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Surface lowering and landform evolution on Aldabra

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Aldabra landforms are the result of the karstification of carbonate rocks distributed on surfaces which have been exposed to erosion for varying lengths of time. Morphometric analysis (which is of interest in both geomorphological and botanical contexts) suggests that the most well developed karst features (closed depressions) occur on what appear to be the oldest surfaces. Morphology also varies with lithology. Measurements of present-day erosion rates suggests that weakly cemented rocks and the most soluble mineral components are eroding most rapidly. The evolution of a dissected morphology is related to lithological heterogeneity in coralline rocks or, in the case of the more homogeneous rocks, to the short residence time of waters on the rock surface (the more rapidly dissolving mineral grains eroding faster). Dissolution also proceeds in fresh water pools, but this may be offset by precipitation in some cases. The surface is mostly case hardened, except under deep organic soils where erosion rates are much higher than in other areas. A mean erosion rate measured at 0.26 mm/a appears to make it feasible that large erosional features, such as the lagoon, could have been formed during periods of emersion as suggested by research workers who have hypothesized that an atoll shape may be substantially derived by subaerial weathering.

Introduction

The aim of the work undertaken on Aldabra was to examine the relation between landform and surface age (as described by geological work by other authors). An attempt was also made to account for variations in the degree of surface dissection with reference to lithological variation and erosional environment. Broad correlative inferences have been made based on geological information and selected examples of morphometric analysis. Detailed studies of erosion rates were undertaken in order to give insight into the process mechanisms involved. Furthermore, information on landform evolution and nature is of interest in terms of the plant and animal ecology of the island and also in the wider context of the evolution of atolls in general.

Aldabra is situated in the western Indian Ocean at 9° S and 46°E. The stratigraphy, evolution and surfaces of the island are described by Braithwaite *et al.* (1973) and earlier geomorphological work is summarized by Stoddart *et al.* (1971). Limestone erosion processes are described by Trudgill (1976*a*) and also in Trudgill (1972, 1976*b*). Palaeosols and other terrestrial sediments are described by Braithwaite (1975). Other work on the island is summarized in Westoll & Stoddart (1971).

Surface morphometry, lithology and surface age

Two major surfaces exist on Aldabra, one at approximately 8 m above present sea level and one at 4 m (Stoddart *et al.* 1971; Braithwaite *et al.* 1973). They appear to have formed in successive periods of emersion since about 80000 a B.P. The upper 8 m surface is cut almost exclusively in Aldabra Limestone but the 4 m terrace and associated lagoonward surface is cut in both Aldabra Limestone and the older Takamaka Limestone. Some morphological contrasts between the two areas are illustrated in figures 1 and 2 and in table 1.

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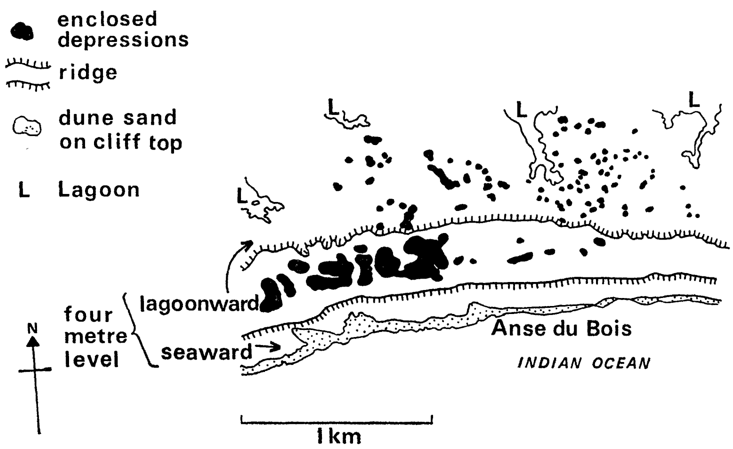

Figure 1. Enclosed depressions, from air photographs 040, 039 and 038, Dune Jean-Louis area.

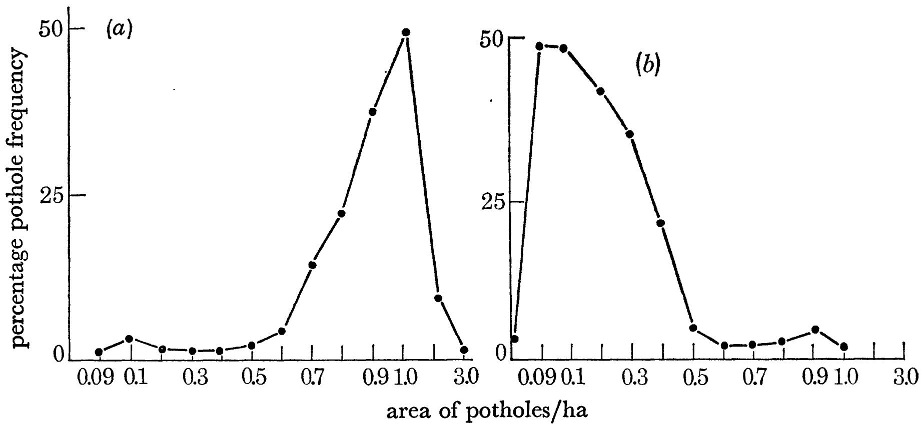

Figure 2. Frequency of potholes of given sizes on (*a*) the 8 m ridge and (*b*) the lagoonward 4 m level.

Table 1. Morphometric parameters in air photograph study quadrat, Dune Jean-Louis, Aldabra (see figures 1 and 2)

parameters†	ridge	4 m level (lagoonward)
study area (A)/km²	1.887	3.108
number of pits (n)	14	98
density of pits† (n/A)/km⁻²	7.4192	31.53
sum of area of pits (A_P)/km²	0.2664	0.2849
% area covered by pits (% A_P)	14.1	9.1
indices of pitting		
(1) i.a.p.‡ $\frac{\text{area}}{\text{area of pits}}$	7.083	10.9091
(2) i.c.p.§ $\frac{\text{\% area covered by pits}}{\text{number of pits}}$	1.008	0.0929

† After Williams (1966, 1969, 1971).
‡ The lower the number the higher the area occupied by pits.
§ The lower the number the more complex and pitted the surface (the complexity of the surface being proportional to the number of pits but inversely proportional to the area of pits).

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It can be seen that the 8 m ridge is characterized by the presence of a few large depressions whereas the lagoonward 4 m surface has a large number of small depressions. Takamaka Limestone is found at the base of some of the larger depressions in Aldabra Limestone and it is not necessarily clear whether a depression represents an erosional feature or an area where deposition was lacking initially. However, it is reasonable to suggest that the surface which has been exposed for the longest period of time, the 8 m surface, has a better developed karst surface with the development of larger depressions.

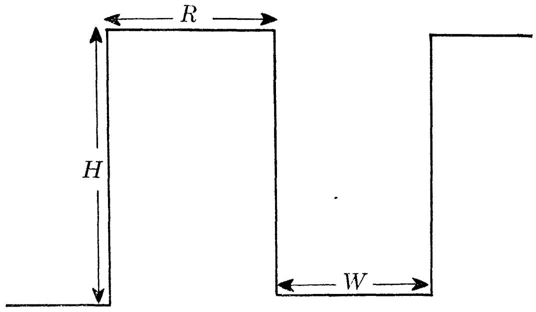

FIGURE 3. Landscape dissection components.

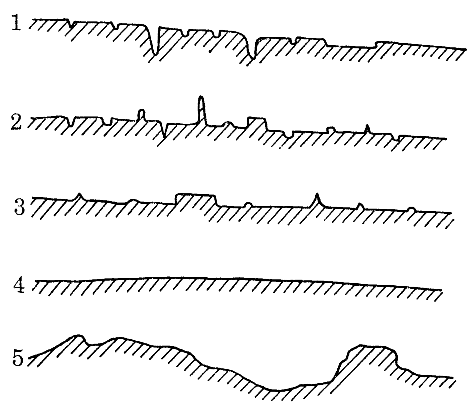

FIGURE 4. Relief classes recognized in morphometric analysis on Aldabra: 1, general surface with negative departures; 2, general surface with negative and positive departures; 3, general surface with positive departures; 4, general surface with no departures; 5, no general surface.

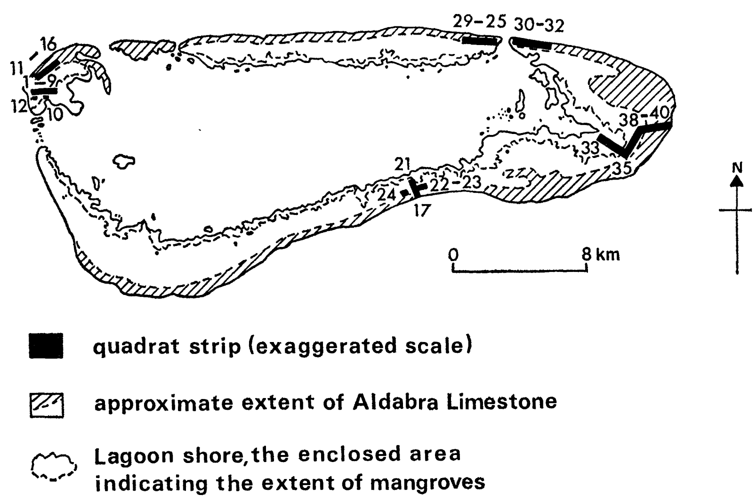

FIGURE 5. Location of quadrats for ground morphometric analysis.

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The 8 m ridge often has a characteristic pavé form (Stoddart *et al.* 1971) whereas the younger surfaces appear to be more closely dissected (champignon) or to have a smooth (presumably pre-existing) surface. In order to have some basis on which to substantiate possible genetic arguments it is useful to be able to describe the landforms in some standard way other than by the use of the terms pavé, platin and champignon. Accordingly, detailed study areas were chosen as representative of various landform types, geology and surface age. In each area landform parameters were measured in accordance with the scheme illustrated in figure 3. The parameters used are H, W and R. H refers to vertical relief amplitude, R to the width of the upstanding intervening portion (residual) between potholes and W to the width of the pothole. The existing morphological terms can be given more precise definition using these parameters:

(1) champignon $H > W$ and $H > R$;
(2) pavé $H \leqslant W$ and $H \leqslant R$;
(3) platin $W \gg H$ and $W \gg R$.

Relief classes were also identified (figure 4) as follows:

(1) general surface, negative departures;
(2) general surface, positive and negative departures;
(3) general surface, positive departures;
(4) general surface, no departures;
(5) no general surface.

Table 2. Morphometric indices for Aldabra quadrats

(*a*) geology	no. of quadrats	$\bar{H}$	A_P	D	I_P	I_G	C	V	P
Aldabra Limestone	20	1.78	33.2	0.11	14.8	10.6	4	90	7
Picard Calcarenite	9	0.74	51.5	0.40	2.2	6.7	29	24	47
Takamaka Limestone	10	0.85	61.9	0.36	6.4	12.2	56	22	22
(*b*) surface									
8 m ridge	11	1.45	25.2	0.08	18.8	6.3	0	89	11
4 m terrace (seaward)	9	0.70	43.3	0.18	3.6	16.0	44	56	0
4 m terrace (lagoonward)	19	0.51	58.1	0.37	8.0	9.2	44	50	6

Table 3. Relief classes, number of observations in each class

relief class	1	2	3	4	5
Aldabra Limestone	4	11	1	3	0
Picard Calcarenite	6	7	1	9	0
Takamaka Limestone	0	2	0	1	1
8 m ridge	1	6	2	1	1
4 m terrace (seaward)	3	5	0	0	0
4 m terrace (lagoonward)	6	9	1	9	0

Forty 10 m × 10 m quadrats were laid out in the study areas (figure 5). These were selected with bias according to ease of access and to represent different rock types and surfaces. Thus the exercise was not a statistical one and in making any inferences this should be borne in mind. The morphometric parameters H, W and R were measured in the field and the general relief class was identified. From the measurements taken the following indices were computed (after the work of Williams 1966, 1969, 1971):

(1) $\bar{H}$, average (mean) depth of potholes;
(2) A_P, percentage area occupied by potholes;

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(3) D, density of potholes (number/m^2);

(4) I_P, index of pitting $= \dfrac{\text{(total area)}}{A_P}$;

(5) I_C, surface complexity index $= \dfrac{A_P}{\text{(number of potholes)}}$.

The percentage of quadrats occupied by champignon (C), pavé (V) and platin (P) were also noted. The data for rock types and surfaces are summarized in tables 2 and 3.

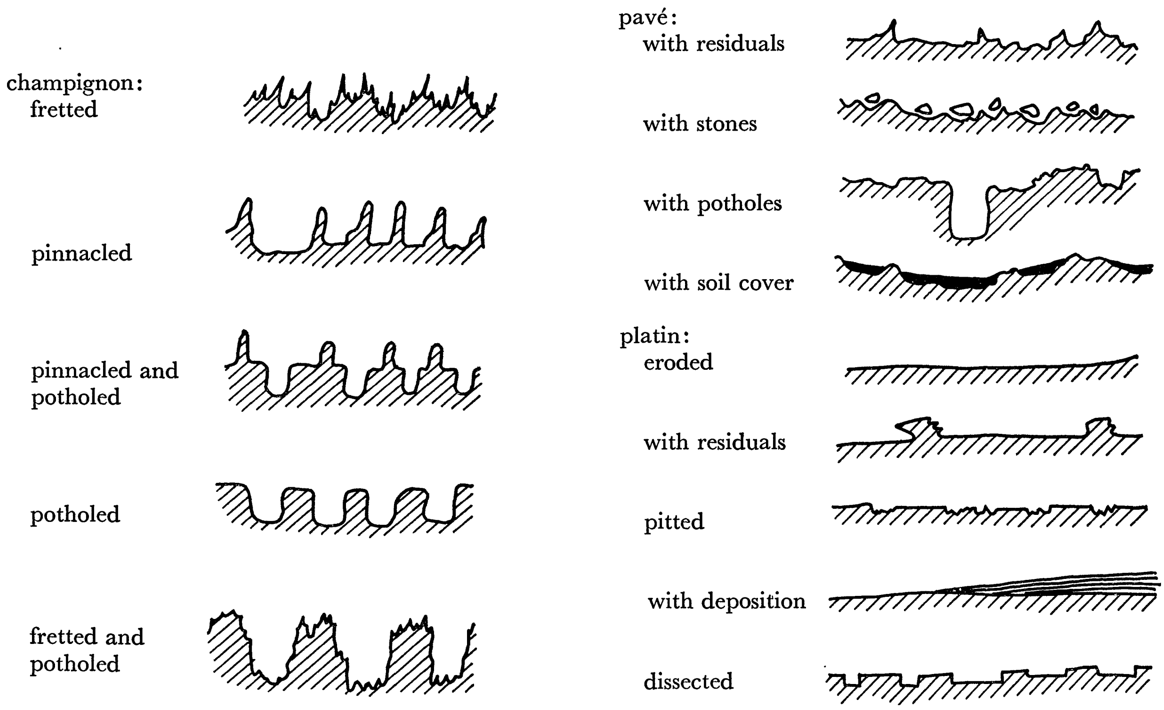

FIGURE 6. Landform subtypes.

Although some of the definition of morphology in the field is necessarily subjective, especially in terms of the edges of potholes, this morphometric approach is felt to be preferable to a completely subjective approach to landform evaluation. One problem is that areas which may appear to be dissected champignon by visual evaluation may be classified as pavé on morphometric grounds as shallow dissected areas are not detected as champignon. A pavé area (morphometric definition) can have a small amount of dissection where the depth of pothole is equal to the width of intervening residual. However, given this qualification and the statistical limitations of the data, it is nevertheless possible to make some inferences from the morphometric data:

(1) Pothole depth appears to vary independently of lithology and be more related to surface age.

(2) The Takamaka Limestone and Picard Calcarenite examples studied have a greater area of potholes, a greater density of potholes and are more pitted than the Aldabra Limestone examples studied.

(3) While on the air photograph scale there appear to be a few large pot-holes on the 8 m ridge, at the 10 m quadrat scale there appear to be a few, narrow and very deep potholes (especially east of Anse Var).

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(4) The area occupied by potholes and the density of potholes is greatest on the 4 m (lagoonward) surface but the seaward 4 m terrace is more pitted than the other surfaces.

(5) The 8 m ridge has the most complex surface.

Some broad generalizations can be made about the surfaces. The greatest dissection appears to occur on the younger (4 m) surface but this is often associated with a platin surface. This can be interpreted as fresh erosion in a differential manner upon a pre-existing planar surface. The modal pothole depths of the champignon measured was 1.2 m. On the older (8 m) surface there were two modes measured, one at 0.45 m and another at about 4 m. A few very deep potholes occur on an otherwise subdued surface.

Various subtypes of the main landform types can be recognized and it is possible that further work will be able to correlate these more closely with geology and erosional environment as well as to establish the nature of any possible influence upon vegetation. Such subtypes could include fretted, pinnacled or potholed champignon, pavé with residuals, loose boulders and stones or potholes, and platin with residuals, pitting, deposition, erosion or dissection (see figure 6).

Erosion processes and the evolution of a dissected surface

The morphometric data allow the following two inferences to be made:

(1) Rocks which are apparently lithologically relatively homogeneous can give rise to a dissected surface as well as those which are lithologically heterogenous and can be expected to show differential erosion.

(2) Differential erosion appears to be rapid at first but, from the evidence of the older surfaces, a subdued relief evolves (assuming that the initial starting point is a planar surface in all situations, which may well not necessarily be the case).

If these inferences are true then it remains to understand the nature of differential erosion processes occurring on relatively homogeneous rocks and to establish how this may become self-limiting over time. In order to elucidate the erosion processes which may be involved, erosion rates were measured on contrasting lithologies and in contrasting environments. Again, this is not a statistical exercise, for practical reasons. A micro-erosion meter method (High & Hanna 1970) was used to measure erosion rates. This has the advantage that accurate measurements of surface lowering may be gained in a short time though there exists the possible disadvantage that the measurement probe may disturb the surface of less well consolidated rocks unless extreme care is taken. The meter consists of a micrometer dial gauge mounted on a tripod framework resting upon three reference studs which are inserted into the rock surface. Successive micrometer measurements of the height of the rock surface relative to the studs gives an accurate indication of the rate of surface lowering of the rock provided that the studs are adequately protected between times of measurement. The results are summarized in table 4.

These data are displayed in figure 7 and it is clear that the results differ not only in their mean value but also in their ranges. The Aldabra limestone shows a wide range, as is to be expected for a heterogeneous rock composed of corals, shells and sand-sized material. The calcarenite (2) shows a wide range of erosion rates. This accords with morphometric observations but does not account for the processes involved. It is, however, clear that where lithological components are juxtaposed then marked differential erosion could occur. One additional comment on the method is that the most rugged topographies do not provide the best surfaces

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for the use of the micro-erosion meter and therefore data on this type of area are lacking. However, it still remains to account for the differential erosion of the calcarenites.

It is felt that, in part, differential erosion could be due to the dislodgement of calcarenite grains subsequent to the dissolution of cement, rather than an even dissolution of the whole surface. Often a point cement may exist, possibly with a more readily soluble mineralogy (aragonite or high magnesium calcite) than the grains themselves (low magnesium calcite).

Table 4. Micro-erosion meter rates and lithology

limestone	dominant mineralogy	erosion rate/(mm/a)	
		mean	range
(1) Aldabra Limestone	aragonite and high magnesium calcite	0.11	0.09–0.62
(2) Picard Calcarenite	low magnesium calcite	0.35	0.09–0.530
(3) Picard Calcarenite	high magnesium calcite and aragonite	0.51	0.49–0.60
(4) Takamaka Limestone	low magnesium calcite	0.10	0.09–0.11

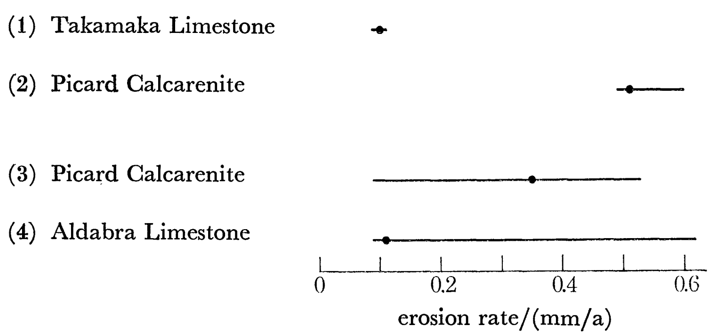

Figure 7. Ranges of measured erosion rates with lithology: •, mean value; ——, range

Alternatively, a more soluble grain with a less soluble cement may be involved. The problem is to establish how this mechanism finds expression at a slightly larger scale. Here it is possible that the short residence time of rain water on a subaerially exposed surface may contribute to the exaggeration of differential erosion of grain and cement, possibly also linked to variations in surface porosity and therefore in water penetration. Any minute depression would retain water and encourage the dissolution of the carbonate material present, whereas slightly upstanding areas would shed water more rapidly. This could become a self-reinforcing process. The rate of dissolution would be more important than the final equilibrium solubility where short residence time of water was involved. The more slowly dissolving minerals would gradually be left as upstanding while the most rapidly dissolving minerals would be preferentially eroded, leaving small eroded areas. After this initial phase, waters would subsequently collect preferentially and for a slightly longer time in the eroded areas. Dissolution of all mineral constituents would become progressively more equal in these areas. Thus flat floored pools may form. Alternatively, if the nature of the surface that was evolving encouraged the rapid runoff of waters then residence time would be kept low and differential erosion would be encouraged. This would require the mineralogical constituents involved to have different rates of dissolution, irrespective of final solubility levels.

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Experiments were undertaken on the dissolution uptake of calcium and magnesium by rain waters running off subaerial surfaces and collecting in fresh water pools.

The results suggested that runoff waters were high in calcium concentrations, often approaching saturation; however, they were low in magnesium content. Magnesium content only rose after water residence in fresh water pools. This suggests that in a mixed magnesium–calcium system, short residence time will lead to differential erosion but that during a longer residence time both magnesium and calcium would come into equilibrium and that the mineralogical constituents would be dissolved equally. The evenness of the surface would increase in long residence time situations where equilibrium levels were comparable and the ruggedness would increase in short residence time situations where the dissolution rates were most disparate.

Table 5. Calcium and magnesium levels (milligrams per litre) in rainwater runoff

water type	$CaCO_3$	$MgCO_3$
rainwater	10 (u)	19 (u)
rainwater runoff in pool soon after shower	100 (s)	12 (u)
semi-permanent rain water collecting pool	80 (s)	63 (u)

(s), saturated; (u), undersaturated.

Given that a feedback may exist between erosion process and morphology then the evolution of some of the landforms becomes easier to understand. It can be hypothesized that eventually the progression outlined above would tend to work down to a base level at which time pothole coalescence would increase and upstanding residuals would gradually be removed. This type of hypothesis is, however, very speculative.

One additional factor in the subaerial evolution of landforms is the presence or absence of a soil cover and the nature of a soil cover where present. Measured erosion rates under deep, acid (pH 6.5) organic soils showed very high erosion rates (5.5–20.4 mm/a). However, the bedrock is not case hardened and is very soft: some surface disturbance by the measurement probe may have occurred. Nonetheless, given this qualification it would still appear that erosion is very rapid under these soils. Erosion under shallow organic soils, which are essentially accumulations of leaf litter, is comparable with subaerial soil-free rates at 0.09–0.13 mm/a (the mean rate for soil free areas being 0.26 mm/a). Erosion under soils with a high carbonate content was slight and some deposition was even indicated at some sites. The fact that soils are spatially limited in their extent makes these data quantitatively unimportant when considering influence on differential erosion on a small scale. Again, a feedback may exist in that hollows may encourage soil accumulation and the feedback would further encourage deepening if the soil was organic and acid or it would limit erosion if the soil was high in carbonates, as many of the soils occurring on the pavé areas may have a high carbonate content this could have some effect upon the lack of differential erosion in these areas.

Long-term speculative extrapolations of erosion rates and the evolution of Aldabra

The works of MacNeil (1954) and Flint *et al.* (1953) suggest that an atoll shape may be derived from subaerial weathering during times of emersion as much to the initial peripheral growth of corals. The work of Braithwaite *et al.* (1973) also stresses the importance of erosional

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events in the evolution of Aldabra. Although it is a somewhat unwarranted extrapolation it is tempting to convert the erosion rates measured over 2 years on Aldabra to rates per thousand years in order to investigate the feasibility of the rôle of subaerial weathering in the evolution of the atoll shape of Aldabra. It is a speculative extrapolation simply because it makes the assumption that the climate of the 2 year measurement period can be equated with past climates and also that the data are statistically representative, neither of which is true. However, order of magnitude estimates are possible.

The measured micro-erosion meter rates are higher than that suggested by Stoddart *et al.* (1971) of 0.05 mm/a. This was, however, based on assumptions of rainfall and calcite solubility and constancy of conditions over the atoll. Given these difficulties with the data it is probably best to work with minimum and mean estimates of erosion rates and to qualify carefully the interpretations thus gained. This is a reasonably valid procedure in the absence of any better information.

The summary of the evolution of Aldabra is given in Braithwaite *et al.* (1973) with some possible and one definite date for certain events. Given these dates it is possible to surmise that emersion periods of 80000, 27000 or 5000 years could have been involved at stages of the island's history. Extrapolations of erosion rates for these periods are given in table 6.

Table 6. Extrapolations of erosion rates (metres) for emersion periods

emersion period/a ...	80000	27000	5000
erosion rates/(mm/a)			
(1) 0.09 (min.)	7.2	2.43	0.45
(2) 0.26 (mean)	40.80	13.77	2.55

If emersion was subsequent to 27000 years and submersion was at around 5000 years a time span of 14000–22000 years is possible. A lagoon some 3.6–5.7 m deep could have formed during this period (using the mean rate) and 0.76–1.1 m using the lowest rate. This does not prove that the lagoon was formed subaerially, it simply does not go against MacNeil's theory and appears to make it feasible.

If the lagoon was formed subaerially, some further problems remain. The most significant is that subaerial surfaces appear to be characteristically dissected. However, evidence, especially from the Cinq Cases area, suggests that present subaerial weathering is dissecting a pre-existing planar surface, not a pre-existing dissected surface. If it is assumed that the pre-existing surface is an emersed old lagoon floor then it can be suggested that the lagoon morphology was formed by marine planation rather than subaerial weathering. This is in accord with other geological and morphological evidence from Aldabra. Since marine planation is largely a lateral process rather than a vertical one, data on shoreline retreat are more pertinent than data on subaerial lowering. Erosion rates measured on Aldabra give a range of 1–3 mm/a for a seaward coast (increasing with exposure) and a rate of about 2–3 mm/a for the lagoon (Trudgill 1976*c*). This gives rates of the order of 1–3 m/ka. It is not clear when sufficient time periods of marine planation that would be necessary to evolve the lagoon could have occurred. As Braithwaite *et al.* (1973) observe, features of only 15 m could have evolved in the last 5000 years at present sea level. The previous period of submergence appears to have been extensive and existing for possibly 125000–80000 a B.P. or later, giving a possible time span of around 45000 years. At 3 m/ka a lateral planation rate of 155 m is possible.

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The questions this type of speculation raises must, of necessity, often remain substantially unanswered and there are few concrete arguments either way. However, it can be suggested that both subaerial and marine erosion have played some part in the evolution of the lagoon. Whatever the erosional environment, however, it can certainly be suggested that the atoll shape could have been formed by one or other erosional process. Central erosion, rather than peripheral coral growth, would appear to be feasible but the time periods and processes involved are as yet unclear.

Conclusions

Erosional events have been important in the evolution of Aldabra as stressed by Braithwaite *et al.* (1973). Extrapolation of present day erosion rates is speculative but appears to make it feasible that large scale erosional features could have been formed during the possible time periods available. These erosional events left three primary land surfaces at the present day. They are the higher 8 m ridge and a seaward 4 m terrace and its lagoonward equivalent. The 8 m ridge, on the scale of morphology detectable on air photographs, appears to show a relatively well developed karst morphology with the occurrence of some large broad shallow closed depressions together with a few narrow and very deep (often tidal) potholes. On the ground, a subdued relief occurs. A large number of small potholes and a dissected surface is found on the other levels. Within any one given surface, morphology can be related to lithology though the contrasts between the surfaces for any one lithology are greater than the contrasts between the lithologies on any one surface. Heterogeneous rocks (often coralline) display marked differential erosion, which is to be expected. Apparently homogeneous rock also shows a dissected surface and also measurable differential erosion rates. These appear to be linked to mineralogy and it is hypothesized that a short residence time of rain water on a subaerial surface would emphasize differences in dissolution rate leading to a feedback between erosion rate and morphology.

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