

**BIOEROSION ON SHORE PLATFORMS DEVELOPED IN THE
WAITEMATA FORMATION, AUCKLAND**

T. R. HEALY

University of Auckland*

Abstract

Bioerosion — the removal of lithic substrate by the erosive activities of living organisms — has not previously been discussed for New Zealand shore platforms. This paper aims at drawing attention to bioerosion as a process active in shore platform development. Detailed reference is made to bioerosion occurring on the alternating sandstones and siltstones of the Waitemata Formation found outcropping on the coastline around Auckland. In this area several facets of shore platform morphology may be attributed to the direct effects of boring and browsing marine organisms. A classification of animals causing bioerosion, based on mechanism of erosion, is presented, and the geomorphic significance of the various groups discussed.

INTRODUCTION

Many writers dealing with erosion of rocky coastlines tend to emphasise physical destruction of the shoreline by waves (Johnson, 1919, 1938; Edwards, 1951; King, 1959, 1963). Others recognise that subaerial weathering in the intertidal and spray-splash zone may warrant equal consideration (Bell and Clark, 1909; Bartrum, 1924, 1935; Hills, 1949; and Mii, 1962).

In contrast, Emery (1946), Ambler and Chapman (1950) and Revelle and Emery (1957) attribute to marine organisms indirect chemical modification of the interstitial waters, tidal pools and nearshore waters, facilitating solution of the soluble components of platform or cliff rock. Other investigators from a wide variety of areas report that direct biochemical erosion of the platform substrate is a process of considerable significance in platform erosion, as well as for sculpturing minor features upon the platform surface (Gardiner, 1903; Jehu, 1918; Ginsburg, 1953, 1957; Newell and Imbrie, 1955; Newell, 1956; Wiens, 1959, 1962; Emery, 1962; McLean, 1964 and others).

In a recent detailed investigation of the shore platforms of the Whangaparaoa Peninsula (Healy, 1967), the writer observed that the phenomenon of *bioerosion* — defined by Neumann (1966) as the removal of lithic substrate by the direct activities of organisms — was a widespread and effective process modifying the contemporary shore platforms.

The Whangaparaoa Peninsula (Figure 1) is an area representative of Waitemata Formation (Brothers, 1954) recently renamed Amokura Formation (Kear and Schofield, 1964). Shore platforms exposed at low tide surround 75 per cent of the coastline, and 3/5 of the remaining shoreline is characterised by platforms merely veneered with either sand or mud. Essentially the rocks consist of sub-horizontal alternating sandstones and muddy siltstones of Miocene age (Turner and Bartrum, 1929; Brothers, 1959). The sandstones are commonly about one foot thick, highly porous, uncemented, and unindurated (Ballance, 1964; Gregory, 1966).

* Now at Monash University, Australia.

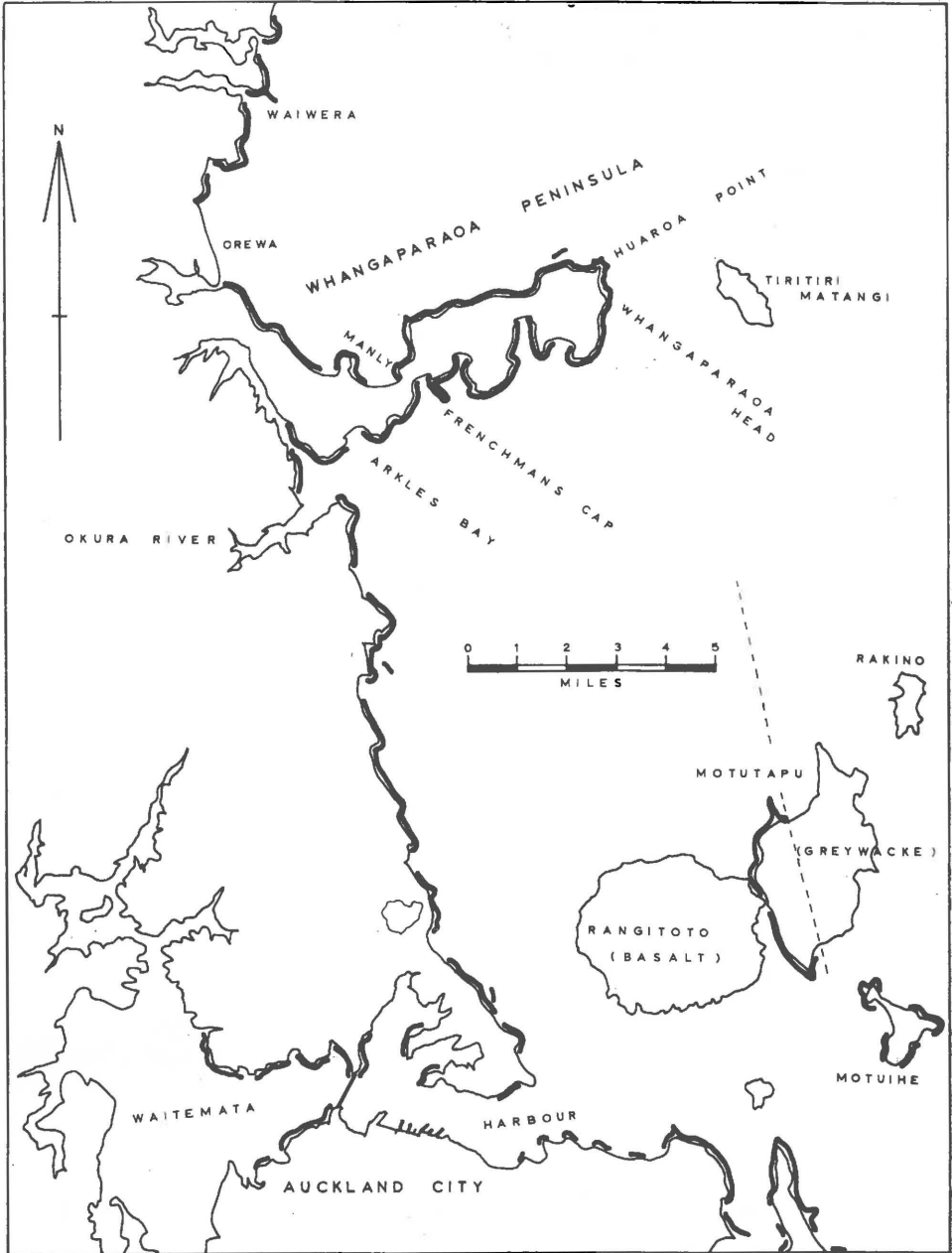


Figure 1. Location of broad inter-tidal shore platforms developed in the alternating sandstones and siltstones of the Waitemata Formation around Auckland.

Interbedded are finer grained often calcareous muddy siltstones. It is on these easily eroded siltstones exposed in the lower mid-littoral and sub-littoral fringe where the rocks are continuously saturated and soft, that the most spectacular effects of biochemical erosion occur.

The profusion of marine animal and plant life on the Whangaparaoa Peninsula is a remarkable characteristic of the lower mid-littoral and sub-littoral fringe. This

and the general ecology of the Auckland inter-tidal shore is presented by Chapman (1965), Morton (1965) and in more detail by Dellow (1950, 1955). The following account is therefore oriented to the geomorphic features and significance of bioerosion.

GEOMORPHIC MANIFESTATIONS OF BIOEROSION

It is difficult to state unequivocally that bioerosive organisms are responsible for certain morphological features on shore platforms. Nevertheless, observation implies that erosion by boring organisms is a major process modifying and causing retreat of the low tidal steps and sea cliffs (Figure 2). Boring organisms preferentially attack the softer muddy siltstones causing retreat by collapse of an overlying sandstone bed (Figure 3A).

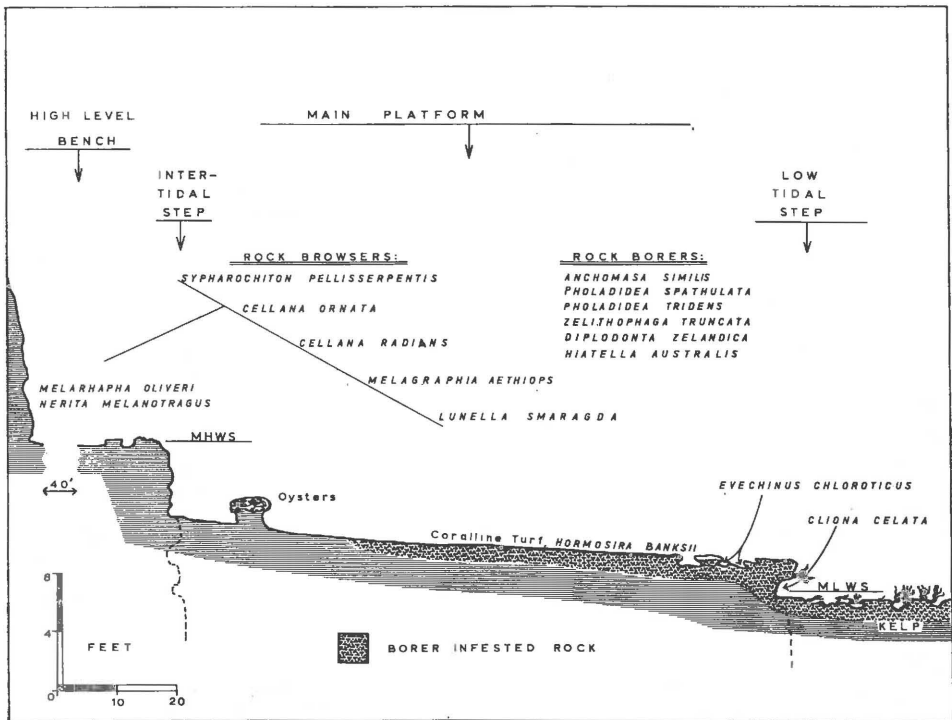


Figure 2. Distribution of bioerosive organisms in relation to shore platform morphology.

Apart from vertical retreat along a structurally controlled plane, certain organisms erode by burrowing into or browsing over the surface rock. The most obvious, in terms of volume of rock removed, is the break-up of the seaward edge of broad subhorizontal platforms by sea urchins (Figure 3B). On a smaller scale, marked pitting is evident especially on massive sandstone beds in the supra-littoral spray-splash zone. Less obvious in the littoral zone are small depressions formed by limpets and chitons.



Figure 3A. Undercut and collapse by bio-erosion at Frenchmans Cap. This is not a storm wave "active nip" but is the work of the boring sponge, *Cliona celata*, at the water level; and above this, the proliferation of rock-boring molluscs. Noticeably the oyster colony acts as a "hard-cap" at the upper midlittoral zone. Present water level is Low Water Spring Tide.



Figure 3B. Honeycomb disintegration of the seaward edge of an inter-tidal platform resulting from the activities of the sea urchin, *Evechinus chloroticus*. About 50 per cent of the platform rock to a depth of nine inches has been removed.

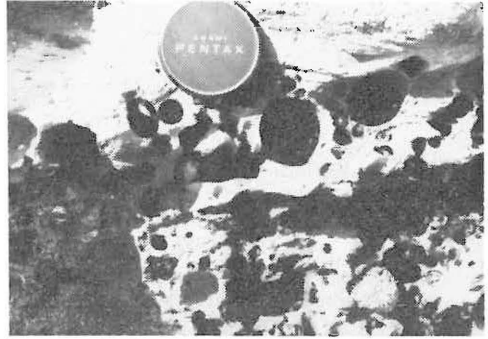


Figure 3C. Destruction of platform rock by a profusion of boring molluscs. The rock borers have preferentially attacked the softer muddy siltstone rather than the overlying sandstone.

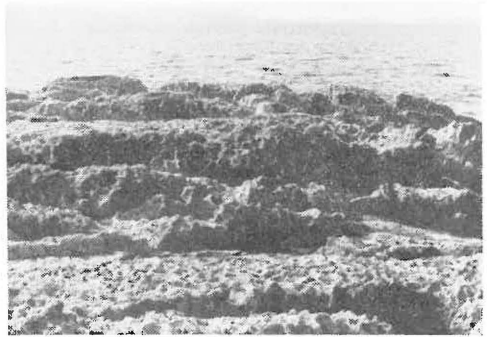


Figure 3D. Pitting in the intertidal zone. Formation of these pits is attributed to spray-splash action. Individual pits are generally polygonal in outline, separated by sharp ridges and reminiscent of solution lapies observed on limestone coasts.



Figure 3E. Bioerosive pitting is especially common on high-level massive sandstone benches, often occurring around pools and solution basins. Large populations of tiny *Melarhapha oliveri* are extensively distributed over the surface after rain, but during hot dry periods they congregate in pits and depressions. Their activity at this time causes enlargement and deepening of the pits.

Table 1. A classification of animals causing bioerosion on Whangaparaoa shore platforms.

ROCK BORERS:

A. *Boring by Mechanical Processes*

Active borers:

Anchomasa similus
Pholadidea spathulata
Pholadidea tridens
Evechinus chloroticus
Stylarioides plumosa

Passive Settlers — take over previously formed holes and adapt them. Boring rate is the growth rate of the animal:

Hiatella australis
Notirus reflexa
Diplodonta zelandica
Cleidothareus maorianus

B. *Boring by Chemical Processes — acid secretion:*

Zelithophaga truncata

C. *Boring by Chemical and Mechanical Processes:*

Dendrostromum aeneum
Cliona celata

ROCK BROWSERS: remove grains of rock while “grazing” the surface:

Sypharochiton pellisserpentis
Cellana radians
Cellana ornata
Melarhapha oliveri
Nerita melanotragus
Melagraphia aethiops
Lunella smaragda

**BIOEROSIVE ANIMALS FOUND ON WAITEMATA FORMATION
SHORE PLATFORMS**

Animals causing bioerosion are here classified either as *rock borers* or as *rock browsers* (Table 1). The former include the rock-boring molluscs, the sea urchin, worms and the boring sponge; while the latter consist of the browsing gastropods and chitons which “graze” the surface of the platforms as part of their feeding habit.

1. *Rock Boring Organisms*

Molluscs: Rock-boring molluscs constitute the most important agents of bioerosion on the Whangaparaoa shoreline. Four main species are observed, all occurring in the lower midlittoral. They are the acid-boring date mussel, *Zelithophaga truncata*, *Pholadidea spathulata*, *Pholadidea tridens*, and the rock-augering *Anchomasa similus*.

Earlier workers, especially in limestone, chalk and coral reef areas have concluded that rock-boring molluscs are the most effective animals causing bioerosion. Jehu (1918) reported five species of *Pholas* in Britain which were estimated to be eroding chalk at a rate of 1 - 2 cm. per year. Yonge (1930, 1951) and Otter (1927) both stated the view that bivalve molluscs, especially the acid-boring date mussel *Lithophaga* were the most important agents of coral reef destruction.

On the Whangaparaoa Peninsula the rock borers are normally found deeply embedded in the soft muddy siltstones and fine sandstones. When occurring on broad intertidal platforms they weaken the platform surface, considerably aiding wave action, abrasion, and browsing gastropods to “polish” and smooth the platform surface. Where platforms drop vertically to the water at their outer edge the animals preferentially colonise the soft muddy siltstones and fine sandstones on the vertical face. This further weakens the already susceptible muddy siltstones, and consequently they are easily eroded and transported by very gentle wave action.

A striking example of biomechanical erosion is illustrated in Figure 3C located on the sheltered western edge of Frenchmans Cap. Here a multitude of

rock-boring molluscs have created a labyrinth of "burrows". Individual burrows may be six inches long and one and a-half inches in diameter. Noticeably the larger openings are secondarily colonised by worms and anemones. As shown in the plate, approximately 60 - 70 per cent of the rock has been removed by the boring molluscs — mainly pholadids.

Mechanism of boring varies specifically. An early view (Jehu, 1918) considered that *Pholodidea* and *Anchomasa* bored by the rasping of siliceous particles held by the foot. Another view regards rotation of the crenate shell as the boring mechanism, especially for *Anchomasa*. In contrast, the date mussel, *Zelithophaga*, apparently bores by chemical secretion of acids reacting against the substrate — a process reflected in the chitinous shell of the animal (Yonge, 1930, 1951).

The effect on the rocks of the rock-boring molluscs (and rock-borers in general) may be considerable:

Table 2. Strength of bored rocks.

Rock Type	Compression Strengths (lbs/sq. in.)			Ratio of Reduction in Compression Strength of Bored Rock
	Natural Range	Mean	Bored Rock (Mean)	
Firm sandstone (damp)	200 - 600	400	20	20
Muddy Siltstone (damp)	400 - 1000	700	20	35

- (i) There is a marked increase in the surface area of rock exposed to chemical decay by oxidation of Fe to limonite, and thereby facilitating rock weakening by chemical processes.
- (ii) Experiments show that the physical strength (that is, compression strength) of the surface three inches of the rock is catastrophically diminished by (a) the high percentage removal of rock, and (b) the chemical decay arising from the metabolic activities of the boring organism (Table 2).¹ Consequently, areas infested by rock borers are more susceptible to wave attack.
- (iii) Often the burrows left by rock-boring molluscs are secondarily colonised by passive settlers. Examples observed on the Whangaparaoa Peninsula include *Hiatella australia*, *Notirus reflexa*, *Diplodonta zelandica*, and *Cleidothareus maorianus*. In addition to the rock decay caused by their highly acid excretion products, movement of these animals within the burrows creates a further corrosive effect. In fact for a British species of *Hiatella* boring is believed to be almost entirely mechanical and the rate of boring is equal to the growth rate of the animal (Hunter, 1949).
- (iv) Considerably more rock may be removed by rock-boring organisms than is obvious from casual observation, for many of the burrows have the form of an inverted conical flask with only a narrow opening to the exterior.

Other Rock-Boring Animals

The echinoid sea urchin (*Evechinus chloroticus*) is another animal prominent in bioerosion. Echinoderms have been reported as causing marked pitting, especially on tropical limestone coasts (Kaye, 1959; McLean, 1964, 1967; Neumann, 1966) as well as on soft sandstone shores in Britain (Jehu, 1918; Fewkes, 1890). On the Whangaparaoa shorelines, they occur in the lower midlittoral and sublittoral fringe zones, again in the softer rocks. On the seaward edge of broad

¹ Tests were carried out by the writer at the Ministry of Works Testing Laboratory, Auckland, with technical assistance from Mr G. Duske.

intertidal platforms, they burrow and grind out hemispherical hollows under ledges and in rock pools. Their activity causes considerable undermining and break-up of the seaward edge of the platforms in the vicinity of the low tidal step (Figure 3B). They are also responsible for creating elongated pits commonly coalesced into a maze of channels. Formation of burrows, according to Fewkes (1890) is entirely mechanical, through the abrasive action of spines and loose rock fragments in the burrows. However, recent studies suggest that urchin spine movement results in a plucking action rather than a purely abrasive one (McLean, 1967). Grinding and wearing away of the substrate probably also occurs during rapid growth of the animal. McPherson (1965) reports that some tropical sea urchins attain a size of 30 - 70 mm. during the first year of growth, although it is unlikely that they create a burrow this size in such a short time span.

Until recently, sea urchins were found in prolific numbers on the Whangaparaoa Peninsula, but owing to ravages by seekers of seafood delicacies, the *Evechinus* population has declined drastically. Evidence of their activities still remain (Figure 3B).

Two other types of rock-borers may be observed on the Whangaparaoa Peninsula. Polychaete (bristle) worms, e.g. (*Morpha depressa* and *Stylarioides plumosa*) and the sipunculoid peanut worm, *Dendrostonum aeneum*, are found in the lower mid-littoral zone. They form small burrows along joint cracks and planes of weakness, thereby aiding subaerial weathering by increasing surface area. Their erosional capacity is not great compared to the rock-boring bivalve molluscs.

Of greater erosional significance is the action of the brilliant yellow-orange rock-boring sponge *Cliona celata*. Distribution of *Cliona* is restricted to a narrow zone at the general level of low water spring tides and to areas with non-turbid waters.

Cliona is commonly associated with a limestone substrate (Neumann, 1966). Erosion results from pseudopodial expansions of mesenchymal cells relentlessly plucking out small chips of calcareous substrate. These are passed through the mesenchyme and ejected into the water (Warburton, 1958). Probably removal of the limestone chips is partly a result of localised chemical dissolution of the calcareous matter where cell processes come into contact with it (Goreau and Hartman, 1963).

Because of this erosion mechanism and their narrow tolerance range, rock-boring sponges characteristically erode a horizontal saw cut into platforms at the spring low tide level. Inevitably this leads to collapse and cliffward recession of the platform, all other factors being equal, *at the spring low tide level*. At Huaroa Point, for instance, *Cliona celata* has carved out a saw-cut gallery or notch with an overhang of five feet, comparable in form to similar galleries illustrated by Goreau and Hartman (1963) and Neumann (1966). The roof of the notch is characteristically flat which distinguishes it from an "active nip" of exposed coastlines. Elsewhere on the peninsula, in areas of subhorizontal sandstones and siltstones, the rock-boring sponge preferentially erodes the soft calcareous muddy siltstones. A low tide notch is formed, often overhung by a sandstone ledge.

2. Rock-Browsing Organisms

Rock browsing organisms, without actively boring into the rock platforms may still modify the surface configuration. The rock browsers are mainly gastropods but also include some chitons. Doty and Morrison (1954), Doty, *et. al.* (1954), Newell and Imbrie (1955) and Hodgkin (1964), report that gastropod snails feed by applying their radulas (a file-like ribbon) to the substratum, and transferring bits to the mouth by a scraping action. In this manner the substratum is worn down and if the animals concentrate in one area a depression or pit may be formed.

In the wave zone, chitons and limpets are common. Chitons are supposedly capable of significant surface reduction as they graze the algal-coated rocks with teeth composed of the mineral magnetite (Lowenstam, 1962). The limpet, *Cellana ornata*, produces a similar corrosive action by the use of its radula. When not grazing, some limpets and chitons return to a particular spot and eventually form a small depression. On the Whangaparaoa shoreline, chitons and limpets are not present in numbers sufficient to cause formation of intertidal nips as described by Revelle and Fairbridge (1957), Emery (1962), and Hodgkin (1964).

Prominent in the midlittoral zone are the gastropod snails *Lunella smaragda* and *Melagraphia aethiops* grazing on the coralline turf. They work in the lower intertidal zone and probably contribute to the development of smoothed surfaces in the wave zone.

In the supralittoral spray-splash zone, the black *Nerita* and tiny *Melarhapha* (c.f. *Littorina*) are found extensively grazing the surface rocks. Their grazing activity undoubtedly aids maintenance of the smooth walebacked interflues on the platform surface (Figure 3E). After rainfall or stormwaves washing over the platform, they have a wide distribution, but during dry spells and calm conditions, the supralittoral platform environment becomes exceedingly arid and the animals then cluster together in small depressions or joint cracks, creating their own micro-environment. Under these conditions, as described below, considerable pitting is likely to eventuate.

PITTING IN THE SPRAY-SPLASH ZONE: A DISCUSSION

Pitting in the supralittoral zone has commonly been attributed to the effect of splash and spray from breaking waves (Edwards, 1941, 1951; Kaye, 1959). However, some investigators credit pit formation to the direct action of supralittoral snails (Welch, 1929, quoted by North, 1954); or to the flaking off of rock fragments by the action of mat-forming algae (Purdy and Kornicker, 1958). Marine ecologists generally are undecided on the matter. Accordingly, the investigation and conclusions presented here may, perhaps, shed some light on the problem.

There appear to be two distinct types of pitting. Firstly, there are pits supposedly formed by the action of splash and spray drops from the breaking waves (Figure 3D). When well developed, these small pits are rhomboidal in form, three inches in diameter and have sharp intervening ridges similar in appearance to solution lapies developed on limestone. Conceivably, size of the pits may be related to the intensity and size of the splash drops. Splash pitting occurs from low tide upwards in the intertidal zone, and the size, degree of development and number of pits decreases away from the splash zone in the supralittoral. Splash pit morphology is noticeably polygonal in outline which possibly may reflect the most efficient mechanism for concentration of a number of random splash drops over a given area. In addition, these "lapie type" pittings have almost 100 per cent barnacle cover (*Chamaesipho columna* and *Elminius plicatus*). Pitting is therefore unlikely to have been formed by the erosive activities of browsing gastropods. Similar pits to those described and illustrated here are reported on limestone coasts by Kaye (1959) and others.

The second type of pitting varies considerably in morphology and distribution, as illustrated in Figure 3E. They are normally smaller in size ($\frac{3}{4}$ - $1\frac{1}{2}$ inches in diameter), hemispherical in shape and occur with random distribution over the supralittoral platform surface. From their characteristic form and situation it is concluded that they develop primarily as the result of the bioerosive activities of

the supralittoral populations of *Melarhapha* and *Nerita*. Relevant features of this type of pitting are listed briefly as follows:

- (i) They occur only in the spray-splash zone of the massive, relatively fine-grained sandstone beds forming high tidal benches.
- (ii) Only at times of storms are they washed over by waves.
- (iii) They are concentrated on the steeper slope facets of the platform micro-morphology, on the walls surrounding rock pools, and along joint cracks.
- (iv) Aspect is significant with noticeably greater concentration of pitting in the sun-protected locations.
- (v) Organic life is sparse with *Melarhapha oliveri*, interspersed with the occasional *Nerita melanotragus*, being the only common species.
- (vi) From the traverses taken, the pits are numerically concentrated about 12 feet shoreward from the mean high tide mark (Figure 4).

Arising from these observations, several relevant deductions may be drawn:

- (a) From consideration of the location, distribution, and lack of development over much of the horizontal platform area, formation of the pits can hardly be attributed solely to splash and spray action.
- (b) As these "high tidal" benches are not washed daily by high tides, the supralittoral platform environment may become very arid with extremes of temperatures and a lack of algal growths. Immediately following rainfall the pools may be brackish but after a short time of high daytime temperatures and evaporation, the pools become highly saline and dry out leaving deposits of evaporite crystals on the surface.

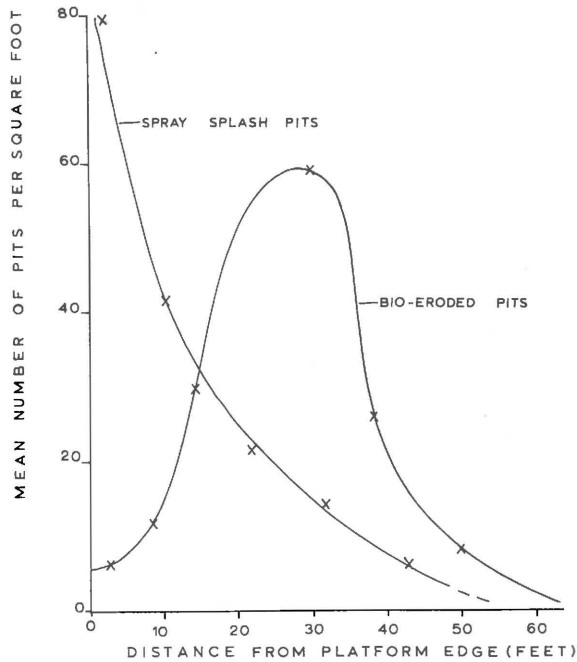


Figure 4. Distribution of pitting on a high-level platform.

Consequently, the populations of *Melarhapha* and *Nerita* cluster together in groups, presumably to alleviate the problem of desiccation. The most favourable spots are naturally those facing away from the direct glare of the sun, which will be moister and suffer less extreme temperatures. It is in these locations that the highest concentration of snails and pitting is found. Obviously a group of snails with a density of perhaps 50 - 70 per square inch, will have a considerable erosive effect both by the mechanical scarping of the surface rock as well as by the biochemical effect of their excretion products. It thus seems possible to attribute this type of pitting occurring in massive even-grained sandstone (high tide) benches in the Waitemata Formation to the erosive activities of the supralittoral snails, *Melarhapha oliveri* and *Nerita melanotragus*.

Finally, it is worth noting that littoral and supralittoral spray-splash pitting and bioerosive pitting are distinct in form and genesis from the cavernous or honeycomb weathering described by Blackwelder (1929); Bartrum (1936); Segerstrom and Henriquez (1964). Nevertheless it is quite plausible that intergrades exist between various types in which several pit-forming processes occur together. For example, honeycomb pits formed in grit by differential weathering may also be subject to biochemical weathering arising from the excretion products of the supralittoral *Melarhapha oliveri*.

THE ROLE OF SUBLITTORAL BROWN ALGAE

Briefly, the sublittoral brown algae (seaweed) play at least two roles in bio-erosion. Owing to mode of attachment and location on the low tidal step, or in the sublittoral zone, the profusion of holdfast and mass of vegetation often hinders direct wave attack on the seaward edge of the platforms.

Brown algal hinderance of wave attack may be more apparent than real, however. Everyone is familiar with the great piles of brown algae left upon a beach after a gale. During such storms, tremendous wave pressures pluck the brown algae off their standpoint, and in the process of doing so remove a fair amount of substrate entangled within the holdfast. Most obvious case of this process of erosion in this area is afforded by the broad-fronded kelp, *Ecklonia radiata*. Yonge (1930) and Edwards (1941, 1951) report examples of similar species being thrown on to a reef-platform by storm waves with sizeable rock matter weighing up to 20 lbs attached to their roots.

RATE OF BIOEROSION

In the lower midlittoral, boring pholadids have been known to bore at a rate of 1.3 cm. per year in a chalk substrate (Jehu, 1918), while in areas where it is active the rock-boring sponge, *Cliona celata*, may erode at a rate of 1 cm. per year (Neumann, 1966).

The rates of erosion of rock-browsing animals are much less than for the midlittoral boring molluscs. Emery (1946) reports a rate of 0.05 mm. per year for the browsing action of snails on sandstones comparable to those of the Waitemata Formation. Maximum erosion rates commonly reported for browsing snails are about 1 mm. per year (Kaye, 1959; Hodgkin, 1964). North (1954) for example estimated that supralittoral populations of *Littorina* deepen pools by 1 cm. per 16 years as a result of their feeding activities.

Sea urchins possess greater erosive capacities. McLean (1967) reports that an urchin with a body diameter of 3.0 cm. is capable of excavating 14 cc. of substrate per year.

CONCLUSION

Bioerosion — the complex of processes by which organisms attack the lithic substrate — has not previously been described in New Zealand. On the soft fine sandstones and muddy siltstones of the Waitemata sediments it is a notable erosive feature especially in the lower midlittoral zone, the low tidal steps and the sea cliffs. Most prominent in terms of material removed and distribution are the rock-boring molluscs although the sea urchins and boring sponges create impressive morphological manifestations of bioerosion. Grazing organisms, mainly gastropods, contribute to the character of platform surfaces, while in response to the adverse conditions of the supralittoral environment they may initiate and propagate processes of pitting. From cursory examination, average rates of this and other bioerosion, varying from 1 cm. per year in the upper midlittoral and supralittoral, seem appropriate for the platforms developed in the Waitemata Formation.

ACKNOWLEDGEMENT

The writer wishes to thank Miss Janfrie Hogg, Department of Zoology, University of Auckland, for field assistance, guidance, and discussion during the investigation; Dr W. Ballantine, Marine Biological Research Laboratory, Leigh, and Dr R. McLean, Department of Geography, University of Canterbury, for reading the script and providing helpful criticism.

REFERENCES

- Ambler, M. P.; Chapman, V. J., 1950: A quantitative study of some factors affecting tide pools. *Trans. Roy. Soc. N.Z.*, 78, 394-409
- Ballance, P. F., 1964: Sedimentology of the Waitemata Group in the Takapuna Section, Auckland. *N.Z.J. Geol. Geophys.*, 7, 466-99.
- Bartrum, J. A., 1924: The shore platform of the west coast near Auckland and its stormwave origin. *Science*, 14, 493-5.
- , 1935: Shore platforms. *Rep. A.N.Z.A.A.S.*, 22, 135-43.
- , 1936: Honeycomb weathering of rocks near the shoreline *N.Z. J. Sci. Tech.*, 18, 593-600.
- Bell, J. M.; Clark, E. D., 1909: Geology of the Whangaroa subdivision. *N.Z. Geol. Surv. Bull.*, 8, 29-32.
- Blackwelder, E., 1929: Cavernous rock surfaces of the desert. *Am. J. Sci.*, 217, 393-9.
- Brothers, R. N., 1954: The relationship of the Waitemata Formation and the Manukau Breccia, Auckland, N.Z. *Trans. Roy. Soc. N.Z.*, 81, 521-38.
- , 1959: Waitemata Group, in *Lexique Strat. Int. (N.Z.)*, ed. C. A. Fleming.
- Chapman, V. J., 1965: Maritime botany of Auckland, in *Science in Auckland*, Handbook 11th N.Z. Sci. Congr., 48-53.
- Dellow, V., 1950: Intertidal ecology at Narrow Neck reef, New Zealand. *Pacif. Sci.*, 4, 355-74.
- , 1955: Marine algal ecology of the Hauraki Gulf, N.Z. *Trans. Roy. Soc. N.Z.*, 82, 1-91.
- Doty, M.; Morrison, J. P., 1954: Inter-relationships of the organisms on Raroia aside from man. *Atoll Res. Bull.*, 30.
- ; Newhouse, J.; Miller H. A.; Wilson, K., 1954: Floristic and plant ecology of Raroia Atoll. *Atoll Res. Bull.*, 33.
- Edwards, A. B., 1941: Stormwave platforms. *J. Geomorph.*, 4, 223-36.
- , 1951: Wave action in shore platform formation. *Geol. Mag.*, 88, 41-9.
- Emery, K. O., 1946: Marine solution basins. *J. Geol.*, 54, 209-88.
- , 1962: Marine geology of Guam. *U.S.G.S. Prof. Paper*, 403-B, 1-76.
- Fewkes, J. W., 1890: On excavations made in rocks by sea urchins. *Am. Naturalist*, 24, 1-21.
- Gardiner, J. S., 1903: The origin of coral reefs as shown by the Maldiv Islands. *Am. J. Sci.*, 16, 203-13.
- Ginsburg, R. N., 1953: Inter-tidal erosion on the Florida Keys. *Bull. Marine Sci. Gulf Caribbean*, 3, 55-69.

- , 1957: Early diagenesis and lithification of shallow water carbonate sediments in southern Florida. *Spec. Pub. Soc. Econ. Paleontologists and Mineralogists*, 5, 80-100.
- Goreau, T. F.; Hartman, W. D., 1963: Boring sponges as controlling factors in the formation and maintenance of coral reefs. *Am. Assoc. Adv. Sci. Pub.*, 75, 25-54.
- Gregory, M. R., 1966: *Waitemata rocks of the Whangaparaoa Peninsula, Northland*. Unpub. M.Sc. Thesis, Univ. Auckland, 223 pp.
- Healy, T. R., 1967: *The shore platforms of the Whangaparaoa Peninsula*. Unpub. M.Sc. Thesis, Univ. Auckland, 89 pp.
- Hills, E. S., 1949: Shore platforms. *Geol. Mag.*, 86, 137-52.
- Hodgkin, P., 1964: Rate of erosion of inter-tidal limestone. *Zeit. Geomorph.*, 8(4), 385-92.
- Hunter, W. R., 1949: The structure and behaviour of *Hiatella gallicona* and *H. arctica*, with special reference to the boring habit. *Proc. Roy. Soc. Edinburgh*, 63B, 271-89.
- Jehu, J. T., 1918: Rock-boring organisms as agents in coast erosion. *Scot. Geog. Mag.*, 34, 1-10.
- Johnson, D. W., 1919: *Shore processes and shoreline development*. Hafner, New York, 584 pp.
- , 1938: Shore platforms — Discussion. *J. Geomorph.*, 1, 268-72.
- Kaye, C. A., 1959: Shoreline features and Quaternary shoreline changes, Puerto Rico, U.S.G.S. *Prof. Paper*, 317B, 49-140.
- Kear, D.; Schofield, J. C., 1964: Stratigraphic summary, Ngaruawahia subdivision. *N.Z. J. Geol. Geophys.*, 7, 892-3.
- King, C. A. M., 1959: *Beaches and coasts*. Arnold, London, 403 pp.
- , 1963: Some problems concerning marine planation and the formation of erosion surfaces. *I.B.G.*, 33, 29-44.
- Lowenstam, H. A., 1962: Magnetite in denticle capping recent chitons (Polyplacophora). *B.G.S.A.*, 73, 435-8.
- McLean, R. F., 1964: *Mechanical and biological erosion of beachrock in Barbados, West Indies*. Unpub. Ph.D. Thesis, McGill University.
- , 1967: Erosion of burrows in beachrock by the tropical sea urchin, *Echinometra lucunter*. *Can. J. Zool.*, 45, 586-8.
- McPherson, B. F., 1965: Contributions to the biology of the sea urchin. *Bull. Marine Sci. Gulf Caribbean*, 15, 228-64.
- Mii, H., 1962: *Coastal geology of Tanabe Bay*. Sci. Rept., Tohoku Univ., Second Series, 34(1), 1-42.
- Morton, J. E., 1965: The Auckland inter-tidal shore. *Science in Auckland, Handbook*, 11th N.Z. Sci. Congr., 54-8.
- Neumann, A. C., 1966: Observations on coastal erosion in Bermuda and measurements of the boring rate of the sponge, *Cliona lampa*. *Limnology and Oceanography*, 11(1), 92-108.
- Newell, N. D., 1956: Geological reconnaissance of Raroia Atoll, Taumotu Archipelago. *Am. Mus. Nat. Hist. Bull.*, 109, 315-72.
- ; Imbrie, J., 1955: Biogeological reconnaissance in the Bimini area, Great Bahama Bank. *Trans. N.Y. Acad. Sci.*, 18, 3-14.
- North, W. J., 1954: Size distribution, erosive activities and gross metabolic efficiency of the marine inter-tidal snails, *Littorina planaxis* and *L. scutulata*. *Biol. Bull.*, 106, 185-97.
- Otter, G. W., 1927: Rock destroying organisms in relation to coral reefs. *Gt Barrier Reef Expedn., 1928-29, Sci. Repts.*, 1(12), 323-52.
- Purdy, E. G.; Kornicker, L. S., 1958: Algal disintegration of Bahamian limestone coasts. *J. Geol.*, 66, 97-99.
- Revelle, R.; Emery, K. O., 1957: Chemical erosion of beachrock and exposed reef rock. *U.S.G.S. Prof. Paper*, 260T, 699-709.
- ; Fairbridge, R. W., 1957: Carbonates and carbon dioxide. *Geol. Soc. Am. Mem.*, 67, 239-96.
- Segerstrom, K.; Henriquez, H., 1964: Cavities or "tafoni" in rock faces of the Atacama Desert, Chile. *U.S.G.S. Prof. Paper*, 501C, 121-5.
- Turner, F. J.; Bartrum, J. A., 1929: The geology of the Takapuna-Silverdale district, Waitemata County, Auckland. *Trans. N.Z. Inst.*, 59, 864-902.
- Warburton, F. E., 1958: The manner in which the sponge *Cliona* bores in calcareous objects. *Can. J. Zool.*, 36, 555-62.
- Welch, J., 1929: *Littorina* perforations in indurated chalk. *Irish Nat. J.*, 2, 131-9.
- Wiens, H., 1959: Atoll development and morphology. *A.A.A.G.*, 49, 31-54.
- , 1962: *Atoll environment and ecology*. New Haven, Yale Univ. Press, 102-35.
- Yonge, C. M., 1930: *A year on the Great Barrier Reef*. Pitman, London, 72-82.
- , 1951: Marine boring organisms. *Research*, 4, 162-7.