The Dust Generation of Soils/Sediments in the Southern Aral Sea Basin, Uzbekistan

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Introduction

The Aral Sea, at an altitude of 53 m.a.s.l., is located in the Central Asian Republics of Uzbekistan and Kazakhstan, with the southern section located in the Autonomous Republic of Karakalpakstan. Due to its location in the center of a vast mainland far from oceans, the Aral Sea maintains a continental climate. Temperatures in the region attain 40°C in the summer and in winter temperatures drop to -20°C. Average precipitation, principally in the form of rain, is below 200 mm.yr^{-1}. The Aral Sea is fed by two rivers, the Amu Darya that flows northwest from sources in the Pamirs and enters the Sea in the south, and the Syr Darya that flows west from sources in eastern Uzbekistan and enters the Sea in the north-east (Fig. 1).

Fig. 1: Aral Sea

As a result of intensive irrigation along the two rivers feeding the Aral Sea, the volume of water reaching the sea to replace the enormous evaporation losses (~60 km^3.yr^{-1}) has decreased drastically. Once the fourth largest lake on earth, the Aral Sea has been drying up over the last four decades. By 1994, the Sea had lost 2/3 of its original water volume of 1,090 km^3, and its surface of 66,900 km^2 had shrunk by more than half (Fig. 2). 42,000 km^2 of the former sea bottom are now exposed. Water level in this period fell by 17 m. The shore line had receded in places (the southern part) by 150 km. Salinity of the water had risen from 1% in 1960 to 3.5% in 1994.

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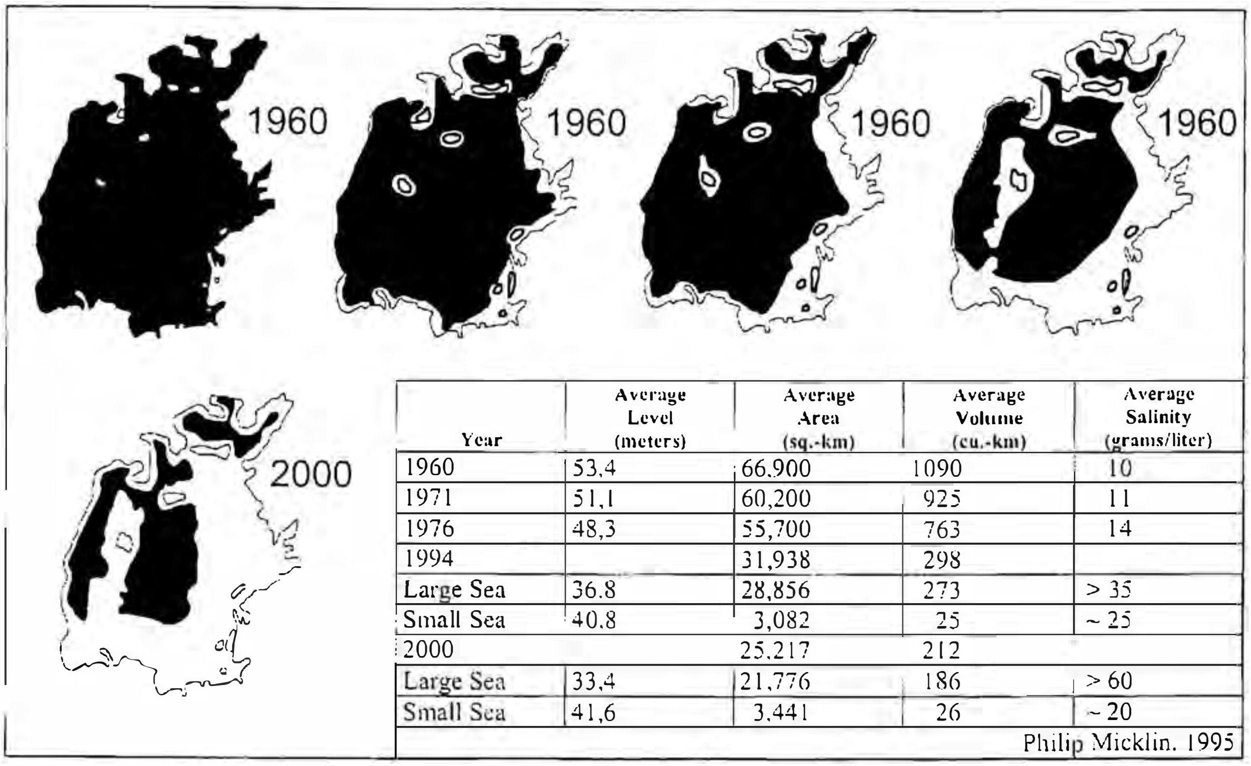
[4] According to the FAO Soil Classification System. The USDA classification equivalents are Orthids.



Year	Average Level (meters)	Average Area (sq.-km)	Average Volume (cu.-km)	Average Salinity (grams/liter)
1960	53,4	66.900	1090	10
1971	51,1	60,200	925	11
1976	48,3	55,700	763	14
1994		31,938	298	
Large Sea	36.8	28,856	273	> 35
Small Sea	40.8	3,082	25	~ 25
2000		25.217	212	
Large Sea	33,4	21,776	186	> 60
Small Sea	41,6	3.441	26	~ 20

Philip Micklin. 1995

Fig. 2: Shrinkage of the Aral Sea (after Micklin, 1996).

The lowering of the sea level of the Aral Sea is still continuing. The water level in 1999 was about 33.8 m m.a.s.l. and the surface area of the sea was about 24,400 km^2. It is envisaged that by continuous drying out, the sea will soon be separated into 2 water bodies, into the deeper Western Aral Sea and the shallower Eastern Aral Sea.

Caused by the drying out of the eastern part of the Eastern Aral Sea, the formation of another huge open salt desert has taken place. While the dry sea floor on the areas desiccated during the 1960s and the 1970s have a low salinity, with a sparse plant cover, the areas from the 1980s and the 1990s have already turned into salt deserts (the Aralkum desert) with isolated plants. As a result of the increase in salt desert areas, salt and dust storms have become frequent.

Since the 1980s, on the dry sea floor almost exclusively Solonchak deserts have formed. The open dry sea floor Solonchak desert is a huge salt flat and a source of salt dust. The Solonchaks[4] have developed on sediments of variable texture, deposited from the Aral Sea water after being introduced by the two major river systems. These are young soils with undeveloped profiles and slight organic matter accumulation. Their most distinct characteristic is salt accumulation, frequently in the form of a salt crust on the soil surface. An increasing drying of the sea floor will create even more and greater saline flats, and thus an increased potential for salt dust storms in the near future. This is a threat to the agricultural areas adjacent and beyond the southern and eastern former coastline. Thus, salt desertification is spreading throughout the whole Aralkum and surrounding areas (Breckle et al., 2001; Rafikov, 1999).

Different earth materials (soils, sediments) have been shown to emit different amounts of $PM_{10}/PM_{2.5}$ as related to wind speed (Zobeck et al., 1999). Emission has been shown to be related to source sediment texture, moisture content, surface roughness and local factors such as soil crusts. Field studies of aeolian dust produced at or near the source of intense dust storms are difficult to conduct. As a result of efforts to develop methods for the study of PM_{10} generation of earth materials under controlled laboratory conditions, a new system has been proposed by Zobeck and Amante-Orozco (2001). This equipment has been used for the examination of 8 earth materials from the Southern Aral Sea Basin (SASB), with the purpose of determining the PM_{10} and $PM_{2.5}$ dust generation potential of these materials, that represent a large proportion of the surfaces in the area. The objective of this study was to assess the contribution of the major soil/sediment surfaces in the Southern Aral Sea Basin (SASB) to the dust generation potential of the area.

Table 1. *Development of the environmental crisis in the Aral Sea Basin (from: http://www.grida.no/aral/aralsea/english/arsea/arsea.htm)*

	1966	1976	1996	2000
Exposed dried sea bed (km^2)		13,200	38,000	42,000
Mass of potential dust/salt (10^6 ton)		550	2300	3300
Area affected by dust storms (10^3 km^2)		100–150	250–300	400--450
Dust transported (kg $ha^{-1}year^{-1}$)		100--200	500--700	700--1100
Population in the area affected (10^3)		500–600	3000–3500	3500–4000

Source: Aral Sea Crisis. Communique on the results of the international technical meeting on the Aral Sea Basin problems, Tashkent, 1997.

Soils and the desiccated Aral Sea bed

Most of the soils of the Amu Darya River Delta (ADRD) had formed on river alluvium, that is frequently layered and with variable texture, close to the present (or former) river bed. Some, on more elevated areas, removed from the river bed, had formed on eroded Tertiary and Early Quaternary rocks.

The soils can roughly be divided into soils associated with and affected by the floodplain (former and present) of the river. These include wetlands consisting of hydromorphic meadow and bog soils with a relatively high clay content, that are slightly to moderately saline (Fig. 3).

These soils, that were closest to the river and form most of the river delta to the north, were subjected to annual spring flooding and were therefore only in limited agricultural use; their extent is approximately 800,000 ha. Other soils, south-east of Nukus, in a narrow strip along the river, are hydromorphic meadow and bog soils formed on alluvium, that are non-saline or only slightly saline. Being fertile, they have been under agricultural use (with irrigation) for a very long time; their extent is about 148,000 ha. Finally, to this group of soils also belong hydromorphic meadow soils that are mildly to strongly saline and can therefore be termed Solonchaks; many of these soils are covered by a 1-2 cm thick salt crust; their extent is over 460,000 ha.

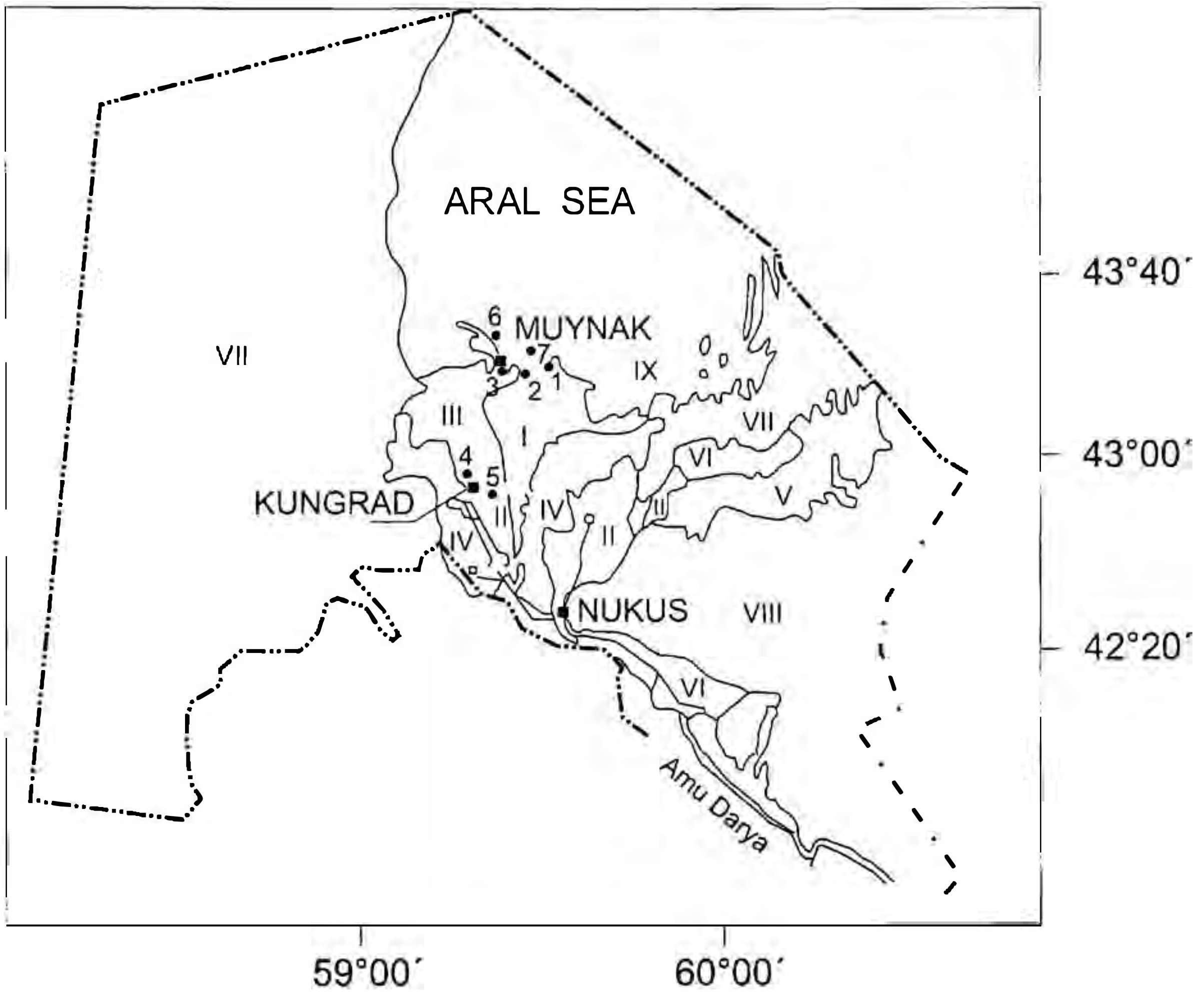


Figure 3.: Schematic soil map of the southern Aral Sea Basin (after.Soviet Soil Survey Staff, 1969). Sampling sites are marked by numbers 1-7: I. Hydromorphic meadow soils (Aquents,Fluvents) with a well-developed upper Ap horizon, developed on alluvium. Only slightly saline, highly fertile soils, that have been under cultivation for a long time. II. Slightly hydromorphic meadow soils (Aquents, Arents, Fluvents) developed on alluvium, transition to Solonchaks. Moderately to highly saline. With light to moderate drainage. Partly cultivated; delta of the Amu Darya river. III. Hydromorphic, low-lying bog and meadow soils with a clay texture, with poor drainage. Prone to flooding, slightly saline; mostly uncultivated. IV: Fine-grained Takyr soils (cambic gypsiorthids) slightly to moderately saline, transitional to Solonchaks (Salorthids). V. Takyr soils, in complexesth Solonchaks and sands (Psamments). Ancient floodplain of Amu Darya river; in patches irrigated, mostly pasture. VI. Grayish-brown soils, sandy to loamy, slighly sodic; moderately saline, stony, on hilly topography; mostly pasture. VII. Usturt Plateau, grayish-brown soils, in complexes with Takyr soils, Solonchaks and sand fields; mostly shallow, occasionally gravelly, with gypsic horizons (Gypsids); not suitable for irrigation; mostly pasture. VIII. Kizyl Kum desert, sand fields, in complexes with desert soils and Solonchaks; low-grade pasture. IX. Water.

A second group of soils, more removed from the riverbed or even the floodplain, are Takyr[5] soils. Takyr soils are soils of the desert zone of Central Asia, distinguished by their hard, polygonally-cracked surface. They exhibit a light-gray, 1-2 cm thick surface crust, compact on its upper surface, highly porous on its lower surface that had formed as a result of high sodicity in the surface layer from which salts had been partly leached. The crust is very hard when dry, sticky when wet, slightly to moderately calcareous, does not curl upon drying. The Amu Darya Takyrs are mildly to moderately saline, and also partly sodic[6]. Their extent is over 1 million ha; associated with them are gray-brown, sandy to loamy soils that are slightly saline; their extent is 306,000 ha. Finally, more removed from the river bed and on more elevated terrain to the west, on the Usturt plateau, are shallow, stony soils that are saline to varying degrees, from slightly saline when they are sandy, to more developed gypsic soils; their extent is 740,000 ha (Soviet Soil Survey Staff, 1969).

This distribution of the ADRD suggests that with time and development, the river sediments develop either into strongly saline Solonchak types of soils, or into less saline Takyr types of soils (Singer et al., 2001). The most salient features of most Solonchaks and Takyrs are their crusts.

Dust generation and transport in the Southern Aral Sea Basin

The desiccation of the Aral Sea has resulted in a dramatic increase in wind erosion processes. The number of dust storms has increased considerably. Up to 10 major dust storms are now registered annually in the region. In the past, the original large sea water surface, with the associated wet sea atmosphere, reduced the strong northerly and north-easterly wind activity (Fig. 4).

With the drastic reduction in the sea surface, this protective action has now been reduced significantly. Together with the strong reduction in plant cover, resulting from salinization and anthropogenic activities, this has led to deflation of huge dimensions in some areas, deposition of deflated materials in others.

There are differing estimates of the volume of material removed, transported and deposited. The average rate of removal from the dried sea floor has been calculated at 2 $mm.yr^{-1}$. This has been corroborated by measurements which showed that during the past 3 decades, a 6-9 cm thick layer of soil/sediments has been removed by wind from the newly dry surfaces (Semenov, 1990). According to Razakov and Kosnazarov (1996) however, the removal rate during 1982-1989 was much higher, 40-135 $mm.yr^{-1}$. The Institute of Geology and Geophysics of the Academy of Uzbekistan give a removal rate of 22.8 $ton.ha^{-1}yr^{-1}$, and a total figure for the years 1960-1983 of 43 million tons (Razakov and Kosnazarov, 1996). The dust includes large concentrations of salt.

There are differing estimates of the volume of material deposited. According to some calculations, in the Amu Darya Delta region, on an area of 10,000 km^2, on the average 90,000-100,000 tons of material are deposited annually (90-100 $kg.ha^{-1}$). On 13,000 km^2 of the Usturt Plateau, about 40,000-50,000 tons (31-39 kg $ha^{-1}.yr^{-1}$) have been deposited (Orlovsky et al., 2001). Though, as mentioned before, some

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[5] According to the Russian Soil Classification System (Kovda, 1973; Egorov et al., 1987). A "takyric soil horizon" is also recognized in the FAO 1998 World Reference Base for Soil Resources (FAO, 1998).

[6] Saline soils: Soils that contain large amounts of soluble salts, appreciably more soluble than calcium sulfate (Singer and Munns, 1999).

deposition occurs in the Aral Sea bed (particularly in the portions that are not yet dried up), the overall balance is that of deflation and the desiccated and exposed sea bottom is considered as one of the major dust sources.

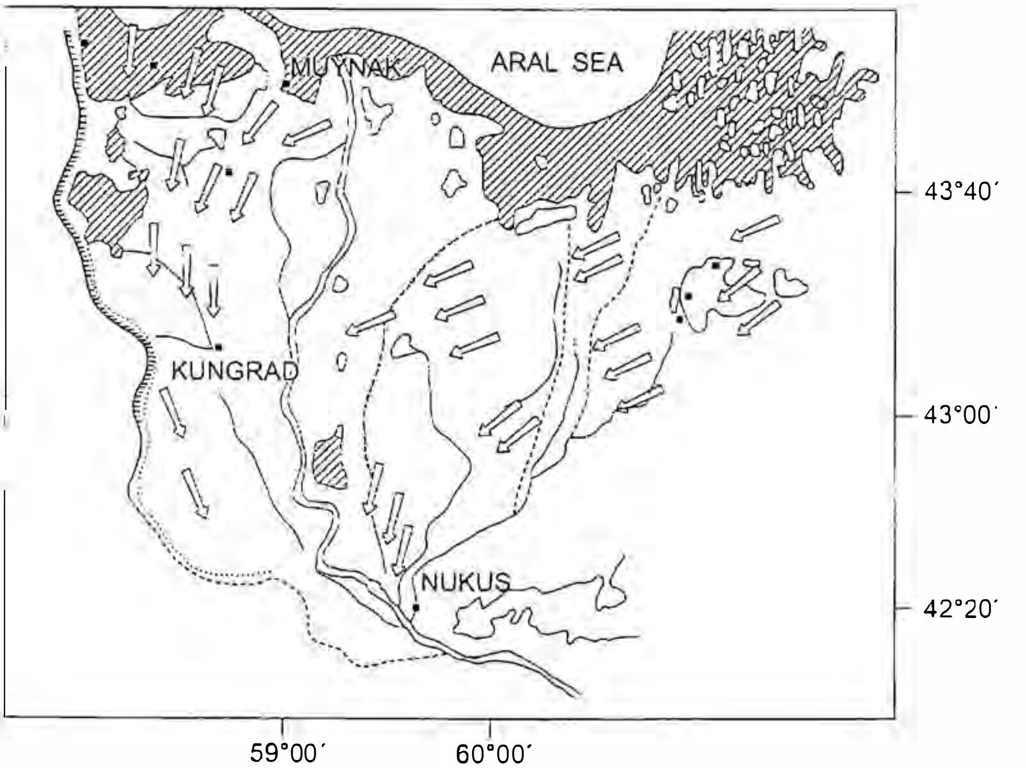

Fig. 4: Average wind direction distribution in the Southern Aral Sea Basin (after Razakov and Kosnazarov, 1991).

The gravest ecological consequence of the dust transfer in the southern Aral Sea Basin is the salinization of lands. The dust includes large concentrations of salt. In summer, the salt content in the dust is in the range of 30-40%, but in winter it may pass 90% (Hydrometeorological Center of Uzbekistan). As a result, huge amounts of salt are transferred from the dust source areas (principally the dried Aral Sea bottom) and distributed over the soils of the Amu Darya River Delta (Fig. 5). The principal sources for saline dusts are the Solonchak soil areas. Between 12-20 ton $ha^{-1}yr^{-1}$ of salt are deflated from Solonchak soils (Kosnazarov, 1985). This figure indicates that up to nearly 300 $kg.ha^{-1}$ of salt were deposited in some areas of the delta during 1986 (Tolkacheva, 1995). According to Tsitasov (1990), from 0.2 to 5 ton $ha^{-1}.yr^{-1}$ of salt are deposited in some places in the Amu Darya river delta by atmospheric deposition. Values vary between 111-802 $kg.ha^{-1}.yr^{-1}$ for the exposed Aral Sea bottom and 41-384 $kg.ha^{-1}.yr^{-1}$ for Amu Darya River delta soils. Some of the atmospherically transported salt reaches the intensively irrigated and cultivated soils far to the south, hundreds of kilometers from the source areas.

Methods of Examination

Crust samples were collected manually, soil samples using a shovel. The micromorphology and chemical composition of crust materials was examined using a model JSM-5410LV scanning electron microscope to which an energy-dispersive x-ray spectrometer (EDSA) was attached. Particle size distribution was determined by the sedimentation method, supplemented by wet sieving and also by a Malvern Mastersizer Laser. Aggregate size material and measuring the amount of CO_2 evolved (Bundy and Bremner, 1972). Organic C was determined using a CNS analyzer. Soluble salts were extracted and analyzed by ICP and ion chromatography.

Suspended dust produced during a wind storm is mainly caused by abrasion of soil aggregates and crust by saltating particles (Gillette, 1977). Abrasion studies have shown that the mass lost per impact is directly proportional to the kinetic energy of the impacting particle (Greeley and Iversen,1985). The USDA, Agricultural Research Service, Wind Erosion and Water Conservation Research Unit in Lubbock, Texas developed the Lubbock Dust Generation, Analysis and Sampling System (LDGASS) to simulate dust emissions generated by applying kinetic energy to a dust source sample (Gill et al., 1999).

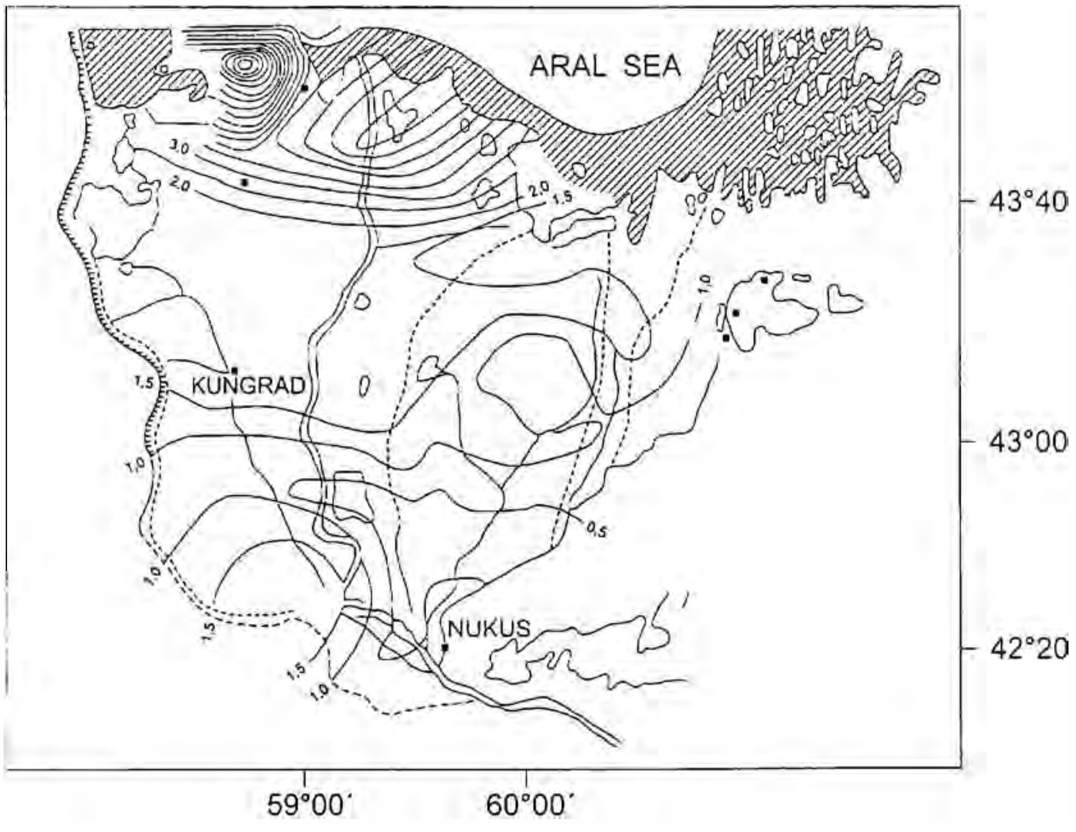

Fig. 5: Distribution of dry aerosol deposits in the Southern Aral Sea Basin for 1986, in tons ha^{-1} $year^{-1}$ (after Razakov and Kosnazarov, 1991). Sea shore line is for 1986; shaded areas are low-lying marshes.

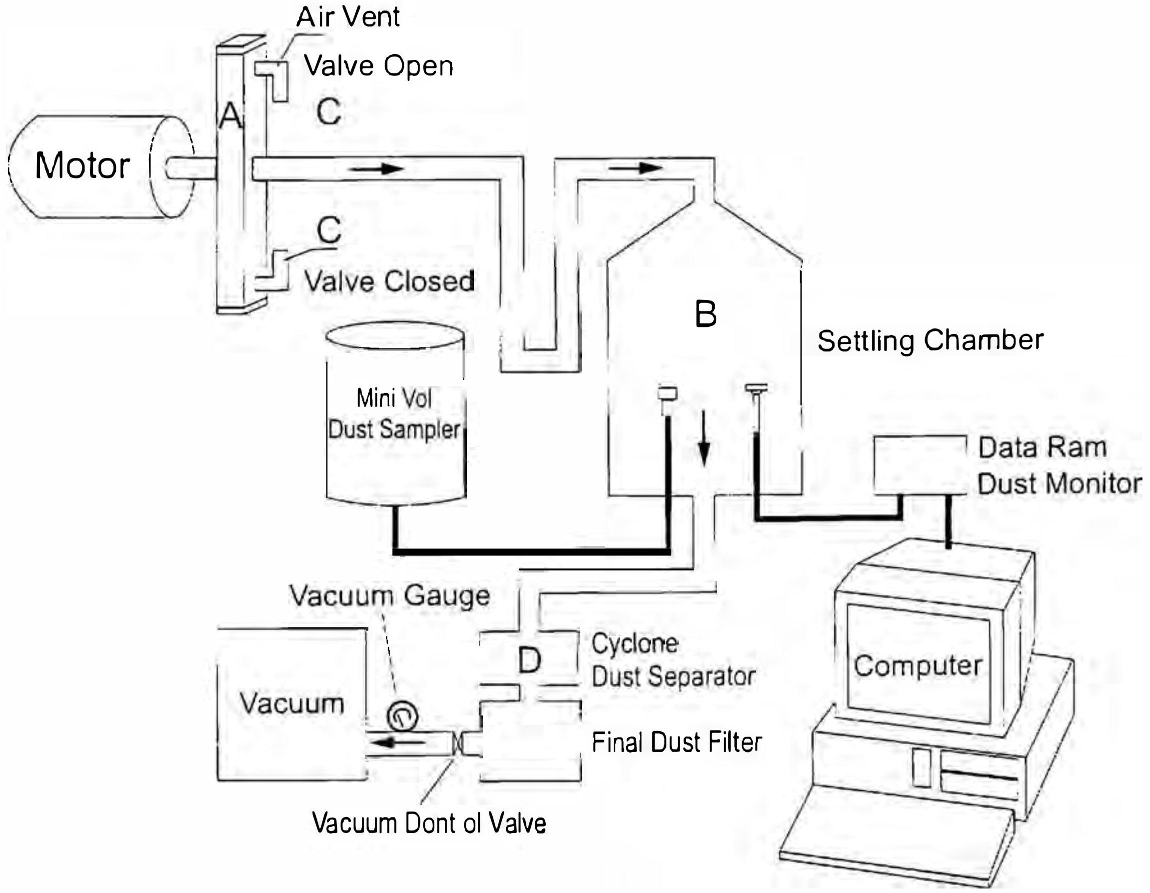

Fig. 6: The Lubbock Dust Generation, Analysis and Sampling System (LDGASS).

RESULTS

Soil/sediment and crust characteristics

Particle-size distribution

The salt-free particle-size distribution of the soil sediment and salt crust are given in Table 2. Fine sand dominates in all materials except the desiccated sea bottom crust. Coarse sand is negligible; medium sand is present in minor quantities only. The Takyr crust from Site 2 contains a sizable silt fraction. The Takyr-like soil at Site 3 has a similar grain-size distribution. The sub-crust at Site 1 below the salt crust has a grain-size distribution similar to that of the salt crust. In the Solonchak soils from Sites 4 and 5, fine sand and silt dominate. The amounts of clay and coarse sand are very low.

Aggregate size distribution is shown in Table 3. The Takyr crust from Site 2 had the highest proportion of very fine aggregates, the salt crusts from Sites 1, 4, 6 and 7, the highest proportions of very coarse aggregates.

Table 2

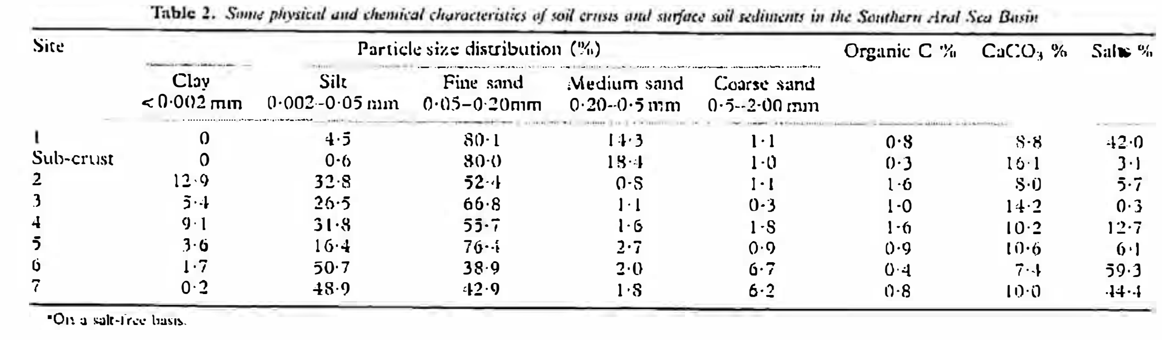

Table 2. *Some physical and chemical characteristics of soil crusts and surface soil sediments in the Southern Aral Sea Basin*

Site	Particle size distribution (%)					Organic C %	$CaCO_3$ %	Salts* %
	Clay <0·002 mm	Silt 0·002–0·05 mm	Fine sand 0·05–0·20mm	Medium sand 0·20–0·5 mm	Coarse sand 0·5–2·00 mm			
1	0	4·5	80·1	14·3	1·1	0·8	8·8	42·0
Sub-crust	0	0·6	80·0	18·4	1·0	0·3	16·1	3·1
2	12·9	32·8	52·4	0·8	1·1	1·6	8·0	5·7
3	5·4	26·5	66·8	1·1	0·3	1·0	14·2	0·3
4	9·1	31·8	55·7	1·6	1·8	1·6	10·2	12·7
5	3·6	16·4	76·4	2·7	0·9	0·9	10·6	6·1
6	1·7	50·7	38·9	2·0	6·7	0·4	7·4	59·3
7	0·2	48·9	42·9	1·8	6·2	0·8	10·0	44·4

*On a salt-free basis.

Table 3

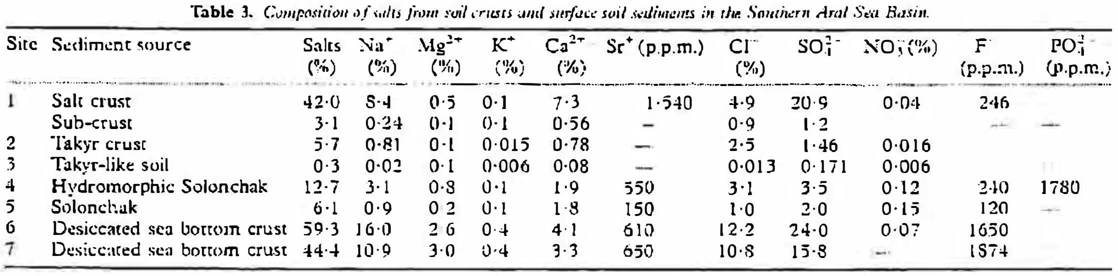

Table 3. *Composition of salts from soil crusts and surface soil sediments in the Southern Aral Sea Basin.*

Site	Sediment source	Salts (%)	Na^+ (%)	Mg^{2+} (%)	K^+ (%)	Ca^{2+} (%)	Sr^+ (p.p.m.)	Cl^- (%)	SO_4^{2-}	NO_3^- (%)	F^- (p.p.m.)	PO_4^{3-} (p.p.m.)
1	Salt crust	42·0	8·4	0·5	0·1	7·3	1·540	4·9	20·9	0·04	246	
	Sub-crust	3·1	0·24	0·1	0·1	0·56	–	0·9	1·2		—	—
2	Takyr crust	5·7	0·81	0·1	0·015	0·78	—	2·5	1·46	0·016		
3	Takyr-like soil	0·3	0·02	0·1	0·006	0·08	—	0·013	0·171	0·006		
4	Hydromorphic Solonchak	12·7	3·1	0·8	0·1	1·9	550	3·1	3·5	0·12	240	1780
5	Solonchak	6·1	0·9	0·2	0·1	1·8	150	1·0	2·0	0·15	120	—
6	Desiccated sea bottom crust	59·3	16·0	2·6	0·4	4·1	610	12·2	24·0	0·07	1650	
7	Desiccated sea bottom crust	44·4	10·9	3·0	0·4	3·3	650	10·8	15·8	—	1874	

Fig. 7 A presents the salt-free particle size distribution of the salt crust from Site 1 as determined by laser. Particles of 100 µm equivalent diameter absolutely dominate. Coarse and medium sand and clay are negligible; silt is present in minor quantities only. SEM observations however showed that the size of the salt crystallites varied between 5-10 µm. They were arranged in one dense, interlocking matrix (Singer et al., 2001). A second generation of smaller, apparently less crystalline particles was sometimes located on top.

The soil below the crust from Site 1 and the Takyr-like soil from Site 3 have similar particle size distributions. In the Takyr crust from Site 2, on the other hand, the maxima had shifted to lower sizes, with a major peak at about 65 µm and a smaller peak at 8 µm. This corresponds to finer sand and a sizeable silt fraction.

The laser particle size distribution curves of the Solonchaks from Sites 4 and 5 (Kungrad area) and of the Aral Sea bottom sediments (Sites 6 and 7) is shown in Fig. 7 B.

In the Aral Sea bottom sediments, ~20 µm particles dominate, in distinct contrast to the salt crust from Site 1, where 100 µm particles dominate. In the Kungrad Solonchak soils from Sites 4 and 5, peaks at 60-80 µm indicate the dominance of fine sand.

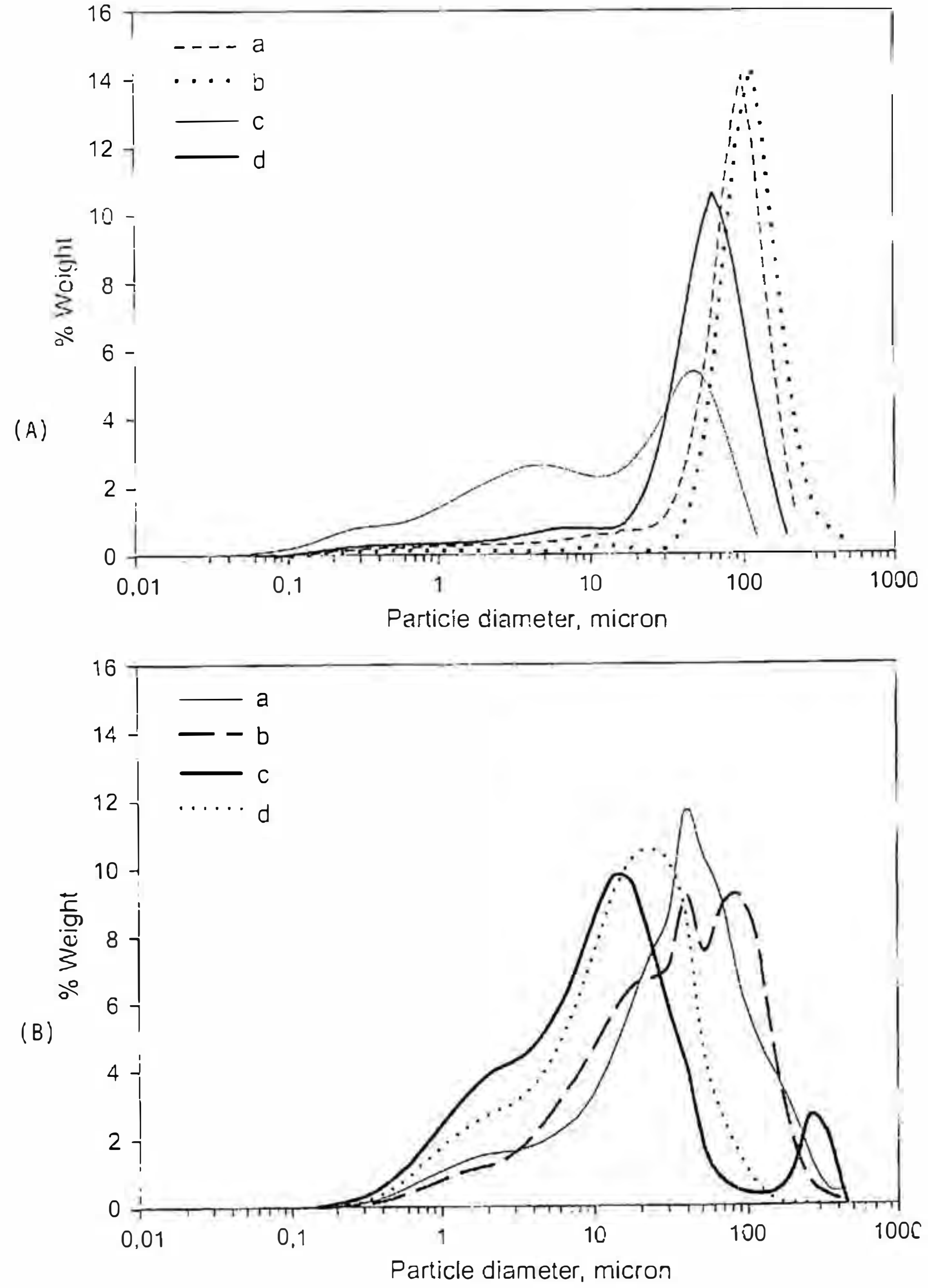

Fig. 7: Particle size distribution (salt free) as determined by Malvern Mastersizer Laser of materials from **(A)** Sites 1-3 (after Singer et al., 2001): a-1, salt crust; b-1, 1-25 cm; c-2, Takyr crust; d-3, 0-25 cm soil. **(B)** Sites 4-7: a-4, hydromorphic Solonchak; b-5, Solonchak; c-6, desiccated sea bottom crust; d-7, desiccated sea bottom crust.

All materials contain moderate amounts of carbonates (Table 2). The sub-crust below the salt crust of Site 1 contains the highest amount of carbonates, the dried sea bottom crust from Site 6, the lowest (7.45%). The only carbonate present is calcite, except in the Solonchak from Site 4, where some dolomite is present too.

Organic carbon is present in all materials in low amounts only (Table 2). The highest amount (1.62% org. C) was found in the hydromorphic Solonchak of Site 4, the lowest amount (0.28% org. C) in the sub-crust of Site 1.

All soils contain salts (Table 2). The highest amounts (59.3 and 44.4%) are present in the salt crusts of the dried sea bottom soils from Sites 6 and 7. The salt crust of the Solonchak soil from Site 1 contains 42.0% salt. The lowest amounts were determined in the Takyr-like soil of Site 3. In the hydromorphic Solonchak from Site 4 and in the Takyr-like soil from Site 3, sulfates dominate over chlorides (Table 4). In all other materials, chlorides and sulfates are represented in about equal proportions. Nitrates in very minor amounts were identified in the Takyr crust from Site 2, in the salt crusts from the dried sea bottom and in the hydromorphic Solonchak from Site 4. Trace to minor amounts of fluorides were identified in the materials from Sites 4-7. The dried sea bottom salt crusts also contained traces of bromine. Among the cations, calcium dominated, except in the crusts, where sodium was the dominant cation. Potassium in significant amounts was present in the soil below the salt crust of Site 1. Sodium is the dominant cation in the soils/sediments of Sites 5-7. It is followed by magnesium in the salt crusts of Sites 6 and 7, and by calcium in the Solonchak soils of Sites 5 and 6. Significant amounts of potassium were present in the salt crusts too. Minor amounts of strontium were identified in the extracts of all materials. For the mineralogy of some of the soils/sediments see Singer et al. (2001).

Table 4. *PM_{10} and $PM_{2\cdot5}$ dust generation by the Lubbock dust generator from the South Aral Sea Basin soils/sediments*

Site	Dust (PM_{10}) conc. ($\mathrm{mg\,m^{-3}}$)	Dust ($PM_{2\cdot5}$) conc. ($\mathrm{mg\,m^{-3}}$)	Relative $PM_{2\cdot5}$ conc. (%)
1	39·6	19·1	48·2
Sub-crust	81·6	16·5	20·2
2	579·3	261·1	45·1
3	379·5	135·0	34·0
4	115·3	25·6	22·2
5	520·5	167·7	32·2
6	252·3	85·1	33·7
7	111·6	25·4	22·8

Fig. 8 shows the particle size distribution curve (PDC) of the generated PM_{10} dust. Only very little PM_{10} dust (39.6 $\mathrm{mg.m^{-3}}$) had been produced by the salt crust of Site 1, but a relatively large proportion of that dust, 48.2% is $PM_{2.5}$ (Table 5). The dust produced from the salt crust on Site 1 has a distinctly bimodal distribution curve, with one major maximum at about 1.5 µm and a second at 5 µm (Fig. 8 A). Since there is no aluminosilicate clay and very little silt (Table 2) in the crust, most of this dust must have been composed by salt particles. Also very little PM_{10} dust (81.6 $\mathrm{mg.m^{-3}}$) was produced by the subcrust soil from Site 1. About 1/5 of that dust was $PM_{2.5}$. The dust produced from that soil has a nearly uni-modal distribution, peaking at 9 µm.

Table 5

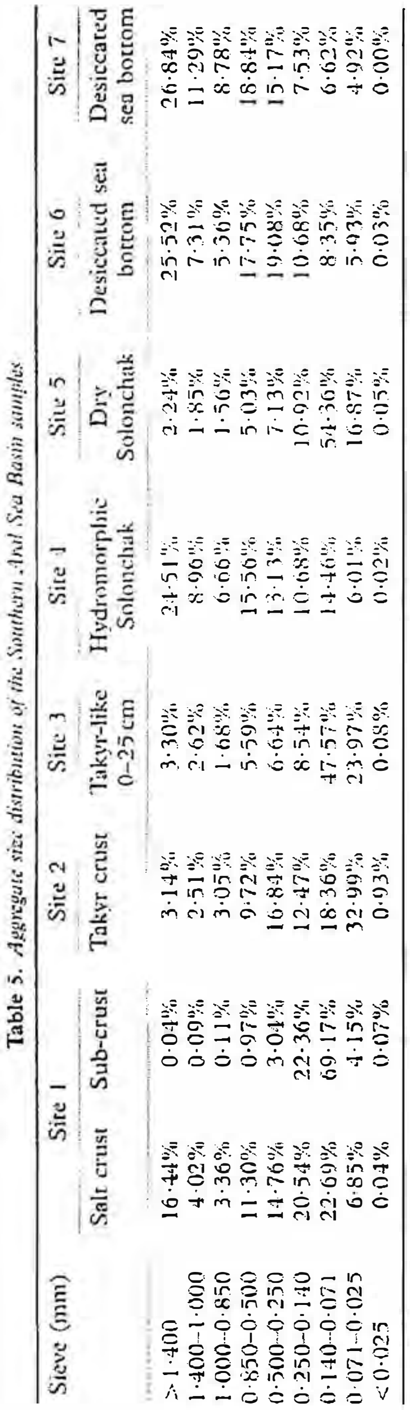

Table 5. *Aggregate size distribution of the Southern Aral Sea Basin samples*

Sieve (mm)	Site 1		Site 2	Site 3	Site 4	Site 5	Site 6	Site 7
	Salt crust	Sub-crust	Takyr crust	Takyr-like 0–25 cm	Hydromorphic Solonchak	Dry Solonchak	Desiccated sea bottom	Desiccated sea bottom
>1·400	16·44%	0·04%	3·14%	3·30%	24·51%	2·24%	25·52%	26·84%
1·400–1·000	4·02%	0·09%	2·51%	2·62%	8·96%	1·85%	7·31%	11·29%
1·000–0·850	3·36%	0·11%	3·05%	1·68%	6·66%	1·56%	5·36%	8·78%
0·850–0·500	11·30%	0·97%	9·72%	5·59%	15·56%	5·03%	17·75%	18·84%
0·500–0·250	14·76%	3·04%	16·84%	6·64%	13·13%	7·13%	19·08%	15·17%
0·250–0·140	20·54%	22·36%	12·47%	8·54%	10·68%	10·92%	10·68%	7·53%
0·140–0·071	22·69%	69·17%	18·36%	47·57%	14·46%	54·36%	8·35%	6·62%
0·071–0·025	6·85%	4·15%	32·99%	23·97%	6·01%	16·87%	5·93%	4·92%
<0·025	0·04%	0·07%	0·93%	0·08%	0·02%	0·05%	0·03%	0·00%

In strong contrast to the salt crust, the Takyr crust generated a very large amount of PM_{10} dust (579.3 $mg.m^{-3}$), about 14 times more. The proportion of $PM_{2.5}$ in this dust, however, was similar to that in the salt crust (45.1%). The distribution curve obtained from this PM_{10} dust was distinctly uni-modal, peaking at 3 µm (Fig. 8 B). It should be noted that the Takyr crust contains relatively large amounts of silt (Table 2).

The amount of PM_{10} dust generated from the Takyr-like soil at Site 3 was, with 379.5 $mg.m^{-3}$, still large but smaller than from the Takyr soil crust. The $PM_{2.5}$ proportion in this dust was also smaller than in the dust from the Takyr soil crust, 34%. The PDC from this soil was also uni-modal, but displayed two bulges, one in the clay sized particle range, the other at about 15 µm. The peak of the curve was at 4 µm (Fig. 8 C).

From the Solonchak from Site 4, little PM_{10} dust was generated, only 115.3 $mg.m^{-3}$, and only about one-fifth of that dust was $PM_{2.5}$ (22.2%). Very much larger (520.5 $mg.m^{-3}$) amounts of PM_{10} were produced from the Solonchak at Site 5, and a larger proportion (32.2%) of that dust was **$PM_{2.5}$**. The PDC curves of Solonchaks 4 and 5 dust were distinctly uni-modal, with the maxima at 6 µm for Site 4 and 3 µm for Site 5.

Different amounts of PM_{10} dust were generated from the Aral Sea bottom crusts. From one crust (Site 6), the amount of dust obtained was 252.3 $mg.m^{-3}$, from the other crust (Site 7) it was much lower, 111.6 $mg.m^{-3}$.

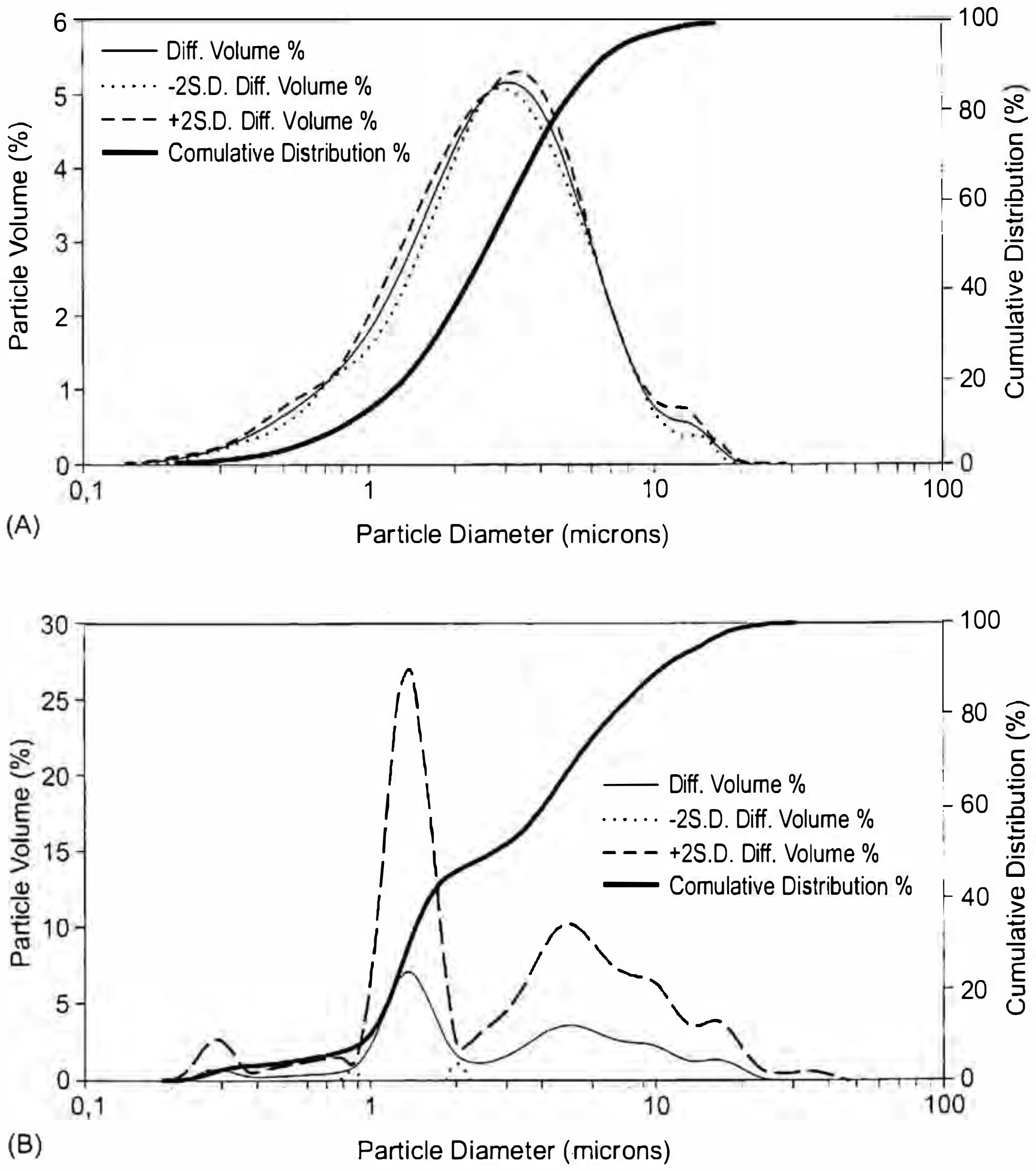

Fig. 8: Particle size distribution curves of PM10 dust generated by the Lubbock dust generator southern Aral Sea basin soils / sediments.

(A) Site 2, Takyr crust; **(B)** Site 1, salt crust; **(C)** site 3, Takyr-like soil; **(D)** Site 6, desiccated sea bottom crust.

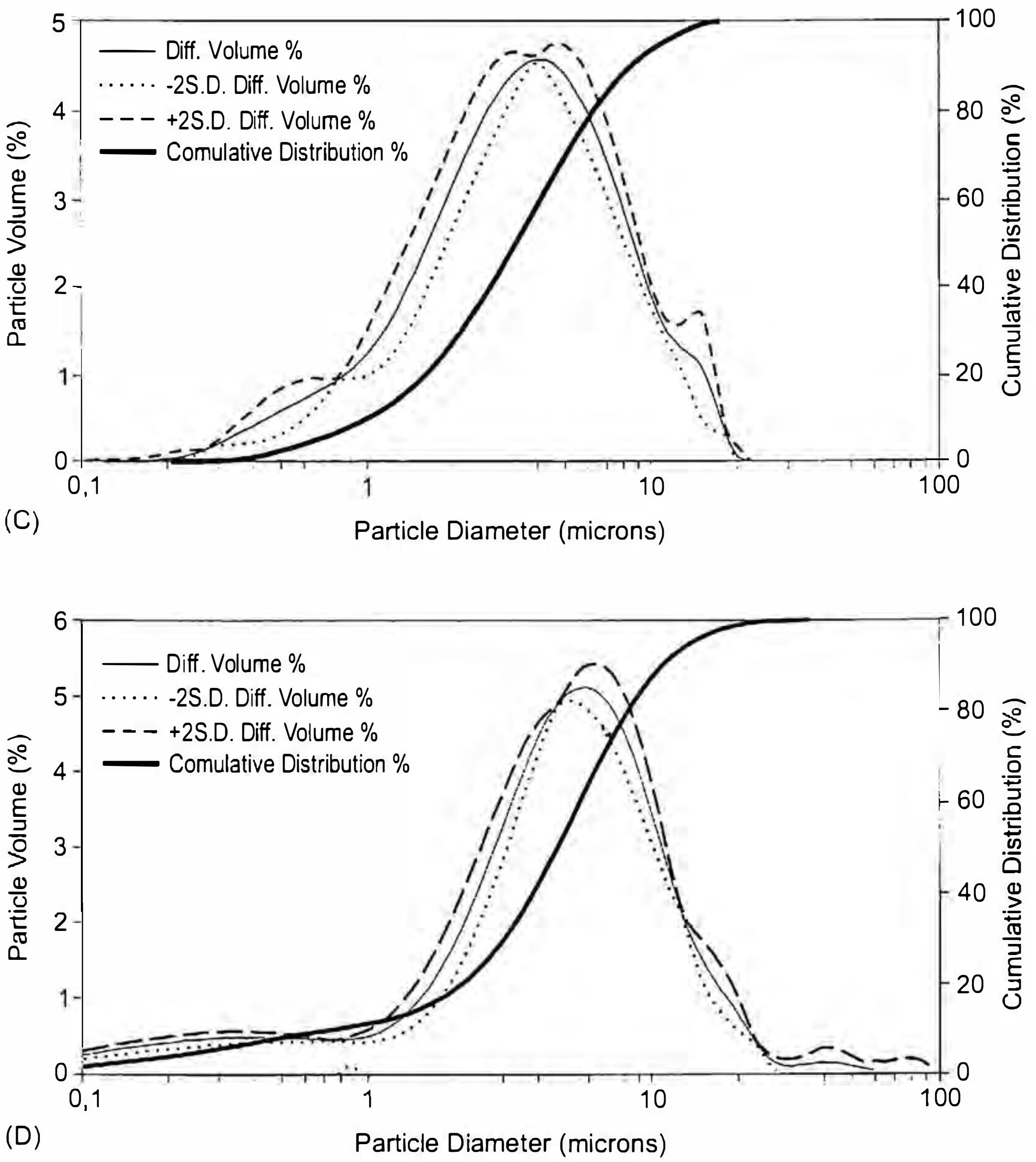

Fig. 8 (continued)

DISCUSSION

The highest amount of PM_{10} dust was generated by the Takyr crust from Site 2. This suggests that Takyr crust material potentially has a very high PM_{10} dust generation capability. The $PM_{2.5}$ dust generation of this material too is very high, 45.1% of the PM_{10} dust (Table 5). This material contains relatively large amounts of clay and silt, and is only mildly saline and calcareous. Noteworthy is the dominant proportion of very fine aggregates (<71 µm).

Zobeck et al. (1999) found for a large group of soils from Lubbock, Texas, that PM_{10} concentration by texture group varied from 35 $mg.m^{-3}$ for clay soils to 500 $mg.m^{-3}$ for sandy clay soils. In general, PM_{10} concentration increased with increasing clay content with the exception of the clay soil samples.

The mean PM_{10} concentration for two fine sandy loam soils from west Texas, measured by the same procedure as that in this study, was 84.7 mg m^{-3} (Zobeck et al., 2000). For the examination of the effects of texture on dust emission, the technique of particle size determination, i.e. dry sieving or dispersed particle sizing is important. Chandler et al. (1998) found strong trends between the soil dustiness index (D) and both clay and silt contents in soils analyzed by mechanical sieves and aerodynamic sizing. Similar trends did not exist between D and soil texture classes as determined by dispersed particle sizing. This intuitively suggests that dust generation of soils is a measure of the dust freely available in a natural-aggregated condition. This is confirmed by the SASB soils and sediments, where the highest PM_{10} dust concentrations were generated by the Takyr soil crust material which also had the highest proportion of fine aggregates (<71 µm) (Table 3).

In contrast, PM_{10} dust generated by the hydromorphic Solonchak from Site 4, which also has a fairly high clay and silt content, was much lower. This should be explained by the fact that this material had a much lower proportion of fine aggregates. On the other hand, the Solonchak from Site 5, which had low amounts of clay and silt, but large amounts of fine aggregates, generated large amounts of PM_{10}. The subcrust material from Site 1 (1-15 cm), with only a very low amount of fine aggregates, generated only very low concentrations of PM_{10} dust. The Takyr-like soil from Site 3, with a sizeable amount of fine aggregates, generated relatively large amounts of PM_{10} dust. The Aral Sea bottom sediments from Sites 6 and 7, with low amounts of fine aggregates, produced only low amounts of PM_{10} dust. The trends in $PM_{2.5}$ dust production were similar.

Particularly low PM_{10} dust emissions are from soils with high salt contents. The salt crust from Site 1 had the lowest PM_{10} dust emission. The materials from the desiccated sea bottom (Sites 6 and 7), that were covered with salt crusts, emitted relatively low PM_{10} dust concentrations. Also the hydromorphic Solonchak from Site 4, that contained nearly 20% salts, had a very low PM_{10} dust emission.

Apparently salts diminish PM_{10} dust generation. The materials from the Sites with the highest dust generation (Sites 2, 3, and 5) had also the lowest salt contents. The differences in dust generation between the Solonchak materials from Sites 4 and 5 and between the desiccated sea floor materials from Sites 6 and 7 are associated with differences in salt content. Most salt crust crystallites are in the size group of fine silt, 5-10 µm (Singer et al., 2001). This size-group should be susceptible to suspension as dust. But apparently these salt crystallites are aggregated into much larger units, which appear to be stable. In the salt crust from Site 1, the crystallites can be seen to have formed a tightly interfitting mosaic (Singer et al., 2001).

From Table 3, the salt crust materials can be seen to have disintegrated into a high proportion of large (>1,400 µm) aggregates, and into a low proportion of small (<140 µm) aggregates. In contrast, the materials with the lowest contents in salts, have low proportions of very large aggregates. It must be concluded that high salt contents (of evaporitic origin) in surface crusts of soils/sediments induce the formation of large, stable aggregates, that do not generate much PM_{10} dust. Salt crusts from the SASB, examined in a wind tunnel, had very high threshold shear velocities (Argaman et al., 2002, personal communication).

Yet according to Razakov and Kosnazarov (1996), the salt crust in sandy and sandy-loam soils from the exposed bed of the Aral Sea, was destroyed and removed by even light winds (velocity of 2.5-5.0 m.sec^{-1}). On loam and clay soils, the salt crust was destroyed by winds exceeding a velocity of 7 m.sec^{-1}. This suggests a high susceptibility of the salt crusts to wind erosion. The very high salt contents in atmospheric dusts collected from over the SASB also suggest salt crusts as potential sources for dust generation.

CONCLUSIONS

From their high PM_{10} dust generating capability, it can be concluded that the Takyr and Takyr-like soils from the SASB constitute the surfaces with the highest potential for being the source for the severe dust storms of the area. These are the fine-grained, slightly to moderately saline Takyr soils (cambic gypsiorthids) on the left and right hand of the Amu Darya river bed, somewhat removed from the bed (Fig. 5). Their extent is over 0.5 million ha. Some Takyrs are in association with solonchaks and sands. The extent of their soil association, to the east and even more removed from the river bed, is over 600,000 ha. On the Usturt Plateau, to the west of the Amu Darya River Delta, are soil associations that include Takyr and Takyr-like soils too. This indicates that huge areas, of over 1 million ha, have a prime potential for generating PM_{10} dust. In addition to the Takyr soils, Solonchak soils too have a PM_{10} dust generating capability, some directly, as shown in this study for the Solonchak from Site V, and others if the abrading action of saltating sand grains is taken into account. Including the Solonchak soils as potential sources for PM_{10} dust, would add at least 1 million ha in the Amu Darya River Delta, as well as a sizeable portion of the 4 million ha of desiccated Aral Sea bed.

The implication is that left in their present state, large areas in the SASB will continue under the impact of prevailing strong winds, to generate huge amounts of dust with all its negative ecological consequences. Probably the most efficient measure to counteract this is a massive program of phytomelioration for the conservation of the natural vegetation and by complementary revegetation by suitable plants (Wucherer and Breckle, 2001).

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