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EXPERIMENTS ON THE GRANULAR DISINTEGRATION OF GRANITE BY SALT ACTION

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ABSTRACT – In the first part of this paper a review is given of the current theoretical explanations of the apparent ability of salts to produce granular disintegration of hard rocks. These are crystallization of supersaturated solutions in rock pores, thermal expansion of enclosed salt crystals, adsorption of water of crystallization by hydrate forming salts and crystal growth.

In the second part of this paper an account is given of some experiments designed to test the validity of the theory of salt hydration. To that end granite samples, partly immersed in water and saturated solutions of $CaSO_4$, $MgSO_4$, $NaCO^3$, Na_2SO_4 and NaCl, were exposed to various conditions of temperature and relative humidity in a climatic cabinet with an automatic climate cycling device. Also it was examined whether salt weathering can occur under arctic conditions in addition to frost weathering, as is assumed by Kelly and Zumberge (1961). Major conclusions are:

1. The amount of weathering material is dependent on the nature of the salt present, other things being equal.
2. The grain size distribution of the weathering debris shows in addition to a peak in the 210-300, 300-420 or 420-600 micron size grade a second peak in the 16-50 micron size grade. Maybe this is the "rock meal" mentioned sometimes in field descriptions of salt weathering.
3. Na_2SO_4 produces granular disintegration under conditions, which do not allow hydrate formation. Also the rate of hydration of Na_2SO_4 under conditions favourable to hydrate formation is very slow. This induces the author to reject hydrate formation and to accept crystal growth as the mechanism responsible for the disintegrating power of Na_2SO_4 under the diurnal change in temperature and humidity.
4. Salt weathering can indeed take place under freeze-thaw conditions.

1. INTRODUCTION

Weathering forms like granular disintegration, cavernous weathering (taffonisation) and honeycomb weathering (alveolation) are often found in association with crystallised salts like mirabilite, halite and gypsum. Field evidence of rock weathering in connection with salt crystallization is reported from the 20 – 40° latitude planetary dry belts (Futterer 1902, Walther 1924), from warm sea coasts with long enough dry spells to allow evaporation of sea spray (Tricart 1959), from the Arctic (Nordenskjöld 1914, Meckelein 1965) and recently from Antarctica (Kelly and Zumberge 1961, Cailleux 1962, Wellman and Wilson 1965, Nichols 1966, Prebble 1967), where salt accumulation is a widespread phenomenon (Tedrow and Ugolini 1966) as are granular disintegration and cavernous weathering (Cailleux and Calkin 1963, Calkin and Cailleux 1962). The effects of salt weathering have further been very carefully observed in building and monumental stone (Hirschwald 1912, von Moos und de Quervain 1948, Knetsch 1952, Winkler 1965).

For a more detailed discussion of the field evidence of salt weathering see the extensive and very useful, critical review of the literature on the subject by Evans (1967).

2. STATEMENT OF THE PROBLEM

The often observed joint occurrence of some specific weathering forms and salts is generally taken as evidence of a causal relationship between them. The presence of salts is seen as one of the causative factors of the weathering forms they are associated with. Laboratory experiments by Birot (1950, 1953, 1954), Pedro (1957 a, 1957 b) and Tricart (1960), who succeeded in producing granular disintegration by treating granite samples with salt solutions, lend strong support to this view.

When salts are accepted as effective rock breakers, future research should be aimed at establishing:

1. The velocity and intensity of the process.
2. The necessary and sufficient environmental conditions regarding climate and rock properties, which cause salts to become active and allow them to exert their influence.
3. The mechanism of the process.
4. Diagnostic criteria to identify the process.

These four aspects of rock disintegration by salt action are closely interrelated. A measure of the rate and intensity of the process may be found in the amount and mechanical composition of the weathering material. From the velocity of the process under different conditions the environment favourable to rock disintegration by salts may be inferred. By analysing the environmental conditions favourable to salt action and by studying the physico-chemical properties of the salts involved knowledge may be gained concerning the mechanism of the process. Criteria with diagnostic value of salt weathering may be found in the nature of the weathering debris, e.g. in its mechanical composition.

An experimental approach of these problems as the present one should necessarily start from a hypothesis concerning the mechanism of the process and should consist of an attempt to verify or falsify it. Designing an experiment one cannot but start from some preconceived idea concerning the phenomenon to be studied, though it very well may prove to be false.

3. PRESENT STATE OF KNOWLEDGE

In the current notions on salt weathering salts are assumed to be present in preexisting rock pores and to exert a pressure on the walls of these pores, exceeding the tensile strength of the rock. The origin of the pressure is sought in the tendency of salts to increase their volume against the confining force of the rock. This volume expansion can be of a different nature (Correns 1949, Barth, Correns, Eskola 1960):

1. Crystallization of supersaturated solutions with the resultant salt crystals together with the remaining solution occupying a larger volume than the original solution.
2. Thermal expansion of crystallised salts (Louis 1968).
3. Adsorption of water of crystallization by hydrate forming salts.
4. Crystal growth.

ad 1. Volume expansion by crystallization of supersaturated solutions is unlikely to be an important cause of rock disintegration. The only case reported in the literature on salt weathering is alum (Correns 1949).

ad 2. Thermal expansion of salt crystals enclosed in rock pores may be of some importance, e.g. the cubic coefficient of thermal expansion of NaCl is three times that of quartz.

ad 3. The hydration of hydrate forming but temporarily anhydrous salts has been theoretically treated by Mortensen (1933). According to this investigator, during the daytime when soil surface temperatures are high, capillary rising solutions of salts like Na_2SO_4, Na_2CO_3, $MgSO_4$ and $CaSO_4$ give near or at the surface formation of crystals without or low in water of crystallization. During the night, when temperatures are low, these anhydrous salts or lower hydrates pass into (higher) hydrates by adsorption of water vapour from the atmosphere, but only when the pressure of this atmospheric aqueous vapour exceeds the dissociation pressure of the hydrate involved (Findlay 1951). Given a certain vapour pressure of the atmosphere this means that temperature, controlling dissociation pressure, should fall below a certain value for transition to take place. From this it will be clear, that high relative humidities accompanying a fall in temperature are merely side effects, having nothing to do as such with the formation of salt hydrates. In addition to transition vapour pressures some salts also have transition temperatures above which only the anhydrous form or a lower hydrate is stable. For Na_2SO_4 the transition temperature is 32.4 °C. Below this temperature it is dependent on vapour pressure whether the anhydrous salt or the decahydrate is the stable form. Transition vapour pressures and temperatures of some salts are given in table 1.

	dissociation vapour pressure, mm		transition temperature, °C.
	15° C.	20° C.	
$CaSO_4.2H_2O$	4.21	6.24	
$MgSO_4.7H_2O$			30 – 60
$6H_2O$			80 – 100
$2H_2O$			100 – 120
$Na_2CO_3.10H_2O$	9.00	12.69	32
$7H_2O$	8.00	11.55	35.4
$Na_2SO_4.10H_2O$	8.60	12.50	32.4

Table 1. Dissociation vapour pressures and transition temperatures of some hydrates. $CaSO_4$, Na_2CO_3 and Na_2SO_4 data after Mortensen (1933). Transition temperatures of $MgSO_4$ hydrates determined by means of DTA – TGA, heating rate 2° C/min.

From a consideration of the effect of increasing external pressure on the dissociation pressure of a hydrate (Moore 1962), it appears that hydrate formation against a confining force can only make progress until the dissociation pressure, raised by the developping expansion pressure, equals the saturated vapour pressure of free water. For the calculation of the pressure, a hydrated salt can withstand, Mortensen gives the following theoretically derived equation:

$$P = \frac{189\ T \log (p_1 - p_2)}{V}$$

P = hydration pressure, atm.
T = absolute temperature, °K.
V = molar volume of water of crystallisation, ml.
p_1 = aqueous vapour pressure of the atmosphere at T, mm Hg.
p_2 = dissociation pressure of the hydrate at T, mm Hg.

Some calculated hydration pressures at 20 °C and vapour pressure 15.79 mm (relative humidity 90%) are:

Na_2SO_4	→	$Na_2SO_4.10H_2O$	338 atm.
$Na_2CO_3.H_2O$	→	$Na_2CO_3.7H_2O$	458 atm.
$Na_2CO_3.7H_2O$	→	$Na_2CO_3.10H_2O$	362 atm.
$CaSO_4.½H_2O$	→	$CaSO_4.2H_2O$	1594 atm.

Some conditions must be fulfilled to allow rock disintegration by salt hydration:
1. The process of hydration must be fast enough as to be accomplished for the greater part within about 12 hours, otherwise it cannot be brought about by the diurnal change in temperature.
2. The hydrating salt must not be able to escape from the pore it is in, otherwise no hydration pressure will be developed.
3. The hydration pressure must exceed the tensile strength of the rock at the site of hydration.

ad 4. In a recent discussion on rock weathering by salt action (Evans 1967) the conclusion is reached, that crystal growth is the experimentally and theoretically most firmly based cause of volume expansion capable of overcoming a counterpressure. Experiments by Becker and Day (1905, 1916) and Taber (1916) indeed clearly demonstrate the ability of crystals to grow against pressure. A review of the older literature on the geological significance of the force of crystal growth is given by Andree (1912). A more recent work, treating crystal growth from a purely physico-chemical point of view, is that of Buckley (1951).

One of the first to give a theoretical analysis of the phenomenon of growth pressure was Correns (1926). See also Correns and Steinborn (1939a, 1939b). He arrived at the conclusion, that salt crystals can but continue to grow against a confining pressure, when a film of solution is maintained at the salt-rock interface. This depends on the values of the interfacial tensions at the salt-rock interface, the salt-solution interface and the solution-rock interface. It is only when the sum of the latter two is smaller than the first, that solution can penetrate between the salt and the surrounding rock. The magnitude of the exerted pressure is determined by the degree of supersaturation of the solution. The higher the degree of supersaturation, the higher the pressure the salt crystals can withstand. Correns (1949) gives the following equation for this pressure:

$$P = \frac{RT}{V} \cdot \ln \frac{c}{c_s}$$

P = pressure on the salt
R = gasconstant
T = absolute temperature
V = molar volume of crystalline salt
c_s = concentration of a saturated solution without pressure effect
c = concentration of a saturated solution under external pressure P

A more sophisticated analysis is given by Weyl (1959, in Evens 1967), who considers the force of crystallization as the antithesis of pressure solution. He starts from the stress conditions at the surface of contact between [illegible] adjacent crystals. If the stress

two

diminishes with increasing distance from the center of contact, pressure solution takes place. In the reverse case solution diffuses inward and crystallization occurs. This approach can without objection also be applied to the contact salt-rock. It is preferable to Correns' theory of interfacial tensions, which takes into account only one of the conditions necessary for crystallization.

A third theoretical approach of crystal growth in rock pores is that of Wellman and Wilson (1965). These investigators start from the tendency of any system to reduce the area of its interfaces to a minimum, which is a consequence of the tendency toward minimum free energy. For a system containing crystals in equilibrium with a saturated solution this means, that the larger crystals will grow at the expense of the smaller ones. According to Wellman and Wilson the same behaviour is displayed, when crystallization occurs in a porous solid with large pores and small pores in contact with each other. The crystals in the large pores refuse, as it were, to grow out in the small pores, because of the great increase in area attendant on a small increase in volume this would involve. So they continue to grow in the larger pores even when they entirely fill them. For the pressure that is built up in this way Wellman and Wilson give the following equation:

$$P_l - P_s = \sigma \frac{dA}{dV}$$

P_l = pressure in the liquid
P_s = pressure in the solid
dA = increment of area
dV = increase in volume
σ = interfacial tension between a crystal face and its saturated solution

According to Evans (1967) this theory is an unpermitted extrapolation of gasliquid and liquid-liquid interactions to liquid-solid interactions.

4. PURPOSE OF THE INVESTIGATION

The main purpose of the present investigation was to examine whether and to what extent different salts differ in weathering ability, and to make a start with the determination of the temperature and humidity conditions favourable to salt weathering. Arctic conditions were included in the experiment because of the recent reports about salt weathering from those regions (Kelly and Zumberge 1961, Wellman and Wilson 1965, Prebble 1967). Mortensen's hydration theory was taken as starting point for the experiments.

5. MATERIALS AND METHODS

A. Materials

The granite samples used in the experiments were obtained by sectioning a large block of granite with a diamond saw down to pieces of the desired dimensions (7 cm long, wide and high). As preliminary experiments had shown that granite samples with smooth surfaces were hardly, if at all, attacked by salts, the salts were offered more points of attack by roughening the smooth and even saw surfaces of the samples with a hammer. The thus treated samples were freed of loose adhering particles by brushing them with a steel-brush and very thoroughly cleaning them with a hard jet of water. The weight of the samples is about 950 g.

To the unaided eye the granite has a somewhat mottled rusty appearance. The iron spots are concentrated around the biotite crystals. The felspars are whitish gray. Microscopic examination of thin sections showed it to be a two mica granite with a 5-20% anorthite containing plagioclase, and orthoclase and microcline representing the alkalifelspar group. The rock is coarse grained and it has an allotriomorphic fabric. X-ray examination of some finely ground granite powder smaller than 1 micron revealed the presence of a trace of smectite.

The following salts were used in the experiments: $CaSO_4$, $MgSO_4$, Na_2CO_3, Na_2SO_4 and NaCl. The first four salts are all capable of forming one or more hydrates. The last one is a non-hydrate forming salt. Transition temperatures and dissociation vapour pressures of some hydrates are given in table 1.

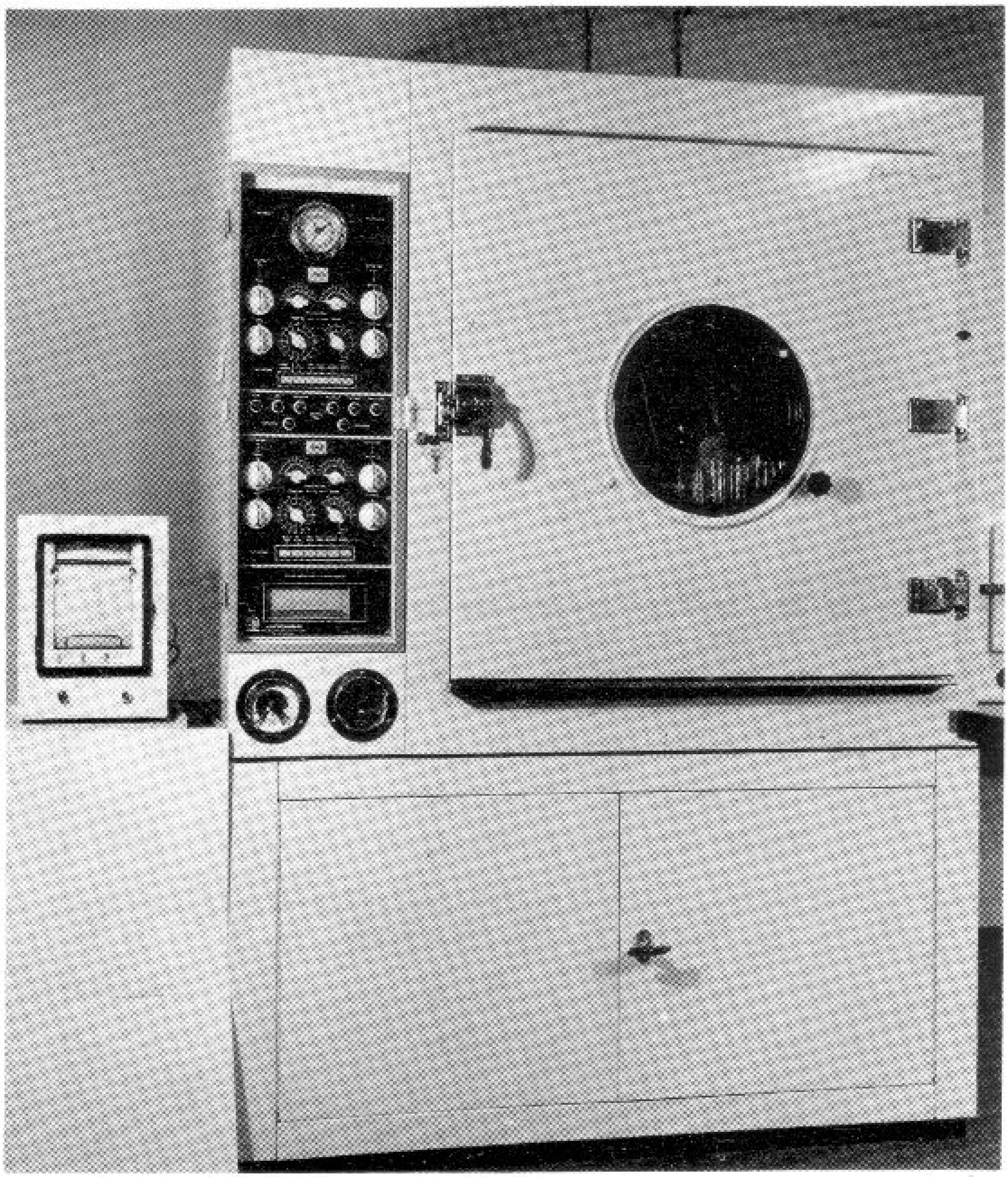

Fig. 1. Climatic cabinet.

B. Apparatus

For the exposure of the granite samples to controlled climatic conditions a climatic cabinet with an automatic climate cycling device was used (see fig. 1). Temperature range −30 °C to +90 °C, relative humidity variable between 10 and 95% (only at temperatures above zero). Heat exchange in the cabinet is accomplished by a forced air circulation along the samples and along electric heating elements or the cooling coils of a refrigerator. No radiation heat can be applied. Moisture is supplied in the vapour form by blowing air saturated with water vapour into the test space. Drying is brought about by switching on the refrigerator. Working space dimensions are 80x80x80 cm. A continuous record is kept of wet and dry bulb thermometer readings by a multi channel recorder. This allows a check on the correct functioning of the cabinet e.g. during the night and the week-end.

For one of the experiments (continuous exposure to 60 °C) an ordinary drying oven was used.

C. Procedure

The granite samples were immersed for one third of their height in water and in saturated solutions of the above mentioned salts (not all salts were used in all experiments, see table 2). This experimental design allows capillary ascension of liquid in the rock, a pre-requisite of Mortensen's theory (see fig. 2).

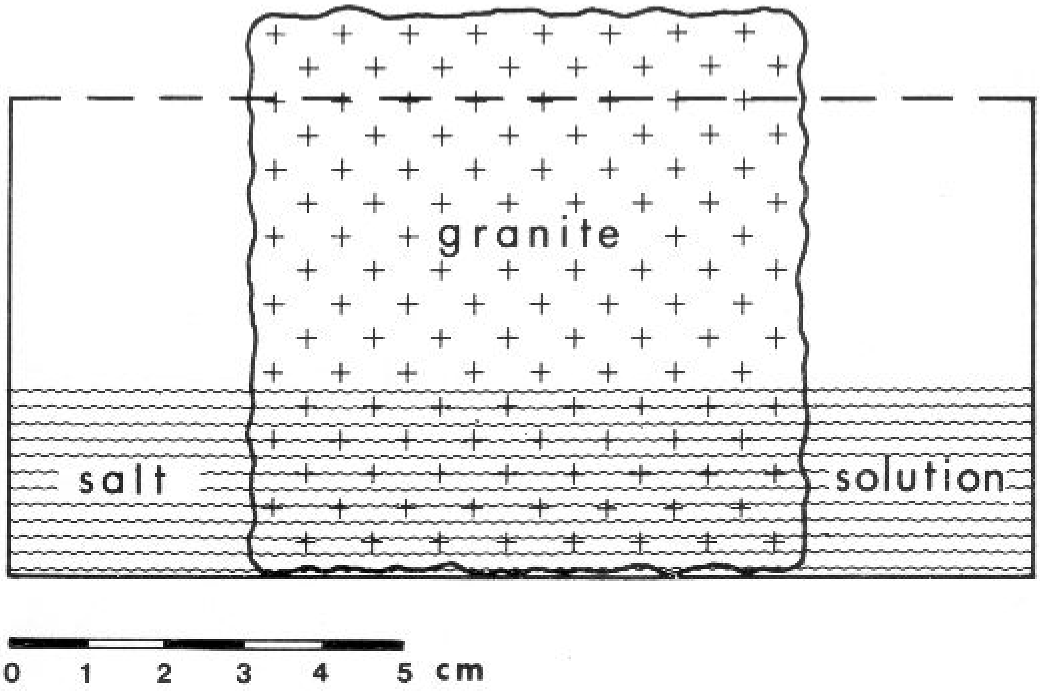

Fig. 2. Granite sample immersed in salt solution at the start of the experiment.

The following experiments were carried out:

1. Alternate exposure to relatively cold-humid and warm-dry conditions (15 °C/relative humidity 90% and 70 °C/relative humidity 10%). Time of exposure always 12 hours. Total duration of the experiment 8 weeks (NaCl 4 weeks). Atmospheric vapour pressure at 15 °C/90% is 11.51 mm.

number of rock sample	temperature and relative humidity conditions	nature of salt	period of two weeks	amount of weathering material in grammes
1	15°C/90% and 70°C/10%, alternating every 12 hours	dry	first	-
			second	-
			third	-
			fourth	-
2		water	first	-
			second	-
			third	-
			fourth	-
3		$CaSO_4$	first	-
			second	-
			third	-
			fourth	-
4		$MgSO_4$	first	3.52
			second	3.58
			third	3.98
			fourth	2.72
5		Na_2CO_3	first	6.95
			second	5.31
			third	5.06
			fourth	7.73
6		Na_2SO_4	first	18.61
			second	17.73
			third	14.12
			fourth	25.69
7		NaCl	first	1.83
			second	2.64
8	20°C/30% and 60°C/10%, alternating every 12 hours	Na_2SO_4	first	10.89
9		duplicate	first	12.92
10		NaCl	first	2.42
11		duplicate	first	4.63
12	continuously 20°C/30%	Na_2SO_4	first	5.46
13		NaCl	first	4.77
14	continuously 60°C	Na_2SO_4	first	1.77
15		NaCl	first	3.27
16	–20°C and 20°C/40%, alternating every 6 hours	water	first	0.16
			second	0.27
17		Na_2SO_4	first	1.42
			second	1.60
18		NaCl	first	2.80
			second	1.98

Table 2. Synoptic table of the results of the salt weathering experiments.

% >2 mm of total grus	mechanical composition in % of particles < 2 mm													median size of < 2 mm grade
	1400-2000μ	1000-1400μ	600-1000μ	420-600μ	300-420μ	210-300μ	150-210μ	105-150μ	75-105μ	50-75 μ	16-50μ	2-16μ	< 2μ	
5	5	3.5	5	8.5	10	11.5	11	11.5	9	5.5	13	3	3	170
1	4	3	4.5	8	10	11	12	11.5	9.5	5.5	14.5	2	4	160
5	3	4	5	9.5	12	13	12	11.5	9.5	5	11.5	1	3	190
2.5	4.5	5.5	7	10.5	12	13.5	11.5	10.5	8	4.5	9	0.5	3	225
1.5	2	3	4	7.5	9	11.5	11.5	10.5	10	6	17	5.5	2	142
4.5	3.5	4.5	5.5	9.5	12	12.5	11	10	8	5.5	13	3.5	2	190
21	6	5	5	9	11	11.5	11	11	7.5	4.5	11.5	2	5	197
18.5	9	6	6.5	10.5	11	11.5	10	8.5	7	4.5	10	2.5	2.5	240
5.5	6.5	4.5	5.5	9.5	10.5	11.5	10	11	9	6	10.5	4	1.5	200
9	7	5.5	6.5	11	11.5	12	10.5	10.5	7.5	4.5	9	3	0.7	230
8.5	11.5	8	9	13	12.5	11.5	9	7.5	6	3	6.5	2	0.7	340
17	15.5	9.5	10	13	12	11	8	6.5	5	2.5	4.5	1.5	0.7	390
0.7	3.5	2	3.5	7.5	10	11.5	11.5	12	9.5	5.5	14.5	2	6.5	150
10	5.5	4.5	5	11	11.5	13	11.5	10.5	7.5	4	11	2.5	2.5	212
16	9.5	6	14.5	13.5	10.5	10	10.5	8.5	5	3.5	5.5	2	0.5	340
10	8	6.5	14.5	15	11	10.5	10.5	8	5	3.5	4.5	1.5	0.5	350
2.5	3.5	2.5	9	13.5	13	12	13.5	10.5	6	5	7	1.5	3.5	230
3	3	2	6	10.5	11	12.5	16	12.5	7	6	9	3	1.5	190
14	9.5	7.5	14	14	11.5	10.5	10.5	8	4	3.5	4.5	0.5	1	360
9	4	3.5	10	10.5	10	10.5	12.5	11	6.5	6	10.5	3.5	1.5	280
1.5	4.5	3	8	10	10.5	11.5	14	11.5	6.5	6	7	1	6.5	200
1	4	3	9.5	13.5	12.5	12.5	14.5	11	6	5	6	1.5	1	240
1	2	3	6.5	9	11	10.5	15	13	8	6.5	10.5	4.5	1.5	175
0.5	3	7	7	9.5	11	11	15	12.5	7.5	6.5	9.5	1.5	2.5	200
7	5.5	4	9.5	12	12	11.5	13	10	6.5	5.5	8	1	2	240
5.5	3.5	3.5	9	11.5	12	12	13	11	6.5	6	8	0.5	2.5	220

2. Alternate exposure to relatively cold-dry and warm-dry conditions (20 °C/relative humidity 30% and 60 °C/relative humidity 10%). Time of exposure always 12 hours. Total duration of the experiment 2 weeks. Atmospheric vapour pressure at 20 °C/30% is 5.26 mm.

3. Continuous exposure to 20 °C/relative humidity 30%. Duration of the experiment 2 weeks.

4. Continuous exposure to 60 °C/relative humidity less than 10%. Duration of the experiment 2 weeks.

5. Alternate exposure to −20 °C and to +20 °C/relative humidity 40%. Time of exposure always 6 hours. Total duration of the experiment 4 weeks. The NaCl solution was half saturated in this case. Atmospheric vapour pressure at 20 °C/40% is 7.02 mm.

It has been common procedure to refill the sample containers with distilled water to the 2.5 cm mark every time evaporation was complete, except for experiment 5, where water was refilled every 24 hours regardless of how much water was evaporated.

In the course of all experiments weathering products were collected every two weeks. This was done by completely dissolving the crystallised salts with water and by gently rubbing the surface of the granite with the hand. The samples thus freed of loose particles were then put back into the experiment. The weathering debris was washed with water until free of salts, dried at 105 °C and weighed. Subsequently its mechanical composition was determined. In one case the very few particles smaller than 1 micron were concentrated and x-ray examined. Two silt size grades of the same sample were microscopically studied by means of the phase contrast technique (Riezebos 1968).

In order to establish the hydration velocity of some hydrate forming salts an hourly record was kept of their change in weight during a 12 hours exposure to 20 °C/relative humidity 90%. First the salts were dried at 105 °C. Hydration of $MgSO_4$ was checked by x-ray analysis.

6. RESULTS

A very conspicuous phenomenon observed during the exposure of the samples to various climatic conditions was the "creeping" of the crystallising salts from the solutions upward along the samples, ultimately resulting in salt crusts completely covering the samples.

Table 2 summarises the amounts of weathering debris liberated in the course of the experiments and gives the mechanical composition of the weathering products.

From experiment 1 it appears that:

1. disintegration of granite is really caused by the activity of the salts and not merely by changing temperature and humidity, as the sample in pure water and the one dry do not show any sign of attack.

2. the amount of weathering material is dependent on the nature of the salt present. Na_2SO_4 is by far the most destructive under the conditions of experiment 1, followed by Na_2CO_3, $MgSO_4$ and NaCl. $CaSO_4$ does not effect the granite at all under these conditions and in the investigated period of time. It should be remembered however that the solubility of $CaSO_4$ is much less than that of the other salts, so that only a few crystals will form on evaporating a saturated solution of $CaSO_4$.

3. the disintegration of granite by salt action seems to proceed at a rather constant rate. Compare the amounts of weathering material released in the four periods of two weeks.

Comparison of the amounts of weathering material produced by Na_2SO_4 and NaCl under the various conditions these salts were exposed to (experiments 2, 3, 4 and 5) reveals that, once evaporation (and crystallization) is possible, climatic conditions do not seem to influence the activity of NaCl very much, contrary to Na_2SO_4 which is very much dependent on temperature especially. Changing temperature seems to promote rock disintegration by Na_2SO_4, whereas evaporation and crystallization at constant temperature, especially high temperature, seems to slacken the activity of Na_2SO_4. It should be noted here that on continuous exposure to 60 °C Na_2SO_4 exhibited practically no crystal creeping, the granite remaining free of a salt crust, while on continuous exposure to 20 °C/relative humidity 30% a very thick crust of crystalline Na_2SO_4 was formed. Also the evaporation of the Na_2SO_4 solution was very slow at 60° C. The rate of evaporation and measure of crust formation of NaCl did not differ much under the various experimental conditions.

Regarding experiment 5 the observation was made that the NaCl solution did not freeze completely at −20 °C. There remained always some brine. Crystal creeping did occur. Notice that salts produce more debris than water under freezing conditions.

The mechanical composition of the weathering debris is essentially the same in all cases. Perhaps the Na_2SO_4 grus is slightly coarser than the grus produced by the other salts. It generally has a two phased character. Modal classes are 16-50 micron and 210-300 micron. Sorting is bad.

Microscopic examination by means of the phase contrast technique of the 8-16 and 16-50 micron size grades of Na_2SO_4 grus revealed no signs of mineral transformations. X-ray analysis of the smaller than 1 micron size fraction of the same sample showed that it contained some smectite, also present in the unweathered granite.

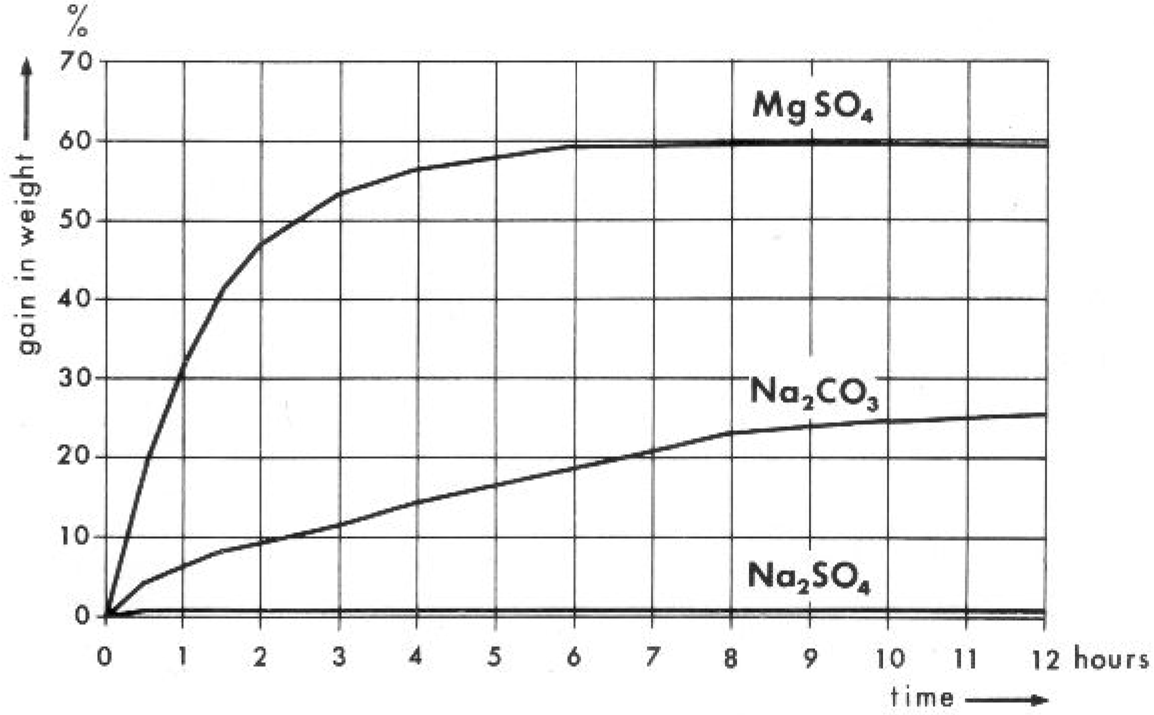

Fig. 3. Hydration rate of Na_2SO_4, Na_2CO_3 and $MgSO_4$ at 20 C. and relative humidity 90%. Salts dried to constant weight at 105 C. before the experiment.

Fig. 3 shows the velocity of hydration of some salts. It is very important to note that Na_2SO_4 does not adsorb any water of crystallization during the 12 hours period of observation. The observed change in weight of $MgSO_4$ is in accordance with x-ray findings that $MgSO_4.H_2O$ after 7 hours exposure to 20 ° C/90% has become $MgSO_4 .6H_2O$.

7. DISCUSSION

Because of the forcefully roughened surfaces of the granite samples no absolute meaning can be attached to the observed amounts of weathering material, but they can very well be used as a measure of the relative intensities the various salts are attacking the granite with.

The results of the experiments, e.g. the observation that different salts produce different amounts of weathering material other things being equal, should be accounted for by any theory on the mechanism of salt weathering. It is not so easy to interpret the results of experiments in terms of one of the theories presented in the third paragraph of this paper (present state of knowledge), because none of these theories allows quantitative predictions concerning the amounts of weathering material to be produced by different salts under different circumstances. It only can be said that NaCl stays within the terms of the theory of crystal growth, whereas Na_2SO_4 clearly exceeds the limits of Mortensen's hydration theory by being active when no hydrate formation can take place (experiments 2, 3, 4 and 5). Attention is also drawn to the very low hydration velocity of Na_2SO_4. All things considered the writer tends to accept the theory of crystal growth as valid for Na_2SO_4 also. The following consideration may be of help in explaining the difference in behaviour that irrefutably exists between NaCl and Na_2SO_4, particularly concerning the effect of changing temperature.

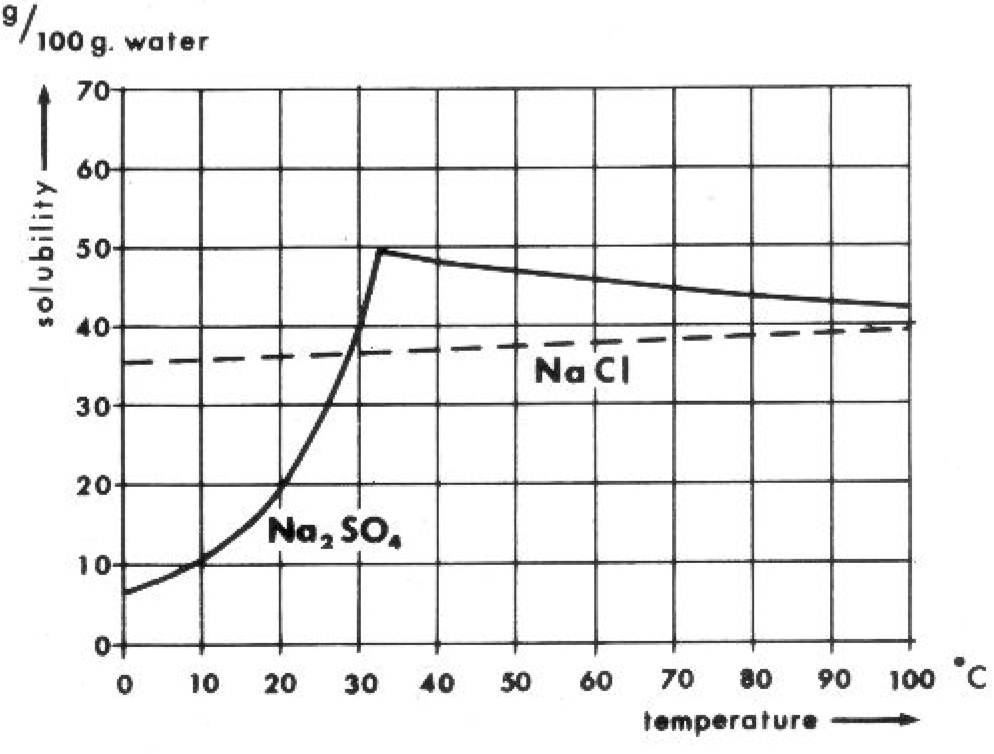

Fig. 4. Solubility of Na_2SO_4 and NaCl.

A solution starts to crystallise when saturation is reached, provided that sufficient nuclei are present. This can occur by:

1. Evaporation of the solvent.
2. Freezing of the solvent.
3. Temperature fall, provided that the solubility of the substance in question decreases with falling temperature.

The solubility of NaCl does not change much with temperature. The solubility of Na_2SO_4 sharply increases with rising temperature (see fig. 4). This means that a change in temperature has a far less pronounced effect on NaCl than on Na_2SO_4. Crystallization of a salt solution on a temperature fall (Na_2SO_4) affects a much larger volume of salt per time unit than crystallization induced by evaporation (NaCl) which is a gradual process. Possibly the crystallization of Na_2SO_4 forced by a fall in temperature contributes to its rock breaking power.

Concerning the mechanical composition of the weathering material the high proportion of particles in the coarse silt size grade (16-50 micron) should be noted. Perhaps this is the "rock meal" some investigators (Wellman and Wilson 1965) write about when discussing field evidence of salt weathering.

The results of experiment 5 (freezing conditions) should be seen in the light of the following statement by Kelly and Zumberge (1961) concerning a disintegrated quartz diorite at Marble Point, Antarctica:

"Added to the effects of frost-heave are the disruptive forces that may be associated with crystallization of sodium chloride in the weathering rock. Repeated formation of halite by evaporation of sea spray may have played a significant role in disintegration of the rocks at Marble Point, but at present we do not have the data necessary to evaluate the relative importance of this process as compared to frost action. Experimental studies of the mechanism, along with comparitive studies of weathering under salt free but otherwise similar conditions, will be required for such an evaluation. However, the unusual degree of breakdown (to particle sizes as small as 0.003 mm without any substantial chemical or mineralogic changes involving the major ingredients of the rock) displayed by this suite may well point to the effectiveness of salt activity when superposed on the frost-thaw process which affects all the rocks exposed in this region."

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