Frost and salt weathering of chalk shore platforms near Brighton, Sussex, U. K.

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Revised MS received 9 *June,* 1986

ABSTRACT

Extensive spalling and cracking of chalk exposed in cliffs and on shore platforms in the vicinity of Brighton was observed during severe weather in January 1985. Quadrat analysis of the shore platforms is used to show a progressive downshore decline in the frequency of spalling. Laboratory simulations of tidal cycles support the field evidence that chalk exposed on the upper reaches of the platforms would have been subject to destructive freeze-thaw action L&oratory evidence supporting the idea that frost damage is increased by the presence of salts in seawater is also presented, and it is suggested that the combined action of frost and salt weathering may be an effective weathering process in temperate coastal environments.

KEY WORDS: Frost and salt weathering, Chalk shore platforms, Freeze-thaw, Laboratory simulation, Sussex

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INTRODUCTION

Laboratory experiments by Goudie (1974) and Williams and Robinson (1981), demonstrated that saturated solutions of Na_2SO_4 and NaCl, could enhance the weathering of rocks by frost. However, McGreevy (1983, using more dilute solutions, found that salts could actually inhibit frost weathering under certain conditions. None of the authors gave detailed field evidence of frost and salt operating as a weathering mechanism, but Williams and Robinson mentioned that the surfaces of chalk shore platforms in south-east England were severely disrupted during exceptionally cold weather in the winter of 1962/3, and suggested that this may have been a demonstration of the efficacy of frost and salt weathering in a temperate environment. Field and laboratory work by Trenhaile and Rudakas (1981) led them to con-&de that frost and salt weathering was an important weathering mechanism affecting shore platforms in a rather harsher environment at Gaspé, Québec.

Shore platforms cut mostly in Upper Chalk and backed by chalk cliffs 30 to 200 m in height are extensively developed along the south coast of England for some 35 km between Brighton and Eastbourne (Fig. 1), (Castleden, 1982; Robinson and Williams, 1983). The platforms ascend from low water level to the base of the cliffs as a series of broad almost horizontal benches separated by vertical risers 0·1 to 0·5 m high. The overall gradient of the platforms is generally less than 5°. The junction between the platform and the cliff is usually obscured by a short beach of flint gravel with a gradient that varies with the prevailing wind and wave conditions, but which-is normally greater than 5°. Between Brighton and Newhaven, the base of the cliffs is protected in many places by a defensive concrete wall surmounted by a walkway.

Chalk shore platforms have unique characteristics that make them particularly susceptible to the combination of frost and salt weathering. Chalk is a soft limestone with a high porosity which makes it extremely susceptible to frost damage (see Williams, 1980). In very cold winters, the surfaces of shore platforms are liable to freeze whenever they are exposed to the air during periods of low tide. When the tide returns, submersion in seawater, with its high thermal conductivity, will lead to thawing. Thus, frost-susceptible chalk, saturated or nearly saturated with seawater, may be subjected to two freeze-thaw cycles every 24 hours.

In January 1985, south-east England again experienced a prolonged period of exceptionally cold weather. The mean maximum daily air temperature

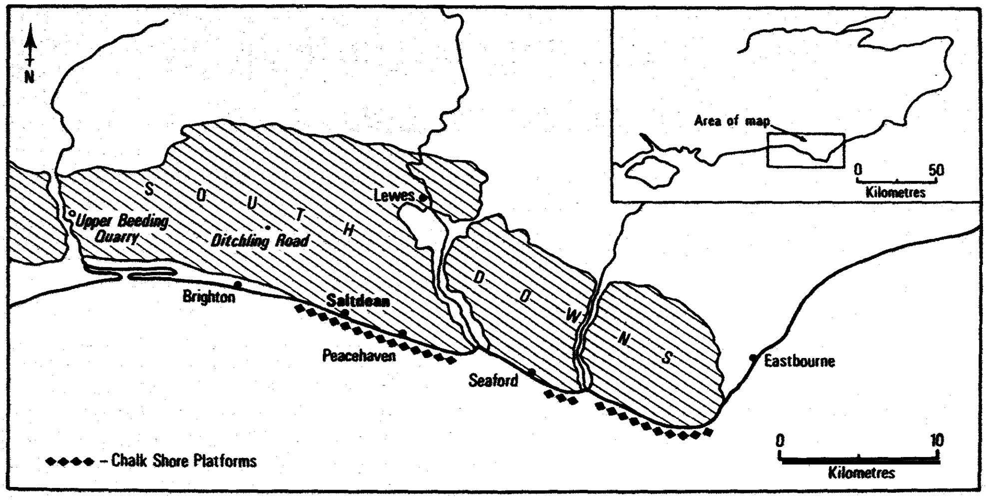

FIGURE 1. Location diagram of chalk shore platforms, field survey site and chalk quarry

recorded at Ditchling Road, Brighton, was 2·8°C compared with a January mean of 4·2°C for the previous ten years. The mean minimum, for January 1985 was -3·9° C compared with a previous ten year mean of - 1·7°C. The minimum air temperature recorded was –9·2°C on the 15th January, and temperatures below 0°C were recorded on 20 consecutive days between the 1st and 20th of the month. Frost occurred on a total of 22 days in the month. No seawater temperatures are available for Brighton, but at Eastbourne, the surface seawater temperature declined from 8·2°C on January 1st, to a low of 1·5°C on the 17th. The equivalent temperatures for January 1963 were a mean maximum daily air temperature of 1·1°C, a mean minimum of – 3·2°C, a minimum air temperature of – 8·3°C and a minimum sea temperature of – 1·1°C.

FIELD OBSERVATIONS

Cracking and spalling of the surface of the chalk platforms was widespread during the cold weather of January 1985. The cliffs were also extensively damaged, and when thawing occurred, large volumes of frost shattered chalk and flint debris fell to the base of the cliffs. In the vicinity of Brighton, danger from broken rock falling from the cliffs and obstruction by the mass of frost-shattered debris that accumulated at their base necessitated the closure of the undercliff walkway for some three months.

Spalling of the platform surface was shown by fresh white scars which varied in size from less than 0·001 m^2 to more than 0-1 m^2. Some of the smaller spalls of chalk were less than 0.01 m thick, but many of the larger were 0·05 m or more in maximum thickness with irregular feathered edges. Many spalls of coherent chalk fell or were washed into adjacent hollows or runnels on the platform surface where they remained for several days and sometimes weeks. Others broke up during detachment or were weakened by miriads of cracks, and rapidly disintegrated in a few tidal cycles.

Visual inspection of the shore platforms at a number of sites suggested that damage was more widespread on the upper parts of the platforms than on the lower. At Saltdean (Fig. I), this observation was quantified by measuring the distribution of spall damage by quadrat analysis. Using the foot of the cliff as a base line, the foreshore exposed at low tide was subdivided into six zones (Fig. 2). Each of the five upper zones extended 20 m in the downshore direction, but the lowest zone, abutting low tide, varied between 20 and 35 m. The uppermost zone comprised the beach, the lower five zones, the shore platform. The damage to the chalk within each zone of the platform was measured by means of ten randomly located quadrats. Each quadrat was divided into 20 subdivisions each 0·15 X 0·15 m. Within each of these subdivisions, the presence or absence of spalling of the platform surface was noted and the results converted into a percentage frequency of damage for each zone. No attempt was made to quantify the

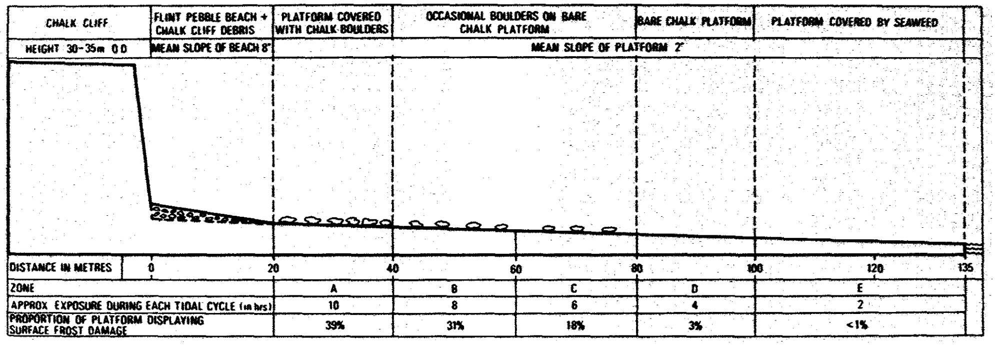

FIGURE 2. Idealized diagram of the chalk shore platform at Saltdean showing sampling zones, tidal exposure patterns and frost damage. (The platform surface has an irregular relief, dissected by runnels etc and therefore the periods of exposure during tidal cycles are only crude approximations)

extent of damage within each of the small 0·15 x 0·15 m squares.

The results show a progressive downshore decline in the proportion of the platform surface visibly damaged. It was also observed that damage within each zone was not randomly distributed. Small projections of chalk standing above the general level of the platform, the top edges of risers, and the upper edges and corners of the drainage runnels that dissect the platforms were more commonly affected than were the flatter areas. Some small, slightly domed areas of the platform were completely destroyed by masses of fine cracks which reduced the chalk to the consistency of a fine paste.

Many large boulders of chalk up to 0·5 m^3 lying on the upper platform were also severely damaged. Damage varied from surface spalling and flaking to the total disintegration of entire boulders as a result of penetration by miriads of intersecting cracks (Fig. 3). Occasionally, large boulders were cracked cleanly in two by a single break through their centre (Fig. 4). The proportion of boulders suffering from large-scale spalling or cracking was measured along three randomly located transects, each 20 m in length, laid across the upper platform. Each boulder touched by the transect tape was inspected and any boulder with at least one clearly visible crack more than 0·1 m long or a fresh break more than 0·01 m^2 in area was classified as showing major damage. The results are shown in Table I. All the boulders examined had suffered minor damage, 87 per cent had suffered major damage and some were completely shattered.

Damage to flints was slight even where nodules projected above the general surface of the platform. Fresh, seemingly undamaged flints were often the only large pieces of coherent rock material that survived the severe shattering that completely destroyed some chalk boulders.

DISCUSSION OF FIELD EVIDENCE

The progressive downshore decline in platform damage supports the idea that the mechanical weathering described is related to frost action. The upper zones of the platform are exposed to freezing temperatures for a much longer period in each tidal cycle than are the lower zones. Upon retreat of the tide, freezing will not be instantaneous. The chalk and its porewater has to cool to the freezing point of seawater, which is depressed below 0°C by the presence of salts. Once freezing commences, latent heat is released and this has to be dissipated. before further cooling can take place (see Jerwood, Robinson and Williams, in press). The minimal damage suffered by the lower zones of the platform suggests that at least five to six hours of exposure to low temperatures is necessary for destructive freezing to occur. Variation in the distribution of damage within each zone can also be explained by variations in the intensity of freezing. Boulders lying on the platform, upstanding projections of chalk, edges and comers of risers and hollows will all cool more rapidly than the main mass of the platform surface because the area of chalk surface exposed to cooling is greater in these locations. Boulders Will be particularly susceptible to chilling and freezing because of their much smaller mass compared to that of the platform.

LABORATORY SIMULATION

In an attempt to ascertain whether the chalk shattering observed on the shore platforms was likely to be

FIGURE 3. A boulder destroyed by many intersecting cracks. White scars on the surrounding platform are the result of surface spalling

FIGURE 4. A boulder displaying extensive spalling and broken in two by a single crack

TABLE I. *Boulders displaying major damage on 20 m transects*

Transect	*No. of boulders on the transect*	*No. of boulders displaying major cracks or spalls*	*% boulders displaying major cracks or spalls*
1	21	17	81
2	22	20	91
3	18	16	89
	Total 61	53	Mean 87

the result of frost and salt acting in combination, a series of freeze-thaw tidal cycles were simulated in the laboratory. Cubes of chalk 76 x 76 x 76 mm were cut from blocks of fresh Upper Chalk obtained from Upper Beeding Quarry, (Fig. I). The chalk was from the Micraster Zone which is less porous and more frost resistant than the Offaster chalk, (see Table II), which forms the Saltdean shore platform, (Williams, 1980). Unfortunately no Offaster chalk was available from local quarries and that exposed on the foreshore was unsuitable for the experiments because it had been weathered by exposure and impregnated with salts by seawater. Fifteen cubes were placed in separate polythene containers each 100 mm x 100 mm x 130 mm and allowed to saturate for 48 hours in a bath of sea water at 2.5°C. The containers and their chalk cubes were then removed from the bath and drained of all except a small volume of seawater (c. 50 ml), which was left to ensure that the cubes remained

TABLE II. *Moisture-related characteristics of Micraster and Offaster chalk*

	Porosity		*Water absorption capacity*		*Saturation coefficient*		*Dry density* $kg\ m^{-2}$	
	mean %	*S.D.*	*mean %*	*S.D.*	*mean %*	*S.D.*	*mean*	*S.D.*
Micraster chalk[1] (Upper Beeding quarry)	31·5	1·59	31·0	1·76	0·99	0·01	1702	30·99
Offaster chalk[2] (Saltdean shore platform	40·8	2·84	39·2	1·84	0·96	0·03	1582	35·17

Notes: S.D.–standard deviation;
[1] mean of 12 samples;
[2] mean of 6 samples

saturated during freezing. They were then placed in a Climatic Cabinet (Fisons Model FE l000H/MU/R40-IND LH FRIDGE), to freeze, with the cabinet air temperature set at – 9·0°C. After two hours, two containers were taken out of the cabinet, transferred to a bath of seawater maintained at a temperature of between 2·5°C and 4·5°C in a second temperature controlled cabinet, and allowed to thaw for ten hours. This treatment was intended to simulate the most intense freeze-thaw conditions likely to have been experienced during January 1985 in Zone E, the lowest zone of the platform (see Fig. 2).

Freeze-thaw cycles on progressively higher zones of the platform were simulated by removing two further containers from the cabinet after four hours, two more after six hours, another two after eight hours and the final two after ten hours. Each pair was placed in the seawater bath, and the chalk allowed to thaw for eight, six, four and two hours respectively. Twelve hours after the commencement of the freeze-thaw cycles, all containers were removed from the thawing baths and drained of all but a little seawater, before being replaced in the cabinet and the cycles repeated. This was continued for one week by which time all blocks had undergone fourteen simulated freeze-thaw, tidal cycles. Each simulated cycle is paired with its equivalent zone on the platform e.g. Cycle A represents conditions in Zone A.

Cubes subjected to Cycles A, B, and C, which simulated freeze-thaw conditions experienced on the upper three zones of the chalk platform, all suffered breakage and disintegration (Table III). Cubes subjected to Cycles D and E, which simulated freeze-thaw conditions on the lower zones, suffered no breakage or disintegration, The cubes subjected to these last two cycles actually weighed slightly more at the end of the experiment than they did at the beginning- This phenomenon has been encountered in previous freeze-thaw experiments (Williams and Robinson, 1981), and may result from either the accumulation of salts within the cubes or an increase in the pore water content due to pore enlargement either by frost action or solution. In the present experiment the dry weight of chalk cubes after fourteen freeze-thaw cycles had also increased, suggesting that salt accumulation was *a* major component.

TABLE III. *Mean percentage disintegration of chalk cubes after fourteen simulated freeze-thaw tidal cycles in seawater*

Tidal cycle	*Freezing period (hr)*	*Thawing period (hr)*	*% original wet weight remaining as a coherent mass*	*Standard deviation*
A	10	2	84·2	22·03
B	8	4	95·3	6·68
C	6	6	46·0	4·28
D	4	8	100·8	0·07
E	2	10	100·7	0·42

The temperature and freezing regimes within the chalk cubes during the simulated tidal cycles were investigated by means of thermistors inserted into the centres of cubes. A hole 5 mm in diameter was drilled to the centre of each of the five remaining cubes of chalk. A thermistor was placed into each hole and the hole then sealed with chalk powder. Each thermistor was connected to a Grants Squirrel multi-channel data-logger and temperatures were recorded at 15-minute intervals. The chalk cubes were placed in plastic containers and subjected to simulated freeze-thaw in seawater, one cube to each of the five tidal cycles described previously.

The prominent feature of all the temperature curves is the asymmetry between the cooling and warming rates (Fig. 5). The temperatures of the cubes decline very slowly when they are cooled in air in contrast to the speed with which their temperatures rise in seawater. The minimum temperature reached by any of the cubes was - 8·5°C. Only during Cycles A and 3 is the cooling period of sufficient duration for this minimum temperature to be achieved. In the other cycles, the shortening of the period of exposure to freezing conditions produces a progressive decrease in the minimum temperature attained by the cubes, In Cycle C a minimum of – 6°C is reached in six hours, in Cycle D –4·5°C in four hours, and in Cycle E -2·5°C in two hours.

All five cubes cool rapidly to a temperature of – 2 to – 2·5°C, which is the depressed freezing point of seawater. At this temperature ice begins to form, releasing latent heat and causing an arrest in the cooling curve of approximately one hour. Once the water in excess of that required to satisfy the phase equilibria of the salts in solution at this temperature has frozen, the temperature starts to fall again. In Cycle E, the duration of exposure to low temperature is so short that the cube temperature never passes beyond this Point before thawing commences.

In the other cycles, the cooling rate is always much lower after the arrest than it is before. This is for two reasons. First, the temperature differential between the cube and the cold air in the freezing cabinet is reduced as the temperature of the cube decreases and thus the rate of cooling decreases in accordance with Newton’s law of cooling. Second, the phase equilibria of the salts in solution in seawater are temperature dependent and therefore, as the temperature falls below the initial freezing point, further crystallization occurs releasing more latent heat.

In comparison with their rates of cooling, the temperatures of the cubes rise rapidly during the thawing phase of the cycles because of the much greater specific heat and conductivity of water compared with air. In all cycles the thawing period is long enough for ice to melt and the temperature of the cubes to rise above freezing. In all except Cycle A, the temperature of the cubes reaches approximately 2·5°C, the minimum temperature of the water bath A brief arrest in the rise in temperatures can be seen at around –2·5°C, which is caused by the absorption of latent heat as ice melts.

Six additional cubes of chalk were saturated in distilled water and pairs of blocks subjected to Cycles A, B, and C, with distilled water also used as the thawing medium. None of these cubes suffered any major breakage after fourteen freeze-thaw cycles (Table IV).

The temperature regimes within the cubes during the cycles was studied by inserting thermistors into the centres of three further cubes and subjecting one cube to each cycle. All three cubes reached a minimum temperature close to the air temperature of – 9·0°C (Fig. 5), at which point much of the porewater must have been frozen (Bouyoucos, 1923 and Mellor, 1970 have both shown that small quantities of unfrozen water can remain in small pores at temperatures well below freezing). Pure water freezes and melts at 0°C, and this causes arrests of approximately two hours on both the cooling and warming limbs of the temperature curves. Below this temperature’ the release and absorption of latent heat due to freezing and melting of any remaining porewater is insufficient to affect the cooling and warming rates. There are also no salt-related phase changes and thus cooling and warming rates are more rapid than in seawater, although cooling rates do decrease as they approach the air temperature of the cabinet in accordance with Newton’s law of cooling. In Cycle A, the immersion phase is too short for the blocks to fully thaw and hence the temperature within the block never rises above 0°C. In Cycles B and C, the immersion phase is of sufficient length for thawing to be complete and the temperatures of the blocks rise above 0°C, but reaches the temperature of the water only in Cycle C.

DISCUSSION OF RESULTS

The laboratory simulations dearly suggest that the air and seawater temperatures encountered during January 1985 in south-east England would have combined to subject chalk exposed on shore platforms to repeated freeze-thaw cycles. The chalk cubes froze during all five simulated cycles using seawater, although to only a limited extent in Cycle E. However, the rank order of zones based on the frequency of spalling recorded on the shore platforms at Saltdean is not identical to that obtained in the simulated cycles (Table V). Greatest damage to the platform was recorded in Zone A, but Cycle C was the most destructive of the simulated cycles. The reason for this discrepancy remains unknown. It may result from the substitution of Micraster for Offaster chalk, from random chance or from one or more of a number of differences between the simulated conditions and those actually existing on the exposed shore platforms. These include probable differences in

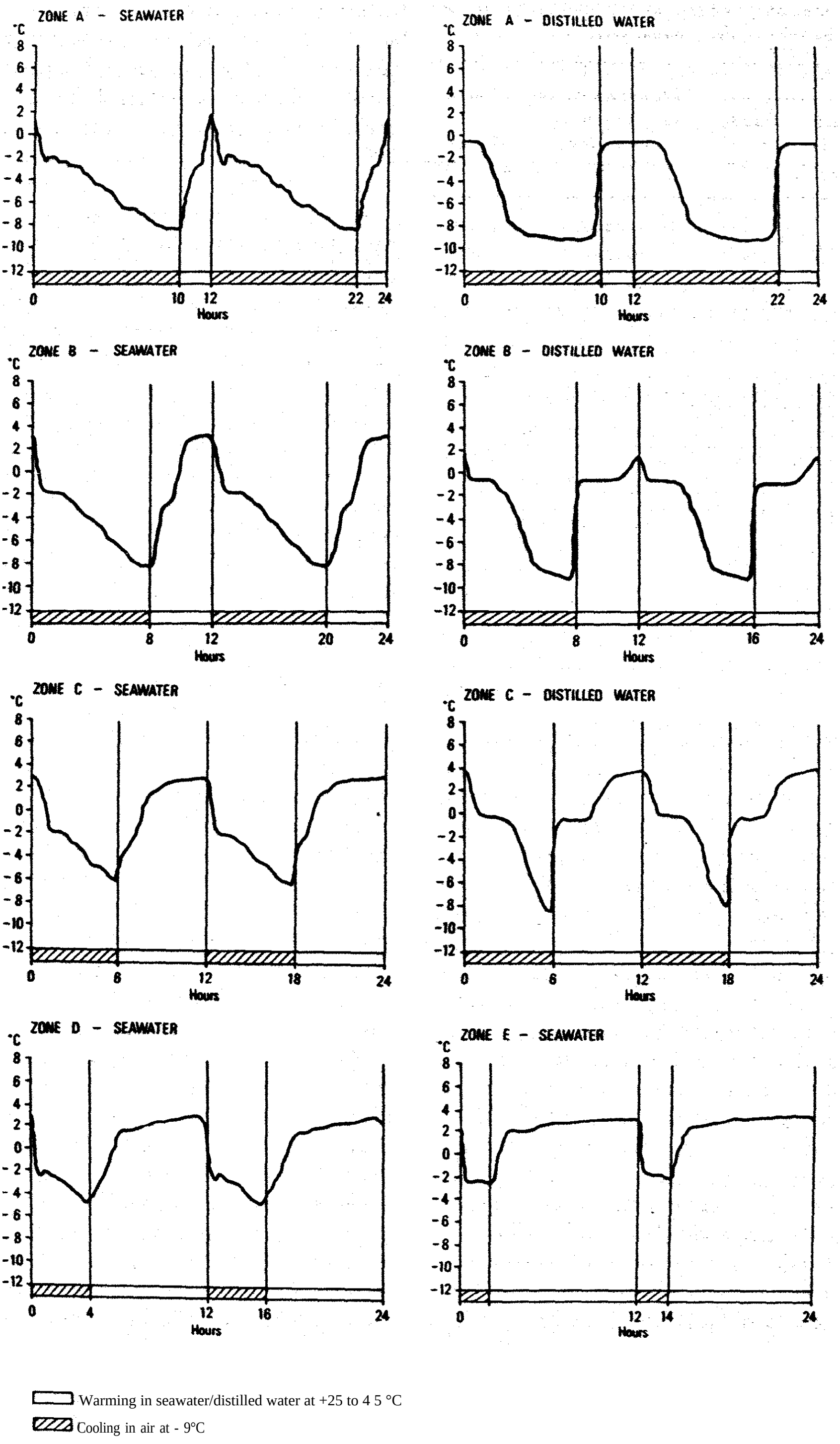

FIGURE 5. Rock temperatures recorded in the centres of 76 mm cubes of chalk during simulated tidal cycles

TABLE IV. *Mean percentage disintegration of chalk cubes after fourteen simulated freeze-thaw tidal cycles in distilled water*

Tidal cycle	*Freezing period (hr)*	*Thawing period (hr)*	*% original wet weight remaining as a coherent mass*	*Standard deviation*
A	10	2	99·9	0·15
B	8	4	100·4	0·64
C	6	6	101·1	0·64

TABLE V. *Rank order of damage on platform zones and in simulated freeze-thaw tidal cycles*

Rank	*Platform zones*	*Simulated cycles*
1	A	C
2	B	A
3	C	B
4	D	No damage
5	E	No damage

the rates of freezing and thawing due to the relatively small cubes of chalk used in the laboratory compared with the large continuous chalk mass of the platforms; likely increases in the rates of thawing by the sea, of at least the surface of the platforms, because of the much larger and moving volumes of water both providing and dissipating heat; and possible variations between zones of the platform in the susceptibility of the chalk to frost action due either to natural variability or weakening caused by other shore processes such as solution or battering by flint pebbles.

Despite a difference in the rank order of breakdown, the simulations appear to confirm the deduction, based on field evidence, that it is necessary for chalk to be exposed to freezing temperatures for several hours before frost damage occurs. This agrees with the work of Lautridou *et al.* (1975) who also found that a period of five to ten hours may be necessary for freezing to occur in saturated specimens of rock. No loss in weight was recorded in cubes frozen repeatedly for two and four hours in Cycles E and D but all cubes frozen fur six, eight and ten hours in Cycles C, B, and A respectively, lost weight due to the onset of disintegration. The minimal damage suffered by cubes subjected to freezing and thawing in distilled water clearly supports the suggestion by Williams and Robinson (1981) that it is the combination of frost and salt, and not the action of frost alone, that is particularly destructive to these shore platforms during periods of exceptionally cold weather. Frost alone is capable of causing saturated chalk to breakdown (see Williams 1980 for details), but frost damage is markedly increased by the presence of salts.

Why the combination of frost and seawater should have such a destructive effect under the relatively mild freezing regimes encountered in south-east England even during such severe winters as 1962/3 and 1984/5, is problematical. The freezing point of pure water is about 0°C and, under normal conditions, water below this temperature can exist only in the solid form, Thus, when a rock, saturated in distilled water, is cooled to below 0°C, all, or nearly all, the water within the rock is converted to ice. Because ice is less dense than water, the space required by the ice is approximately 9 per cent greater than that occupied by the water before freezing, and it has often been suggested that the stresses on pore walls, cracks and flaws within the rock resulting from this volume increase are the major cause of frost damage, (Embleton and King, 1975; Washburn, 1979). However, when seawater, which is a dilute solution of salts of remarkably uniform composition, dominated by NaC1, see Table VI., is cooled below its freezing point of approximately - 2·5°C, only part of the water solidifies and a liquid brine remains. Crystallization of salts from the brine does not commence until – 8·2°C, when $Na_2SO_4.l0\ H_2O$ begins to form (Pounder, 1965). Other salts do not begin to crystallize from the brine until the temperature is reduced to below – 22°C, and some liquid appears to remain even down to temperatures as low as - 80°C. Hence, when ice crystallizes from seawater during cooling to - 9·0°C, the stresses created by volume expansion within the rock are likely to be less than when pure water freezes, because there is a smaller increase in volume to be accommodated and liquid remaining within the pores can be compressed. Thus, whilst it is not the purpose of this paper to identify the precise mechanisms by which salts enhance weathering by frost, the results suggest that the principle cause of rock breakdown is unlikely to be the expansion in volume that occurs when water freezes to form ice.

Recently, Hallett (1983) has suggested that the principle cause of rock breakdown during freeze-thaw cycles is thermodynamic pressure related to the chemical potential at the freezing front. Salts in dilute solution in water increase water transport to the

TABLE VI. *Composition of salt from 1 kg of seawater (salinity = 34·48 per cent) (Pounder, 1965)*

Salt	*NaCl*	*$MgCl_2$*	Na_2SO_4	$CaCl_2$	KCl	$NaHCO_3$	Other	Total
Mass (g)	23·48	4·98	3·92	1·10	0·66	0·19	0·15	34·48

freezing interfaces and this is likely to speed-up the growth of cracks. This theory may therefore explain why frost weathering is accelerated by salts in solution. Alternatively, it has been suggested that the destructiveness of solutions containing sodium chloride may result from the crystallization of $NaCl.2H_2O$ within rock pores when the temperature drops below 0·1°C (Williams and Robinson 1981).

CONCLUSIONS

During periods of exceptionally cold winter weather cycles of freezing and thawing cause spalling and cracking of chalk cliffs, shore platforms, and boulders along the coast of south-east England. The degree of damage on the shore platforms is directly related to the period of exposure to freezing air temperatures during tidal cycles. Most damage occurs to boulders and the upper reaches of platforms, which are exposed to freezing air temperatures for six hours or more during each tidal cycle. Frost action preferentially destroys edges, corners and upstanding protrusions and will therefore tend to smooth out irregularities and flatten the upper surface of the platforms, but in the absence of data on the efficacy of other forms of weathering and erosion on these platforms it is impossible to estimate the importance of freeze-thaw processes on their overall evolution.

Laboratory experiments suggest that the destructiveness of freeze-thaw activity in this coastal environment results from the combined action of frost with salts contained in seawater within the pores of the chalk This agrees with the conclusions of Goudie (1974) and Williams and Robinson (1981), that salts enhance weathering by frost, but conflicts with the conclusions of McGreevy (1982) who found that salts did not enhance frost weathering of Caen Limestone. In an attempt to resolve the conflict between his results and those of the previous authors, McGreevy suggested that perhaps only high concentrations of salts enhanced frost weathering. As seawater is an extremely dilute solution of salts this now seems an unlikely explanation.

The combined effects of salt and frost weathering has never previously been shown to be a major weathering phenomena in this type of temperate coastal environment, although Williams and Robinson (1981) suggested that it might be important and its importance has been recognized in the development of shore platforms under more extreme climatic conditions such as those experienced in eastern Canada (Trenhaile and Rudakas, 1981). The frost weathering investigated in this paper relates to conditions encountered during an unusually severe winter for southeast England. However, cracking and spalling of the chalk platforms, similar to that described, occurs on a lesser scale during most winters,

The precise mechanism by which salt enhances frost weathering requires further work which is currently proceeding., but the increase in volume that accompanies the conversion of water to ice is unlikely to be the major cause of the breakup of the boulders and platform surfaces described.

ACKNOWLEDGEMENTS

The authors would like to thank Blue Circle Industries PLC for free access to samples of fresh chalk, Mr. J. Stubbings for the preparation of the chalk cubes and Dr R. B. G. Williams for his valuable comments on an earlier draft of this paper. The research was carried out while L. C. Jerwood was in receipt of a N. E R. C. Research Studentship.

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