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COASTAL SPRAY WEATHERING OF BEDROCK IN THE SUPRATIDAL ZONE AT EAST PRAWLE, SOUTH DEVON

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ABSTRACT

A variety of microtopographic forms developed on greenschist in the immediate supratidal zone near East Prawle, South Devon, is described. They are interpreted as indicating that weathering is active in this environment. Field measurements show that bedrock surface lowering takes place at a rate of 0.6 mm a^{-1}. Field observations show that this is a weathering-limited situation as the granular products of weathering are rapidly removed by wind or overland flow to expose fresh rock surfaces. The weathering products can be observed to accumulate in hollows and on ledges. Laboratory experiments show that haloclasty—disintegration of the rock as a result of salt crystal growth in pore spaces—is the process most likely to be responsible for the observed weathering.

INTRODUCTION

GEOMORPHOLOGY is a science of many facets. The nature of the problems posed by landforms and erosion processes is such that they permit, indeed demand, that a variety of different approaches be adopted in their study. From the early beginnings of the subject researchers were concerned with describing landforms in qualitative terms and then inferring their evolution through processes of deductive reasoning. Within the last two decades there has been increasing emphasis on methods of quantitative description derived from field observation. Precise measurements of process in the field can be carried out over extensive periods of time with suitable instrumentation. Hypotheses derived from field observation may be tested by laboratory experimentation, in which field processes can be simulated under controlled conditions. Each of these approaches can contribute towards the understanding of a geomorphological phenomenon, permitting existing hypotheses to be tested and new ones to be formulated.

This paper will show how the landforms and processes associated with spray weathering in the supratidal zone (i.e. above High Water Mark: HWM) near East Prawle in South Devon, can be elucidated by employing these several different lines of investigation.

THE FIELD AREA

The study area is a stretch of coastline, some 300 m in length between Sharpers Cove (SX 786 357) and Dutch End (SX 785 355) (Fig. 1). Although detailed studies were limited to this small area, the features described are widely distributed along the coastal outcrops of the greenschists.

The shoreline is formed of solid bedrock. In the classification of Davies (1964) it is a macrotidal storm wave environment, with semidiurnal tides and a tidal range at springs of 5.2 m at nearby Dartmouth. Although no records exist of wave height, steepness and periodicity, an essential corollary of these high energy conditions is the abundance of spray thrown up above HWM by the breaking of waves on the rocky shore.

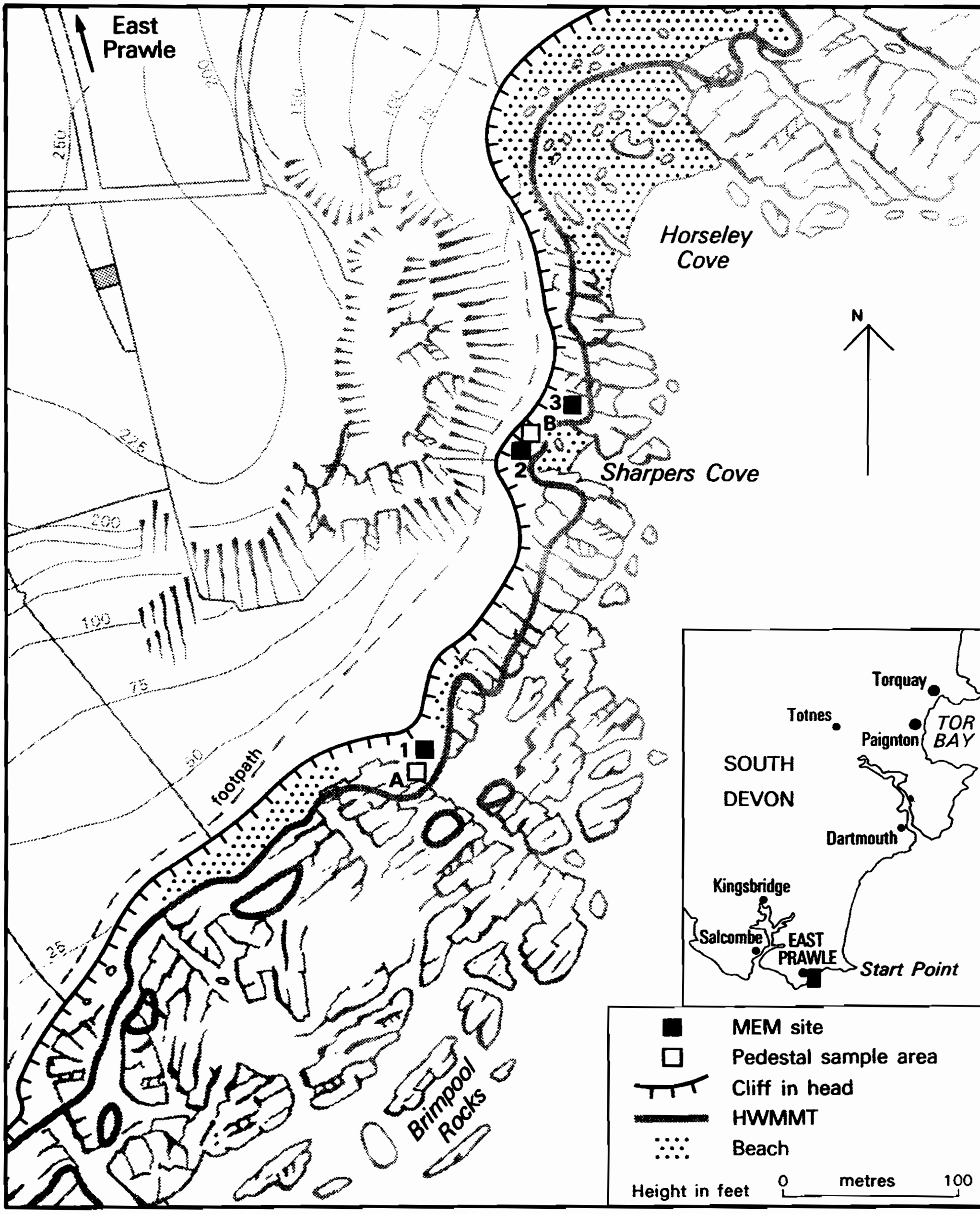

FIG. 1.
Location map and sample sites.

It should be emphasised that, unless otherwise stated, the landforms described in this paper lie above HWM, and are therefore beyond the direct effects of the mechanical energy of the impact of breaking waves. In the present context the significance of storminess, exposure and the rugged shoreline lies in the throwing up of spray on to the rock outcrops above HWM.

Geomorphologically the shore consists of three platforms, one of which is washed by the present sea and is exposed at low tide whilst the other two are raised platforms at approximately 4.5 m OD and 7.5 m OD, formed when the sea level was higher than at present (Orme, 1960). The distinction between the low and middle platforms is clear-cut at Sharpers Cove, whilst a higher platform occurs fragmentarily just west of this locality. Elsewhere the distinction between the platforms is less clear. Erosion under periglacial conditions in the past and under the present high energy marine conditions, allied to the varied fracture patterns in the bedrock, have conspired to create a rocky coastline of highly irregular form.

Fragments of raised beach exist on the higher platforms, but are dwarfed by comparison with the depth of head, rarely less than 4 m thick in this locality, which overlies the platforms and forms a cliff on the landward side. This has been described in detail by Mottershead (1971). It is clear that the head formerly extended much further seawards, but has been trimmed back, by marine and subaerial erosion to form a cliff overlooking the shore platforms, probably since the Flandrian transgression which terminated some 5,000 years ago and brought the sea up to its present level (Morey, 1976).

The solid geology of the study area is composed of the greenschist member of the Start schist complex. The greenschist has been described by Ussher (1904) and Tilley (1923), and is interpreted as representing the low grade dynamic metamorphism of former basic igneous rocks. Hobson (1977) states that the general concensus of opinion favours an Upper Devonian age for the original rocks (Marshall, 1967; Hobson, 1977). The age of the metamorphic episode has been determined (Dodson & Rex, 1971) by Potassium-Argon dating as 300 M years, placing it in the Upper Carboniferous. The greenschists themselves are subdivided into two facies by Tilley; chlorite-epidote-albite schist, and hornblende-epidote-albite schist. The detailed petrology of these rocks is discussed in a later section.

It is apparent that these distinctive rocks have reacted with the weathering conditions of this coastal environment to produce a suite of equally distinctive micro landforms. The presence of pitted and cavernous rock forms in the coastal greenschists was noted by both Ussher and Tilley. Similar forms have been observed on the greenstones of Cornwall (Everard, *et al.*, 1964).

These are interpreted as "weathering limited" landforms, in the sense of Carson & Kirkby (1972), in that their development is controlled by the rate of weathering itself, rather than by the rate of transport (removal) of the weathered debris. The term "weathering" is here used in the strict sense to mean the breakdown of solid rock into transportable debris. The greenschist breaks down into easily-transported fine particles (see p. 678) which may be removed much more rapidly than they can be formed. Fresh rock surfaces are, therefore, continually exposed to further weathering.

Field Observation of Form

Quantitative description of the pitted and cavernous rock forms in coastal environments seems to have been neglected by geomorphologists. In addition to the microtopographical forms sculpted by natural processes alone, there exists evidence that the current rate of weathering may be quite rapid. The author's attention was first drawn to this phenomenon by the presence on the raised platform of small patches of oil resting on small pedestals or plinths which project above the surrounding rock surface which, directly exposed to weathering agents and transportation processes, has continued to be lowered.

These two sets of features, the cavernous weathering and pitting and the oil-covered pedestals constitute the morphological expression of weathering, which can be observed, measured and described using morphometric techniques.

1. Cavernous weathering and pitting: these features are widespread and often produce a highly ornate and rugose aspect to exposed surfaces of greenschist. Rock surfaces thus fretted by weathering processes often seem not to possess any systematic regularity in their patterning. In certain areas, however, where some regularity of pattern is evident different types of pitting can be identified and characterised. The type of weathering pattern appears to be a function of structural control exerted by the pattern of fractures in the bedrock.

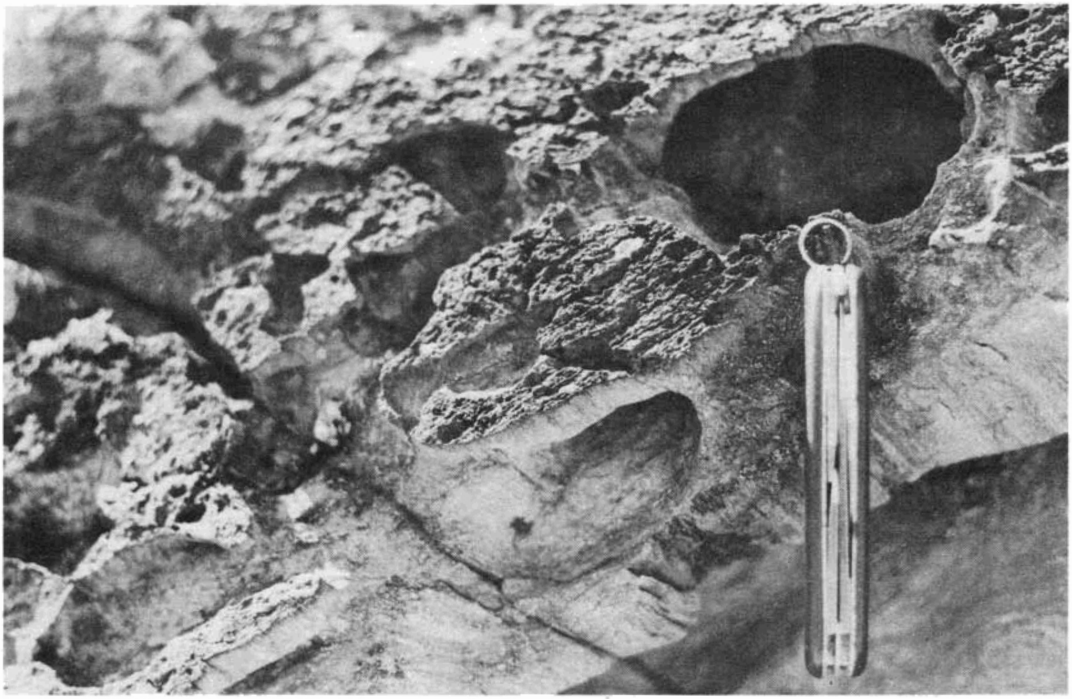

FIG. 2.
Iron impregnated joint face, now exposed to weathering and exhibiting cavernous weathering. Penknife is 90 mm long.

(a) **Cavernous forms:** this term is employed here to describe pits whose lateral internal dimensions are significantly greater than those of the orifice. Cavernous weathering pits do not appear to have any regularity of either spacing or dimension. The orifice is often irregular in shape, and of a size measured in centimetres. The internal dimensions are by definition larger, but impossible to measure because of the restricted orifice. Cavernous forms are found on vertical joint faces, particularly where the face is armoured with an impregnation of iron. They occur at Sharpers Cove just beyond the descent of the footpath, and again some 50 m west of the cove on the bluff between the middle and upper platforms. The iron impregnation is best

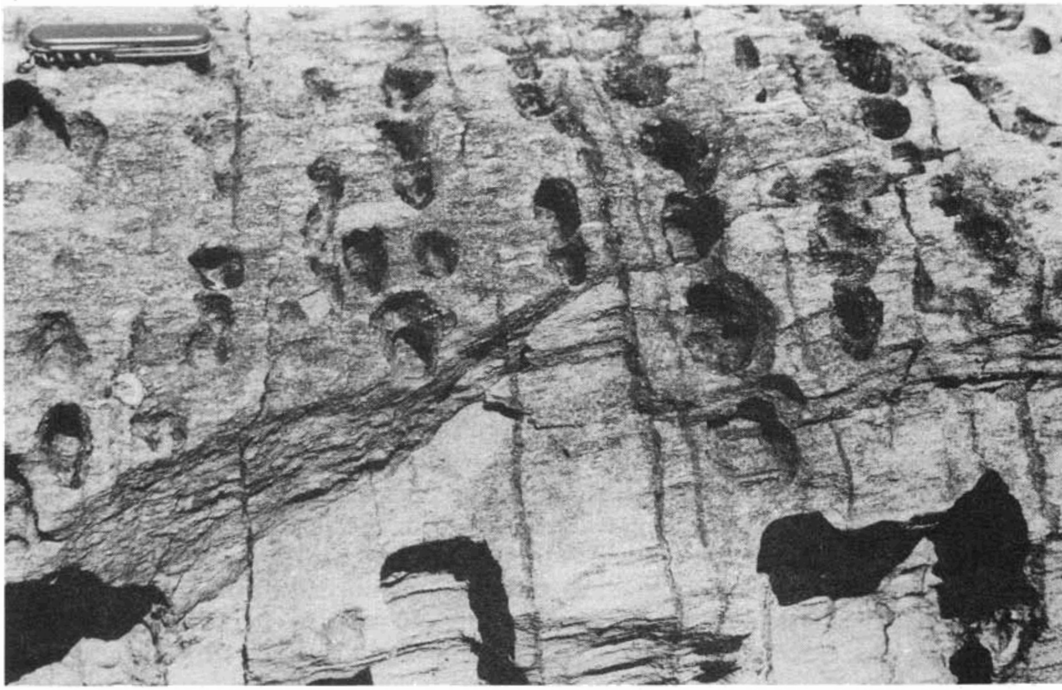

FIG. 3.
Cylindrical weathering pits. Note antipathetic relationship with iron-armoured joints.

displayed at the latter site. The iron, probably limonitic, attains a thickness of 3–4 mm (Fig. 2). Its likely derivation is from the weathering either of the formerly-overlying head, or of iron-rich minerals within the greenschist itself, and their redeposition along vertical joints. When a joint block of rock has been removed, one face of the joint remains exposed to subaerial weathering.

The development of cavernous weathering appears to be intimately related to the armouring. Once the resistant armour is breached, weathering can attack the less resistant schist behind, thereby enlarging the cavern both laterally and inwards.

(b) **Cylindrical pits:** These are defined as pits whose interiors are cylindrical in form, with approximately parallel sides (Fig. 3). A sample area of 1,500 cm^2 included 46 pits (a density of 307 m^{-2}), which were subjected to morphometric analysis. Maximum (D_1) and minimum (D_2) diameter of the orifice was measured with calipers, and also the depth (d). From these data the following descriptive parameters are derived:

Mean diameter: $$\frac{D_1 + D_2}{2}$$

Circularity ratio: $$\frac{D_1}{D_2}$$

Diameter/depth ratio: $$\frac{D_1 + D_2}{2d}.$$

These are plotted as frequency histograms in Fig. 4. Mean diameter is shown to be

26.4 mm, and mean depth is 22.1 mm ranging from 5–55 mm.

Cylindrical pits are found on surfaces parallel to the schistosity, mainly on the horizontal but also on inclined and vertical planes. Where the surface is inclined, the orifices tend to become elongated and coalesce. Where two surfaces, both cylindrically pitted, intersect to form an edge, then the rock pitted from both directions resembles a honeycomb or sponge. In a more advanced state of decay only remnants of the interstitial rock may remain.

The depth of pitting extends commonly from 10 to 40 mm, and blocks of cylindrically pitted rock often stand proud of the surrounding smooth rock surface. This suggests that there is a limit to the depth of pitting, and that once the pitted layer is removed, then weathering becomes uniform across the plane rock surface.

There is a clear antipathetic relationship between the pattern of cylindrical pits and vertical joints normal to the schistosity. The joints are armoured with iron and stand slightly proud of the general rock surface. The pits are located in the schist between the joints. Since the joints have a regular spacing, so there is a regular spacing in the cylindrical pits. Once present the pit will tend to retain water thus enhancing weathering, and the pit will tend to become self-perpetuating.

(c) **Conical pits**: these are defined as pits whose sides converge inwards towards a point. They appear to be confined to vertical faces normal to the schistosity that show little or no sign of armouring. An area 20 cm × 10 cm was sampled and yielded 42 pits, a density of 2,100 m^{-2}. Diameter and depth were measured as for cylindrical pits and the results can be compared in Fig. 4. Conical pits are shown to be significantly smaller in depth and in diameter, the latter accounting for their greater density per unit area. The difference in form is emphasised by the much higher depth/diameter ratio than for the cylindrical pits. Lines of conical pits appear to follow lines of weakness defined by the schistosity. It seems probable that once an original point indentation is present, then the pit will develop both by broadening and deepening.

The abundant weathering forms in the spray zone can thus be divided into distinct types and described quantitatively. The occurrence of these types is closely related to geological structure. The direction of schistosity, the presence of joints, and the existence of joint armour are evidently factors which exert a close control on weathering forms.

In addition to differential weathering at the scale of weathering pits, the same process also occurs at the granular scale. A rock surface exposed to spray weathering usually possesses a granular texture with the larger and more resistant albite crystals standing out from the surface, a feature noted by Ussher.

2. **Oil pedestals**: these features exist on more or less horizontal surfaces above HWM where a rock platform forms a promontory and is not covered by beach sediment (Figs. 5 and 6). In these locations waves break close by and throw up abundant spray during storms. The pedestals are, however, confined to the greenschist outcrops, and do not occur on quartz mica schists.

The oil is apparently of differing types, sometimes thin and runny, elsewhere thick and tar-like. From this it can be deduced that more than one spill is represented, and it appears probable that the oil has been deposited episodically over a period of time. If this inference is correct then it seems likely that the concentration at particular sites is favoured by factors which cause waves to break and throw up spray at those locations.

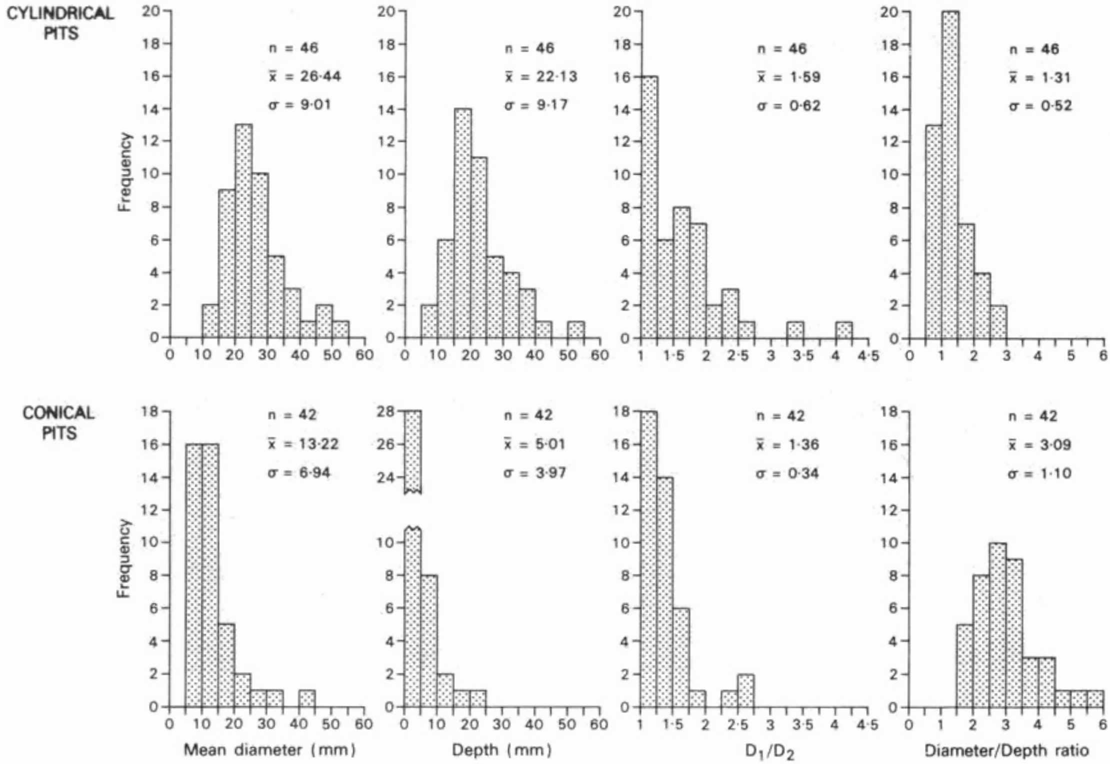

FIG. 4.
Morphometric characteristics of pitting types.

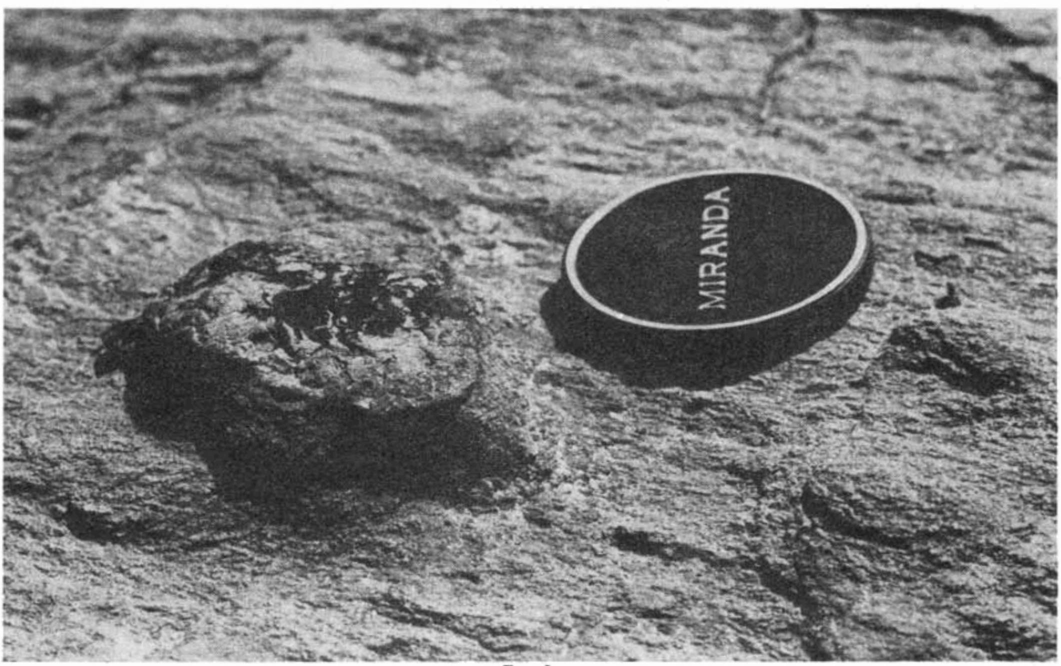

FIG. 5.
Oil pedestal, with frayed oil cover. Note the sloping shoulders of the pedestal form. (Lens cap is 51 mm in diameter, 6 mm deep).

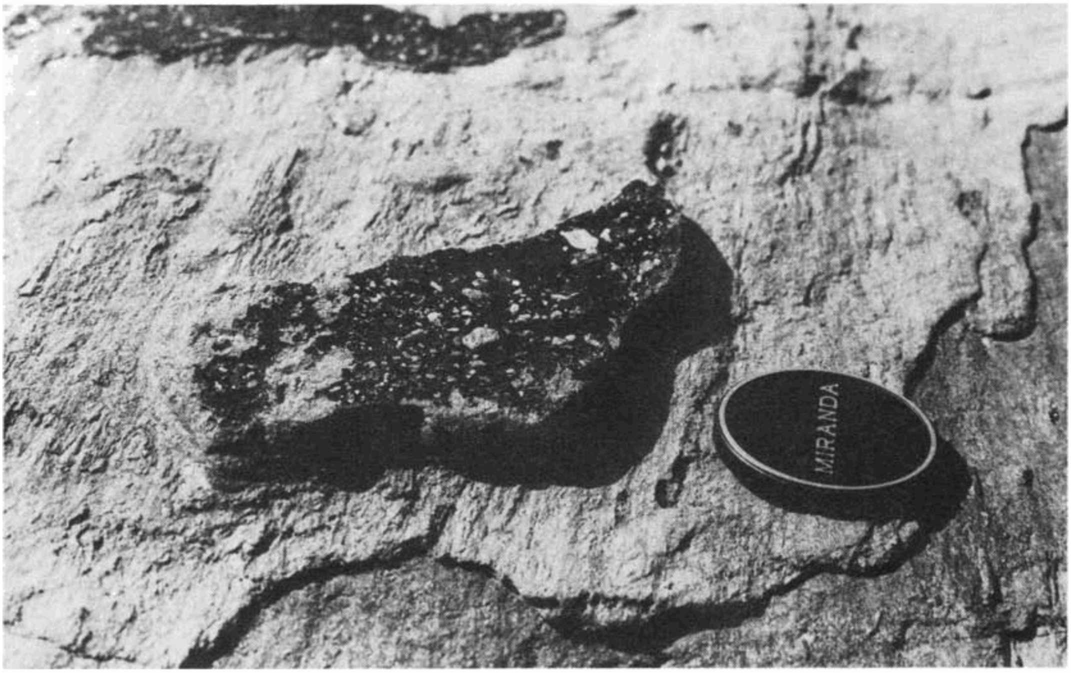

FIG. 6.
Oil pedestal 11 mm high. Note the congruence between the oil outline and pedestal planform. The oil cover is patchy. Modern beach sediment adheres to the oil.

These are conditioned by the degree of exposure and local topography of the surface on which the waves break. It is concluded therefore that the oil has reached its present site having been thrown up by spray above HWM, and that it has accumulated episodically whenever suitable wave and tide conditions coincided with a suitable supply of oil.

There is a very close congruent relationship between the planform of the oil patch and the pedestal beneath, particularly in the case of the many well-developed pedestals. The clarity of this relationship, and the sharp edges of both the oil patch and the shoulder of the pedestal, strongly suggest that the pedestals have emerged subsequent to the deposition of the oil as a result of the lowering of the surrounding rock surface. An alternative hypothesis, that the oil has merely been stranded on pre-existing knobs of rock may be discounted on the grounds that oil so deposited may be expected to be draped over the rock knobs without demonstrating the same sharpness of outline or congruence of planform.

The morphology of the pedestals was assessed at two sample sites, each 2 m^2 in area; Dutch End (Plot A) and Sharpers Cove (Plot B). These were sites at which the pedestals were particularly abundant and well developed. Mostly circular or elliptical in planform, maximum and minimum diameter was measured for each pedestal, and averaged to yield a measure of mean diameter. The height of each pedestal was measured using calipers at a minimum of four locations on opposed diameters. These values were averaged to give a mean value of height for each pedestal. Due to the limitations of the instrument employed, it was not possible to measure heights less than 0.5 mm, and incipient pedestals lower than this were therefore excluded from analysis.

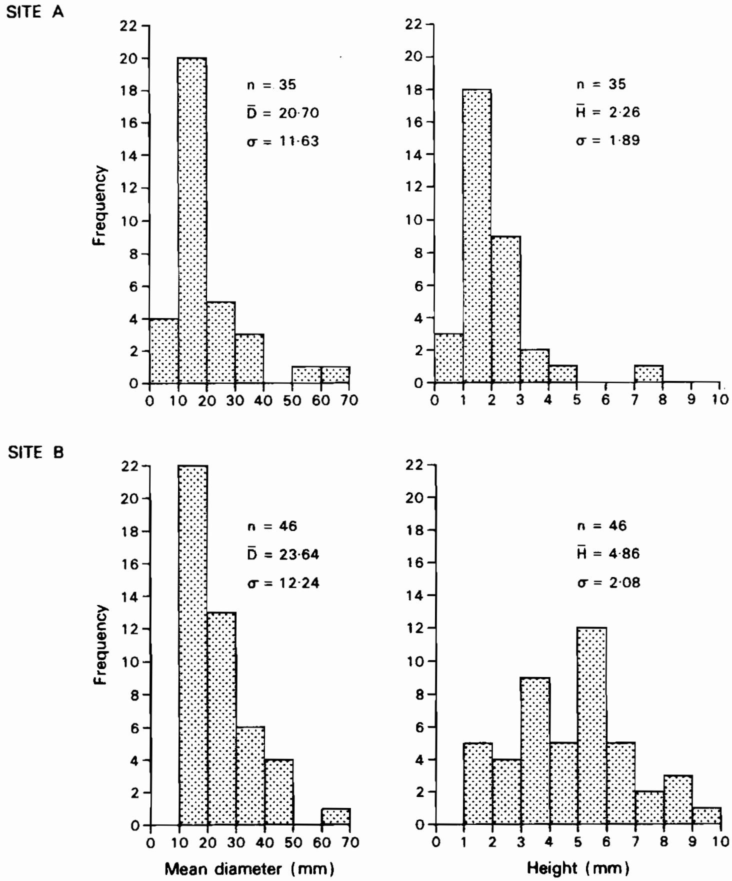

FIG. 7.
Morphometric properties of pedestals.

The morphometric properties of pedestals are presented in Fig. 7. Plot A yielded 35 measurable pedestals, Plot B provided 46. The mean diameter of pedestals does not differ significantly at the two sites. This is not surprising, since pedestal planform and size are closely dependent on the form of the original patch of oil and there seems no reason to expect a systematic variation between sites. Mean pedestal height, however, does appear to differ significantly, Plot A yielding a maximum value of 7.15 mm and a sample mean of 2.26 mm, whilst Plot B has a maximum value of 9.96 mm and a sample mean of 4.86 mm. Maximum values of pedestal height observed in the vicinity of the sample plots, although not included in the analysis, were 11.19 mm adjacent to Plot A and 10.04 mm near Plot B.

The pedestal samples at each site were subdivided according to the degree of completeness of oil cover. A simple threefold classification was employed, according to whether the oil cover on the pedestal was *complete* (i.e. it covered the planform of the pedestal completely), *frayed* (i.e. marginally weathered, back from the edges, but otherwise continuous) or *patchy* (i.e. it had thinned such that bare rock was exposed within the outline of the patch).

The median elevation of pedestals was calculated for each of these categories at each site (Table 1).

Table 1. *Median pedestal height, in relation to oil cover*

	Plot A			*Plot B*		
	n	H (mm)	Range	n	H (mm)	Range
Patchy	6	1.92	1.2 – 7.1	12	5.60	2.9 – 8.6
Frayed	19	1.77	0.8 – 3.4	28	4.75	1.9 – 9.6
Complete	10	1.61	1.1 – 3.2	6	2.55	1.9 – 6.3
Maximum		11.19			10.04	

The subsamples represented by these categories are sometimes small, and the data unsuitably distributed for statistical analysis. Comparison of median values, however, reveals a pattern which is repeated at both sample plots. Although there is a considerable overlap between categories, there is a general increase in elevation from *complete,* through *frayed* to *patchy* oil cover. Some significance can be attributed to the observation that the same pattern occurs at both plots, although the difference between the categories cannot be demonstrated to the normal levels of statistical confidence.

This pattern can be interpreted as representing the progressive weathering of the oil cover. It is reasonable to postulate an initially complete oil cover of each pedestal. Thinning of the oil at the margin would produce the frayed condition, with continued thinning causing the oil to become patchy. If this interpretation is valid then the youngest pedestals are the lower ones with the complete cover, whilst the oldest pedestals are the higher ones with the patchy cover. As long as oil is present to protect the subjacent rock, differential weathering and erosion continue to increase the elevation of the pedestals. Once the oil is completely removed then the pedestal will decay. Occasionally well-formed pedestals may be seen without any oil cover, but these are rare. Degradation seems to begin with a rounding of the top edges of the pedestal as the oil frays back. The frequent occurrence of small ill-formed knobs of rock may well represent degraded pedestal remnants from which the oil has been removed by decay.

A significant relationship appears to exist between pedestal height, and pedestal mean diameter. These parameters are plotted against each other for both sample plots (Fig. 8). In both cases the relationship is positive and significant, in the case of Plot B, highly significant, at the 0.1% level. The significance of the correlation at Plot A is reduced by the occurrence of large diameter pedestals of low elevation. If the interpretation outlined earlier is valid, that pedestal height is related to age, then it is possible to speculate that these large but low pedestals represent recent spills of oil that have not yet attained their maximum potential height. It therefore seems reasonable to regard them as incipient forms. These results suggest that larger patches of oil persist longer, and therefore allow more time for the attainment of greater pedestal height.

It is concluded therefore that pedestal height is related to both age and diameter. The height to which they develop, 10–11 mm, is as remarkable as the clarity of their form. On an exposed rocky shore such as this, in a high energy wave environment

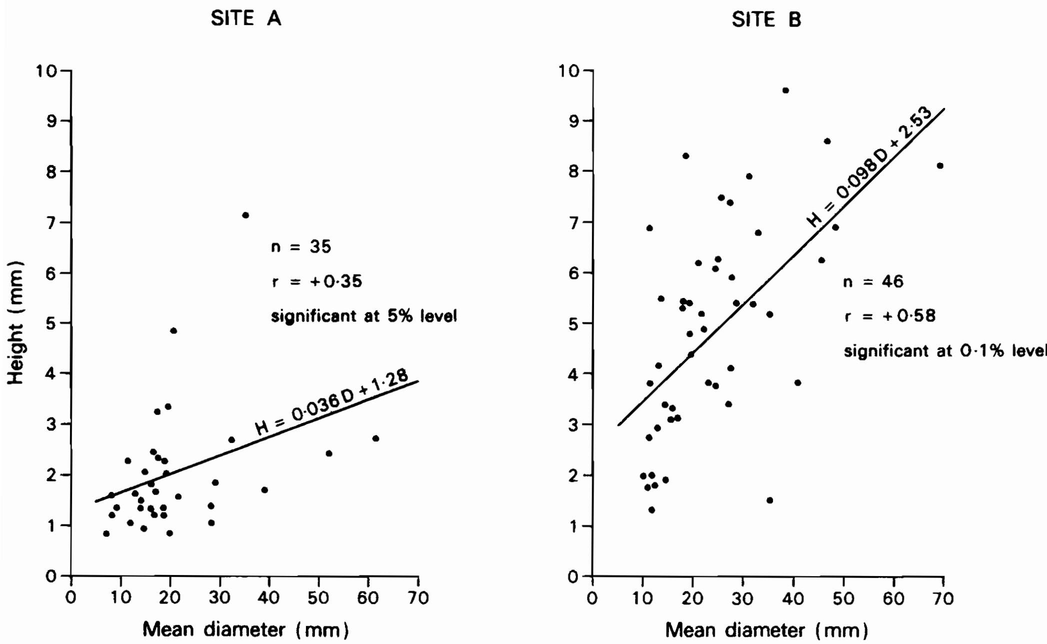

FIG. 8.
Morphometric relationships of pedestals.

with abundant spray, the duration of the oil spots can be expected to be limited, since the oil itself can be expected to weather away during a decade or two (A. L. Bloom; M. Spooner, *personal communication*). The attainment of such elevations therefore implies a considerable rate of lowering of the exposed surrounding rock surfaces. This in turn implies a high rate of weathering and the ready removal of the weathering products. The inferences derived from the oil pedestals taken together with the abundance of pitted and cavernous forms are suggestive of very active weathering.

Field measurement of process

Experimental measurements of rock surface lowering in the supratidal zone were made using a micro-erosion meter (MEM), described by High & Hanna (1970). This instrument consists of a dial gauge with probe, mounted on a triangular platform with a leg at each corner, 15 cm apart (Fig. 9). It is designed to be located and precisely relocated on metal studs set into the rock surface. The instrument permits a reading of rock surface elevation relative to the fixed studs to a precision of 0.001 mm. Repeated measurement at intervals of time therefore permits a direct determination of the rate of lowering of the rock surface.

Using an array of six studs, four contiguous triangles were set up at each site (Fig. 10). Since the probe is off-centre to the triangle, three different measurement points are possible from each triangle, with different orientations of the MEM. Thus a maximum possible total of 12 measurement points may be gained from the complete array. To date measurements have been obtained for three sites over a period of one year.

The location of the sites is indicated in Fig. 1. Site 1 is adjacent to Plot A, some 100 m southwest of Dutch End. It is located *ca.* 1 m above HWM and some 8 m from

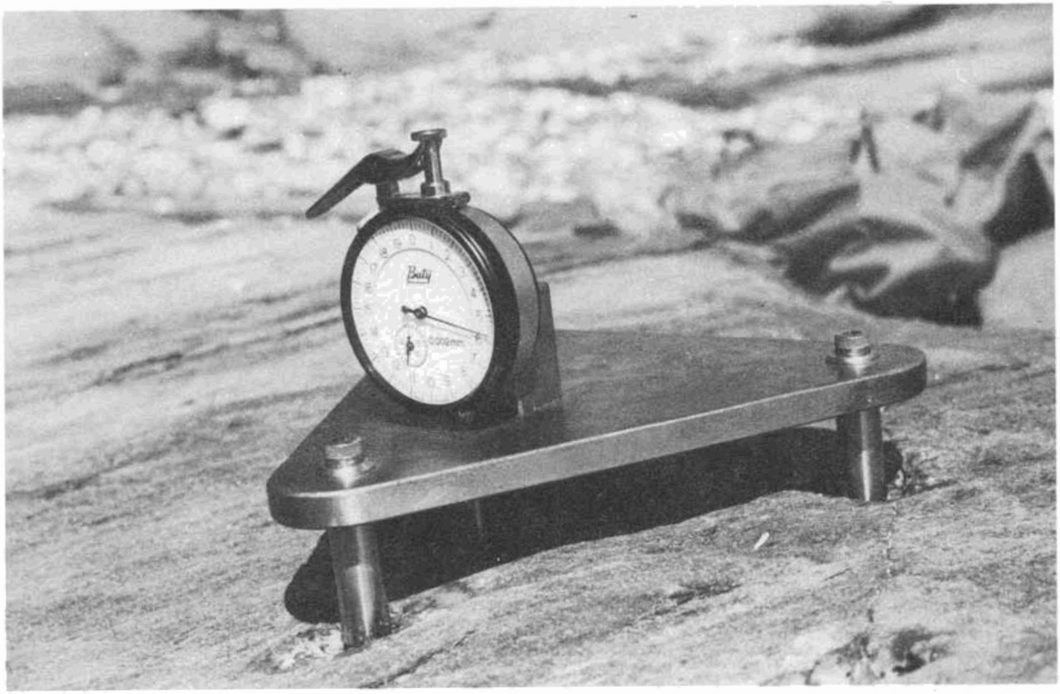

FIG. 9.
MEM in operation. Note the probe visible beneath the gauge.

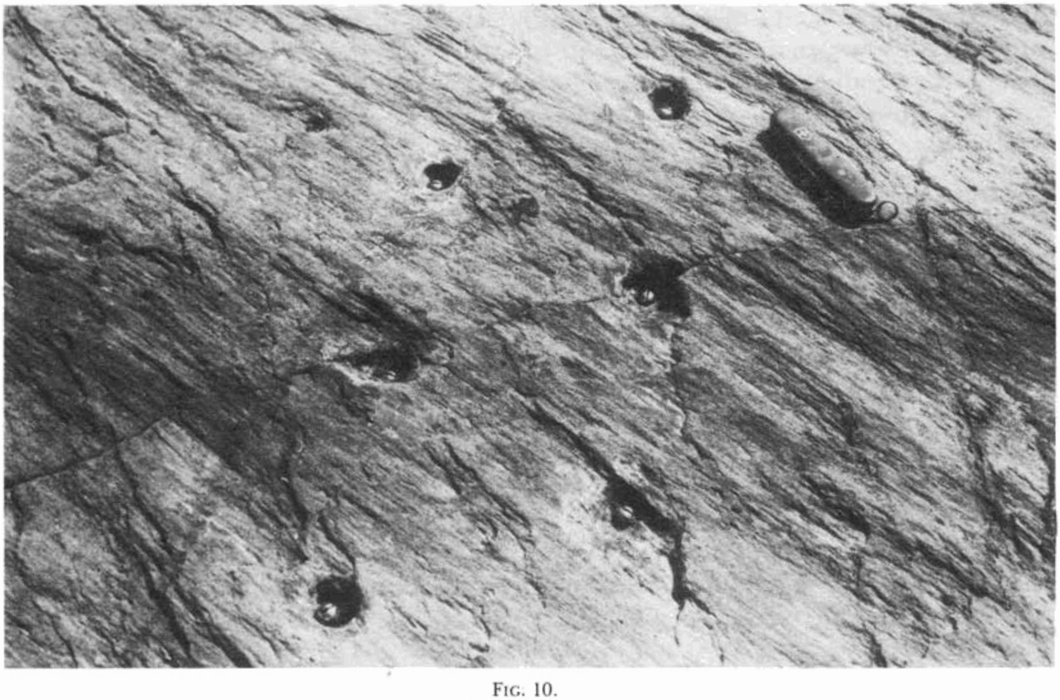

FIG. 10.
Array of studs at MEM Site 1.

the waterline at high tide. Sites 2 and 3 are at Sharpers Cove, adjacent to Plot B. Site 2 is *ca.* 3 m above HWM and 2 m from the high tide line, while site 3 is 1.5 m above HWM and 3 m from the waterline.

The results of twelve months measurement (2.1.80–30.12.80) are summarised in Table 2. Readings were taken at approximately three-monthly intervals. No clear seasonal trends emerged, and the measurements are therefore aggregated to yield an annual rate of lowering.

Table 2. *Rates of surface lowering derived by MEM*
*(*Mean of 12 points, †Mean of 10 points)*

	Site 1 mm a^{-1}	Site 2 mm a^{-1}	Site 3 mm a^{-1}
Mean	0.642*	0.554†	0.630*
Max.	1.687	1.931	1.010
Min.	0.160	0.035	0.036

These results show the magnitude of surface lowering, together with the range of values obtained. They indicate a mean annual rate of lowering per site ranging from 0.55 to 0.64 mm a^{-1}*. There is a considerable range of values for each site, indicating the highly variable rate of point lowering measurements at the micro scale, a feature noted by other workers (High & Hanna, 1970; Robinson, 1976; Spencer, 1981). The degree of similarity between sites, however, suggests that the rate of lowering is generally uniform on a broader scale. It is considered, therefore, that 0.6 mm a^{-1} represents a reasonable estimate of rock surface lowering, applicable throughout the spray zone.

The surface lowering measured in the field by MEM represents the combined effect of both weathering and the removal of weathering products by transporting agents. The fine calibre of the weathering products renders them susceptible to transportation by both wind and running water. Both occur frequently at this exposed coastal site. Sea spray and rainwater both produce rapid runoff by overland flow on the impermeable rock surfaces, washing the weathering products into pans and ledges.

Several quantitative investigations of denudation in littoral environments have been carried out to date, many of which are listed by Kirk (1977). Yet most of this work has been concerned with processes in the intertidal zone—marine abrasion and quarrying, solution, and erosion by marine organisms. Although active rock weathering in the spray zone has been commented on by previous authors, e.g. Trenhaile (1980), Gill (1981), quantitative studies of this process appear to have been strictly limited.

Emery (1941) estimates the retreat of cliffs of calcareous sandstone in California at 0.5 mm a^{-1} as a result of spray weathering. Trudgill (1976) suggests that spray weathering is an important though unquantified component of the denudation of gently shelving slopes of limestone in the upper intertidal zone at Aladabra Atoll. Values of surface lowering of 3–4 mm a^{-1} were obtained for three sites. Spencer (1981) quotes mean rates of 0.47 mm a^{-1} and 0.53 mm a^{-1} for calcarenites on Grand Cayman Island sometimes exposed to salt spray. None of these three studies is

* a^{-1} = per annum

directly comparable to the present one however, for all are concerned with calcareous rocks and none refers explicitly to rock surface lowering in the immediate supratidal zone.

The rate of weathering of the greenschist is shown to attain values which, for an insoluble rock in its unweathered state, well indurated and mechanically sound, are remarkably high in comparison with values obtained elsewhere. (Embleton and Thornes, 1979, Table 4.12.) Thus the rate of weathering inferred from the pedestal measurements is both demonstrated and quantified. It is clear that the exposed surface of the greenschists is breaking down very rapidly under the conditions to which they are currently exposed, close to HWM in the supratidal zone. The next stage in the investigation, therefore, was to consider the nature of the weathering processes involved.

A consideration of weathering processes

Weathering is the breakdown of rock. It can be expressed in a simple equation thus:

$$\text{Weathering agents} + \text{Bedrock} \rightarrow \text{Weathering products}$$

The nature of the weathering processes is a function of the weathering agents present, and the mechanical and chemical properties of the rock. When the products of weathering are examined and considered in relation to the weathering environment (the conditions under which weathering operates), inferences may be made about the weathering processes responsible. At that stage simulation experiments may begin, in an attempt to replicate various aspects of the weathering environment under controlled conditions. As a prelude to a discussion of process, we will examine the component elements of the weathering equation.

The Weathering Environment: air temperatures range from below 0°C probably to above 25°C. Although no records are available for the field site, a station maintained by Slapton Ley Field Centre some 10 km to the north recorded minimum and maximum air temperature values of −5.6°C and 26.5°C during the period 1960/1973 (Ratsey, 1973). These probably represent a fair guide to the range of air temperatures in the study area, although temperatures at the exposed rock surface will certainly show a wider range of extremes.

Atmospheric humidity probably remains fairly high in such close proximity to the sea. Episodic inundation of the rock surface takes place by rainwater, and by sea water spray during rough weather, especially at high tides. Retention of the water is limited, and rapid runoff takes place across the impermeable rock. Any remaining moisture is readily removed by evaporation under the prevalent air temperature and wind conditions. Consequently alternate wetting and drying is a common occurrence.

Weathering agents: the potential agents of weathering are rainwater and seawater.

Ions present in solution in seawater which are available for weathering reactions are listed in Table 3a.

The normal salinity of seawater is 34.3‰. On evaporation the ions combine to form salts, whose abundance is indicated in Table 3b. These salts may also act as weathering agents.

The bare rock surface with which this study is concerned is completely devoid of vegetation, although other parts of the rock platform more than a few metres away

Table 3

(a) *Ions in solution in seawater*		(b) *Salts crystallising out of seawater*	
	gm kg^{-1}		gm kg^{-1}
Cl^-	18.98	NaCl	27.21
Br^-	0.065	$MgCl_2$	3.81
SO_4^{--}	2.65	$MgSO_4$	1.66
HCO_3^-	0.14	$CaSO_4$	1.26
Mg^{++}	1.27	K_2SO_4	0.86
Ca^{++}	0.40	$CaCO_3$	0.12
K^+	0.38	$MgBr_2$	0.08
Na^+	10.56		

(after Kuenen, 1950)

from HWM do possess a cover of lichens. It is also above the range of grazing by limpets and periwinkles. For the purposes of this investigation, therefore, the biotic influence may be considered to be negligible.

Bedrock: samples of bedrock were taken from the raised platform adjacent to MEM site W. The mineral assemblage determined by thin section analysis is shown in Table 4. The composition of the minerals present is also shown, together with their abrasion pH as quoted by Stevens & Carron (1948).

Table 4. *Mineralogy of the Prawle greenschists*

Constituent minerals	Estimated abundance %	Composition	Abrasion pH
Albite	35–40	$NaAlSi_3O_8-CaAl_2Si_2O_8$	9–10
Actinolite	25–30	$Ca_2(MgFe)_5Si_8O_{22}(OH)_2$	11
Chlorite	15–20	$(MgFe)_5Al(AlSi_3)O_{10}(OH)_8$	7–9
Epidote	10–20	$Ca_2Al_3(SiO_4)_3(OH)$	8
Sphene	5	$CaTiSiO_5$	9
Muscovite	5	$KAl_2(AlSi_3)O_{10}(OH,F)_2$	7–8
Quartz	2	SiO_2	6–7

The major minerals present are basic in composition, as indicated by their abrasion pH values. The abrasion pH of the rock as a whole is the combination of the values for the constituent minerals in appropriate proportions, and was determined in the laboratory to lie between 8.0 and 8.5.

All the major constituent minerals are silicates containing an abundance of metallic cations. Most are hydrous forms, incorporating hydroxyl ions. The significance of these component ions will be considered later. The textural properties of the rock may be observed in thin section. Crystal size is commonly 20 × 300 μm, with albite forming larger crystals ranging up to 700–1,500 μm.

Weathering products: these may be observed in two forms, weakened rock and the products of disintegration. The rock surface where weathering is taking place rapidly is clearly weakened. It can be easily scratched with a penknife, and the top 10 mm proved readily penetrable with a hand drill, and disintegrated into constituent grains. In contrast, fresh unweathered rock, as exposed on the shore where it is abraded regularly by beach sediment, is much tougher, does not disintegrate readily and is mechanically much more sound.

The products of disintegration accumulate in ledges and hollows on the surface of the platform. Table 5 shows the results of mechanical analysis of three such samples. In spite of the fact that these are transported sediments, and have been subject to at least some degree of sorting, they are practically identical in particle size distribution to the *in situ* weathering products scraped from a weathered rock surface.

Table 5. *Mechanical analysis of weathering products, expressed as percentage in different size grades*

		Transported weathering debris			In situ
	Sample No.	1	2	3	weathered rock
Granules	> 2000 μm	1	8	1	5
Sand	60–2000 μm	63	65	54	69
Silt	2–60 μm	35	26	44	26
Clay	< 2 μm	1	1	1	0

Sand and silt are the dominant modes present in all cases, with negligible clay content. This may be compared with the modal analysis of the parent rock, whose constituent minerals fall within the same size range. Microscopic analysis of the weathering products show that they consist of crystal aggregates, individual crystals, and crystal fragments, the latter often displaying cleavage faces or crystal form apparently unmodified by breakage or solution pitting.

It may be concluded therefore, that the dominant mode or rock breakdown is granular disintegration. Failure of the rock has therefore taken place along crystal boundaries or cleavage planes as a result of the breaking of cleavage and intercrystalline bonds. Chemical alteration appears to be strictly limited, since no evidence was found of significant solution or formation of clay minerals.

A consideration of the weathering products therefore affords considerable evidence as to the mode of rock breakdown; it is fundamentally a mechanical, rather than a chemical process, although it is still possible that limited chemical alteration may have facilitated granular disintegration by weakening cleavage and intergranular bonds.

Given the nature of the weathering environment, the agents and the mineral present in the rock, some estimate of the possible importance of different weathering processes can now be made. The major processes of weathering will be considered in turn, and an assessment made of their likely significance in the present context.

Thermoclasty:—rock breakdown by repeated expansion and contraction due to temperature changes. The temperature range to which the rock surfaces are exposed renders this process a possibility. Experimental evidence, however, has suggested that this process in isolation is unlikely to generate sufficient stress to lead to rock breakdown (Goudie, 1974).

Gelifraction:—rock breakdown due to the formation of ice crystals exerting tensile stresses within the rock. The abundance of water and the occurrence of occasional sub zero temperatures mean that gelifraction may take place. Its effectiveness will be strictly limited, however, by the rarity of frost, and by the fact that the salinity of seawater depresses its freezing point. Gelifraction is therefore unlikely to be important.

Haloclasty:—this is the process of salt weathering, whereby growth of salt crystals in pore spaces within rock exerts tensile stresses on the rock and tends to produce disintegration at a granular or crystalline scale. Thus the growth of these chemical substances can produce a mechanical effect. The effect of salts in promoting rock breakdown has long been known in respect of building stone (Schaffer, 1932; Winkler, 1966). Only recently has it come to be recognised as a significant geomorphological process (Wellman and Wilson, 1965; Cooke and Smalley, 1968; Winkler and Singer, 1972; Johnston, 1973). The relevant literature is well reviewed by Evans (1970), whilst Goudie, Cooke and Evans (1970), and Goudie (1974) have shown experimentally that saline solutions can be highly effective in causing disintegration of porous rocks of low mechanical strength.

Salt weathering operates in two main ways. Salt crystal growth by crystallisation from a saline solution creates a *force of crystallisation.* This varies with different salts and is a function of the molecular weight and density of the salt concerned. Certain salts exist in both anhydrous and hydrated forms, and may change their hydration state according to temperature and humidity. During hydration they may undergo considerable volumetric expansion thereby creating *pressure of hydration.* Both of these processes may operate within rock pores, the former when the rock is saturated with a saline solution, and the latter when salts already emplaced within the rock by crystallisation are subject to temperature and humidity fluctuations.

According to previously reported experiments, seawater is not an effective solution for promoting haloclasty (Goudie, 1974). Within the present context, however, the abundance of seawater, and the frequency of dowsing and evaporation render this process a significant contender.

Hydrolysis:—this is the weathering reaction between the H^+ cations or OH^- anions in water, and the elements comprising the rock forming minerals. These constituent ions of water may dissociate from each other and recombine with ions in the rock forming minerals. A common form of hydrolysis is for the H^+ ion to enter the mineral structure, displacing a cation which then combines with the OH^- ion to form a soluble weathering product. This can be a potent mechanism in the weathering of silicate minerals, of which the greenschists are composed. The abrasion pH of a mineral is a guide to its susceptibility to cation hydrolysis—higher pH indicates higher susceptibility (Table 4).

Other Ion Exchange Processes:—a variety of variously charged ions is present in seawater (Table 3a), and these may create potential for weathering by combination with the ions of the rock forming minerals when seawater and rock come into contact. The possibility of unspecified weathering reactions of this kind cannot be ruled out at this stage.

Oxidation:—exposure to atmospheric oxygen permits the possibility of the oxidation of metallic cations in rock forming minerals to produce mobile compounds.

Slaking (wetting and drying):—wetting causes water molecules to adhere to rock minerals. Water molecules possess polar electrical changes and may be attracted to mineral surfaces in an ordered manner, i.e. positive to negative, or vice versa. Thus an ordered layer of similarly oriented water molecules may accumulate at a mineral surface. Repeated slaking may cause successive layers of water to build up, by mutual attraction of the positive and negative ends of water molecules in successive layers. Such accumulations of layered water within a rock may create tensile stresses leading to rock failure (Ollier, 1969; Winkler, 1975).

Given that the mechanical processes of gelifraction and thermoclasty seem unlikely to be important in the present context, interest therefore focuses on those processes associated with seawater and its contained salts. Accordingly, experiments can be designed to test the relative effectiveness of the various possible individual processes under controlled conditions in the laboratory.

Laboratory simulation of weathering processes

In an attempt to simulate field weathering conditions, rock samples were submitted to a daily cycle of inundation and drying under controlled conditions in the laboratory.

In order to isolate the effects of the individual processes operative in the field, four different weathering environments were employed. In all cases the rock samples were immersed for one hour, then allowed to stand at air temperature for the remaining 23 hours of the diurnal cycle. It was not possible to control air temperature, but maximum and minimum values were recorded for each 20-day period. The four different experimental treatments were as follows:

A. Deionised water with air drying
B. Deionised water with humid atmosphere
C. Seawater with air drying
D. Seawater with humid atmosphere

The humid atmosphere was attained by suspending the samples in a bowl containing water, such that they were above the water level. The top of the bowl was sealed with foil thus retaining a 100% humid atmosphere within the bowl. The rock samples subject to this treatment always remained in a moist condition.

The conditions treat the actual weathering processes involved as black box systems, but nevertheless permit some inferences to be made concerning the processes likely to be operating. A particular process may be inhibited, permitted or accelerated under a given treatment. Table 6 summarises the processes inferred to be operating in each treatment. Thus a comparison of the effects of treatments A and B with C and D permits the distinction between the effects of water alone, and those associated specifically with salt water. Comparison of A and C with B and D permits discrimination between humid conditions alone, and alternate wetting and drying.

Table 6. *Postulated effectiveness of various weathering processes under different experimental regimes*

	Haloclasty	Oxidation	Hydrolysis	Ion exchange	Slaking
A. Deionised, air dry	Nil	Permitted	Limited	Nil	Permitted
B. Deionised, humid	Nil	Nil	Permitted	Nil	Nil
C. Seawater, air dry	Accelerated	Permitted	Limited	Permitted	Permitted
D. Seawater, humid	Nil	Nil	Permitted	Accelerated	Nil

Samples were taken from the surface of the raised platform close to MEM site 1. Rock cores 32 mm in diameter and ranging from 24.4–58.8 gm in weight were cut such that they displayed the surface which was exposed to weathering in the field. Four rock cores were subject to each experimental treatment. At the termination of each 20-day period, all the rock samples were leached by boiling in deionised water

Air temperature °C

maximum	31.0	33.0	36.0	27.0	24.5	20.5	20.5	18.5	15.0
minimum	17.0	15.0	16.0	13.5	12.0	10.5	5.5	4.5	5.0

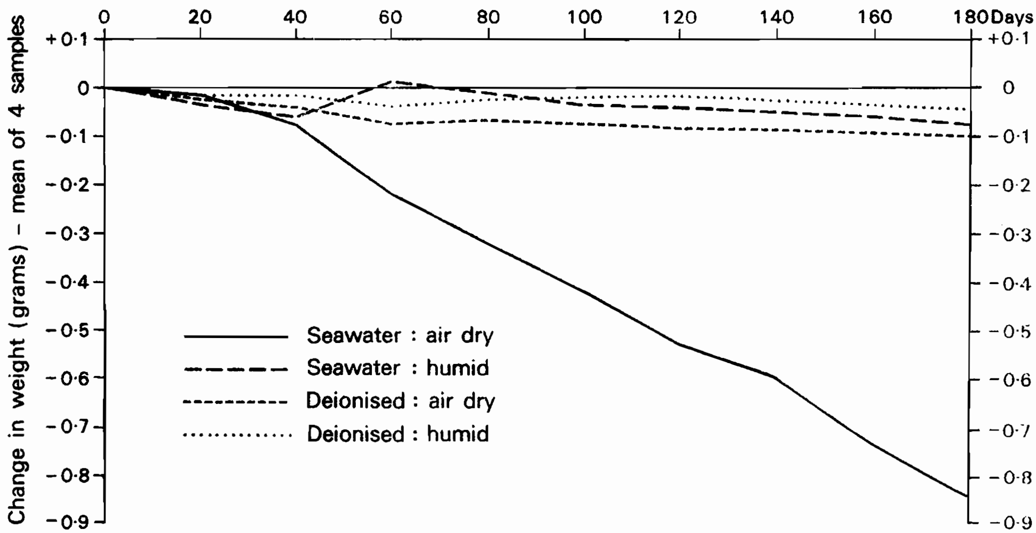

FIG. 11.
Experimental weathering of greenschist, as indicated by weight loss.

for one hour in order to remove any soluble weathering products or accumulated salts. The mechanical agitation involved in this also had the effect of removing any mineral fragments loosened or detached by weathering. The amount of weathering was assessed by determining the weight loss over each 20-day period.

The results of the weathering experiments over a period of 180 days are presented in Fig. 11. The weathering losses under Treatments A, B, and D are seen to be insignificant compared to Treatment C, in which the four sample cores showed a mean weight loss of 0.832 gm (range 0.475–1.103 gm). The regime of wetting and drying in seawater has a manifestly far greater effect on the greenschist than any of the others. Reference to Table 6 reveals that the process uniquely associated with Treatment C is haloclasty. It is therefore concluded that this is the process most likely to be responsible for weathering the greenschist. The other processes which may be operating in Treatment C—oxidation, hydrolysis, ion exchange and slaking all appear to have a negligible effect in comparison, since they produce negligible effects in the other weathering treatments.

During the course of the experiment flakes, crystals, and rock fragments became visibly detached from the top surface (the surface formerly exposed to weathering in the field) of each core. This confirms that granular disintegration is the dominant mode of breakdown, replicating the observation made in the field. Furthermore, it is apparent from Fig. 5 that the rate of weathering is approximately constant and is apparently unrelated to seasonal temperature changes. It is possible that a small proportion of the observed weight loss may be ascribed to loss of soluble minerals. An earlier series of experiments, however, of 100 days duration and using *un*weathered cores, showed insignificant weight loss when subject to the same treatments. It is therefore concluded that

(i) weight loss due to removal of solubles is insignificant,
(ii) granular breakdown due to haloclasty takes place only from weathered surfaces, not fresh ones,
(iii) the rate of weathering is independent of temperature.

The saline components of seawater are listed in Table 3b. By far the most abundant is sodium chloride (NaCl). Winkler (1975) shows that the force of crystallisation for this particular salt is quite considerable and greater than any of the others present in seawater. With the exception of calcium carbonate ($CaCO_3$) which exists only in minute concentration, it is the first salt to reach saturation and therefore begin to crystallise as the seawater evaporates. It seems likely that the salt most responsible for the breakdown of the greenschist is therefore sodium chloride, by virtue of (i) its force of crystallisation, and (ii) its abundance. Four of the less abundant salts (Magnesium chloride, $MgCl_2$; Magnesium sulphate, $MgSO_4$; Calcium sulphate, $CaSO_4$; Magnesium bromide, $MgBr_2$) exist in both anhydrous and hydrated forms. It is possible that these may also contribute to salt weathering, although their effectiveness is likely to be limited by their low abundance.

The weight loss recorded from the cores under Treatment C can be converted into volumetric loss, and dividing this into the surface area of the core yields a rate of lowering based on the assumption that all the weathered material is lost from the top surface of the cores. The mean weight loss is therefore equivalent to a maximum surface lowering rate of 0.77 mm a^{-1} (range 0.44–1.02 mm a^{-1}), which compares favourably with the mean value of surface lowering recorded in the field of 0.61 mm a^{-1}. Thus the simulation experiments appear to replicate the field conditions to a satisfactory degree. The higher weathering rate produced in the laboratory probably reflects the frequency and thoroughness of inundation of the rock samples. Doubtless rock surfaces in the field do not experience the same regularity of wetting and drying, or the same frequency. Continuous field monitoring would be necessary to establish precisely the frequency and regularity of inundation, and this would be an expensive operation. Nevertheless the simulation experiments do clearly indicate that wetting and drying in seawater is the dominant effective process, and that it is well capable of producing a rate of breakdown of the greenschist of sufficient magnitude to account for the field observations of surface lowering.

Consequences and Implications

From field observation, it is apparent that the high contemporary rate of weathering and surface lowering are limited to a zone immediately above HWM and not more than a few metres in width. Below HWM rock surfaces are daily washed by the sea, and abraded by littoral sediment, and they commonly exhibit a smooth and polished surface of sound unweathered rock. More than a few metres landward of HWM the rock platform has an extensive lichen cover, which therefore precludes the operation of rapid weathering of the kind described since lichens require a stable substrate. The occurrence of the pedestals immediately adjacent to HWM suggests that the most rapid weathering occurs in this zone, and it is here that the

MEM measurements were made.

An interesting anomaly is the sporadic occurrence of pitted forms in the intertidal zone below HWM. These features are apparently not developing at the present time since they are covered by anchored seaweed, and may represent survival from a period of formation in the past. This raises the possibility that some of the pitted forms above HWM may have formed during a former period when the sea was at approximately the same level as at present. Clearly the spray zone will fluctuate in position and elevation according to fluctuations of mean sea level. At the present time, therefore, they are apparently undergoing a period of renewed development since they have once again come under the influence of the spray zone.

The observed rate of lowering of the bedrock surface is, in effect, the rate of emergence of the pedestals. This provides an applied aspect to the study, for it is therefore possible to generate an estimate of the age of the pedestals and hence the oil upon them. In this way an estimation may be made of the duration of oil spills on this rocky shore (Mottershead, 1981). Applying the observed rate of lowering of 0.6 mm a^{-1} to the data in Table 1 yields a maximum age of pedestals with a complete oil cover of 5 years (Plot A) to 10 years (Plot B). Thinning of the oil and recession of the margins may begin after 1–3 years. Patchiness first appears after 2 and 5 years respectively. The highest pedestal observed, 11.2 mm, would have an age of over 18 years.

Conclusion

A variety of approaches has thus been brought to bear on the problem. A geomorphological problem was first recognised by subjective use of the intuitive eye. Morphometric techniques were employed to describe in quantitative terms the observed forms. The rapidity of weathering inferred from these observations was confirmed by field measurement of process. Finally, the weathering process responsible was identified by employing a laboratory simulation experiment.

As a result of these investigations it is clear that the greenschist undergoes rapid weathering and denudation in the coastal spray zone. This is inferred from the variety of microtopographic features displayed by these rocks above HWM. These forms are described and quantified. Active weathering and erosion are verified by field measurements of surface lowering. Laboratory simulation of different aspects of the weathering environment strongly suggest that the process most likely to be responsible is salt weathering, or haloclasty.

Although previous experiments by other authors on other types of rock have shown seawater to have little effect in this respect, it would appear that the greenschist is particularly susceptible to this process.

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