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# Surface crusts on soils/sediments of the southern Aral Sea basin, Uzbekistan

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**Abstract**

Soils and sediments of the southern Aral Sea basin of Central Asia are commonly covered by salt-bearing surface crusts. These crusts represent a potential source of salt-rich dust that can contribute to salinisation of soils in a large area. Crust types include takyric crusts, surface crusts on Solonchaks, and salt crusts covering dry parts of the lake bed. The takyric crusts are structural crusts, showing features related to flooding and shrinkage. Gypsum, formed within the sediment matrix, is the only evaporite mineral they contain. One studied Solonchak crust is fine-grained, with a thin thenardite and bloedite coating along the irregular surface and halite coatings along the sides of pores. All salts in this crust formed by evaporation of solutions contained in the groundmass. A Solonchak crust with a sandy texture contains prismatic gypsum crystals that formed in a water-saturated surface layer, as well as bloedite, eugsterite and halite, formed by evaporation of interstitial brines. The lake bed crust is a pure accumulation of salt minerals (bloedite, hexahydrite, halite, kainite), with synsedimentary and diagenetic features. Salt mineral assemblages in the three crust types are those that form during successive stages of evaporation of Aral Sea waters, in agreement with published theoretical predictions.
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*Keywords:* Soil crust; Takyric crust; Solonchak; Bloedite; Kainite; Hexahydrite

## 1. Introduction

The Aral Sea in Central Asia has undergone a dramatic decrease in volume since the early 1960s, due to the withdrawal of water for irrigation along the main rivers that feed the lake (Micklin, 1988). As a result, the area of the lake has been strongly reduced and lake water salinity has increased. One of the problems caused by this evolution is the development of saline soils and surface deposits (e.g. Stulina and Sektimenko, 2004). As reviewed by Singer et al. (2003), large quantities of surface material are being removed from the exposed lake bed by deflation (22.8 ton $ha^{-1}$ $year^{-1}$). The dust that is produced has a high salt content (up to >90% in winter), resulting in salt enrichment of soils in areas where the deflated material is deposited, south of the Aral Sea. Deposition of wind-transported salts is estimated to be up to 150 kg $ha^{-1}$ $year^{-1}$ in parts of the Amudarya delta region, but it also affects intensively cultivated areas farther south.

Salt-affected soils in the southern Aral Sea basin include Solonchaks and soils with takyric surface horizons (FAO, 1998). Soils of both types, each occupying areas of more than 1,000,000 ha (Argaman

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et al., 2006), are characterised by the presence of surface crusts. Solonchak soils, which are highly saline, generally have a surface crust with a high salt content. Takyric crusts, defined as heavy-textured surface horizons of periodically flooded soils, have a lower salinity, their formation being related to the development of high sodicity following leaching of soluble salts. A third type of surface crust is represented by salt crusts covering parts of the lake bed that became exposed by desiccation (ca. 4,000,000 ha total exposed area).

Earlier studies of the surface crusts of the southern Aral Sea basin mainly dealt with their susceptibility to deflation (Singer et al., 2001, 2003; Argaman et al., 2006). The main objective of the present study is reaching a better understanding of the mode of development of the crusts. This was mainly obtained by a thin section study of the nature of salt mineral occurrences. A second objective is an assessment of the possible relationship between micromorphological characteristics and deflation behaviour.

## 2. Material and methods

### 2.1. Materials

Undisturbed samples of the three main types of surface crusts in the southern Aral Sea basin were studied. They were collected at sites that were considered to be representative for soils/sediments with these crust types in the study area (Fig. 1). The main features of the sampling sites and crusts are described in earlier reports (Singer et al., 2001, 2003; Argaman et al., 2006) and are only summarised here. Basic textural and chemical properties of the crusts can be found elsewhere (Singer et al., 2003; Argaman et al., 2006).

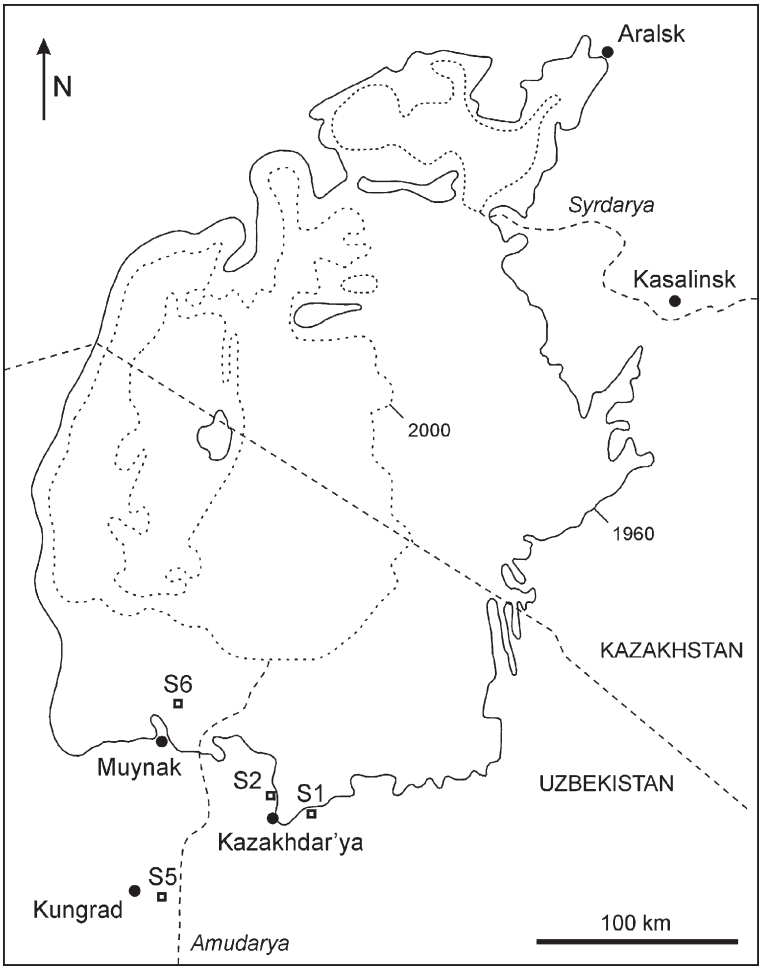


Fig. 1. Location of sampling sites in the southern Aral Sea basin (base map with 1960 and 2000 shoreline positions after Breckle et al., 2000).

A takyric crust was sampled north of Kazakhdar'ya, near the 1960 lake margin, in a partially vegetated uncultivated field (Site 2). The crust is 0.5 cm thick and shows a polygonal cracking pattern (5–10 cm polygon size). One of the studied Solonchak crusts was sampled near Kungrad, in a former bay of the Aral Sea (Site 5). It is 2–3 cm thick and includes a thin salt crust, in an area with a sparse vegetation cover. A second Solonchack crust was sampled east of Kazakhdar'ya, near the 1960 shoreline (Site 1). This crust is a 2–3 mm thick salt crust, forming a nearly continuous cover in an area with small patches of reeds. The lake bed crust is a 1–1.5 cm thick salt crust, sampled on the dry lake bed north of Muynak (Site 6), in a level area without any vegetation. In this area, the lake bed has been exposed since about 1990.

All samples were collected in April. The mean surface air temperature during this month is about 7 °C, as opposed to −10 °C in January and 25 °C in August (Benduhn and Renard, 2004).

### 2.2. Methods

Two to four thin sections were prepared for each crust, following the impregnation of samples with a cold-setting polyester resin. Mineral identification was checked by EDS analysis, using uncovered thin sections (Noran Vantage microanalysis system, Jeol JSM-6400 scanning electron microscope). X-ray diffraction data were obtained for the lake bed crust (Phillips X'Pert system, CuKα radiation).

Detailed analyses were carried out on the lake bed crust to identify residues of pesticides. These determinations, using various preparation techniques and Gas Source Mass Spectrometry, failed to produce any detectable concentrations. Toxics were either initially absent or they deteriorated with time due to exposure to light and heat.

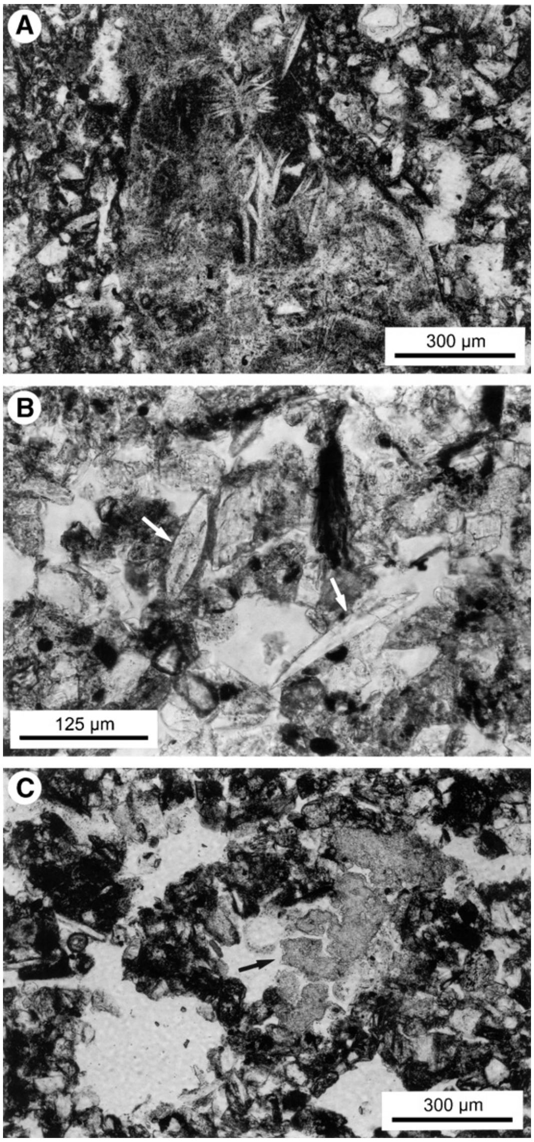


Fig. 2. Takyric crust. (A) Aggregate of narrow lenticular gypsum crystals (centre), with a high concentration of fine sediment as inclusion (plain-polarised light, PPL). (B) Lenticular gypsum crystals [arrows], developed in the sand-rich sediment matrix (PPL). (C) Aggregate of small tabular gypsum crystals in a pore [arrow] (PPL).

## 3. Results

### 3.1. Takyric crust

The takyric crust has a high sand content in most parts (see Fig. 2). It also includes fragmented horizontal fine-grained (clayey) layers or lenses (250–750 µm thick), with a parallel alignment of the clay particles, a very low sand content and an admixture of micritic carbonates. An upward decrease in fine sand content is recognised along the base in some parts of these layers. The pore system is dominated by vesicles in some parts.

Gypsum ($CaSO_4 \cdot 2H_2O$) is the only salt mineral that is recognised for the crust. It occurs mainly as dense aggregates (up to 0.75 by 1.5 mm) consisting of narrow lenticular crystals, with an important amount of calcareous fine sediment as inclusion (Fig. 2A). A similar type of gypsum occurrence is recognised as part of some fragmented fine-grained layers. Gypsum also occurs as scattered narrow to wide lenticular gypsum crystals throughout the crust (Fig. 2B), locally in high concentrations. Aggregates of small sub/euhedral tabular gypsum crystals in pores represent a third type of gypsum occurrence (Fig. 2C).

### 3.2. Solonchak crust

The Solonchak crust from Site 5 consists of fine-grained calcareous material with a low sand content (see Fig. 3A). It has a high total macroporosity in the lower part, represented by irregular pores. Vesicles are common in the more massive upper part (Fig. 3A).

The irregular surface of the crust is partly covered by a rather coarse-crystalline thenardite coating ($Na_2SO_4$) with a xenotopic fabric (up to 150 µm thick) (Fig. 3B). Bloedite ($Na_2Mg(SO_4)_2 \cdot 4H_2O$) occurs along the base of this coating in some parts. This bloedite occurrence contains a greater amount of groundmass material as inclusion than the thenardite coatings (see Fig. 3B).

Gypsum occurs as scattered lenticular or anhedral crystals throughout the crust. Some crystals are partly replaced by bassanite ($CaSO_4 \cdot 0.5H_2O$) or anhydrite ($CaSO_4$) along their sides, producing topotactic replacement patterns. The sides of some crystals with bassanite/anhydrite remnants are covered by microcrystalline gypsum. In some parts of the crust, pores are lined by thin halite coatings (NaCl) (see Fig. 3A). Locally, the crust contains clusters of acicular crystals with low interference colours, occurring partly as radial aggregates (probably eugsterite, cf. Site 1). Similar crystals occur as inclusions in some halite coatings.

A crust on a Solonchak soil sampled at another location (Site 1) has a sandy texture. It contains scattered gypsum crystals that are mainly prismatic, with enclosed sand grains in some larger subhedral crystals (Fig. 3C). Other salt mineral occurrences, largely confined to the upper 2 mm of the sample, are xenotopic aggregates of small bloedite crystals and aggregates of acicular eugsterite crystals ($Na_4Ca(SO_4)_3 \cdot 2H_2O$) (Fig. 3D). Halite mainly occurs as thin coatings, covering bloedite and eugsterite occurrences in some parts (see Fig. 3D).

### 3.3. Lake bed crust

The crust covering the dry lake bed is a nearly pure accumulation of evaporite minerals. As described below, it typically consists of three successive units: (i) a basal unit of microcrystalline to fibrous hexahydrite ($MgSO_4 \cdot 6H_2O$), followed by (ii) an interval with a high bloedite content and with hexahydrite aggregates and coatings, followed by (iii) an accumulation of halite crystals with associated kainite ($KMg(SO_4)Cl \cdot 3H_2O$). XRD analysis confirms the presence of all mentioned

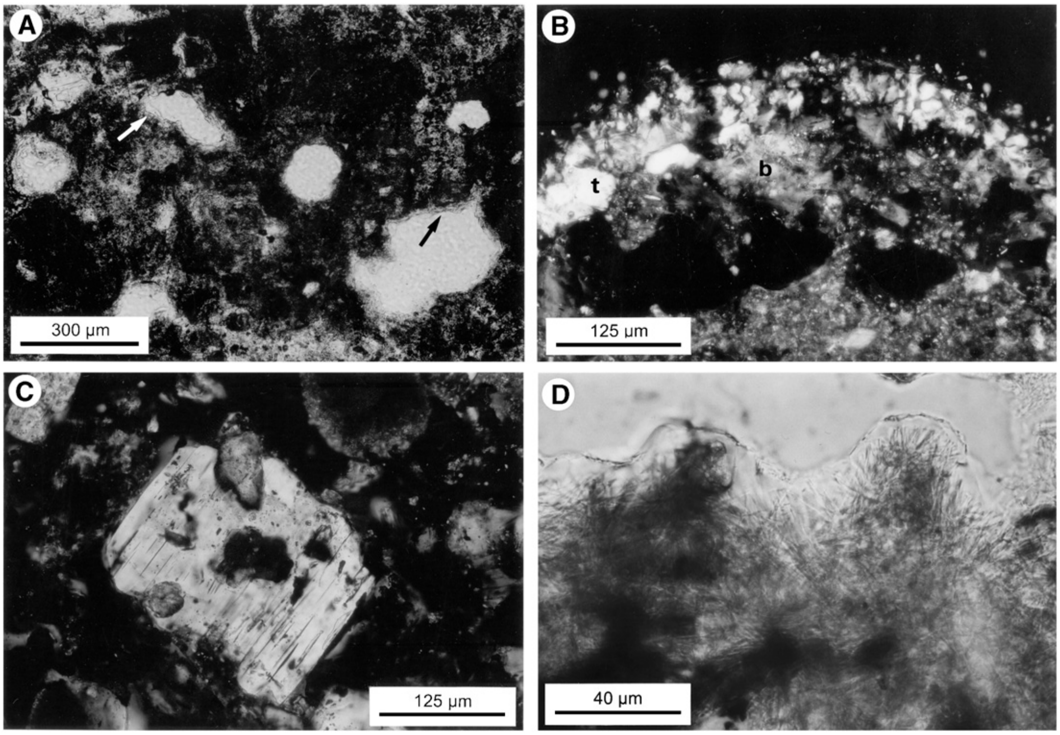


Fig. 3. Solonchak crust. (A) Vesicles, developed in the fine-grained sediment matrix, partly lined with thin halite coatings [arrows] (Site 5) (PPL). (B) Xenotopic thenardite coating (top) [t], with bloedite along the base in some parts (larger crystal size, higher sediment content) [b] (Site 5) (cross-polarised light, XPL). (C) Prismatic gypsum crystal, enclosing sand-sized detrital grains (Site 1) (XPL). (D) Aggregate of acicular eugsterite crystals covered by a halite coating (Site 1) (PPL).

components, and it also suggests the occurrence of minor amounts of gypsum in the basal unit.

In thin sections, the basal unit mainly consists of brownish fine-grained material, which is partly fibrous (see Fig. 4A, lower part). This material is identified as hexahydrite, based on EDS results and on the optical properties of the coarser fibrous parts.

The bloedite-dominated middle unit is characterised by a high macroporosity. Bloedite occurs as horizontal lenses and as isolated crystals, and locally as radial intergrowths. Three successive lenses or layers are recognised in one sample. Several lenses contain a thin layer of small subhedral halite crystals in the centre (Fig. 4A). Brownish microcrystalline hexahydrite, similar to hexahydrite in the lower unit, occurs between the bloedite crystals and as thick bands around bloedite occurrences (Fig. 4B). These bands, which have an equal thickness along all sides of the surrounded bloedite, mainly occur in the upper part of the unit. They are locally entirely absent in the lower part, where the crust is characterised by subhedral bloedite forms and a high porosity (Fig. 4C). Some hexahydrite aggregates between the bloedite crystals show zonation in the outer part. The unit also contains some halite crystals, occurring mainly in pores, covering the hexahydrite aggregates and coatings. Some scattered halite crystals embedded in the microcrystalline hexahydrite mass are also present. Kainite locally occurs in one of the bloedite lenses, and it is associated with halite in some pores. Acicular crystals with low interference colours (eugsterite), partly forming radial aggregates, occur in pores and as inclusions in halite crystals and in some bloedite crystals.

The upper unit consists of an accumulation of sub/euhedral halite crystals (Fig. 4D), commonly with a high concentration of fluid inclusions. Kainite occurs as isolated, anhedral to euhedral, equant to short prismatic crystals (Fig. 4D), and locally as radial aggregates. It mainly occurs between the halite crystals, but it is also recognised in cavities.

## 4. Discussion

All studied crusts contain evaporite minerals, as discussed below. Salt minerals that have previously been described for the Aral Sea basin include bloedite, gypsum, glauberite ($Na_2Ca(SO_4)_2$), halite and mirabilite ($Na_2SO_4 \cdot 10H_2O$), occurring in Early Pleistocene to late

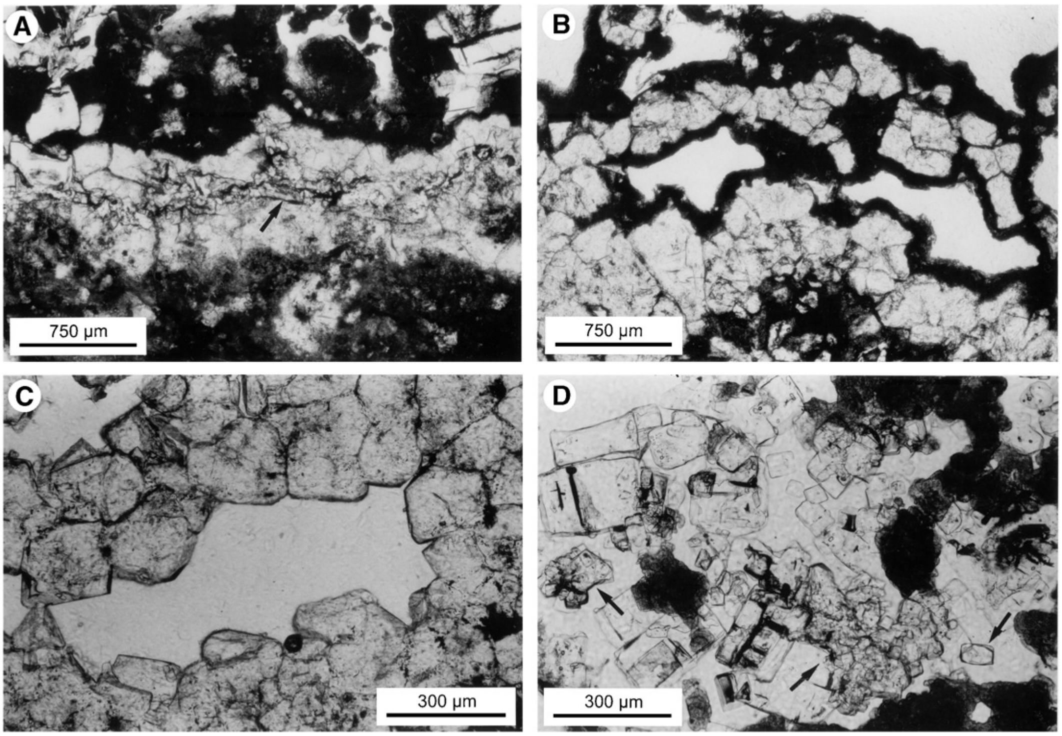


Fig. 4. Lake bed crust. (A) Bloedite layer with a thin halite layer in the middle [arrow] (basal part of middle unit) (PPL). (B) Bloedite lenses surrounded by thick hexahydrite coatings (dark) (PPL). (C) Eu/subhedral bloedite crystals, in a part of the crust without associated hexahydrite (PPL). (D) Accumulation of mainly euhedral halite and kainite crystals [three kainite occurrences indicated by arrows] (upper unit) (PPL).

Holocene deposits (Létolle and Mainguet, 1997; Boomer et al., 2000). At present, only calcite and gypsum are forming as direct precipitates from the lake water (Létolle et al., 2005).

### 4.1. Takyric crust

The takyric crust is derived from layered deposits. Fine-grained layers were formed by settling of dispersed clay particles after flooding. These layers subsequently became fragmented by shrinking. Swell-shrink processes, which affected the more coarse-grained parts as well, also resulted in the development of a polygonal network of cracks (Singer et al., 2003). The vesicular structure is another expression of wetting and drying cycles, causing the entrapment of air (e.g. Miller, 1971). Vesicular structures have already been reported for takyric crusts and the underlying horizons (Paletskaya et al., 1958; Evenari et al., 1974).

Gypsum is the only salt mineral in the crust. It formed in conditions with a lower salinity than the other crusts, which contain more soluble salts. Gypsum mainly occurs as aggregates of lenticular crystals, developed in a fine-grained sediment matrix. This demonstrates that gypsum formed preferentially in the clay layers, by evaporation of interstitial brines that were contained in this material. This did not result in the formation of gypsum along the sides of the layers or along macropores, which may have been absent at that time. In some parts, gypsum aggregates are the only remnants of the clay layers.

Saline solutions may have been derived from flood waters rather than from a shallow groundwater body. An influence of flooding is also suggested by the presence of small sub/euhedral tabular gypsum crystals in pores. This type of gypsum forms in brine-filled macropores that extend to the soil surface (Mees, 1999), without crossing the crust in this case. There are no indications that the formation of these gypsum aggregates was associated with local dissolution of gypsum that formed at an earlier stage.

### 4.2. Solonchak crust

The fine-grained Solonchak crust from Site 5 shows no sedimentary structures or microfabrics, suggesting a strong degree of pedoturbation. Its partly vesicular structure, which also characterises the takyric crust, is again an indication of flooding.

The crust contains bloedite and thenardite along its irregular surface, halite along the sides of pores, and isolated gypsum crystals within the groundmass. The presence of bloedite and thenardite along the surface, containing sediment inclusion in some parts, is not related to the evaporation of surface brines. They formed by evaporation of soil solutions contained in the groundmass. There are no indications that thenardite formed by dehydration of a mirabilite precursor. The absence of bloedite or thenardite in lower parts can be related to the lack or low rates of evaporation in pores that are nearly or entirely closed. Halite coatings did develop in some parts of the pore system, at a different stage.

Gypsum formed at an earlier stage than the other salt minerals, at lower salinities. Gypsum crystals were partly transformed to bassanite, in conditions with high pore water salinities and high temperatures (e.g. Blount and Dickson, 1973). Locally, these dehydration products were converted again to gypsum, but not in the form of topotactic replacement.

The sandy surface crust from Site 1 contains gypsum crystals that formed in a water-saturated surface layer following flooding, resulting in the development of non-lenticular forms that partly formed by non-displacive growth. The development of all other salt occurrences are related to the evaporation of interstitial brines, which are not necessarily derived from the surface.

### 4.3. Lake bed crust

The crust covering the dry lake bed is mainly composed of bloedite, hexahydrite and halite, with subordinate amounts of kainite. Bloedite has been described as a component of recent salt lake deposits and soil crusts from several locations (e.g. Vizcayno et al., 1995; Sánchez-Moral et al., 1998). Hexahydrite and especially kainite are much rarer minerals.

Hexahydrite is stable at higher temperatures than epsomite ($MgSO_4{\cdot}7H_2O$) (e.g. Keller et al., 1986), which is a more common Mg-sulfate phase. Hexahydrite generally occurs as the only Mg-sulfate mineral in salt efflorescences during summer, whereas epsomite is present during other seasons (e.g. Timpson et al., 1986). Hexahydrite has also been described for surface horizons of soils containing epsomite at greater depths (e.g. Doucloux et al., 1994). In the Aral Sea basin, epsomite is known to occur (Boomer et al., 2000; Singer et al., 2001; Benduhn and Renard, 2004), and synsedimentary hexahydrite formation is predicted based on present lake water composition (Létolle et al., 2005).

Kainite has been described as a synsedimentary deposit in only few marine and lacustrine basins

(Holwerda and Hutchinson, 1968; Garcia-Veigas et al., 1995). Other occurrences are interpreted as diagenetic formations (e.g. Schaller and Henderson, 1932; Lowenstein and Spencer, 1990).

The Aral Sea lake bed crust displays synsedimentary features, indicating that it formed from surface brines. These features include the presence of horizontal bloedite layers, partly with intercalations of sub/euhedral halite crystals. The high macroporosity of the middle unit is caused by a loose stacking of bloedite crystals and rafts, rather than by post-depositional dissolution of a more soluble synsedimentary phase. The loose accumulation of halite crystals along the top of the crust also represents a subaqueous precipitate. Associated kainite, which party occurs as sub/euhedral crystals, could also be synsedimentary. Its local presence in dissolution cavities in halite crystals records a difference in timing of development for at least some occurrences.

Diagenetic features include the occurrence of thick hexahydrite coatings around bloedite occurrences. They formed by pseudomorphic replacement, during an interaction with Mg-rich brines. The equal thickness of the coatings indicates that the crust was completely pervaded by brines of this type, suggesting subaqueous conditions. Other hexahydrite occurrences, including those of the lower unit, can also be diagenetic formations. The fibrous texture of hexahydrite is in any case more compatible with mineral formation by replacement. Other diagenetic features include the presence of halite crystals in voids, locally with associated kainite. Continued bloedite growth or recrystallisation after its synsedimentary formation is recorded by the presence of mineral inclusions in some crystals.

In summary, the development of the crust started with subaqueous bloedite sedimentation. A change in brine composition, with an increase in magnesium content, resulted in the replacement of bloedite by hexahydrite, in subaqueous conditions. During a final stage, halite and kainite formed along the surface and locally in pores, from brines with higher concentrations of potassium, which behaved as a conservative element up to that moment.

### 4.4. Comparison between sites

The takyric and Solonchak crusts consist of slightly calcareous siliciclastic material. In the takyric crust, salts have crystallised within the groundmass, mainly in parts with a fine-grained texture. In the fine-grained Solonchak crust (Site 5), evaporite minerals mainly formed along the surface and along the sides of pores. In the Solonchak crust with a sandy texture (Site 1), salt minerals occur in the pore space between sand grains. These differences illustrate the effect of hydraulic properties, determining the location of sites where evaporation takes place within a soil horizon. In contrast to these crusts, the salt crust on the dry lake bed is a pure salt accumulation formed from brines that covered the surface.

Taken together, the three studied crusts are characterised by a Ca–Na–Mg–(K)–$SO_4$–Cl salt mineral assemblage. This is largely compatible with earlier reports about evaporite mineral occurrences in the Aral Sea basin. The salt mineral assemblages in the crusts represent products formed at successive stages in the evolution of Aral Sea waters. The observed mineral associations are in agreement with theoretical predictions for this basin, which state that calcite and gypsum formation is followed by the sequence gypsum + halite, mirabilite + halite, bloedite + halite, hexahydrite + kainite + halite, followed by the formation of other Mg-sulfate minerals (Létolle et al., 2005).

## 5. Conclusions

The takyric, Solonchak and lake bed crusts represent three distinct morphological types of surface crusts encountered in the southern Aral Sea basin. The takyric crust and the fine-grained Solonchak crust are structural crusts, in which the presence of salts does not contribute noticeably to crust development. In the Solonchak crust with a sandy texture, the salts do partly act as a cement that provides coherence. In contrast to the other crusts, the lake bed crust is entirely the product of salt accumulation.

The surface crusts are a potential source of salts that can be distributed over a wider area by deflation. Crystal growth did not increase the susceptibility of the takyric and Solonchak soils to surface deflation, and the main part of the lake bed crust is a coherent intergrowth rather than a loose accumulation of salt crystals. The resistance of the salt-rich crusts against deflation was confirmed by wind tunnel experiments, using laboratory-produced equivalents (Argaman et al., 2006). However, the crusts can still yield significant amounts of salt-bearing dust, which is mainly generated by an interaction with saltating particles.

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