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MINERALOGY OF AL-HASA DESERT SOILS (SAUDI ARABIA)

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Abstract—X-ray mineralogical examination of the 2–20 μm fraction of oriented samples from a highly calcereous swamp soil and neighbouring Mio-Pliocene strata in Al-Hasa showed a wide range in mineralogy: attapulgite, illite, montmorillonite, chlorite and kaolinite, in decreasing order. Powder X-ray diffraction revealed an abundance of attapulgite, calcite, quartz and in a few samples, traces of dolomite, Fe-oxides, feldspars and gypsum.

The soils are believed to have been formed by deposition of highly calcareous wind-borne silt particles in an already formed swamp. The surface and subsurface horizons are underlain by an organic residue layer, 30–50 cm thick, containing 14–36% organic matter. The whole profile sits on hard, impervious, sedimentary layers that mineralogically resemble some strata of the outcrop.

Attapulgite and illite are the most abundant and common clay minerals in the soils and strata, but are most pronounced in the latter. Attapulgite not only occurs in Al-Hasa, but is widely distributed in the Arabian Peninsula; from east of the Mediterranean through the deserts of Syria and Iraq down to eastern Saudi Arabia, where it occurs only in association with limestone parent material. In this area of extreme aridity (Al-Hasa), the origin of the minerals and their relative abundance is believed to be associated with the source of sediment since minimum alteration seems to have taken place after deposition.

INTRODUCTION

General

Scarcity of good cultivable soil rather than water could be the major physical problem confronting agricultural development in the coastal regions of arid lands. Thus detailed studies of soil profiles, preferably down to bedrock, are prerequisites for sound management of the scarce soil resources of arid regions. Al-Hasa oasis has been chosen for intensive soil studies because its agricultural potential is dependent on the accessibility and management of soil resources.

Al-Hasa oasis is located in the Eastern Province of Saudi Arabia (Maps 1 and 2). One hundred and sixty-two natural springs yielding a total flow of 15 m^3/sec, 80% of which is from thermal sources (Saxon, 1968), have made the area historically, presently and potentially of great agricultural importance.

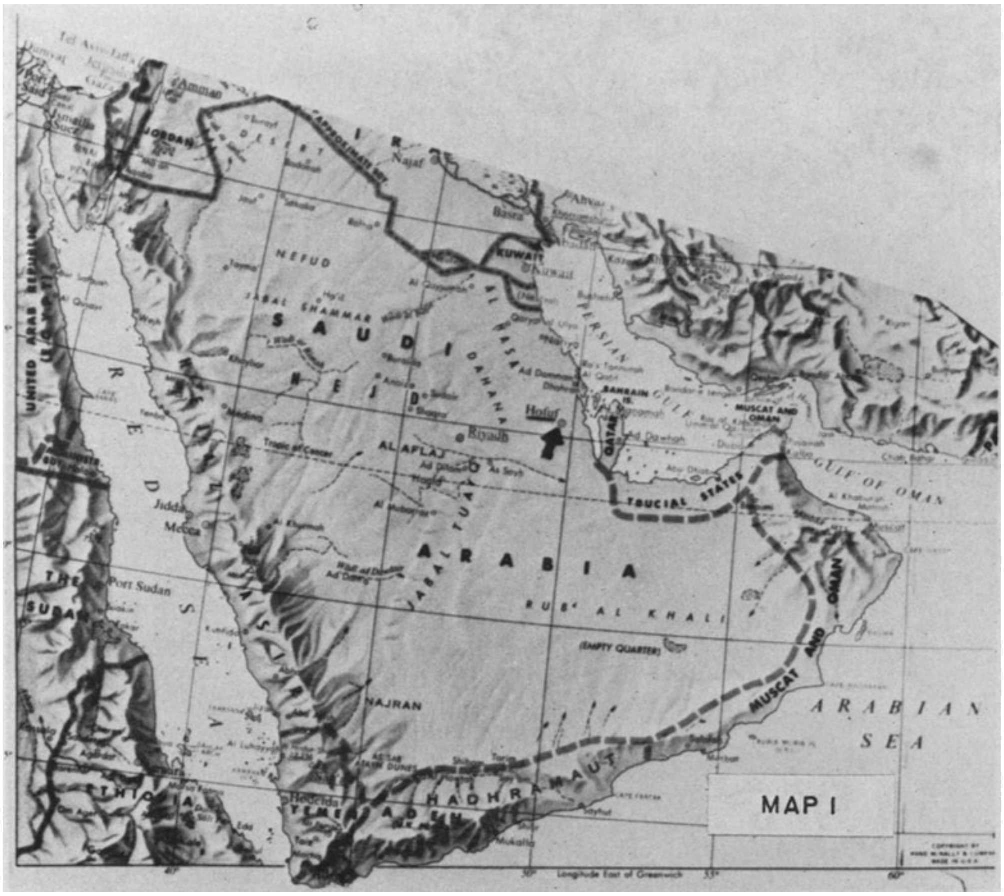
Salinity of the irrigation water (1500 ppm), lack of adequate drainage and an impervious layer at a depth less than 2 m resulted in salinization of the soils. Swamps were formed in depressions, aided by the uncontrolled flow of the natural springs. The only natural drainage to the north of the oasis has been blocked by advancing sand dunes which progressively threaten the oasis and have already buried some villages. Wind erosion is also a serious problem.

Two major developments have taken place in recent years. A one hundred million dollar irrigation and drainage network has been completed, covering an area of 50,000 acres. Advancing sand dunes have been successfully stabilized by planting ethel (Tamarix). As a result, the area has gained its agricultural potential.

The properties of the soils of Al-Hasa, particularly drained swamp soils, are currently being studied with a view to developing a management program. Only mineralogical studies dealing with a profile of the drained swamp, samples from suspected clay layers all over the oasis and samples from individual strata of an outcrop in the middle of the oasis are reported herein. A brief soil description is included but other detailed studies will be reported elsewhere.

Geology

The Arabian Peninsula is divided into the Precambrian plateau with extensive older Paleozoic outcrops in the west adjacent to the Red Sea graben. Eastward slopes the so called Arabian Foreland covered by Paleozoic, Mesozoic and Neozoic formations extending to the Arabian Gulf graben. In the Gulf coastal plain, where Al-Hasa is located, moving sand dunes rest on salt beds and miopliocene strata outcrop (Hofuf formation). In this area, rocks show less reworking, feldspathic sandstones are common, shales tend to be silty and limestones more argillaceous, beds are frequently repeated and the strata are thick (Mitchel, 1957). The coastal plain lies in a geosynclinal zone of sedimentation, the earliest being of terrestrial ori-



Map 1. General topography and drainage of Saudi Arabia (Stewart, 1962). Arrow at Hofuf indicates location of area studied.

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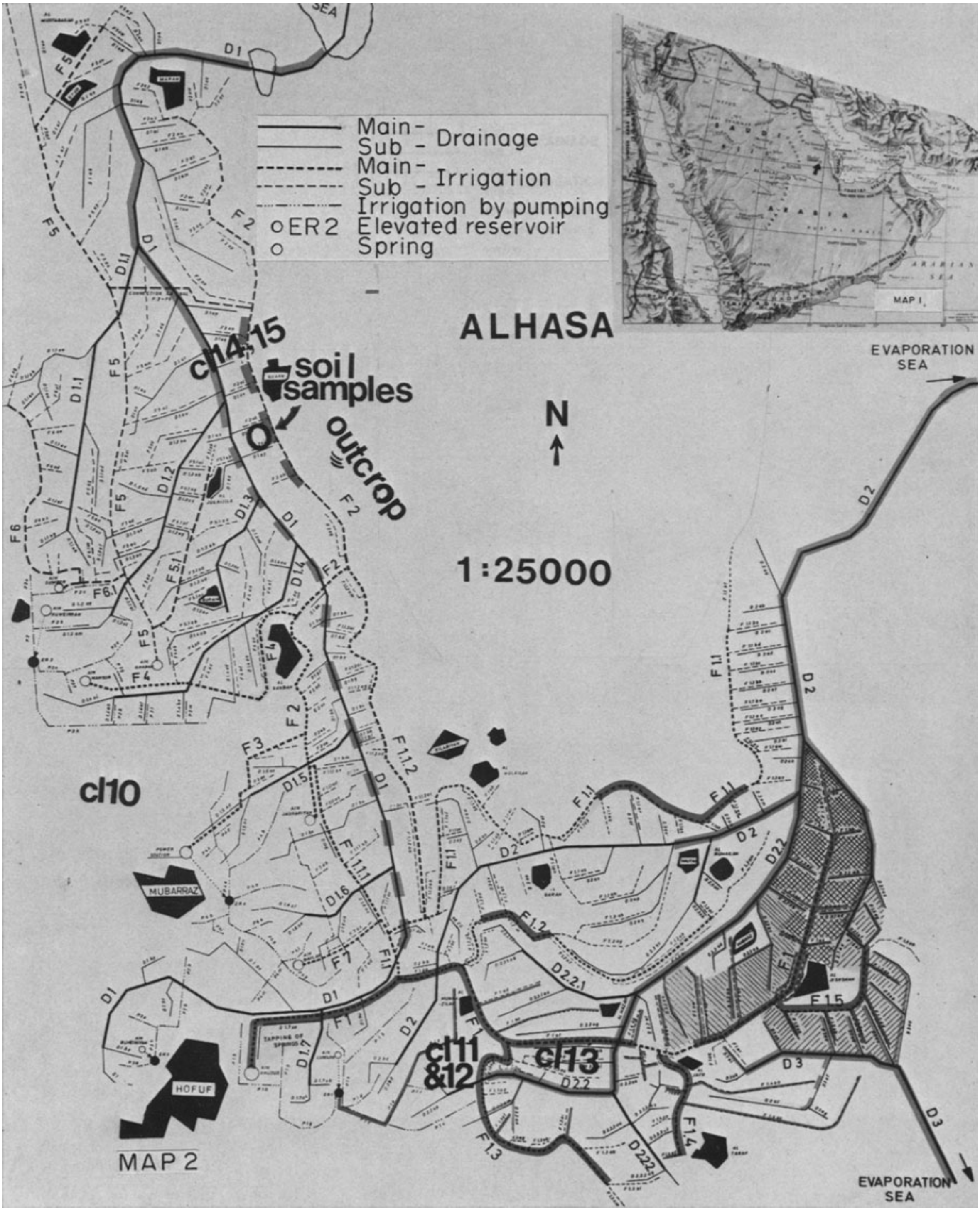

Map 2. Al-Hasa oasis showing sample location and the irrigation and drainage network.

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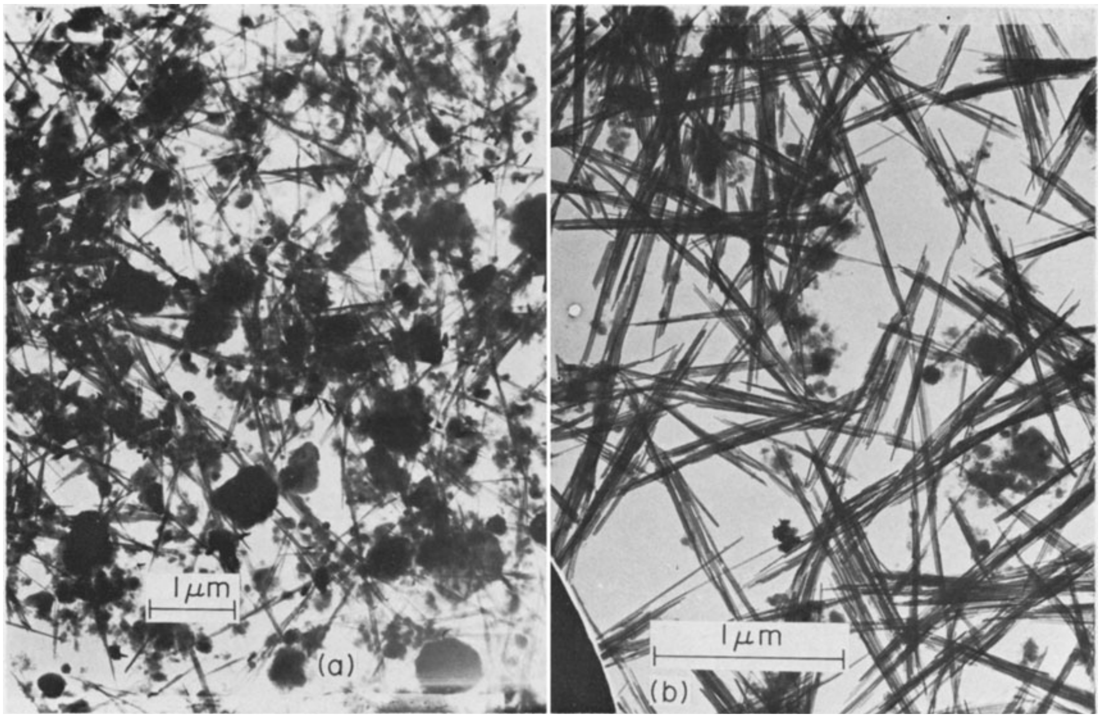

Figure 4. Electron micrographs of attapulgite particles from a desert soil of Al-Hasa region of Saudi Arabia (a—18,000×; b—40,000×).

gin, followed by marine, with intercalation of both. Marine–continental–lagoonal facies are associated with the geosynclinal belt (Mitchel, 1957).

Soils

The area studied is a gently sloping basin with the only natural drainage to the north blocked by advancing sand dunes. On the periphery of the basin an underlying impervious sedimentary layer protrudes close to the surface and is covered by a thin desert pavement. Within the basin, excluding sand dunes, swamps and hills, the shallow soil profile is composed of two horizons, loamy sand to sandy clay. The latter is of low permeability and may constitute the top of an underlying impervious sedimentary layer. In both horizons the organic content is less than 1%.

The drained swamp soils are almost level, are deep and have differentiated profile characteristics. The surface horizon (30 cm deep) is puffed, of calcareous (70–80%) silt loam with granulated weak structure and organic content of 5%. The subsurface (20–50 cm) is more calcareous, structureless silt with slightly higher organic matter. The upper horizons are underlain by a darker layer of organic residue (30–50 cm deep) containing some undecomposed plant stems and the organic content is 14–36%. In other profiles, the organic residue layer is repeated, each layer being overlain by silt. The whole profile is underlain by an impervious layer of fine silt and clay, the colour of which resembles some beds in the adjacent outcrop.

MATERIALS AND METHODS

Field sampling

Two sampling procedures were followed depending on the objective of the study. For soil studies of the drained swamp an area of 1 km^2 was divided into three locations and a zigzag composite horizon sampling was carried at a distance of 50 m between profiles (Sayegh *et al.*, 1958). For mineralogical studies, samples from all over the oasis were collected at different depths depending on the occurrence of a clayey layer within 2-m depth. Beds in an outcrop in the middle of the oasis were sampled to aid in the interpretation of the origin of the clay.

Mechanical analysis

Sand, silt, and clay were determined by the pipette method. Carbonates were determined in each fraction. The 2–40-μm fraction constitutes the bulk of the soil samples (46.3–68.8%) and a carbonate content of 5.2–56.8%. The clay fraction constituted 11.5–14.9% but was mostly carbonate in composition (66.8–89.9%) except for the clay of the organic layer which was 12.7% carbonate. During the particle separation for the mineralogy study, when carbonates were removed, the bulk of the sample was in the 2–20-μm fraction.

Sample preparation

Samples were dispersed and freed of carbonates and organic matter according to Jackson (1956) using pH 5 NaOAc. Particle size of 2–20 μm, which constituted the bulk of the carbonate-free samples, was separated and saturated with K and Mg. The oriented samples were prepared according to the paste method of Theisen and Harward (1962), after experimentally finding that X-ray powder diffraction peaks of thus prepared specimens were superior to the conventional suspension drying.

Seven soil samples were selected and the $CaCO_3$ was removed. Iron was extracted three times with the Na–dithionite–citrate–bicarbonate method according to Jackson (1956). The amorphous materials were extracted by 0.5 N NaOH (Jackson, 1956), and then organic matter was removed. The samples were X-rayed.

X-ray powder diffraction

Powder and oriented samples were X-rayed with nickel-filtered Cu K_α radiation from a Norelco diffractometer equipped with a graphite crystal monochromator, 1/2° divergence and scatter slits and 0.006 in receiving slit. Scanning speed was 1°/min at 45 kV and 20 mA. A proportional gas flow detector and a chart speed of 30 in./hr were used.

RESULTS

Clay minerals of the soils

X-ray powder diffraction of the 60-mesh untreated soil powders of the sampled horizons showed mainly quartz, calcite and inconspicuous peaks of some clay minerals due to the presence of $CaCO_3$, organic matter and amorphous materials (Table 1).

The calcium carbonate, organic matter and amorphous materials for the three horizons of profile IC is given in order to illustrate this effect. The carbonate content of IC1 and IC2 horizons was 80–89%: while the amount of amorphous material on carbonate free basis, was 15.5 and 20%, respectively. The IC3 horizon contained 22% carbonates, 22.6% amorphous material on a carbonate-free basis and 14.5% organic matter.

Oriented 2–20-μm fractions that were treated to remove carbonates and organic matter generally showed weak peak intensities of kaolinite, illite, attapulgite, chlorite and montmorillonite (Figure 1 and Table 2). Removal of iron and amorphous material from carbonate-free samples resulted in sharper and more intense peaks (Figure 2 and Table 3). When parts of the same samples were additionally treated to remove organic matter, peak intensity and sharpness were strikingly improved (Figure 3). The characteristic increase in the 001 peak intensity of chlorite after heating (Jackson, 1964) became evident only after removal of iron and amorphous material and increased after removal of organic matter. Heating

Table 1. Relative amounts of minerals of soils and beds of adjacent outcrop in Al-Hasa from X-ray powder diffractograms of powdered samples

Sample No.	Horizon	Attapulgite	Quartz	Calcite	Dolomite	Gypsum	Feldspars	Others
				Soils				
IC1	Surface	S (4)*	S (5)	H (50)	—	—	—	—
IC2	Subsurface	S (3)	S (4)	VH (60)	—	—	—	—
IC3	Organic	S (6)	H (32)	M (16)	—	—	—	—
IF1	Surface	—	S (6)	H (50)	—	—	—	—
IF2	Subsurface	S (3)	S (3)	VH (60)	—	—	—	—
IF3	Organic	S (7)	M (15)	M (15)	—	S (5)	—	S-iron oxides
IIC1	Surface	S (3)	S (3)	H (50)	—	—	—	—
IIC2	Subsurface	S (4)	S (5)	H (50)	—	—	S (6)	—
IIC3	Organic	S (6)	VH (100)	S (8)	—	—	M (15)	—
				Clayey layers in soils				
CL10		S (5)	S (5)	S (12)	—	M (20)	—	—
CL11		S (5)	H (30)	M (23)	S (5)	S (10)	—	—
CL12	Green	S (6)	M (24)	S (10)	—	—	—	—
CL12	Pink	S (6)	H (32)	H (30)	—	—	—	S-iron oxide
CL13		N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
CL14		—	VH (60)	H (30)	—	—	—	—
CL15		S (5)	S (12)	H (38)	—	—	—	—
				Outcrop beds				
CL1	Bottom strata	S (6)	M (20)	M (25)	—	—	S (4)	—
CL2		N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
CL3		S (12)	S (13)	S (7)	—	—	S (6)	—
CL4		S (12)	H (38)	S (5)	—	—	S (11)	—
CL6		N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
CL7		S (7)	VH (70)	S (6)	S (10)	—	S (5)	—
CL8		S (6)	H (40)	M (20)	—	—	S (5)	—
CL9	Top strata	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.

* Numbers in brackets indicate relative peak intensities.
N.D. not determined, S small—5–15%, M medium—15–25%, H high—25–50%, VH very high—50%.

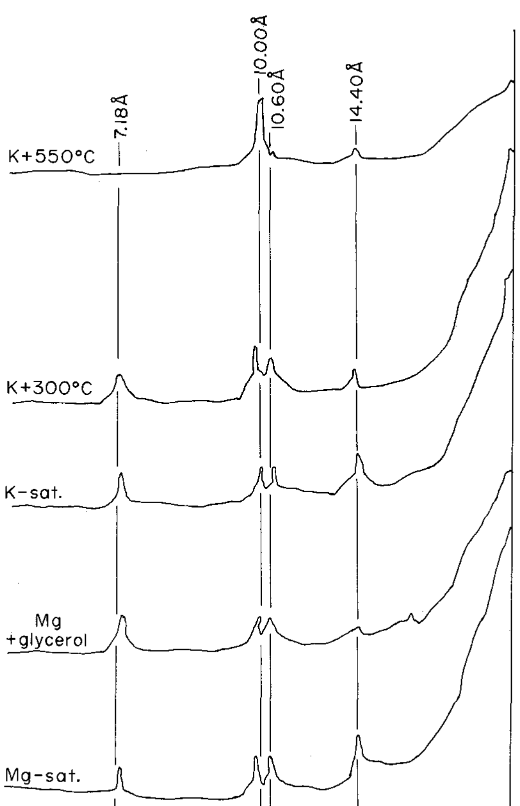

Figure 1. X-ray diffractograms for different treatments of a soil sample after $CaCO_3$ and organic matter were removed.

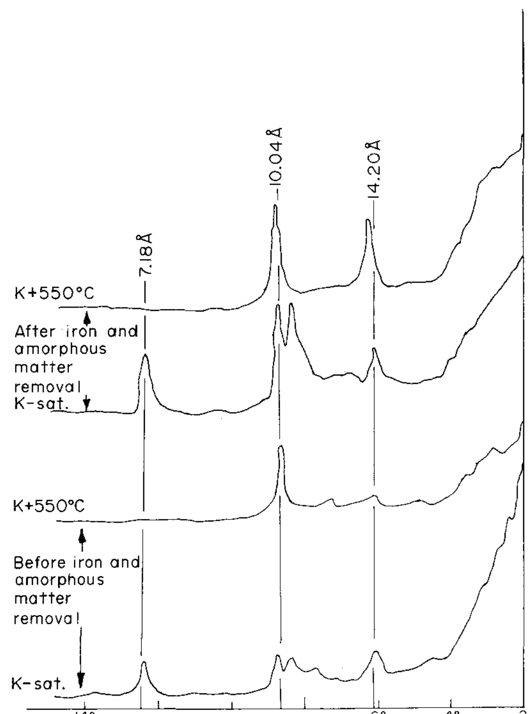

Figure 2. X-ray diffractograms of K-saturated and K-saturated and heated at 550°C of a soil sample before and after iron and amorphous materials removal. Calcium carbonate was already removed from the sample.

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Table 2. Relative amount of minerals of soil horizons and beds of adjacent outcrop in Al-Hasa, from X-ray powder diffractograms of oriented samples of 2–20-μm fraction from which organic matter and $CaCO_3$ were removed

Sample no.	Horizon	Kaolinite	Illite	Attapulgite	Chlorite	Montmorillonite
			Soils			
IC1	Surface	S (4)*	S (6)	S (6)	S (6)	S (6)
IC2	Subsurface	S (6)	S (6)	S (6)	S (6)	S (6)
IC3	Organic	S (4)	S (7)	S (6)	S (6)	S (6)
IID1	Surface	S (10)	S (13)	M (16)	S (14)	S (14)
IID2	Subsurface	S (7)	S (13)	M (16)	M (16)	M (21)
			Clayey layers in soils			
CL10		M (17)	S (13)	S (14)	M (20)	H (30)
CL11		S (12)	M (24)	H (29)	M (18)	H (25)
CL12	Green	S (6)	H (27)	M 24)	S (7)	S (6)
CL12	Pink	S (12)	H (25)	H 28)	M (20)	M (20)
CL13		S (6)	S (11)	S (12)	S (7)	S (7)
CL14		S (13)	M (23)	S (12)	S (13)	H (30)
CL15		S (10)	M (19)	M (15)	S (13)	M (21)
			Outcrop beds			
CL1	Bottom strata	S (5)	M (18)	M (18)	M (18)	H (33)
CL2		S (6)	S (10)	H (30)	S (7)	S (6)
CL3		S (5.5)	M (21)	H (37)	S (8)	—
CL4		S (14)	M (22)	M (23)	M (18)	H (34)
CL6		M (20)	H (31)	H (35)	M (18)	M (18)
CL7		S (6)	M (21)	H (29)	S (14)	S (6)
CL8		M (17)	H (31)	M (22)	S (12)	S (6)
CL9	Top strata	S (4)	S (13)	H (30)	S (10)	M (15)

* Numbers in brackets indicate peak intensities.
N.D. not determined, S small—5–15%, M medium—15–25%, H high—25–30%, VH very high—>50%.

K-saturated samples to 550°C greatly diminished the attapulgite peak.

The clayey samples CL10, CL11, CL12 green, CL12 pink, CL13, CL14 and CL15, were collected from 2-m depth at different locations of the oasis. These samples are distinctly different from the upper surface and subsurface horizons; they are hard, blocky and have distinct pink, green, gray and reddish colors. X-ray powder diffraction of the untreated 60 mesh powder showed peaks in the 10.5–10.7 Å range. This mineral was subsequently identified to be attapulgite by electron microscopy (Figure 4). X-ray powder diffractograms of oriented 2–20-μm fractions, that were treated to remove organic matter and carbonates, revealed as wide a range in mineralogy as was found in the upper soil horizons. The relative mineral content, as reflected by measured peak intensities, was much higher than the upper soil horizons (Table 2).

Clay mineralogy of the outcrop beds

Exposed beds of an outcrop located in the middle of the oasis were sampled (CL1–CL9) for mineralogical analysis. The intention was to compare clay minerals in the soils with the sedimentary soft rocks of the outcrop. This would aid in the interpretation of the origin of soil clay minerals.

X-ray powder diffraction of CL3, CL4, CL7 and CL8 revealed weak peaks of the 14.5 Å minerals and

Table 3. Relative amount of minerals of some soil horizons and beds of adjacent outcrop in Al-Hasa from X-ray powder diffractograms of oriented samples of 2–20-μm fraction from which $CaCO_3$, organic matter, iron oxides and allophane were removed

Sample no.	Kaolinite	Illite	Attapulgite	Chlorite	Montmorillonite
			Soils		
IC1	S (10)*	M (16)	S (10)	S (12)	S (11)
IC2	S (12)	M (22)	S (14)	M (16)	S (14)
IC3	S (6)	S (12)	S (12)	S (14)	S (14)
			Clayey layers in soils		
CL10	M (25)	M (24)	M (20)	M (17)	M (20)
CL14	S (15)	M (20)	S (10)	S (12)	H (30)
CL15	S (14)	M (22)	H (27)	M (22)	VH 62)
			Outcrop beds		
CL1	S (5)	M (17)	M (16)	M (15)	H (40)

* Numbers in brackets indicate relative peak intensities.
N.D. not determined, S small—5–15%, M medium—15–25%, H high—25–50%, VH very high—>50%.

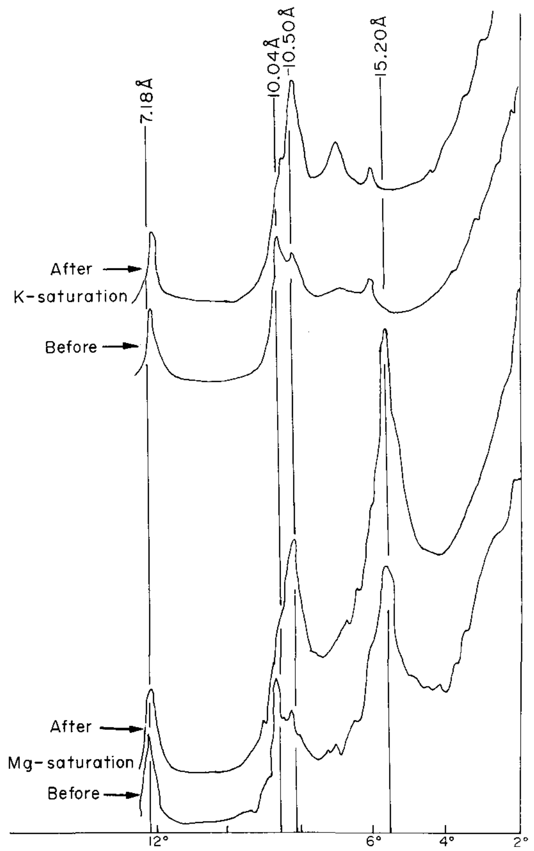

Figure 3. X-ray diffractograms of K- and Mg-saturated samples before and after organic matter removal. Calcium carbonate, iron and amorphous materials were already removed from the samples before the organic matter removal.

of illite and relatively strong peaks of attapulgite (10.5–10.8 Å). X-ray diffractograms of oriented 2–20-μm fractions of all samples from the beds, revealed prominent peaks of attapulgite, illite, montmorillonite, chlorite and kaolinite in decreasing order (Table 2).

Other minerals

Minerals clearly identifiable from powder X-ray diffractions are shown in Table 1. Chemically determined calcite occurred in all samples in quantities ranging from 22% in the buried organic residue layers IC3, IIC3 and IF3, to about 90% in the surface IC1, IF1, IIC1, IID1 and subsurfaces IC2, IF2, IIC2 horizons. The calcite content in the beds of the outcrop CL1–CL9 ranged from 26 to 50%. Pedologic features strongly suggest deposition of wind-borne calcareous silt particles after the water table has risen above the soil surface. Thus, larger quartzitic particles would fall to the submerged surface. The concentration of quartz in the organic residue layers (IC3, IF3, IIC3) may have resulted from the filtering out of freely falling particles in water. Sand dunes encroaching on the oasis from the north, where sandstorms blow, provide quartz in the wind-borne material.

Samples from the beds of the outcrop all showed a feldspar content (Table 1). Dolomite was detected in one sample from the strata (CL7) and one clay sample from the soil (CL11). Iron oxides were detected only in an organic residue layer (IF3) and an underlying green fraction of a soil clay layer (CL12 green).

Gypsum was only identified in an organic residue layer (IF3) and two soil clay samples (CL10, CL11). Its amount, from a measured X-ray powder diffraction peak at 7.56 Å, ranged from small in IF3 to high in CL10.

DISCUSSION

The above results suggest that X-ray powder diffraction for mineralogical investigations may reveal primary minerals and some secondary clay minerals present in these desert soils. Clay minerals in desert regions may be diluted by common and abundant carbonates and coated with amorphous materials such that X-ray peaks of oriented clay minerals become diffuse, broad and weak. Although coatings of clay minerals are generally indicative of weathered soils (Jackson, 1964), pedologic properties of Al-Hasa soils indicate that these soils have not been weathered in place. This is indicated in the expression of the profile and shown in the wind-deposited surface and subsurface horizons as well as in the underlying hard clay layer. The amount of amorphous materials in desert soils may not be high, if expressed on the entire soil basis, but relatively high when expressed on a carbonate-free basis. Amorphous materials in Al-Hasa desert soils may occur partly as coatings on clay minerals, as reflected by the increase of peak intensity and sharpness upon their removal, and as discrete minerals as evidenced by the decrease of the X-ray powder diffraction baseline. The presence of an amorphous coating on the clay minerals of these soils may indicate the influence of an environment in which these clays were formed and from which they were transported.

X-ray powder diffraction of oriented samples, particularly after removal of carbonates, organic matter and amorphous material, revealed a wide range of mineralogy: attapulgite, illite, montmorillonite, chlorite and kaolinite. The swamp soils are very recent and must have been formed by wind transported material in an already formed swamp, as has been stated in the introduction about the soils. Other soils of Al-Hasa are shallow calcareous desert pavements. All the soils of the area are underlain by an impervious sedimentary layer that is believed to represent a discontinuity in the profile. The colour, texture and mineralogy of this relatively hard layer, which is different depending on the locality of the sample, shows great resemblance to some of the exposed beds and may represent buried beds of the same outcrop.

The abundance and general occurrence of attapulgite in the soils and outcrops of Al-Hasa could serve as an index mineral that links the Al-Hasa region with neighbouring regions having geological and mineralogical similarities.

Eastern Saudi Arabia is geologically linked, in terms of parent material and age, with the arid and semi-arid regions of Iraq, Syria and east of the Mediterranean. Attapulgite, in association with kaolinite, chlorite and mica, is of common occurrence in Syrian desert soils and is believed to originate, with little alteration, from the underlying limestone parent material (Muir, 1951). Montmorillonite without attapulgite was found on basaltic soils. Jordanian and north Lebanese soils along the Syrian border contain attapugite.* It is then evident that attapulgite occurs in association with limestone parent material over a large arid or semi-arid region extending from east of the Mediterranean through Syria, Iraq, and eastern Saudi Arabia. The mineral may be formed from lagoonal deposits or pyroxenes and amphiboles through hydrothermal action (Caillere and Hein, 1961), derived from the underlying limestone with no alteration (Muir, 1951) and in lagoonal deposits and dry desert lakes (Grim, 1968; McLean *et al.*, 1972). Although pedogenic origin of attapulgite has been reported (Vanden Heuvel, 1966) more evidence indicates lacustrine or alluvial origin (McLean *et al.*, 1972; Millot, 1970; Parry and Reaves, 1968). In Al-Hasa, extensive large gravels consisting of quartz, various types of igneous and metamorphic rocks and limestone boulders derived from Tuwayq mountains 400 km inland, suggest rapid erosion of the interior in the Miocene age as a result of eastward tilting of the Arabian foreland (Powers *et al.*, 1963). Al-Hasa shows some distinguishing criteria of lacustrine deposits, but in the light of the wide occurrence of attapulgite in areas most commonly related by parent material, an alluvial origin is more likely.

Some clay samples from the bottom of the soil profiles and the beds in the outcrop were found to be rich in montmorillonite, with varying amounts of attapulgite. Although evidence suggests the weathering of attapulgite to montmorillonite (Jackson, 1964; Mumpton and Roy, 1958; Millot, 1972) no trace of montmorillonite was found in the desert calcareous attapulgite rich soils of Syria (Muir, 1951) where rainfall is about three times that of Al-Hasa. It seems likely that the predominance of a certain mineral or mineral group in the beds and the clay layers underlying the soils reflect a particular sediment source and that since deposition minimum alteration has taken place in this area of extreme aridity.

* A. H. Sayegh, unpublished data.

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