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SKELETON ISLANDS OF NEW ZEALAND AND ELSEWHERE

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Abstract

Skeleton Islands are a variety of the class of islands resulting from subsidence of dissected land, subcategory 4*a* of a classification of islands here offered. Such islands are characterised by development of a sprawling outline with a narrow axial ridge from which slender lateral spurs, or ribs, extend more or less at right angles. Extreme skeletonisation is associated with development before a final drowning, or redrowning, of amphitheatre heads in valleys already heading in the main divide. This may be a climatically induced change of the valley form related, in the case of the New Zealand example, Arapawa Island, to cryergic (periglacial) activity in the Pleistocene glacial ages.

Kakeroma Island (Ryukyu Group), an example of a skeleton island described by W. M. Davis, has quite possibly a history different from that of Arapawa Island as regards both the development of the relief of the subsiding lands and, being in a low latitude, the possibly climatic process responsible for shaping its now submerged valley heads and thus emaciating the ribs of the island.

INTRODUCTION

Though there is a close resemblance between the outlines of Kakeroma (Ryukyu Group), which may be regarded as the type of skeleton islands, and the New Zealand example Arapawa Island (in the Marlborough Sounds), the histories of their development to the skeleton form are not necessarily quite similar. This refers both to the origin of the dissected land masses which have subsided to form the islands and the details of valley heads, which contribute to the emaciation of the outline of the extreme variety of skeleton islands (as defined below). It is possible, however, that in the case of each of these islands the valley heads have been shaped by climatic processes.

A CLASSIFICATION OF ISLANDS

A classification of islands is here presented in order to show the place occupied by skeleton islands in a general scheme. This classification is supplementary to that proposed by Fairbridge (1968). It excludes large "continental islands" (Fairbridge, 1968: 569-70) except in so far as these may be included in category 3 (below).

Islands may be formed by:

1. Accumulation due to wave action — generally taking place since the last stabilisation of sea level. Such islands consist either of mineral sand or of calcareous (organic) sand and coral-reef debris.

    (a) "Barriers" (Price, 1968) are built of sand on spits and longshore bars, forming barrier spits and barrier islands in regions (humid-temperate especially) where erosion has produced abundant sand of mineral origin, or where such sand has been concentrated from sediments by wave action. It is piled up above sea level by the surf on spits and longshore bars that are themselves built by wave action, the latter in shallow water

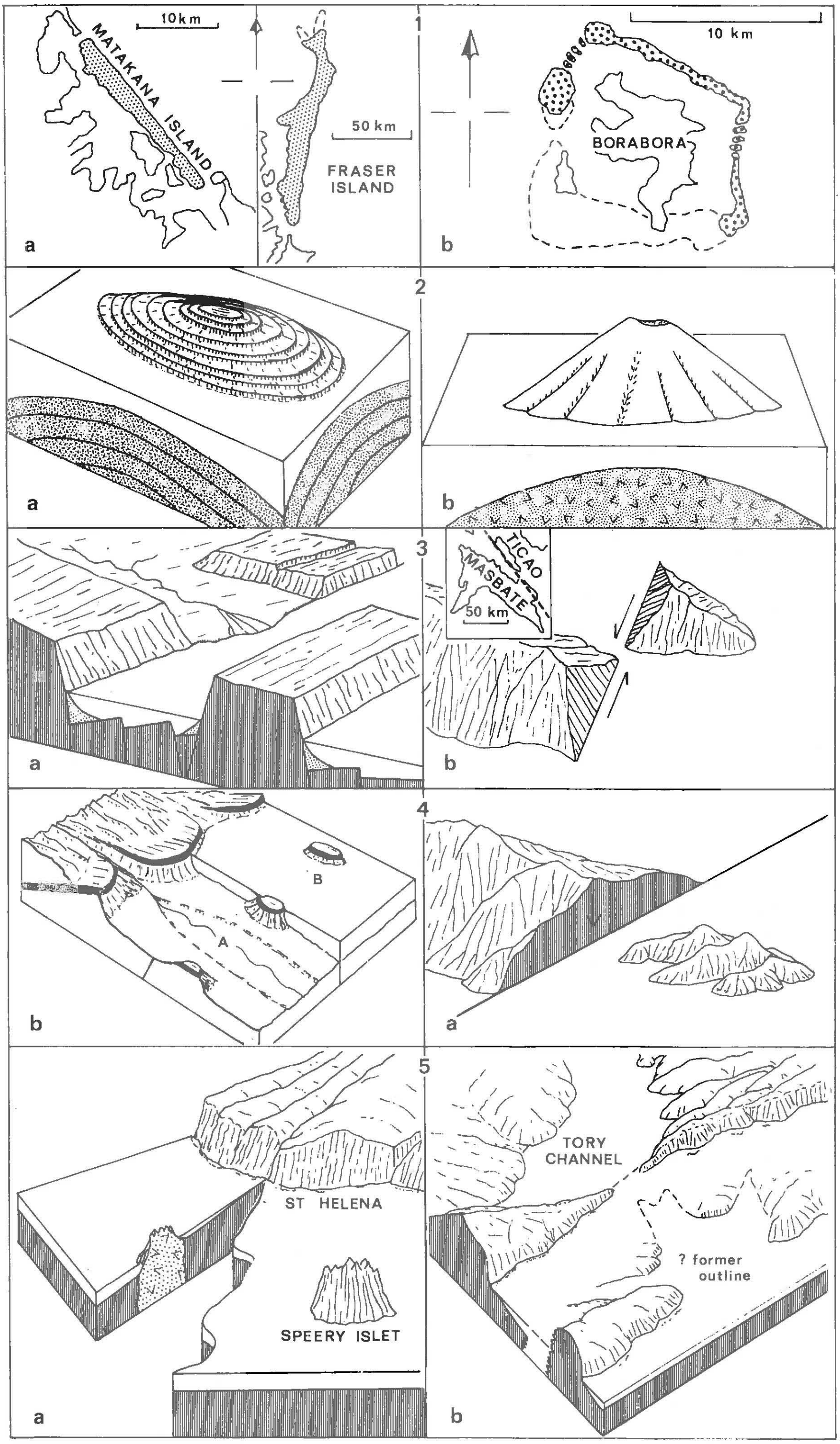

Figure 1. Categories of islands. For explanation see text.

bordering coasts with low seaward gradient. The sand may be dried and piled by wind into dunes that may attain a considerable height, though such islands remain for the most part low-lying. An example is the large Matakana Island, Bay of Plenty (N.Z.), which shelters the harbours of Katikati and Tauranga (Fig. 1, 1*a*); Matakana Island is planted with pine forest. Another is the island bordering the eastern coast of the United States of which Cape Kennedy forms a part.

The largest sand island in the world is Fraser Island (Fig. 1, 1*a*), which, with the similar Stradbroke and Moreton Islands, borders the east coast of Queensland, Australia. Fraser Island has extended northward along the (still-growing) Breaksea Spit, but some sinking of the basement has taken place meanwhile (Whitehouse, 1968). These islands are dune-covered and some of the dunes attain heights of over 200 m, though this is due in part to uplift.

(*b*) Coral islands, or "motus", are built by wave action of coral-reef debris and calcareous sand of organic origin on coral reefs, especially barrier reefs and atolls (Fig. 1, 1*b*). They are found, therefore, only in low latitudes. There are good examples on the barrier reef that surrounds Borabora Island (Society Group).

2. Emergence from the sea.

(*a*) Emergence of parts of the sea floor differentially (generally anticlinally) elevated, in some cases from great depths. Areas thus emerging are subject to attack by waves and are thus reduced to shoals as they emerge above water except in cases where they are protected as they emerge by the growth of carapaces of coral. As the coral reefs are carried up on the crests of the rising anticlines, such islands are covered at the infantile stage by terraced reef caps (for examples see Verstappen 1960; Cotton, 1961) (Fig. 1, 2*a*).

(*b*) Emergence owing to volcanic up-building of submarine cones that become basaltic and andesitic volcanic islands (see Cotton, 1969a) (Fig. 1, 2*b*). New Zealand examples are: Rangitoto Island, at Auckland; Little Barrier Island, in Hauraki Gulf; and White Island, Bay of Plenty.

3. Fragmentation of land masses.

(*a*) By block faulting with blocks downthrown between islands or between a mainland and islands, which are thus outlying horsts. The island of Madagascar may be an outsize example of such a horst island — unless its place is in subcategory 3*c* (below).

(*b*) By transcurrent faulting, which may shear off an outlying portion of a land mass (Fig. 1, 3*b*). In the Philippines Group the island Tieao appears to have been shorn from the larger island Masbate by a sinistral movement of about 50 km along the main fault of the region, which trends NW and shows evidence of recent sinistral displacement on Masbate Island (Allen, 1962; fig. 7).

(*c*) By continental drift. Some of the large continental islands, and perhaps many small ones also, are probably lagging portions that have become detached from drifting continents.

4. Drowning by partial submergence of an accidented (generally dissected) land surface. To produce the local effects, such as the indented shorelines, characteristic of drowning, and especially for the production of skeleton islands (*below*), the cause might be subsidence of the land, perhaps of large measure,

or positive movement of sea level, which may, theoretically, be also of large measure if due to a tectonic cause or to outpouring of vast lava floods on the floor of the ocean, which would reduce the capacity of the ocean basins. The result of a rise of sea level would, theoretically at least, be distinguishable from that of subsidence of the land, as it would be world-wide, causing everywhere the same amount of submergence, whereas the effects of subsidence, except secondary effects, are confined to the subsiding region and even within it generally vary from place to place. In the Marlborough Sounds district of New Zealand, for example, the amount of subsidence has been observed to vary so as to indicate tilting of a downthrown block (Beck, 1964). It is clear that all eustatic positive movements of large measure must be excluded as possible causes of major drowning if it is confined to a particular region (Fig. 1, 4*a*).

The only eustatic positive movements that remain for consideration are glacio-eustatic — these, except for possible events of the practically unknown early Pleistocene, have been of fairly small measure (< 140 m), and they have in every case been preceded by, and not separated by a long interval of time from, complementary negative movements (caused by the onset of the glaciation preceding the deglaciation indicated by positive movements). As, however, dissection of easily eroded terrains has been in progress during successive glacial-age withdrawals of the sea, there may be no means of distinguishing locally between the effects of subsidence of the land and glacio-eustatic positive movement of sea level if only a moderate amount of drowning of the land surface has taken place.

(*a*) With few exceptions it seems certain, nevertheless, that the origin of widely-extending, ramifying, and initially very deep rias in a terrain of resistant rocks previously dissected and with strong relief (e.g. the Marlborough Sounds of New Zealand) and of the islands that have been formed by their drowning must be explained by regional subsidence. As glacio-eustatic movements of sea level have affected all coasts, it is clear that the effects of such positive movements — and, most obviously of the last of them — will be superimposed on those of regional subsidence of the land where the latter has taken place. On the other hand, it is fairly obvious that many small islands have been formed solely by glacio-eustatic rise of sea level, especially where they lie a short distance off headlands of an indented coast which cannot have escaped renewed drowning by the latest glacio-eustatic rise (but see also subcategory 5*a*, below).

(*b*) Where a terrain that does not as a whole offer great resistance to erosion has been dissected — and perhaps in part planed — (Fig. 1, 4*b*, A) during the successive withdrawals of the sea that have taken place in the later Pleistocene (Günz and post-Günz) glacial ages some isolated hills, perhaps buttes, of the more resistant strata may survive and will remain unsubmerged after the post-glacial drowning as more or less cliffed islands at the present day — like the Pigeon Rocks of Lebanon (Fig. 1, 4*b*, B).

Some hypothetical low-sea-level ages in the almost unknown early part of the Pleistocene (anterior to the Günz age) may have lasted long enough to allow for widespread mature dissection of hard-rock terrains. Areas not very thoroughly dissected may have been drowned by subsidence in the late Cenozoic and later have had their valleys deepened, enlarged, and extended headward during early-Pleistocene regressions. Thus the possibility must not be lost sight of that some of the drowning that produced rias and islands may be due to a glacio-eustatic rather than a quasi-epeirogenic cause — notwithstanding earlier remarks (subcategory

4*a*). Such landscapes, rias, and islands may be looked for, however, rather in areas of only moderate relief, such as parts of the North Auckland Peninsula (N.Z.), than in, say, the Marlborough Sounds region of stronger relief.

(*c*) Another subcategory of category 4 (drowned by partial submergence) may be recognisable, at least theoretically, though confined to high-latitude regions. Some islands may be ascribed to partial emergence (instead of submergence) of an uneven surface. The subcategory includes islands whose form may be due to sculpture of a surface of small relief below sea level — at any rate below present sea level — by anastomosing streams of ice in Pleistocene glacial ages, followed by their partial emergence as a result of glacio-isostatic relief from load as ice melts. Attention has not been focussed on examples of such islands, but it is possible that they occur in the Baltic Sea and Gulf of Finland and in the Canadian Arctic region, and some of the Norwegian skerries may be of this kind.

5. Isolated by marine erosion.

(*a*) Quite obvious and common examples are numerous islets not far from the mainland (compare with subcategory 4*a*) that lie in front of wave-cut cliffs in moderately and even considerably resistant terrains which are intersected by intrusive bodies of more conspicuously resistant rock. Outcrops of these survive as islets if sufficiently resistant to marine erosion (Fig. 1, 5*a*). An unusually large example is Speery Island, formed by a neck of phonolite and standing in front of, and fully a kilometre from, the receding basalt cliffs of the island of St. Helena (Daly, 1927, fig. 3, pls. 1, 16).

(*b*) Other and in some cases much larger islands may be separated from land masses where the necks of peninsulas (generally formed by skeletonisation *(below)* after deep drowning) are cut through by wave action. Such intersection has nearly taken place where the northern rib of Arapawa skeleton island *(below)* is narrowed by cliffing on the Cook Strait side (Fig. 3A). Some enlargement, by marine erosion, of the narrow gap in a divide that forms the Cook Strait entrance of Tory Channel (N.Z.) has taken place after the divide has been either submerged or breached by marine erosion (Fig. 1, 5*b*).

SKELETONISATION OF ISLANDS (Fig. 2*a*)

Skeleton islands, a variety of subcategory 4*a* (above) are islands of sprawling form "characterised by a narrow and serrate axial ridge or backbone with slender lateral spurs or ribs enclosing open bays" (Davis, 1928: 194). From a study of charts Davis discovered that such islands are fairly common in the "coral seas." "This raises the empirical presumption that their development demands the presence of protecting reefs during much of their history." Davis remarks also: "There are no islands of this kind exposed to open ocean waves in the cooler seas." Some examples are known, however, in the "marginal belts" — e.g. in the Lesser Antilles (Davis, 1926) and in the Bonin and Ryukyu Groups (Davis, 1928: 194). Arapawa Island, Cook Strait (N.Z.), conforms to Davis's definition, especially its northern part. This part is composed of deformed greywacke, but lithology does not seem to control the form, as neighbouring headlands attached to the mainland present the same skeletal characteristics though composed of schist (like the southern part of Arapawa Island) (Beck, 1964). The greywackes and schists of this part of the Marlborough Sounds district seem equally resistant to erosion, which produces similar landforms and apparently the same drainage density on them.

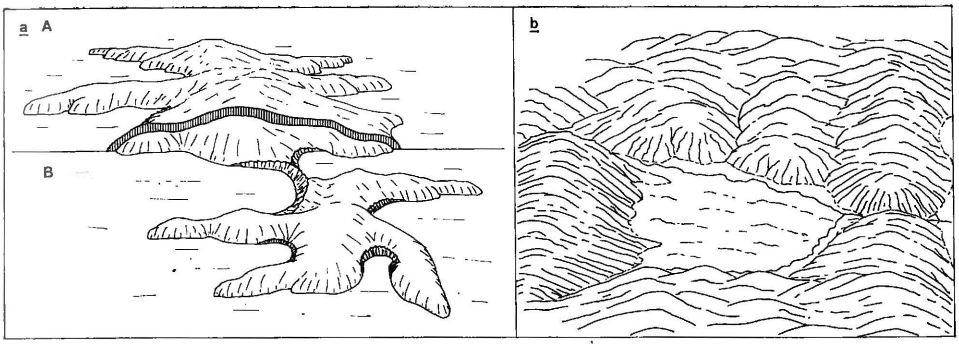

Figure 2. 2a. Skeletonisation of an island.
A: drowning of a normally eroded land surface.
B: at a later stage re-drowning of the land surface, now with amphitheatre-headed valleys, produces a narrow rib.
2b: Cryergic amphitheatre in the headwaters of two tributaries of the R. Ourthe, Central Ardennes, Belgium. From a map by Alexandre.

The skeleton form implies very deep dissection of the land prior to its submergence, low-gradient valleys being opened that retain their width right to the valley heads and, in some cases, even open out there as amphitheatres (Fig. *2a*, B). Little more remains emergent, of considerable parts of the ribs, than narrow and steep-sided, though somewhat high, divides. The first submergence of land of strong relief may have taken place (in the Marlborough Sounds district) before at least the better known later part of the Pleistocene glacio-eustatic oscillation of sea level began (see *below*).

THE RELIEF OF THE MARLBOROUGH SOUNDS DISTRICT OF NEW ZEALAND

Background History

The following notes, in part extracted from an earlier published account (Cotton, 1957a), supply a background for the history of the deeply drowned landscape of which Arapawa Island is a part.

Nearly the whole of the terrain consists of equally resistant Paleozoic greywackes and schists (Beck, 1964). Though the greatest height (at Mt. Stokes, which is centrally situated) is only 1185 m, the relief is strong and all land slopes are rather steep. The whole district is so intricately drowned by branching rias, with some anastomosing channels, that the areas of land and water are about equal (Fig. 3A, inset). Through-channels separate two large islands from the main mass.

The block of country was probably broken up by faulting before it became maturely dissected. This is suggested by the drainage pattern (Beck, 1964) and by the presence of the deeply infaulted block of Oligocene marine strata at Picton, on Queen Charlotte Sound (Beck, 1964). The Oligocene age of the youngest faulted strata may imply that the decipherable geomorphic history of the district began considerably before the end of the Cenozoic. The whole of the mature dissection of the land mass, except for minor modifications introduced probably in Pleistocene glacial ages, may, failing evidence to the contrary, be relict from Cenozoic times. There seems, moreover, to be no evidence that it was not already drowned before the end of the Cenozoic. A minor change in

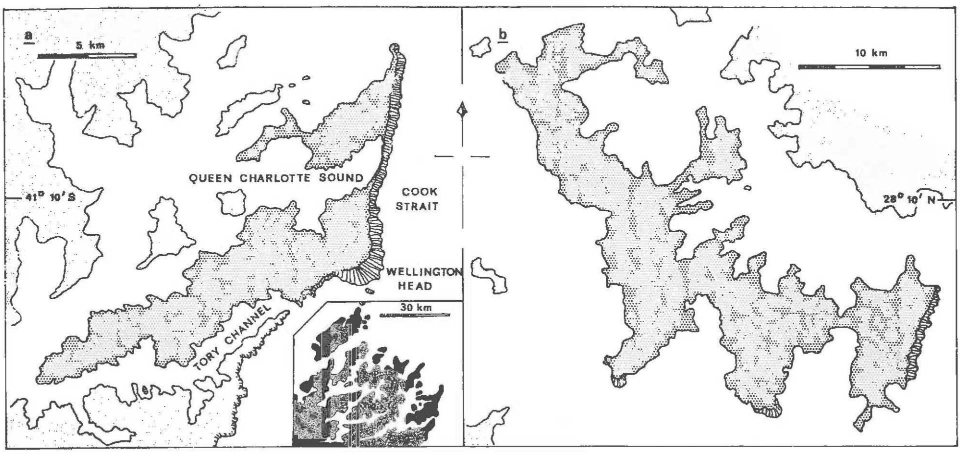

Figure 3. Skeleton islands.
a: Arapawa Island, Marlborough Sounds (N.Z.), bounded by Cook Strait, Queen Charlotte Sound, and Tory Channel. Marine erosion, owing to exposure to the storminess of Cook Strait, has trimmed back the eastern part of the island, substituting for a skeleton outline a nearly straight line of high cliffs. *Inset:* Marlborough Sounds.
b: Kakeroma Island, Ryukyu Group. (See text).

its condition must have taken place within each withdrawal of the sea in Pleistocene ice ages, for these must have laid bare the floors of the rias and channels (already infilled with estuarine sediment). With each transgression throughout the Pleistocene, if this suggested history is correct, the pre-Pleistocene condition of deep branching embayments, like those of the present day, would be restored. After the last of the regressions the gradients of the upper reaches of streams flowing on exposed ria floors would, judging from soundings in the rias, be only about 3 in a thousand. Thus these rivers, though they flowed over unconsolidated silt, would not entrench themselves, because they would be small streams draining small catchment areas. Withdrawals of the sea would not therefore result generally in rejuvenation. As for the contour of ridges and spurs, some at least of these would lose their sharpness, being rounded by solifluxion, which Beck (1964) reports to have been active.

There is another reason for thinking it probable, or at least possible, that except for minor changes mentioned above, the present landforms are practically relict from pre-Pleistocene times. This is as follows (extracted from Cotton, 1957a):

> "The absence of a recognisable relict or former-cycle surface . . . or even any approach to accordance of summit levels with either a horizontal or a warped surface is very striking (Fig. 4). This raises the question whether the mature land surface . . . , where possibly erosion has been arrested, or [better] very much slowed down, at the stage of maturity — with survival, however, of relief up to 1200 m above present sea level and very much stronger relief if measured down to floors of valleys as initally submerged [and since filled in with perhaps 500 m of marine sediment] — could have developed contemporaneously with the K Surface at Wellington [Cotton, 1957b] and also with its deformation and re-dissection. Is it possible to picture such an inhibition of erosion and almost complete immunity from further degradation? An inevitable alternative to this that must be examined is a suggestion that the existing mature landscape, . . . , which displays only one-cycle development, . . . has come into existence after a [surface like the] K Surface once present has been completely destroyed by re-dissection.
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> . . . .
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> "It may perhaps be assumed correctly that Cenozoic strata formed a continuous or nearly continuous cover at one time over the Marlborough Sounds district . . . as they certainly did over the Kaikoura Ranges and northern Nelson, for there [is a] small infaulted outlier of marine Oligocene

at Picton . . . Assuming such cover, and assuming that as seems probable some upheaval accompanied by deformation of the district took place at the same time as the greater upheaval that produced the not far distant Kaikoura ranges, a very deep and fully mature dissection not merely of differentially uplifted anticlinal parts of it but of the whole district has here to be accounted for. In such a case there has been complete removal almost everywhere of a cover of, presumably thick, Cenozoic strata that may have been folded and faulted down in some places and, in addition to this, a dissection of the undermass has taken place which is so far advanced that no remnant survives of a resurrected surface that might have been the floor under the hypothetical cover, or of a contemporaneous peneplain in such areas, if any, as were not covered by deposits . . . .

"There may have been at least such diversity of uplift as would account for consequent development of main rivers [cf. Beck, 1964], if not in deep then in shallow synclines or fault angles of the upheaved surface . . . If, despite . . . negative evidence, at least sufficient development of tectonic relief in the Kaikoura Orogeny [*sensu stricto*] can be assumed to account for such (early) initiation of river systems, and if sufficiently steep slopes can also be assumed at that stage to cause rivers to flow and thus to account for early dissection throughout the interior of the district . . . it is conceivable that the dissection of this district has continued throughout locally anorogenic post-Kaikoura time to the present day. . . . Erosion would be slowed down when the great subsidence of the whole district took place. . . .

"As an alternative hypothesis . . . it may be necessary to postulate its two-cycle (or perhaps polycyclic) origin, with great upheaval taking place between cycles, but the hypothesis is not supported by the known presence of

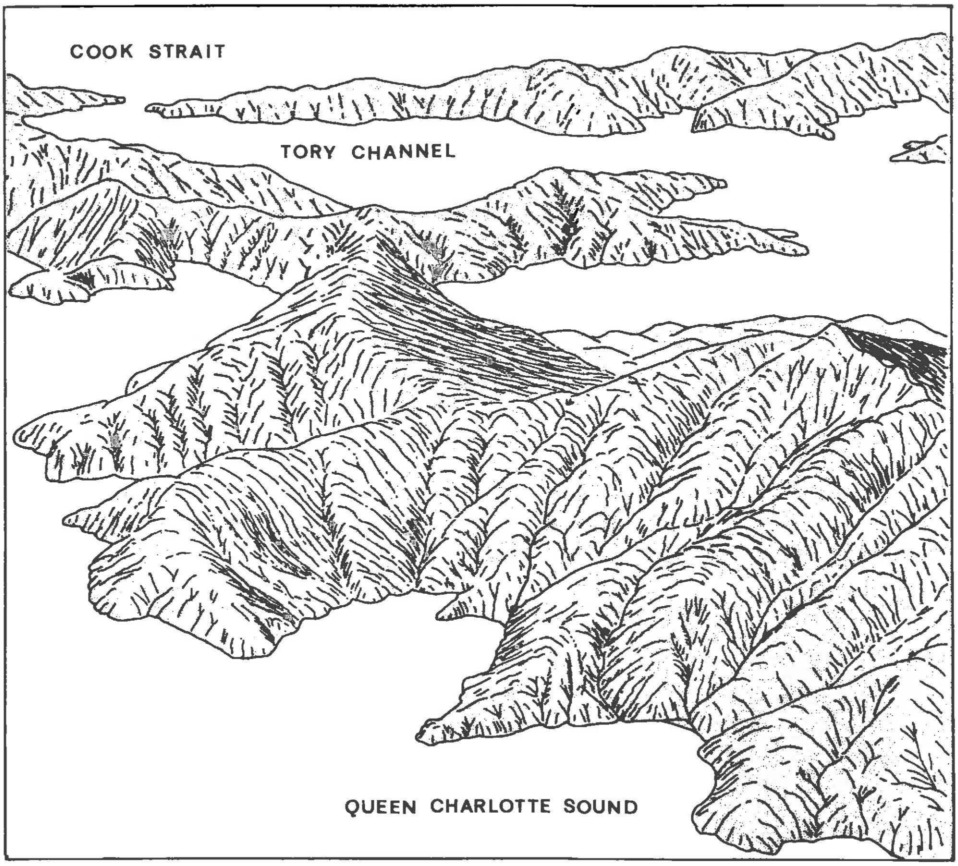

Figure 4 Arapawa skeleton island, Marlborough Sounds (N.Z.), a view looking south-east from Queen Charlotte Sound across the island to Tory Channel and Cook Strait. (From a photograph).

> any forms that are relicts of the topography of the first of such, or of forms dating from intermediate cycles. . . . There is not even any accordance of summit levels, no *Gipfelflur*. Probably a way out of the dilemma without assuming successive upheavals is to be found by assuming a quite early date for the ria-making subsidence that first drowned the Sounds (although it did not give them their present-day shorelines, which obviously date only from the post-glacial eustatic positive movement of sea level) [cf. Cotton, 1955: 71, footnote]."

The theory that drowning took place several million years ago is supported by the relatively shallow depth of water and the absence of gradients on the floors of the very long arms of the sea that form Queen Charlotte and Pelorus Sounds and their branches. Depths are uneven and irregularly distributed, the greatest being 75-70 m. The bottom consists of mud which is probably the upper surface of very thick fine-grained marine sediments, the accumulation of which — under water that is almost always clear — has occupied perhaps two or three million years, for in the absence of rivers the supply of sediment — derived largely by rain wash from weathered slopes of greywacke and schist — is very slow and it is transported in suspension from the point of supply to that of deposition.

> "Undoubtedly very extensive early drowning by eliminating rivers throughout the district [except the Pelorus River at the head of Pelorus Sound], and reducing the land to a skeleton of ridges and spurs, slowed down [progress towards] planation. Thus the apparently one-cycle landscape may be an authentic example of such cyclic development." (*cf.* Cotton, 1913).

This tentative conclusion may be a good reason for dating the first drowning of the Sounds far back in time and for adopting the theory that the relief of the land was first fully developed and then drowned — perhaps by a relatively rapid subsidence such as is indicated in Fig. 5B. Such deep drowning, though it may be the result of a single very rapid, almost catastrophic, subsidence, is not necessarily produced in that way. If subsidence began rather slowly accompanied at first, as such movement generally has been, by marginal cliffing of the land, later rather strong acceleration of subsidence, which would first cause the cliffs to plunge and would later submerge them, would eventually leave in sight only a drowned dissected landscape, as in Fig. 5B. Later the submerged cliffs might be buried by sedimentation.

Considerable confidence in the theory of the one-cycle relief of the Marlborough Sounds district, and in a theory of very slow progress in the development of the landforms there, is inspired by the results of a study of the absolute age of Banks Peninsula (Stipp and McDougall, 1969). Though much less thoroughly dissected than the Marlborough Sounds landscape, the volcanoes of Banks Peninsula are very old. The date of completion of the building of the older (Lyttelton) basalt dome has been found to be approximately 10 million years back, its period of growth being late Miocene, while growth of the younger (Akaroa) dome was completed eight million years ago, its period of growth being early Pliocene. This study affords an example of erosion at an extremely slow tempo and shows that such tempo is very variable. Apparently both in the case of marine erosion (Cotton, 1951) and in that of subaerial erosion (e.g. on Banks Peninsula) the tempo can be hundreds of times faster or slower than normal.

Accompanying its subsidence as a whole the block of country carrying the Marlborough Sounds appears to have been tilted down to the north or NE (see Cotton, 1955: 70, footnote). This is assumed by Beck (1964) to be the explanation of a difference of 600 m in summit altitudes in southern and northern parts of the district. As there is no indication of tilting in gradients of floors of the rias, it would seem that river gradients initially steepened by tilting have been eliminated by sedimentation, and that the mouths of the rias (where they enter Cook Strait) have been thus shallowed by at least 500 m.

Perhaps a recent acceleration of subsidence that had long ago practically ceased, may afford an explanation of the absence of terraces, noted by Beck (1964), because they are now submerged. The terraces may be river terraces of climatic origin or marine benches referable to interglacial episodes when sea level has been higher than at present.

Emaciation of Spurs: Probably in the Pleistocene

While the main (ancient) subsidence can explain the major features of the rias, some details of the cross-section of spurs and ridges seems to have developed in later times. These features (mentioned earlier) are narrow and steep-sided and are apparently associated with amphitheatre-shaped heads in submerged valleys (Fig. 2). They constitute some of the ribs of the northern part of Arapawa skeleton island and appear also on ridges and spurs of the neighbouring mainland.

It may be tentatively assumed that early Pleistocene glacio-eustatic oscillation of sea level began at or after the end of a great and rapid early subsidence. If the "leggy", or "emaciated" stage of rib development had then been already reached it may have persisted ever since, but, alternatively, it seems quite possible that it has been of Pleistocene origin (Fig. 2*a*).

Possible Role of Climatic Processes

An advanced stage of the skeletonisation of islands is marked, according to Davis (1928), by the development of ribs narrowed by near intersection of valley heads of amphitheatre form in small tributary valleys. Granted that it is possible to have skeleton islands developed by drowning of thoroughly dissected landscapes with very deeply eroded valleys of low gradient, one with narrowed ribs produced either by progressive or periodical "emaciation" might be distinguished as an "emaciated" skeleton island. Perhaps this development of valley-head amphitheatres took place very slowly in a succession of Pleistocene episodes of low sea level after subsidence had ceased or had become extremely slow. In the Marlborough Sounds Beck (1964) has reported strong development of cryergic (periglacial) phenomena down at least to present sea level, and a cryergic opening out of the valley form in the Ardennes Mountains in Pleistocene glacial ages has been described by Alexandre (1958: M215), who attributes the principal role to cryoplanation. By this process "pediments and sometimes erosion surfaces" have been cut "at the expense of the valley sides," which must therefore be steepened, especially at valley heads around "amphitheatres". As an example of these in the Ardennes Alexandre (1958, Fig. 10) has mapped a narrow and deep valley enlarged at the head into an amphitheatre 2 km in diameter (Fig. 2*b*).

In the case of skeleton islands in low latitudes in the Bonin and Ryukyu groups described by Davis (1928: 194) another climatic process, tropical weathering, may have been responsible for developing a similar valley-head form and for similar emaciation of divides. In hot-humid regions — notably in the Hawaiian islands — valleys are of the Oahu type, very steep-sided and with "amphitheatre" heads (Hinds, 1925; Cotton, 1943). In the Bonin and Ryukyu islands such development might take place at the times when the sea withdrew in glacial ages — unless tropical weathering was then inhibited, especially in the rather high latitude (28°) of Kakeroma Island, by world-wide cooling of climate If such a theory be rejected, it seems quite possible that at Kakeroma (Ryukyu Group) subsidence had not quite ceased in the earlier Pleistocene. In the early interglacial episodes and even in the long and perhaps exceptionally warm Mindel-Riss episode, if the heads of valleys dissecting skeleton islands were as yet unsubmerged at times of high sea level, tropical weathering was no doubt active in them, developing amphitheatres.

MODIFICATION OF SKELETON ISLANDS BY MARINE EROSION

On one side only, that facing Cook Strait, the outline of Arapawa skeleton island has been destroyed by marine erosion (Fig. 3A), for the other shores of the island are subject to attack only by waves on the sheltered waters of Queen Charlotte Sound and Tory Channel (Figs. 3A, 4). Their side slopes have been regraded by subaerial (probably in part cryergic) processes in glacial ages, but have been scarcely notched by marine erosion since sea level became stabilised several thousand years ago. On the Cook Strait side half of the north-eastern part of the island has been removed and replaced by a north-south line of cliffs which (at Wellington Head) are nearly 600 m high — the cliffs plunging into water 70 m deep (Cotton, 1968: 50). Could the missing part be restored, the island would have as perfect a skeletal form as the "type" Kakeroma Island (Ryukyu Group), as shown in Fig. 3B. Though it is possible that, according to Darwin's principle (Cotton, 1969), some of the truncation of the island by cliffing along the Cook Strait line took place during the early subsidence, much of it is attributable, no doubt, to the successive transgressions of glacio-eustatic origin in the Pleistocene. On Kakeroma Island some high headlands facing the open ocean are cliffed, but their truncation has not proceeded very far. Davis (1928) has explained the cliffing of headlands of Kakeroma as due to disappearance, produced by climatic change, of coral reefs that had previously protected the skeleton shoreline.

ISLANDS IN THE NEAR-SKELETON CATEGORY

There are several almost-skeleton islands or skeleton islands in an immature or arrested stage of development in the New Zealand region, e.g. D'Urville Island, Stewart Island, and Kawau, Great Barrier, and Great Mercury Islands. off the Auckland coast. Among the most conspicuous Australian examples is Whitsunday Island on the east coast of Queensland.

In the case of Stewart Island, though cryergic processes may have produced landform changes, the divides, as initially submerged, were apparently not narrow enough for reduction to true skeletal ribs. It is uncertain whether any of the other islands mentioned above could attain the leggy, or narrow-ribbed, stage of an emaciated skeleton island even with a climatic stimulus that would develop valley-head amphitheatres during glacio-eustatic oscillation of sea level.

In all these cases deep drowning of maturely dissected landscapes must have taken place as the result of subsidence of the land (see subcategory 4*a* of islands, above). In the case of D'Urville Island this would be contemporaneous with that of the rest of the Marlborough Sounds district, but in the case of the other islands it may have been earlier or later. Some of the valleys that became arms of the sea as a result of the first subsidence may have been enlarged later throughout their length by subaerial erosion in the ages of low sea level accompanying Pleistocene glaciations.

PREFERRED HYPOTHESIS IN EXPLANATION OF THE ORIGIN OF SKELETON ISLANDS

The writer's hypothesis of origin of skeleton islands as exemplified in the Marlborough Sounds district may be recapitulated as follows — rather ancient dissection to maturity of a terrain of somewhat resistant rocks takes place, with the excavation of deep valleys and the development of branching systems of rivers. Both the main and the principal tributary streams have gentle gradients nearly to the valley heads. Topographic form is henceforth subject to only very slow change.

Strong and perhaps rapid subsidence supervenes, leading to intricate drowning, with submergence of some divides. This produces islands of skeleton and near-skeleton form. Subsidence either ceases or becomes extremely slow about the beginning of the Pleistocene, and in later time glacio-eustatic oscillation of sea level causes numerous withdrawals of the sea from the rias. These are accompanied by some enlargement of valley-heads to amphitheatres, and are followed by re-submergences. Thus the shorelines of rias and islands, though not very different from those produced by the initial submergence by subsidence, are now actually post-glacial, as is the case in nearly every other part of the world.

AN ALTERNATIVE HYPOTHESIS (THE KAKEROMA THEORY)

Though the same theory might be found applicable to the Ryukyu skeleton islands, of which Kakeroma is an example, the explanation offered by Davis (1928) for the origin and partial submergence of landscape forms is quite different.

Before discussion of Davis's explanatory description of Kakeroma Island a comparison may be made of the erosional results of rapid and slow subsidence of a land mass (Fig. 5). In Fig. 5A a land surface more or less similar to that of the Marlborough Sounds district is shown at the maturely dissected but as yet unsubmerged stage. Sector B shows the result of very rapid submergence, or of perhaps less rapid submergence in the case where a coast is not fully exposed to the attack of ocean waves. Should some cliffing of headlands take place at an early or some later stage of this submergence, the cliffs then cut may be submerged later by acceleration of the subsidence. In a tropical environment, if fringing coral reefs are sufficiently developed at any stage of the subsidence to afford protection, the end product of subsidence and its consequences, would be a coast perhaps as deeply indented by rias as that of Marlborough Sounds.

(In the preparation of Fig. 5 progressive subsidence has been shown as sea level rising relative to the land.) Sectors C, D, and E of Fig. 5 show the effects of rather slow submergence by stages, the total change of relative sea level

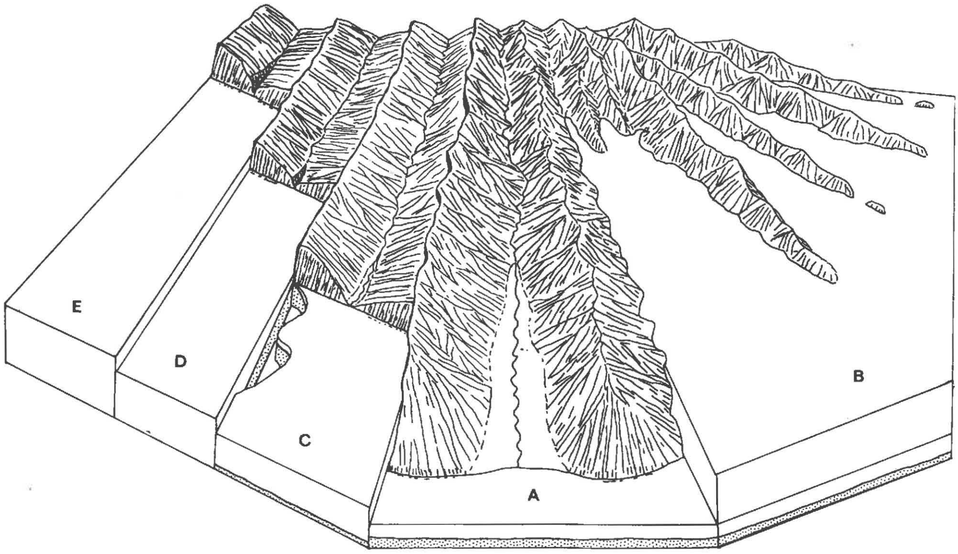

Figure 5. The effects of rapid (B) and slow (C, D, E) subsidence on a thoroughly dissected ancient land surface (A). (See text.)

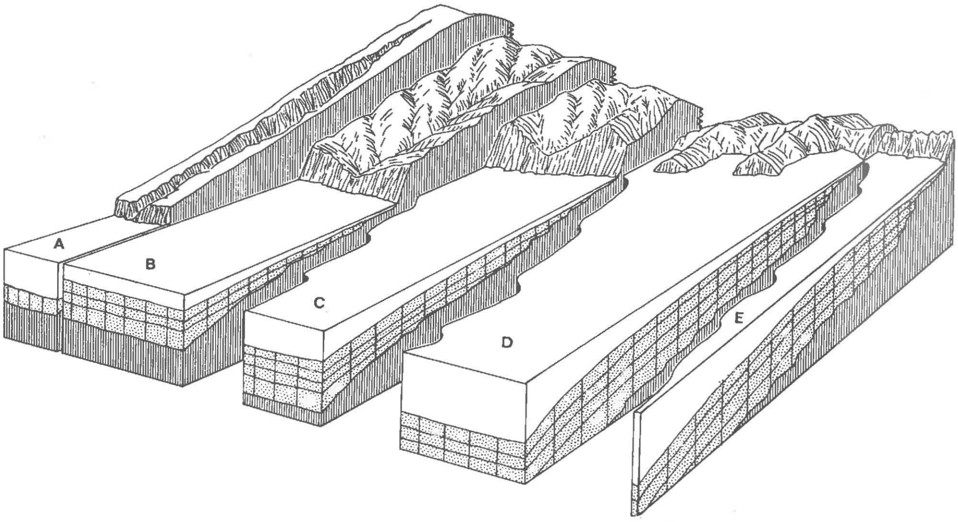

Figure 6. Slightly modified copy of a diagram drawn by W. M. Davis in explanation of the origin of the skeleton islands (especially Kakeroma) in the Ryukyu chain. An origin by dissection stimulated by cliff retreat is assumed for the relief of a landscape later drowned by subsidence. (See text).

being the same as in Fig. 5B. Provided that the coast is exposed to ocean waves, cliffing of the margin goes on progressively with subsidence, a complementary cut platform being developed in front of the cliffs, as shown in Sector D of Fig. 5.

As the coast is progressively cut back by cliffing the influence of sea level as a base level of erosion becomes effective in zones farther and farther inland; the effects of cliff retreat being essentially the same as increase of available relief. Some erosional lowering of the land surface will go on, especially as destruction of a land mass by marginal cliffing is a slow process. Erosional lowering may take place in two ways: (*a*) by dissection to and throughout the stage of maturity by deepening of valleys progressively rejuvenated at their mouths, as well as by the incision of probably numerous newly developing valleys, mainly insequent; and (*b*) by mass wastage. The outline of the land (the coastline) becomes mature at an early stage of cliffing. Though both the processes *a* and *b* will generally be active, one or other may be dominant. In a diagram by Davis (1928, Fig. 89) dominance of the dissection process is assumed, but in Fig. 5, C, D, and E mass wasting is shown as dominant.

A deep dissection of the terrain, with long thoroughly graded valleys similar to the presumable form of the Marlborough Sounds landscape before the great subsidence, is shown in Fig. 5, A. This condition does not favour deepening of lower valleys in an early stage of cliff retreat (Fig. 5, C) because the gradient seaward of the cut rock platform in front of the cliffs (though it depends on the rate of subsidence and cliff-cutting) will almost certainly be steeper than that of the graded valleys as shown (Sector A). At a much later stage of cliff retreat (Sector E), however, the reverse will be the case because of the steepened headwater valley gradients. Until this stage is reached it is clear that the lowering of the land surface by weathering and mass movements may greatly exceed that due to dissection, though obviously erodibility of the terrain and climatic conditions will have to be taken into account in any particular case. The argument of Daly (1927 : 90) that rejuvenation, with development of valley-in-valley forms, is not to be expected in the coastal valleys of St. Helena Island because the gradient of the offshore cut platform, which emerges during withdrawals of the sea, is gentler than that of valley profiles betrunked by cliffing depends on evaluation of the possibility of vertical corrasion by extended streams. It is not here applicable, therefore. Progressive deepening is to be expected in the valleys at stages D and E, however, instead of true rejuvenation which, by making valley-in-valley forms, indicates pauses or reversals in the subsidence; this introduces cases not at present under consideration.

Perhaps an excessive amount of wasting of the land surface is shown in Fig. 5, C, D, E. In the Marlborough Sounds wasting seems to be very slow, landsliding being infrequent, and this seems to be the case in many of the greywacke ranges of New Zealand — except where sliding has been precipitated by severe earthquakes, as it was on the Rimutaka Range in 1855. Lauder (1964) has, moreover, seen little evidence of appreciable change in greywacke slopes in the last 10,000 or 100,000 years. Selby (1967) has, however, found rapid wasting of the surface by mass movements in progress on some greywacke ranges in the Waikato district.

Kakeroma and the adjacent island north of it, like the Marlborough Sounds district of New Zealand, are remnants of a land mass with a core of deformed ancient sedimentary rocks (in part Permian), but with some igneous intrusions (Hanzawa, 1935). A great lowering of the sea level relative to the land, followed by reversal of the movement, has been suggested by Hanzawa (1935: 17, 18) in the whole of the Ryukyu island region as well as in the main islands of Japan. The topography of Kakeroma is of the same type as that of the larger island just north of it, the strait between being a drowned valley (Hanzawa, 1935: 19). The landforms of Kakeroma were explained by Davis (1928) with an assumption that relief developed *pari passu* with the earlier and slower part of a movement of subsidence (Fig. 6, A, B, C), the earliest stage shown of the landscape evolution being a surface (presumably an upheaved surface of planation) sloping seaward, the surface being smooth as yet except for immaturely developed valleys that have been deepened in response to and during the earliest cliffing (Fig. 6, A). This stage can only be regarded as hypothetical and tentative: it is analogous, however, with the initial (constructional) slope of the flank of an oceanic-island volcano, in the case of which dissection of the interior of the island accompanies and is largely a result of retreat of cliffs at the margin. Such dissection becomes more mature and deeper (with increasing available relief) as cliffing of the island proceeds (Cotton, 1969a: 199). Davis's conception of the development of the relief is shown by the stages B and C; marginal cliffs are shown as receding as subsidence goes on, and the relief, developing early to maturity, passes through changes of form according to the procedure (*a*) referred to on an earlier page, by deepening of valleys continuously cut back at their mouths together with development of secondary valleys thereby stimulated.

The succession of changes must be supposed to continue over a long period, for Kakeroma Island is bordered on the exposed (south) side by a shelf 8 to 10 km wide (Davis, 1928, map, fig. 86). This indicates the amount of cliffing back of the land that is postulated (Fig. 6), for, if the assumed history is correct, the shelf must be underlain by the rock platform contemporaneously cut. (Davis's diagram shows this as covered by a thick sedimentary accumulation — somewhat thinned in copying Fig. 6 from Davis's Fig. 87). The depth of the shelf-edge is 180 m (Davis, 1928: 193), whereas the platform that must be postulated as cut during progressive subsidence will probably slope down to a depth of hundreds of metres, and so the outer part of the sedimentary cover on it, if such cover makes the existing shelf, must be of very great thickness. If the shelf were, on the other hand, merely a nearly bare cut platform, such as generally develops during the cliffing back of islands undergoing submergence (Cotton, 1969) its small depth could not be reconciled with the scale of the dissection to strong relief (325 m) of Kakeroma Island, to the relief of which must be added the depth of submergence of the island.

There is an unusually great depth of water on the shelf near the landward margin — commonly 90 to 140 m at a distance of 1 to 2 km from Kakeroma Island. This must be considered with the great depth of the shelf-edge (180 m), which is greater by 50 m than the usual depth at the edge of the continental shelf, and is nearly twice the usual depth at the edge of shelves of the Ryukyu Islands — 100 m (Hanzawa, 1935: 10). These depths seem to indicate the rather recent subsidence of Kakeroma Island and so to confirm the latter part of its history as shown in Fig. 6, D, E.

It seems quite possible, if not probable, that the shelf — in common with most continental shelves — is almost entirely a feature built of accumulated sediment and that the sediment is for the most part not of strictly local origin. It may, moreover, be a rather ancient feature. If a rock platform underlies it this is probably much less extensive than that shown in the diagram by Davis (or in Fig. 6), which implies also that the sediment built into the shelf is derived from the land mass of which Kakeroma Island is a remnant. More probably, however, practically all the debris produced by abrasion in the shallow water bordering retreating cliffs would be pulverised and transported seaward, partly in suspension, to be deposited over a wide area (Cotton, 1969: 196).

Such then is the theory devised by Davis to account for all but the latest stages of development of the land forming Kakeroma Island. Valleys on the island are, without any special explanation of this, assumed to have been opened out at their heads into amphitheatres, and the final skeletonisation has been brought about by acceleration of subsidence (Fig. 6, D, E). In the block diagram accelerations of subsidence are indicated by steepenings of the profile of the cut platform (Fig. 6, B, C, D, E). Incidentally, the rate of subsidence is assumed to be variable throughout the history of the truncation and dissection of the land.

An attempt might be made to apply the Kakeroma theory to the history of Arapawa Island, but, though the north-eastern border of the Marlborough Sounds district may have been at one time exposed to vigorous marine erosion, as the Cook Strait side of Arapawa Island still is, the effects of perhaps three million years of Pleistocene glacio-eustatic oscillation of sea level would have to be evaluated (as has *not* been done for Kakeroma).

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