantly from anthropogenic pollution sources (Zhu Laimin et al., 2002). It can be seen from the information about lead isotopes that the lead industrially discharged from Canada and Russia can possibly be transferred to the Chukchi Sea and adjacent seawaters. The lead in these areas can also possibly come from western America and Canada. Another piece of important evidence for the influence of artificial activities on the geochemical cycle of marine atmosphere over the Arctic is that organic matter and BaSO<sub>4</sub> particles have been detected by scanning electron microscopy and spectroscopy from Arctic marine aerosols (Figs. 5 and 7). Organic particles are one kind of important atmospheric particles with abundant carbon, which amounts for nearly 30% of the total. The existence of Ba salt particles is another characteristic of Arctic aerosols. We suggest that the particles of Ba salt are the secondary particles resultant from reaction between Ba and SO<sub>2</sub>. Because SO<sub>2</sub> in the atmosphere can be oxidized to sulphate by homogeneous and heterogeneous reactions. Cement and timbering industries can discharge Ba, and the combustion of oil and coal can discharge SO<sub>2</sub> into atmosphere.

The enrichment factor of the elements La, Ce, Nd, Sm; Eu, Yb, Lu, Fe, Sc, Cr, Co, Ba, Zr, Hf, Ta, Cs, Mn, Th, and U is close to that of Al, showing that these elements are derived mainly from the crust. Al, Fe, Mn, Co, Sc, Ta, Th and REE in marine atmospheric aerosols are the major components of weathering products and dust. The elements La, Ce, Nd, Sm, Eu, Yb, Lu, Fe, Sc, Cr, Co, Ba, Zr, Hf, Ta, Cs, Mn, Th, and U in Arctic aerosols do not come mainly from ocean, but from inland dust. The ratios of Fe/Sc, La/Sm, Sm/Nd, and Th/U in Arctic atmospheric aerosols are approximate to those of the crust, but greatly different from those of seawater (Table 2), lending great support to the conclusion that Fe, Sc and REE come largely from inland dust. The crust-source particles have been detected by scanning electron microscopy and spectroscopy in Arctic marine aerosols<sup>①</sup>: (1) the particles of bauxite come largely from soil dust, with Si and Al as the major components (Fig. 4), and have contributed a lot to the concentrations of atmospheric particles. There are some reports on bauxite particles in marine atmosphere, quite a number of bauxite particles have been found in marine atmosphere aerosols sampled over vast water areas of the North Sea, English Channel, Black Sea, etc. (Xhoffer et al., 1991); (2) oxides of silicon are dominated by quartz, with Si and O as the major components. Silicate particles and oxides of silicon have been detected in Arctic aerosol samples, suggesting their importance in amounts, and that the

① Zhu Laimin, 1999, Circulation of Arctic aerosol materials and seawater-ice-atmosphere interactions, A scientific report by the Third Institute of Oceanography, State Ocean Administration, p.3 – 10.



terrestrial dust can be long-distance transferred to the Arctic ocean.

**Table 2. Comparison of characteristic element ratios in aerosols over Chukchi Sea and Bering Sea**

Ratio	Chukchi Sea	Bering Sea	Oceanic water	Crust
Mg/Na	0.113	0.115	0.120	1.105
K/Na	0.934	0.389	0.037	0.814
Cl/Na	1.201	2.438	1.800	0.024
Ca/Na	0.063	0.062	0.036	2.063
Th/U	0.673	0.629	0.017	3.671
Rb/Sr	0.117	0.173	0.015	0.283
Sr/Ba	1.102	0.758	266.667	0.825
Fe/Sc	3831	2185	250	3556
La/Sm	1.842	0.818	7.058	4.159
Sm/Nd	0.257	0.244	0.185	0.24
Eu/Sm	0.263	0.545	0.271	0.164

The enrichment factor of the elements Rb, Sr, Ca, Mg is close to that of Al, but also to that of Na. So, Rb, Sr, Ca, and Mg have the characteristics of mixing of oceanic source and crustal source. It is easily understood that the ocean-source elements Ca, Mg, Rb, and Sr resulted from surf and air bladder breaking in the process of seawater-air exchanging, because the mass concentrations of these elements in seawater are very high: Rb  $120\mu\text{g}/\text{dm}^3$ , Ca  $412\text{ mg}/\text{dm}^3$ , Mg  $1290\text{ mg}/\text{dm}^3$ , and Sr  $7900\mu\text{g}/\text{dm}^3$  (Zhou Keyun et al., 1991). Another source of the elements Rb, Sr, Ca, and Mg is crust weathering dust. Weathering of crust surficial rocks can produce large amounts of dust rich in Rb, Sr, and Ca. The average content of Rb in global soil is  $150 \times 10^{-6}$ , and that of Sr is  $128 \times 10^{-6} - 164 \times 10^{-6}$ . Carbonate rocks and carbonate-cemented sandstones and conglomerates developed on the crust surface contain considerable amounts of Ca and Mg (Zhou Keyun et al., 1991; Mu Baolei, 1999). Therefore, Rb, Sr, Ca, and Mg in marine atmosphere may partly come from the crust rock weathering dust. In fact, the enrichment of Ca in marine aerosols is related to the transfer of crust-source materials (Chen Liqi, 1992; Lchiknn, 1978). The chemistry of precipitates along the Japan Sea reflects the remarkable enrichment of Ca and Na in the precipitates. The reason is possibly the long-distance transfer of sandy soil from North China to the Japan Sea.

As viewed from the bulk chemical composition of atmospheric aerosols sampled during CHIN-ARE-1, there would be four kinds of sources: anthropogenic: As, Sb, W, Mo, Au, Cu, Pb, Cd, and V; crust: La, Ce, Nd, Sm, Eu, Yb, Lu, Fe, Sc, Cr, Co, Ba, Zr, Hf, Ta, Cs, Mn, Th, and U; oceanic: Na, K, Ca, and Mg; and mixing source: Rb, Sr, Ca, and Mg. This is in good agreement with other studies (Barrie et al., 1992; Xie et al., 1999a; Sturges and Barrie, 1989).

### 2.3 The flux of trace elements from atmosphere to ocean

Aerosol particles can find their way into ocean by dry and wet subsidence. In reference to the total subsidence rate (GESAMP, 1989), the total subsidence flux of related elements in aerosols can be calculated as follows:

$$F = C_a \cdot V_i \quad (2)$$

where  $F$  is the total subsidence flux ( $\text{mg}/\text{m}^2/\text{s}$ ),  $C_a$  stands for the concentrations of elements in aerosols ( $\text{mg}/\text{m}^3$ ), and  $V_i$  is the total subsidence rate ( $\text{m}/\text{s}$ ). The results of calculation for total subsidence flux of elements in atmospheric aerosols are listed in Table 3. From Table 3 it can be

seen that the flux of trace elements from atmosphere into ocean is much lower than that of Chinese seas and adjacent offshore waters (Yang Shaojun et al. , 1994).

**Table 3. The calculated results of the flux of atmospheric aerosols over Chukchi Sea and Bering Sea**

Element	Chukchi Sea	Bering Sea	Offshore waters of China
As	0.257	0.371	5300
Br	232.230	165.162	106000
Sb	0.813	2.937	690
La	2.722	0.700	1200
Ce	1.788	1.116	2600
Nd	5.754	3.499	-
Sm	1.477	0.855	200
Eu	0.389	0.467	46
Tb	0.389	0.544	37
Yb	0.622	2.448	76
Lu	0.156	0.233	15
Sr	144.789	153.809	-
Fe	1191.439	509.717	1300000
Sc	0.001	0.001	360
Cr	64.852	44.634	3200
Co	5.054	6.221	550
Ni	137.480	208.863	-
Zn	43.809	15.197	42000
Rb	16.874	26.672	4900
Cs	1.788	2.722	410
Ba	131.414	202.876	27000
Zr	89.891	74.650	-
Hf	0.544	0.233	120
Ta	1.166	0.700	40
Th	8.631	8.709	420
U	12.830	13.841	210
Cu	46.104	23.309	-
Pb	9.794	5.631	-
Cd	1.255	1.069	-
V	0.105	0.027	-
K	125.388	29.510	1400
Na	134.253	75.816	2500
Ca	8.398	4.666	1200
Mg	15.163	8.748	-
Al	502.289	92.808	-
Mn	3.234	1.650	-

Note: The flux unit of K, Na, Ca, and Mg: mg/m<sup>2</sup>/month; for the other elements: μg/m<sup>2</sup>/month.

Because trace elements in ocean waters are very chemically reactive, soon after trace elements are transferred from atmosphere into ocean, they will be transferred into marine food chain. Studies showed that the contact of atmospheric aerosols containing a lot of industrial pollutants with seawater will lead to the dissolution of elements. Moreover, the dissolved elements tend to increase with time and can be adsorbed on the surface of colloids and organic mucilage, or find their way as "nutrition" metals into marine food chain. The metal particles undissolved can be concentrated on planktons (as adsorbed on the surface of seaweeds), and then enter into marine food chain. Therefore, although the total amount of trace metals imported into the Arctic Ocean from atmosphere does not vary greatly, the very active geochemical properties of trace metals and the effects of their long-term accumula-

tion can greatly influence the marine ecosystem of the Arctic Ocean.

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