

SALT WEATHERING BY SODIUM CHLORIDE IN THE SAUDI ARABIAN DESERT

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ABSTRACT. Salt weathering is the breaking down of rock by salts that have accumulated at and near the rock surface. This paper describes salt weathering of sandy limestone in Saudi Arabia's arid Eastern Province near the Arabian (Persian) Gulf. Field characteristics of the weathered rock here are: (1) soft, spongy surfaces covered with fine granules and thin exfoliation scales; (2) a zone of very intense weathering at the base of many cliffs and pedestal rocks; (3) readily detectable salt crystals in pores and in small veins on the rock surface; (4) fine-grained weathering detritus (rock meal) at the foot of steep cliffs; and (5) within rock hollows and caves, weathering characteristics similar to those above but less intense.

Geological and chemical studies of an intensely weathered calcareous sandstone bed and a slightly weathered sandy limestone bed show that soluble salts, mainly NaCl, are concentrated in the outer weathered parts. Since the intensely weathered bed contains more salt than does the slightly weathered bed, and since the salt contents of both beds increase from the relatively fresh rock interior outward to the weathered surface, it is concluded that the weathering is the direct result of salt accumulation. The sources of the salt, the causes of salt accumulation, and the causes of rock disintegration are discussed.

INTRODUCTION

General Nature and Extent of Salt Weathering

Salt weathering is a process of rock disintegration by salts that have accumulated at and near the rock surface. It takes place in a variety of environments and affects many kinds of rocks. In arid regions, for example, either the salts are deposited directly on the rock surface from the air or they are collected from within the rock by circulating subsurface water and then precipitated at the rock surface when the water evaporates. Along seacoasts, on the other hand, the salts are derived externally from waves and spray that repeatedly wash the rock surface. Once the salts have accumulated in the pores, capillaries, and crevices, they set up expansive stresses that force the rock constituents apart. Salt weathering is now recognized not only as a widespread geomorphic process but also as one of the principal causes of deterioration of natural stone and brick used in buildings, walls, and monuments in many climates throughout the world.

Many papers have been written on the behavior of salts in relation to rock weathering. Evans (1970) reviewed most of those published up to the year 1970 and discussed the field and laboratory evidence that had accumulated. His review includes an exhaustive bibliography. Since 1970, several other pertinent articles and sections of books have been published (Cooke and Warren, 1973, p. 66-71; Winkler, 1973, p. 119-136; Goudie, 1974 and 1977; Price, 1975; Arnold, Honeyborne, and Price, 1976; Fookes, 1978; Martini, 1978).

Mechanisms of Salt Weathering

Three possible causes of the pressures involved in salt weathering have been suggested: (1) crystallization of salts from solutions in confined

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spaces, (2) volumetric expansion of salts in capillaries as they are heated, and (3) hydration of entrapped salts.

Crystallization of salts.—It has been known for years that pressures of considerable magnitude can be generated by salts that are crystallizing from solutions confined in minute spaces, and that these pressures are often responsible for the rapid disintegration of rocks. Of the natural salts, sulfates, especially Na_2SO_4 , seem to be more effective than carbonates, and carbonates more effective than chlorides. Field observations and laboratory experiments indicate that salt crystallization is the most effective of the three salt weathering mechanisms (Wellman and Wilson, 1965; Evans, 1970; Goudie, 1974 and 1977).

Thermal expansion of salts.—Cooke and Smalley (1968) considered the stresses exerted by the expansion of many salts in confined spaces in rocks as they are heated and suggested that in those deserts where daily air and rock surface temperatures range widely, these stresses might well bring about rock fracturing and disintegration. However, to date the effectiveness of such thermal expansion has not been demonstrated in the field, and laboratory experiments seem to show that the mechanism is probably not an important cause of rock disintegration (Goudie, 1974).

Hydration of entrapped salts.—Mortensen (1933) was the first to recognize salt hydration as a factor in desert weathering. Winkler and Wilhelm (1970) calculated the hydration pressures of several simple naturally occurring compounds and found that at low temperatures and high relative humidities, the recrystallization of some salts in the pores of rocks, from lower to higher hydrates, can develop stresses sufficient to disintegrate rocks. Na_2SO_4 , a relatively widespread salt in nature, undergoes a very large and rapid volume increase upon hydration, and Goudie (1977) suggested that this volume increase is in part responsible for the catastrophic decay of brick buildings and other structures at various archeological sites in Pakistan. However, the effectiveness of salt hydration as a general mechanism of rock disintegration has not yet been determined.

Purpose and Scope of the Present Study

This is an account of the salt weathering in progress over a vast area in Saudi Arabia's Eastern Province west of the Arabian (Persian) Gulf. The specific location of the study is in the deeply dissected "Shedgum area" (Chapman, 1971, p. 2719) in the Al-Hasa district, about 30 km southwest of Abqaiq and 35 km north of the oasis city of Hofuf. The project had two objectives: (1) to familiarize more geologists with the field characteristics of desert salt weathering and to impress them with its importance as a means of rock disintegration, and (2) to identify, insofar as possible, the kinds and quantities of salts involved in this particular region and the manner in which they are breaking down the rock.

Consideration is given first to the climate, bedrock, and topography of the Shedgum area and to their effects on the weathering. This is

followed by a description and interpretation of the results obtained from geological and chemico-mineralogical studies of rock samples from the type weathering locality. Finally, the characteristics of desert salt weathering in the Shedgum area are summarized.

CHARACTERISTICS OF WEATHERING IN THE SHEDGUM AREA

Effects of Climate

The meteorological station closest to the Shedgum area is operated by the Arabian American Oil Company in Abqaiq 30 km to the northeast. According to Schyfsma (1978, p. 31-44), the records there reveal the following information: (1) for the years 1950-1970, the average mean monthly temperatures during the summer months (June, July, August) ranged from 35.3° to 36.8°C and during the winter months (December, January, February) from 15.8° to 17.2°C; (2) for the same period of years, the average mean monthly relative humidities during the summer months ranged from 28.4 to 35.1 percent and during the winter months from 54.4 to 57.6 percent; and (3) from 1960 to 1969, the average annual precipitation was 72.9 mm, all occurring between November and May.

It should be noted also that dry north to northwesterly winds are frequent in the Eastern Province during the year, and these promote rapid evaporation of surface water.

As in most desert regions, the climatic elements in Saudi Arabia vary widely from place to place, and from year to year in the same place, often showing great extremes, so the averages given above should not be taken too rigidly. Nevertheless, they probably do reflect fairly accurately the climatic conditions under which weathering is now proceeding in the Shedgum area.

Effects of Bedrock

The bedrock is the Hofuf Formation, a sequence of flat-lying sedimentary beds of continental origin, very widespread in the Eastern Province. According to Powers and others (1966, p. D97), this formation is either late Miocene or Pliocene in age. In the Al-Hasa district, at the type locality, it is 95 m thick and consists mainly of red-brown, gray to rarely off-white conglomerate, sandstone, sandy limestone, sandy marl, and sandy shale. The uppermost bed is fresh-water limestone. A few thin, red, salty layers are present, the most persistent of which is about 1 m thick and very widespread. Sandy limestone seems to be the most abundant of all the rock types represented in the Shedgum area.

The typical unaltered sandy limestone of the Hofuf Formation is thick bedded, white, and friable, and composed of a very fine-grained, uniform, loosely textured matrix of calcite with embedded grains of detrital quartz. Quartz constitutes 15 to 35 percent of the typical rock, but in a few specimens it approaches or exceeds calcite in abundance. The quartz grains are subrounded to angular with diameters ranging from 0.1 to 1.0 mm. Accessory minerals the writer has noticed are feldspar, goethite, biotite, epidote, sphene, and opaques.

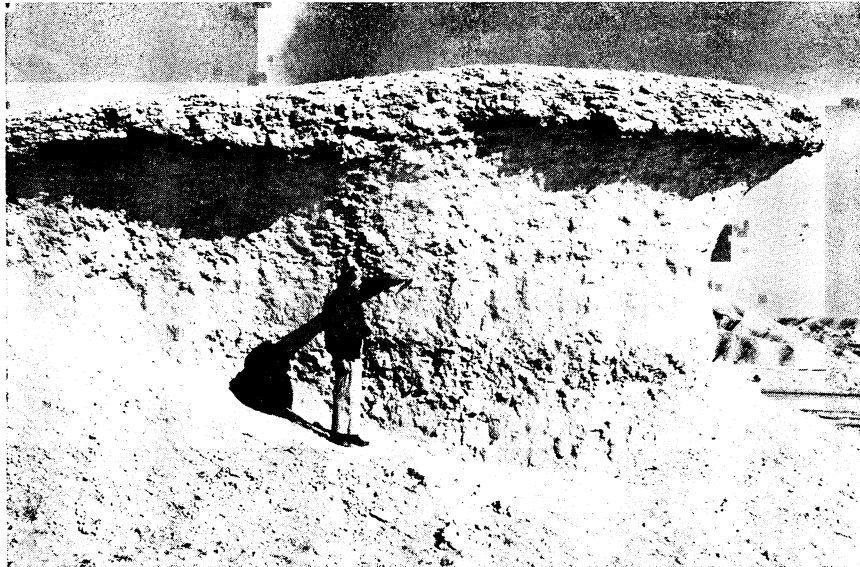
Several characteristics of the Hofuf Formation influence its weathering: (1) the calcareous rock is highly permeable and readily soluble and contains solution features such as cavities and channels that enable ground water to move freely; (2) some of the more sandy beds appear to be more friable and perhaps more permeable than the less sandy beds, and upon weathering, their loose texture causes them to crumble more readily; (3) salts, mostly NaCl, occur as scattered crystals and as thin saline layers in the limestones; and (4) the surface of the bedrock has been altered over most of the area to a calcareous duricrust that greatly retards weathering of the fresh rock beneath.

Topography and Weathering Locations

The principal topographic feature in the Shedgum area is the eastern edge of a high plateau known as the Shedgum Plateau or Summan Plateau. The front of this plateau is a prominent escarpment, 45 to 90 m high, that trends north-south and faces east. The escarpment is believed to have been formed by wave erosion during the Pliocene-Pleistocene marine transgression and regression (Hötzl, Maurin, and Zötl, 1978, p. 59-62; Chapman, 1978, p. 79-80). A large main valley (Scribners Canyon) and a network of deep tributary wadis and gullies cut across the edge of the plateau producing a rugged topography. Bedrock terraces, some deeply dissected, occur along Scribners Canyon and along many of the tributary wadis. Pedestal rocks are common in and near many of the wadis and close to the edges of dissected terraces, and erosional outliers stand out in front of the plateau. Karst features such as sinkholes, solution channels, and caves are common. The caves occur in the plateau escarpment and around the steep faces of the erosional outliers, and they are believed to be the result of wave erosion and subsequent salt weathering along large vertical joints (Hötzl, Maurin, and Zötl, 1978, p. 63-67). The entire topography is covered by resistant calcareous duricrust, several centimeters to over 3 m thick. The nature and origin of the topography and the duricrust of the Shedgum area have been described in detail by the writer (Chapman, 1971, 1974, 1978).

Weathering is taking place principally in two types of locations: (1) surface locations fully exposed to the weather, and (2) deep caves well protected from wind, rain, and the direct rays of the sun. The surface locations, which are the most common, include the walls of deep gullies that have cut through the duricrust, the edges of dissected bedrock terraces (pl. 1), and the steep faces of pedestal rocks (pl. 2-A) and erosional outliers. Most of these surfaces are very steep, concave, and overhung at the top by a projection of duricrust. Some gully walls are vertical and over 15 m high. The horizontal bedding in the sandy limestone is usually obscure in these cliffs, unless it is brought out by differential weathering. The weathered face of a typical cliff is soft and spongy and coated with loose exfoliation scales several centimeters across and with granules and fine powder (pl. 2-B). Near the base of

PLATE I

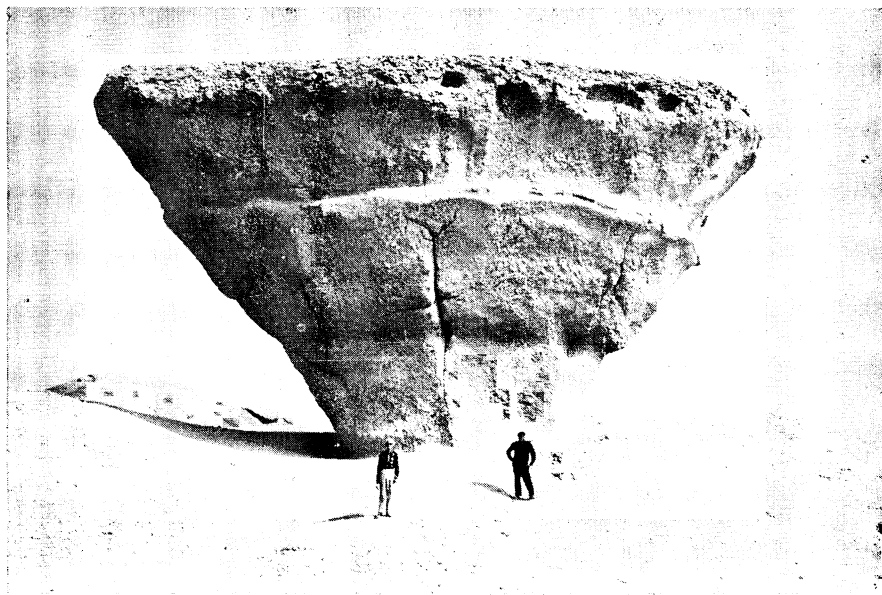


Salt weathering of limestone in the Hofuf Formation at the type locality in Scribners Canyon, Eastern Province, Saudi Arabia. Man is standing on rock meal talus, the top of bed A is at his waist level, the top of bed B is 15 cm above his left hand, bed C merges upward into massive, overhanging duricrust. Man is pointing to hole B, shown by a white marker, and hole A, shown by another white marker, is directly below at his knee level.

many cliffs, mainly in gullies and around pedestal rocks, is a conspicuous band of intense scaling, where weathering is proceeding rapidly. At high levels on the cliffs the rock usually has fewer and smaller scales and is covered mainly with granules. A slope of detritus lies at the base of those cliffs where erosion is not active.

The other type of weathering location is in caves. These are large vertical openings, 15 m or more high and 3 m or more wide, which penetrate deep into the outcrop, in some cases as much as 100 m. Most are widest at the bottom and narrow gradually upward; some are open to the sky. No sunlight reaches into these caves, and their interiors remain relatively cool and dry. The weathering here resembles that at the surface locations but is proceeding more slowly. Disintegration is attacking the walls, leaving them thinly covered with rock powder and fine loose granules; exfoliation scales are relatively rare. Disintegration appears to be more rapid near floor level where the coating of powder and granules is thicker. Since weathering has presumably been in progress in the caves off and on ever since they were formed in Pliocene-Pleistocene time (Hötzl, Maurin, and Zötl, 1978, p. 63-67), and since the weathering products have not been removed, the cave floors are now covered with thick accumulations of fine rock detritus.

PLATE 2



A. Giant pedestal rock 30 km north-northwest of Hofuf, Eastern Province, Saudi Arabia. This interesting landform, composed of horizontally bedded sandy limestone, is capped by resistant calcareous duricrust. Salt weathering is rapidly disintegrating the pedestal, and the resulting debris forms a talus surface on which the men are standing. The finer material is being removed from the talus principally by wind and to a lesser degree by splash erosion and runoff.



B. Close-up view of typical salt weathering of limestone in the Hofuf Formation at Jebel Qarah, east of Hofuf, Saudi Arabia. Rock is exfoliating and crumbling rapidly. Hammer head is resting on rock meal talus.

WEATHERING AT THE TYPE LOCALITY

Geological Study

The weathering shown in pl. 1 is typical of that found at surface locations in the Shedgum area, and the site was chosen as the type weathering locality and the place for detailed study. This cliff is the edge of a dissected stream terrace on the southwest side of Scribners Canyon, 3.2 km from its head. The weathering resembles that on other such terraces and on the walls of deep gullies, pedestal rocks, and erosional outliers. At the top of the cliff is the old terrace surface covered with duricrust, and below this crust are weathered horizontal beds of sandy limestone and calcareous sandstone. It will be noted that the profile of the cliff is generally concave but not regular due to differences in resistance of the beds. At the foot of the cliff are weathering products (rock meal) that have fallen from the cliff face above. A full description of the rock section and the weathering is given in table 1.

The aim of the geological study was to collect rock samples that might show a relationship between the degree of weathering and the quantity of accumulated salts. It was necessary to be rather restric-

TABLE 1
Stratigraphic section measured along a vertical line through
holes A and B at the type locality shown in plate 1.

Rock	Thickness in cm	Description
Duricrust	70	Grayish to brownish layer composed of irregular to rounded calcareous concretions ranging from 5 to 10 cm in diam. Although very porous and permeable, this layer is tough and resistant to weathering and forms a prominent lip overhanging the cliff.
Bed C	100	White to buff sandy limestone, moderately weathered, and less resistant than bed B below and duricrust above. Contains a few widely scattered concretions that are fairly easily weathered and therefore not prominent. Weathered surface covered with granules and some thin exfoliation scales.
Bed B	75	White to buff sandy limestone, rather massive and firm. More resistant than bed C above. Quartz grains, 0.2 to 0.7 mm in diam, are well rounded and frosted. Concretions are a little more numerous and more obvious than those in bed C. Surface only slightly weathered to fine granules and small thin exfoliation scales. Scattered cubes and small veins of halite occur on rock surface near site of hole B.
Bed A	105	White to very light gray calcareous sandstone with a few nonprominent concretions. This bed is nonresistant, and its surface is intensely weathered to a rough, porous, spongy mass of coarse exfoliation scales. These are 1 to 3 cm thick, and some are backed by a salt layer about 1 mm thick. Halite crystals are numerous, and the rock has a salty taste. The deep weathering has undercut bed B above.
Rock meal	—	An accumulation of white granular to powdery detritus (mostly calcite and quartz) and exfoliation scales derived by weathering from the cliff face above.

tive in the collecting because of the limited analytical services that were available. Two contrasting beds in the section were selected: bed A which is intensely weathered, and the overlying bed B which is only slightly weathered (table 1). First, a horizontal hole (hole A), 2.5 cm in diam and precisely 18 cm deep, was driven into bed A, using a rock drill and hammer. Before drilling actually started, some of the exfoliation scale was scraped and collected from the rock surface around the hole site within a radius of 10 to 15 cm. As drilling proceeded, the rock in the hole was found to be very loose and spongy to a depth of 10 to 12 cm, but then it became progressively firmer to a depth of 18 cm. Samples of the cuttings were collected at successive depths in the hole as indicated in table 2.

A second horizontal hole (hole B), 2.5 cm in diam and precisely 7 cm deep, was then driven into bed B immediately above. Again, before drilling started, some of the exfoliation scale was scraped and collected from the rock surface around the hole site within a radius of some 20 cm. The area of collection here was larger than that around hole A, because the scale here was thinner and more sparse. As drilling proceeded, the rock in hole B was found to be reasonably soft to a depth of 1 cm, but then it became very firm and continued so to a depth of 7 cm. Samples of the cuttings were collected at successive depths in the hole as indicated in table 2.

Finally, a composite sample of granules, powder, and exfoliation scales, weathered from the rock face above, was gathered from the foot of the cliff directly beneath holes A and B.

Chemical and Mineralogical Studies

The samples collected at the type locality were submitted to the laboratories of the United States Geological Survey and United States Geological Survey/Directorate General for Mineral Resources for chemical and mineralogical analysis, as explained in the section on "Acknowledgments". The results of the analyses are shown in table 2. They are arranged in three groups according to the relative positions of the samples. The Na₂O and CaO, in percentages of the whole sample, were determined by chemical analysis. The quartz, calcite, halite, and gypsum were determined by X-ray diffraction. The symbol "M" indicates usually an amount of 20 percent or more, but in some samples an amount as low as 10 percent; "m" indicates an amount of the order of 5 percent; and "tr" indicates an amount of the order of 1 or 2 percent. A blank space indicates either that a mineral is not present or that it is in an amount too small to be recognized.

The analysts reported that they specifically checked their X-ray diffractometer charts for certain salts that are believed to be effective weathering agents in other areas, namely CaSO₄ · 1/2 H₂O, Na₂CO₃ · H₂O, Na₂SO₄, MgSO₄ · H₂O, NaCl, and CaCl₂. Only the NaCl (halite) was determined; the presence of the other minerals was not confirmed.

TABLE 2
Analyses of rock samples from the type locality shown in plate 1.

Sample no.	Sample location	Na ₂ O*	CaO*	K ₂ O*	MgO*	Quartz	Calcite	Halite	Gypsum		
Intensely weathered bed A penetrated by hole A											
W-13	Rock scale from broad surface area around hole entrance	15.00	13.90	0.95	0.85	M	m	M			
W-6	Rock from hole, depth 0 to 2.5 cm	20.05	5.02	0.80	0.60	M	m	M	tr		
W-7	Rock from hole, depth 5 to 8 cm	2.70	3.38	1.80	1.19	M	m	m	tr		
W-8	Rock from hole, depth 10 to 13 cm	1.62	20.10	1.27	0.87	M	M	tr	tr		
W-9	Rock from hole, depth 15 to 18 cm	1.46	9.20	1.60	1.09	M	M	tr	tr		
Slightly weathered bed B penetrated by hole B											
W-14	Rock scale from broad surface area around hole entrance	5.30	20.80	1.15	1.00	M	M	m	tr		
W-10	Rock from hole, depth 0 to 2 cm	1.56	37.50	0.84	0.45	M	M	tr			
W-11	Rock from hole, depth 5 to 7 cm	0.56	40.00	0.70	0.45	M	M	tr			
W-12	Composite sample from beneath holes A and B	Rock meal			2.05	22.90	1.03	1.05	M	M	tr

* In wt percent.

Analyst for Na₂O, CaO, K₂O, and MgO: Ibrahim Baraja, USGS/DGMR laboratories, Jeddah, Saudi Arabia.

Analysts for quartz, calcite, halite, and gypsum: Moh'd Naqvi and J. J. Matzko, USGS laboratories, Jeddah, Saudi Arabia.

The analysts also reported that a few rock samples contained water-soluble salts with strong peaks that could not be definitely identified.

Microscopic examination of the samples listed in the table revealed other minerals in small amounts: tourmaline (rounded), goethite, microcline, pseudorutile, palygorskite, lithiophorite, sphene, acmite, albite, almandine, and biotite.

The more obvious relationships among the various constituents of the samples may be summarized as follows:

1. In both bed A (intensely weathered) and bed B (slightly weathered) those samples with a high Na_2O content also have a high halite content, and, conversely, those with a low Na_2O content have a low halite content. Thus, probably most if not all of the Na is in the halite.

2. Samples from bed A have generally higher Na_2O and halite contents than do corresponding samples from bed B. In other words, there is a direct relationship between the degree of weathering and the Na_2O and halite contents of these beds.

3. The Na_2O and halite contents of both beds are highest at the rock surface and decrease more or less uniformly inward. This suggests that these substances have accumulated at and near the rock surface in some manner.

4. The rock scales from the two beds are more similar chemically than are the beds from which the scales were derived. They have a halite content that is consistent with the aridity.

5. The rock meal beneath the two drill holes has much less Na_2O and halite than the surface rock scale near the entrance to either hole. Since the meal is, in fact, a composite mixture of granules, powder, and scales from the rock surface around both holes, its composition at the time of accumulation was an average of the compositions of those products. However, by now much of the Na_2O and halite must have been leached from the meal by rainwater.

6. With one exception, the quantity of halite in each sample varies inversely with the quantity of calcite. Perhaps during weathering CaCO_3 was removed as NaCl was brought in.

7. Except for number W-13, those samples high in CaO contain a larger amount of calcite, and those low in CaO a smaller amount. Probably most of the Ca of the two beds is in the calcite, and a small amount is in the gypsum.

8. On the whole, samples from bed A contain less CaO and calcite than those from bed B, which probably means that bed A now contains more quartz than bed B. Either bed A was more sandy originally, or its quartz content has been increased relatively by the loss of CaCO_3 during weathering.

9. In hole B the percentage of CaO , and perhaps that of calcite also, increases sharply from the weathered rock surface inward.

10. Gypsum, in trace amounts, occurs in all samples in hole A but does not appear in the rock scale at the hole entrance. Conversely, gypsum is absent from the samples in hole B but occurs in trace

amounts in the rock scale at the hole entrance. No gypsum is present in the rock meal, perhaps because it has been leached by rainwater.

11. Neither K_2O nor MgO appears to show any significant variation in amount.

Explanation of the Weathering Process

The field observations and chemical studies discussed above have established the following facts regarding the weathering at the type locality: (1) soluble salts, mainly $NaCl$, are concentrated in the outer weathered parts of the calcareous beds of the Hofuf Formation; (2) the intensely weathered bed A contains considerably more salt than does the slightly weathered bed B; and (3) the salt contents of both beds increase from the relatively fresh rock interior outward to the weathered surface.

Throughout the Shedgum area generally there is ample evidence that the most intensely disintegrated rocks contain the most salts. Most of this evidence is based on megascopic examination, but some is based on chemical data. For example, one rather unusual layer in the Hofuf Formation, about 1 m thick and very red, is conspicuous over a wide area. Three different samples of this layer, collected from a steep gully wall 1 km south of the type weathering locality, were chemically analyzed, and their salt contents, principally $NaCl$, were found to be 42.25, 38.53, and 37.32 percent. This highly saline bed is so deeply weathered that its exposed face has receded 1 m into the cliff, and the rock crumbles very easily.

This direct relationship between the quantity of salts and the intensity of weathering in this area does not prove, in itself, that the salt accumulation is the cause of the rock disintegration, but it is certainly highly suggestive. As noted earlier, it has been shown by many investigators that rocks in other parts of the world have been disintegrated unquestionably by the action of salts that have become lodged in minute crevices and pores. Accordingly, until another, more likely explanation becomes evident, it must be concluded that the weathering in the Shedgum area is, indeed, the direct result of salt accumulation.

Three basic questions must now be considered: (1) what are the sources of the salt, (2) what are the causes of the salt accumulation, and (3) what are the causes of the rock disintegration?

Sources of the salt.—There are several possible sources of the salt. (1) Some undoubtedly occurred as crystals deposited in the original sediments. (2) Some probably came from thin saline layers interbedded with the limestones, such as the layer described in the preceding section. (3) Considerable salt may have been swept up by the wind relatively recently and blown westward from the surface of inland and coastline sabkhahs that are numerous along the Arabian Gulf shore. (4) Similarly, minute salt grains, derived from crystallizing spray along the Gulf shore, may have been transported westward in suspension by strong

easterly winds. (5) Finally, ground water, and perhaps artesian water which is abundant in this part of Arabia, almost certainly supplied some salt from depth.

Causes of salt accumulation.—It is believed that wind, rainwater, and ground water are bringing the salt to the rock faces. Wind drives minute salt particles directly against rock faces, and these particles become lodged in crevices and pores. Rainwater from infrequent, intense showers sinks down rapidly through crevices and along vertical joints in the limestones and then moves laterally along the more permeable beds, dissolving salts on the way. It then emerges on gully walls and on the faces of cliffs and pedestal rocks, generally at higher levels, where it evaporates and precipitates its salts in pores and crevices.

Many cliffs and pedestal rocks have a zone of intense weathering a meter or less thick at their bases, suggesting that rising and emerging water, either local ground water or perhaps artesian water, also plays a prominent role in the salt accumulation. In this hot dry region, saline water is drawn upward and outward by capillarity, where it evaporates and brings about salt crystallization. Disintegration at the bases of cliffs and pedestals is usually more rapid and more intense than at higher levels since the outflow of water is greater. The more intense weathering of bed A may be the result chiefly of this factor.

Causes of rock disintegration.—The distinctive quality of the weathered surfaces of salt-impregnated limestone in the Shedgum area leaves no doubt that disruptive stresses are involved in the disintegration. Just how these stresses arise is the question. Since NaCl, which cannot be hydrated, is the only abundant salt present, and since gypsum occurs only in traces, it is obvious that most of the stresses are not caused by salt hydration. It is equally clear, for two reasons, that the volumetric expansion and contraction of NaCl crystals, as they are alternately heated and cooled in the desert environment, is not an important cause: (1) disintegration in general is as rapid on rock faces sheltered from the hot sun as it is on faces exposed directly to the sun, and (2) disintegration is in progress in the deep caves where temperature ranges are minimal. It is concluded, therefore, that the crystallization of NaCl from solutions confined in minute spaces near the rock surface must provide the major stresses that disrupt the rock.

CHARACTERISTICS OF DESERT SALT WEATHERING

Although salt weathering was first recognized over 75 yrs ago, it is not yet perceived by some earth scientists as a desert weathering mechanism of great importance. Probably this can be attributed to two things: (1) a tendency of many investigators to overemphasize the importance of desert wind in rock destruction, and (2) their failure to recognize on weathered rock surfaces those characteristics that are so diagnostic of salt weathering. Because of these reasons, it seems almost certain that much of the desert weathering that has been attributed to wind activity is, in fact, salt weathering. To prevent such misinterpretations, all field

workers should be familiar with the characteristics of salt-weathered rock surfaces, characteristics that are totally different from those of wind-abraded surfaces.

The characteristics of salt-weathered surfaces are clearly displayed in eastern Saudi Arabia and, accordingly, are worthy of careful note. These are summarized below and some are illustrated in plates 1 and 2.

1. The rock surface is rough, soft, and spongy and can be crumbled easily with the fingers. Fine granules, rock powder, thin friable exfoliation scales, and thicker plates cling to the surface. Fracturing and swelling of the whole rock face is evident.

2. A zone of especially intense weathering, a meter or less thick, occurs at the base of many cliffs and pedestal rocks.

3. Small salt crystals may be detected in the rock pores and in small veins, and thin sheets of salt may back the exfoliation scales. The surface rock may have a salty taste.

4. Beneath the rock face there is usually a loose, white talus of weathered detritus, appropriately called "rock meal." This is a mixture of fine granules, rock powder, and crumbling exfoliation scales derived from the rock surface above.

5. Within rock hollows and caves, where weathering is less intense, the walls are covered thinly with granules and rock powder, but exfoliation scales are rather rare. Rock meal forms the floor of many of these openings.

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The chemical analyses of rock samples reported in this paper were made in the laboratories of Saudi Arabia's Directorate General for Mineral Resources (USGS/DGMR) which are operated by the United States Geological Survey in Jeddah. The X-ray and microscopic indentifications of minerals in the samples were made in the laboratories of the United States Geological Survey (USGS), also in Jeddah. The two laboratories cooperated in making semiquantitative spectrographic analyses of all the samples collected, but the results are not included in this paper because they do not show significant information.

The writer is indebted to the analysts in the above laboratories for their painstaking work. He is especially grateful to John J. Matzko in the USGS laboratories for coordinating all the analytical work of this project and for making some of the X-ray mineralogic identifications.

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