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RURUTU RECONSIDERED: THE DEVELOPMENT OF MAKATEA TOPOGRAPHY IN THE AUSTRAL ISLANDS

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ABSTRACT

The islands of the southern Cook and Austral groups in the South Pacific exhibit astonishing differences in geology and topography, even between closely adjacent islands of similar ages. Some are sea-level atolls, others have low fringes of Pleistocene raised reefs, and others substantial rims of elevated mid-Tertiary limestones, locally known as makatea. On some islands the relief of the makatea is subdued, but on others it is dominated by eroded volcanics, sea-level swamps, and vertical limestone walls. Sixty years ago there was great controversy over whether the makatea of Rurutu represented a reef-growth or an erosional topography. Using insights from Mangaia in the southern Cooks we argue that the makatea relief of Rurutu is of erosional origin, and we identify why the Paparai Valley - seen as a key area in the old arguments, even though none of the protagonists had seen it - holds a key to the great inter-island differences which exist in makatea topography in this part of the Pacific.

INTRODUCTION

In 1928, in The Coral Reef Problem, W. M. Davis devoted two chapters of nearly ninety pages - fifteen per cent of the entire book - to the subject of elevated fringing reefs, barrier reefs, almost-atolls and atolls. He clearly believed that the structural relationships with their foundations which elevated reefs revealed had direct significance for theories of reef development, and as a result of his discussion he had little difficulty in persuading himself of the correctness of Darwin's views.

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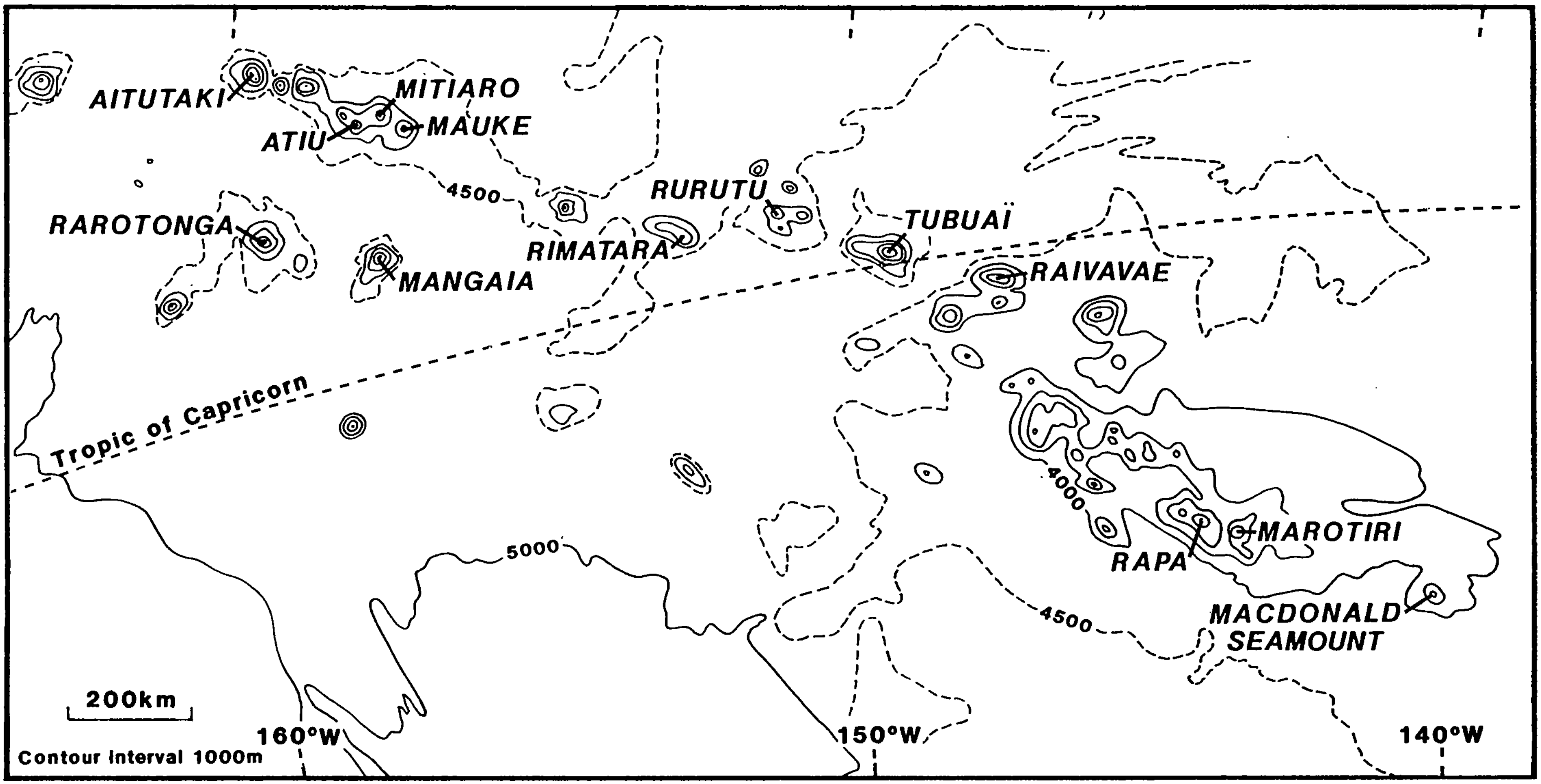

Figure 1. The Southern Cook and Austral Islands

Unfortunately, while he had access to Marshall's (1927) geology of Mangaia in the southern Cooks and to Chubb's (1927a) geology of the Austral Islands, Davis's account predated the great controversy over the significance of raised reefs which developed in the late 1920s and early 1930s, and in particular he did not appreciate the new insights into the erosional development of raised reefs which resulted from the work of H. S. Ladd (1934) in Fiji, J. E. Hoffmeister (1932) in Tonga, and of both in the Lau Archipelago (Ladd and Hoffmeister 1945). These later field studies led to a vigorous renewal of controversy over the coral reef problem in which the conclusions reached differed substantially from those of Davis (Hoffmeister and Ladd 1935, 1944).

Much of this discussion focussed on the reef-capped volcanic islands of Mangaia and Rurutu in southeastern Polynesia. We have recently examined the case of Mangaia (Stoddart, Spencer and Scoffin 1985), and in this paper we reconsider the evidence from Rurutu and comment on other islands in the chain.

Although the volcanoes of the southern Cook and Austral groups are arranged in linear array, broadly increasing in age towards the northwest, the arrangement is far from a simple one (Turner and Jarrard 1982). In the southern Cooks only Mangaia fits the age prediction in terms of plate migration from a hot spot, while Atiu, Mauke and Mitiaro are all substantially younger than predicted. In the Australs actual ages are closer to predicted ages (Figures 1 and 2). Renewed volcanism has also occurred on Aitutaki and Rurutu, substantially later than the initial building of the shielf volcanoes, and broadly coinicdent with the construction of Rarotonga between 2.1 and 1.1 million years B.P.

The most remarkable aspect of the geomorphology of these islands lies in the enormous variability in the development of reefs on them. From southeast to northwest: Marotiri and Rapa have no significant reef development and are indeed extra-tropical; Raivavae and Tubuai have sea-level coral reefs with motus and have no elevated reef limestones (in the case of Tubuai contra Turner and Jarrard 1982, 207); Rurutu and Rimatara have mid-Tertiary reefs elevated to 100 and 11 m respectively; Mangaia has similar reefs believed to be of Oligocene or lower Miocene age, elevated to 70 m; Atiu, Mauke, Mitiaro and Rarotonga have low elevated Pleistocene reefs with (with the exception of Rarotonga) a foundation of Tertiary limestones; and Aitutaki, Takutea and Manuae have no elevated reefs at all, only (like Raivavae and Tubuai) sea-level reefs with motus. The history of these islands has thus clearly been complex in both horizontal and vertical terms (Table 1).

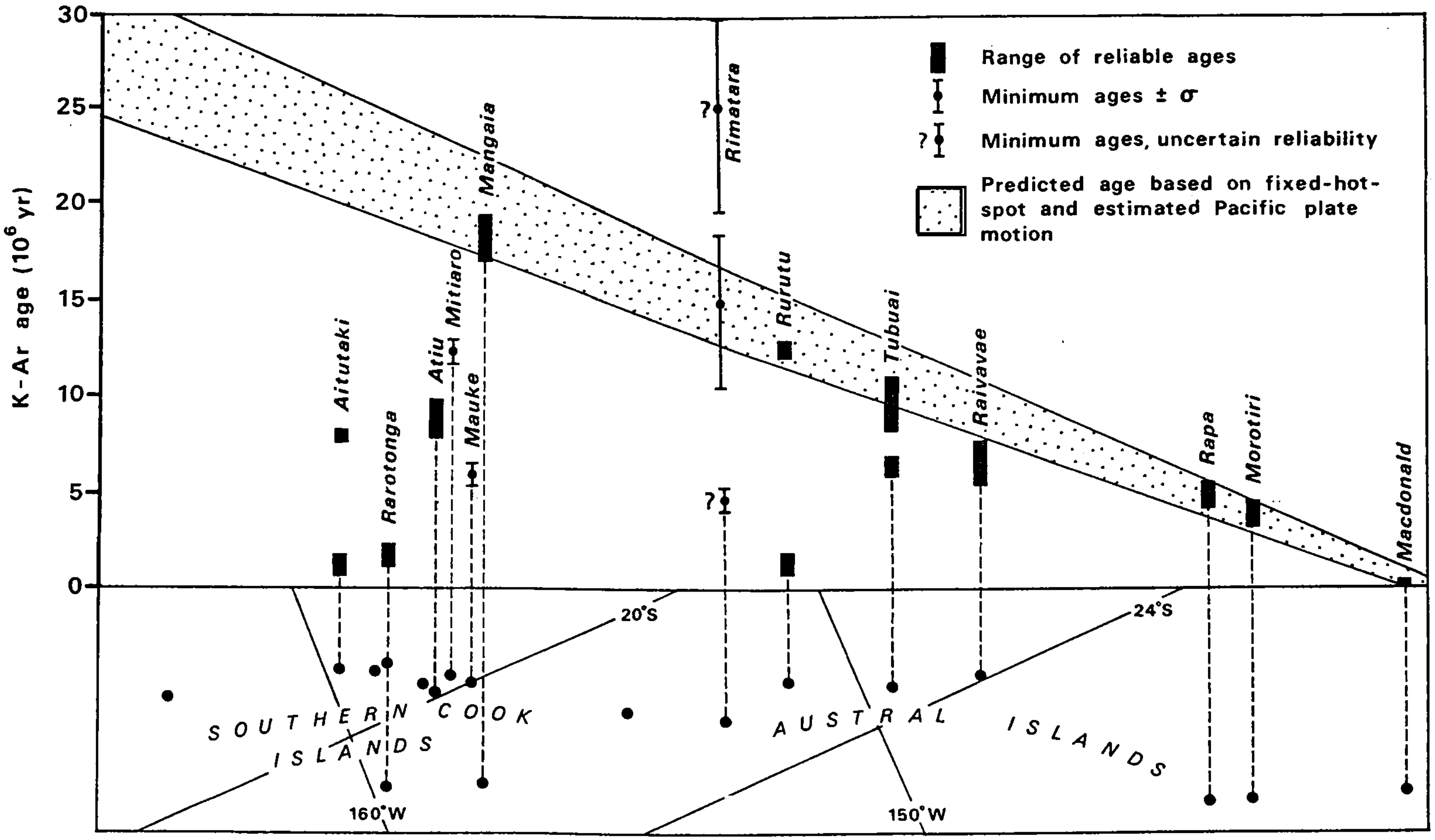

Figure 2. Predicted and actual island age, Southern Cook and Austral Islands chain. Source: Turner and Jarrard (1982), Bellon et al (1980).

Table 1. Age and topography of the Southern Cook and Austral Islands

Island	Age, 10^6 yr	Maximum elevation of volcanics	Maximum elevation of makatea	Maximum elevation of Pleistocene limestones
Rapa	5-5.2	670	nil	nil
Raivavae	5.5-7.4	437	nil	nil
Tubuai	8-10.4	422	nil	nil
Rurutu	12.3 0.6-1.9	389	100	15
Rimatara	>28.6, >21.2 >14.4, >4.8	92	11	?
Mangaia	17.4-19.4	169	73	14.5
Mauke	>6.0	24.4	14.6	10.0
Mitiaro	>12.3	8.9	10.9	9.8
Atiu	8->10	72	22.1	12.2
Rarotonga	>1.6-2.3 1.1-1.4	653	nil	3.5

Sources detailed in text

RURUTU, AUSTRAL ISLANDS

Rurutu is a small volcanic island in the Austral group; it was discovered during Cook's first voyage, though no landing was made. It forms part of a linear chain of volcanoes which extend for 2000 km from the still active Macdonald Seamount in the southeast to the almost-atoll of Aitutaki in the northwest. Rurutu itself extends for 7 km in a north-south direction, and is 1.75-2.4 km wide. The central volcanics have a maximum elevation of 385 m. The island is discontinuously fringed by discrete outcrops of elevated reef limestones, which occupy some 28 per cent of the total area of 32 sq km (Figure 3). The volcanic core consists of submarine basaltic pillow lavas up to 90 m thick at outcrop (the surrounding sea floor is 4-4.5 km deep) (Brousse 1985), dated at 8.6-12.5 million years (Dalrymple et al 1975, Duncan and McDougall 1976, Turner and Jarrard 1982). The pillow laves are discontinuously overlain around the present shoreline by raised reef limestones, dated at late Miocene and up to 100 m thick, with manganiferous clays locally occurring at the contact between the volcanics and the reef deposits. Subsequent to uplift and emergence of the reef limestones there was a renewed phase of subaerial vulcanicity. This formed extensive surface flows dated between 0.6 and 1.1 million years (early Pleistocene). There is a narrow contemporary fringing reef developed in the major bays on the east and west coasts of the island.

The geology of Rurutu was first described by Chubb (1927a) and in greater detail by Obellianne (1955). A summary is given by Bardintzeff, Brousse and Gachon (1985), though the extent and continuity of the makatea limestones is much less than they indicate (compare their Figure 1 and this paper, Figure 3).

THE RURUTU CONTROVERSY

Chubb (1927a, 306) indicated that the elevated limestones of Rurutu 'completely surround the island, except where they are broken through by one of the larger river-valleys', forming a cliffed plateau up to 100 m high. 'Parallel to the south-eastern coast, however, there is a depression, the Paparai valley, running behind the limestone terrace. The drainage down the hillsides reaches the transverse trough, and thence makes its way into the sea by means of caves cut through the base of the limestone' (Chubb 1927a, 306). He inferred a history of episodic uplift of the entire island. He subsequently published (Chubb 1927b) an extended comparison of Mangaia (derived from Marshall 1927) and Rurutu, particularly emphasising the existence at the

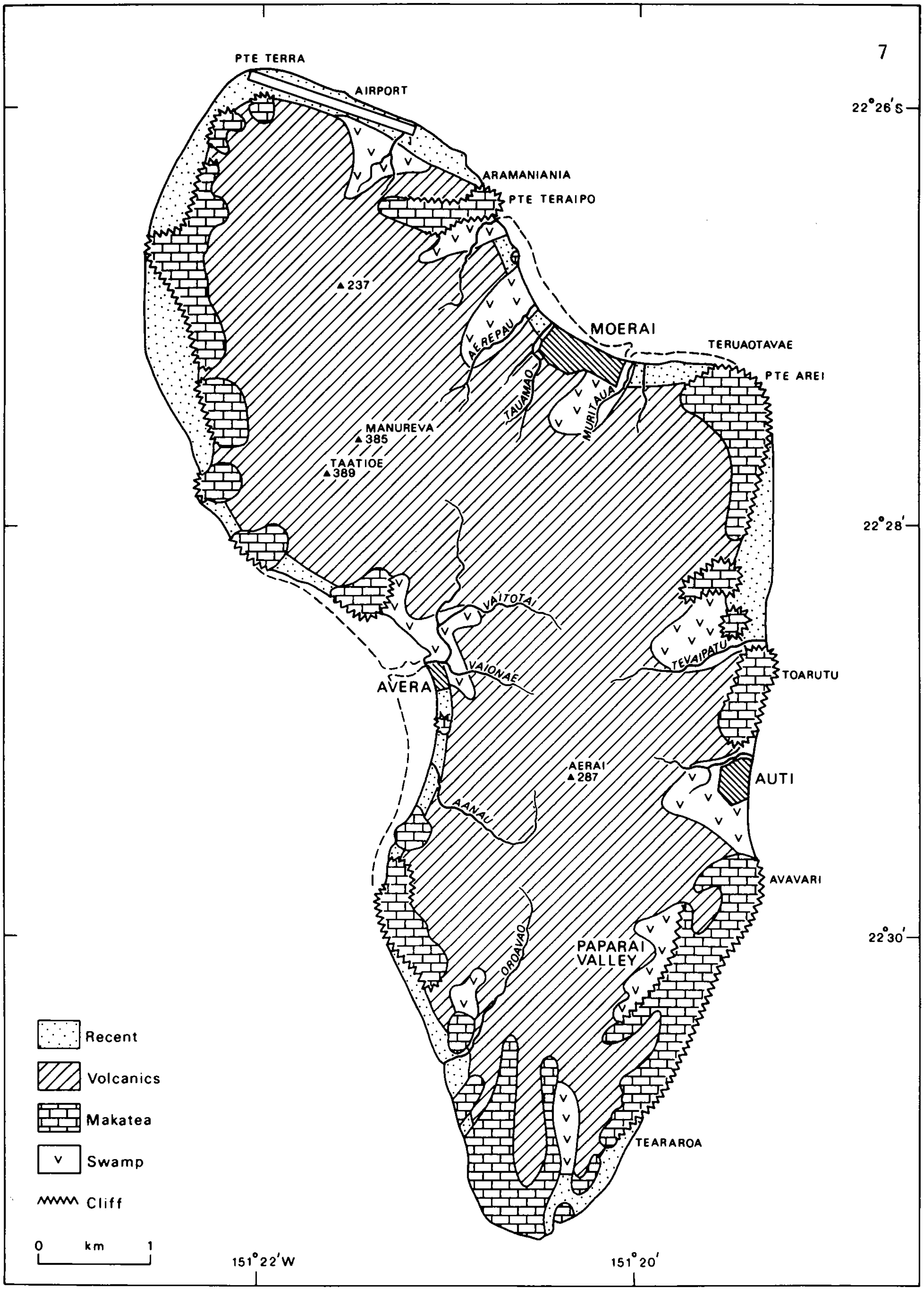

Figure 3. Geology of Rurutu.
Source: Rurutu Carte Touristique (Bureau des Affaires Communales, Moerai, 1977) and sources detailed in text.

former of a swampy depression between the eroded volcanic core and the vertically-cliffed encircling reef limestones. No such depression was found by Chubb at Rurutu, where in the areas seen by him the upper surface of the limestones continued inland to abut the volcanics. The volcanics themselves were drained by streams which flowed seawards on volcanic rocks between the limestone outcrops, rather than, as on Mangaia, through conduits beneath the limestones. Chubb did, however, note the existence on Rurutu of a closed depression, between the limestones and the volcanics, in the Paparai valley, in the southeastern part of the island (Chubb 1927a, 520-521). He suggested that in general the differences between Mangaia and Rurutu could be explained by considering the limestones at Mangaia to have originated as a barrier reef with a lagoon, whereas those at Rurutu had constituted a fringing reef. The depression of the Paparai valley, in spite of its resemblance to the Mangaia swamp depressions, he suggested was the result of subaerial erosion rather than being an inherited barrier-reef lagoon. In summary Chubb believed that the discontinuous nature of the Rurutu makatea resulted from first vertical and then horizontal erosion by surface streams derived from the volcanics, which initially flowed over relatively impermeable limestones and trenched through them. The Paparai valley was formed by subsequent stream development at the contact between the limestone and the volcanics, and Chubb suggested that this process could account in some degree for the Mangaia depressions also.

On the basis of his work at Mangaia and Atiu, Marshall (1929) queried whether the Paparai valley depression could be considered as of subaerial origin, on the grounds of the absence from it of obviously fluvial landforms and sediments and of any undercutting of the makatea slope. He restated his belief that the makatea at Mangaia is a former barrier reef and that at Rurutu a fringing reef, and that their dissimilar modern topographies result from this fundamental difference in origin.

Hoffmeister (1930), from his fieldwork on Eua, considered subaerial erosion a more plausible explanation for the origin of depressions between makatea and volcanics, since few streams are known to flow across limestones or to cut gorges through them, whereas many flow underground at the contact and 'will eventually lead to the formation of a valley lined on one side by the sloping volcanic hills and on the other by a nearly vertical limestone cliff' (1930, 551). But in the case of the critical locality on Rurutu, over which the controversy centred, Hoffmeister cautioned that 'it is true that none of us have seen the Paparai Valley, not even Mr Chubb, who obtained his information second hand' (1930, 550). Neither Marshall nor Hoffmeister, of course, ever visited Rurutu.

There the matter rested. Later French workers such as Obellianne (1955), while adding to geological knowledge, did not discuss the controversy between Marshall, Chubb and Hoffmeister on the origins of the makatea topography, although the importance of karst erosion processes in determining reef morphology became increasingly recognised (Purdy 1974a, 1974b, Stoddart 1973).

EROSIONAL ORIGIN OF MAKATEA TOPOGRAPHY

The main arguments for the erosional origin of makatea topography have been worked out on Mangaia (Stoddart et al 1985) and subsequently on Atiu, Mauke and Mitiaro (Spencer et al 1985). They include:

(a) The aggressive nature of streams draining the volcanics and the fact that these streams drain through discrete conduits in the makatea to reef-flat resurgences. These conduits cannot accommodate flood discharges, so that aggressive waters are dammed back, causing solutional undercutting along the swamp-makatea junction, and ultimately to the formation of a 'karst marginal plain' of the kind often described around tower karst in Central America and Southeast Asia.

(b) This process leads to the slow and episodic retreat of the inner makatea wall. The process may be expected to leave residual outliers, and these are indeed found at Mangaia.

(c) Fluctuations of relative sea-level lead to the relocation of the locus of solutional activity as the swamp-makatea contact is redefined and new conduits and sinkholes develop. There is clear field evidence of this episodic development in abandoned caves and conduits high in makatea walls.

(d) The precise nature of the erosional topography in the Southern Cooks varies with the initial size of the volcanic basement and the consequent geometric constraints on reef development. Thus Mangaia and Atiu have bolder topographies than Mauke and Mitiaro. Uplift history also varies with tectonic context and in particular with arch development around subsequent volcanic loads (McNutt and Menard 1978).

These factors have combined to result in the formation of an extensive depression between volcanics and makatea on Mangaia, and to a lesser extent on Atiu, but not on Mauke (Spencer et al 1985). Thus extensive swamps with high makatea inner walls will only develop where the central volcanos

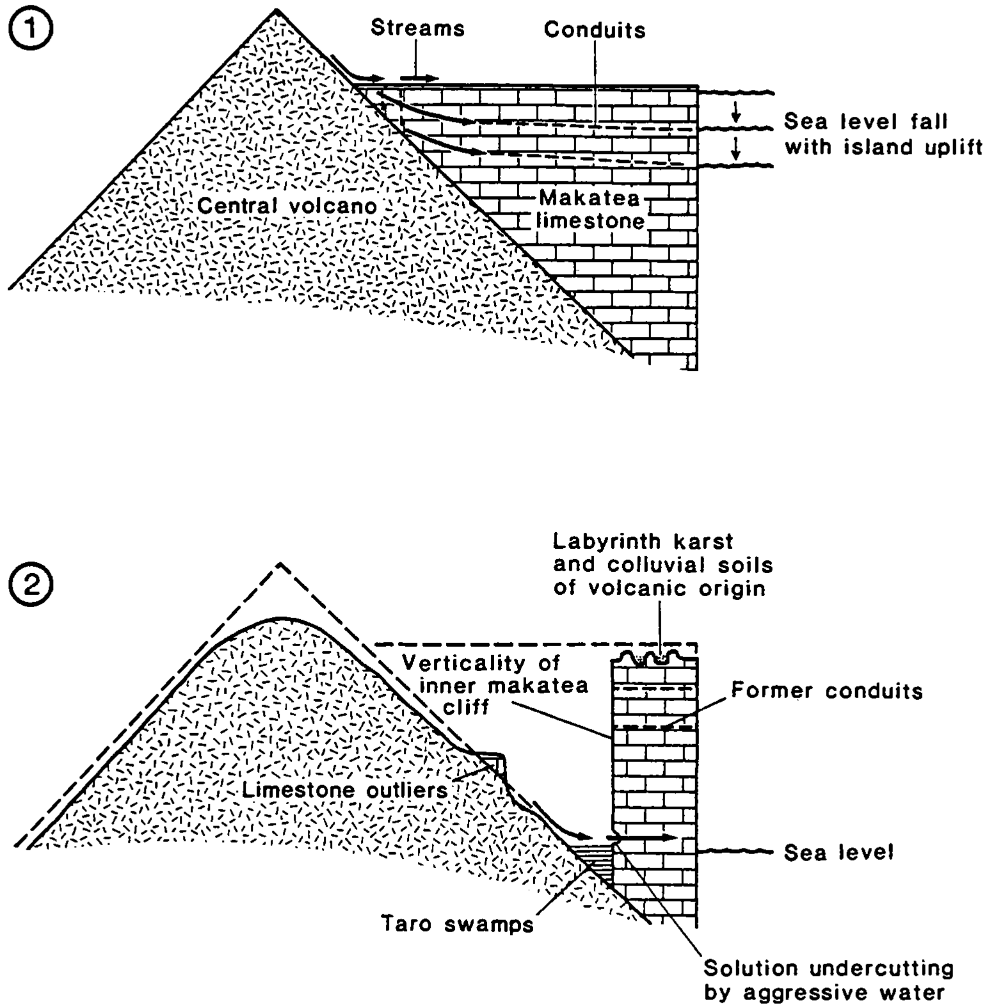

Figure 4. Hypothesis of landform evolution on Mangaia, Cook Islands.

have sufficient area and altitude to deliver enough aggressive water to the swamp-makatea contact. Under these circumstances landforms develop as hypothesized in Figure 4.

THE INDIVIDUALITY OF RURUTU

At first sight the makatea islands of the Australs resemble those of the Southern Cooks. Rimatara in particular repeats the classic pattern of the islands we have just described. Rurutu, however, appears to have had a more complex history. Stratified manganiferous clays occur between the volcanics and the makatea, and the volcanics themselves are identified as submarine pillow lavas. Whereas in the islands of the Southern Cooks the volcanic and reef-building phases were distinct, allowing the development of a complete encircling reef, on Rurutu reef building may have been inhibited by continuing volcanic activity.

The Rurutu makatea now exists as six large (Figure 5) and at least sixteen small separate limestone blocks (Figure 3). Particularly in the northeast the makatea is restricted to the ends of volcanic spurs, and there is, for example, no field evidence that the blocks inland from Pte Teraipo and Pte Arei were ever continuous throug the Moerai lowland.

This has important geomorphological consequences. Whereas on Mangaia drainage from the volcanics is delivered <u>toards</u> the makatea, on Rurutu streams in general drain <u>away</u> from the makatea, located as the latter is on the ends of spurs. There are, of course, some exceptions to this generalisation, for example the southern margin of the block inland from Pte Teraipo (Figure 6), the area immediately north of Auti village, and that northwest of Avera. In all of these locations streams and swamplands abut directly against the makatea and cause solutional undercutting, but this is not a common situation on Rurutu.

As Hoffmeister recognised, the Paparai valley is of particular interest in explaining Rurutu landforms. The valley forms a transverse depression inland from the most laterally-extensive of all the makatea outcrops on the island. In particular this makatea strip terminates to both north and south on prominent volcanic spurs. Unlike any other location on Rurutu, but as generally occurs on Mangaia, aggressive drainage waters are trapped in an enclosed swamp fed by an extensive catchment area on the volcanic slopes to the west. The inner wall of the makatea in the Paparai valley (Figure 7) is an undercut vertical cliff, repeating precisely the common situation at Mangaia (compare Stoddart <u>et</u> <u>al</u> 1985, figure 4). The cliff has clearly retreated by basal solution, and, as at Mangaia, this retreat has left

Figure 5. Isolated makatea block at Toarutu, east coast of Rurutu, seen from the north. Note the prominent seaward depositional dips in the limestones, and the numerous horizontal erosion features (raised intertidal notches and caves) in the vertical limestone wall.

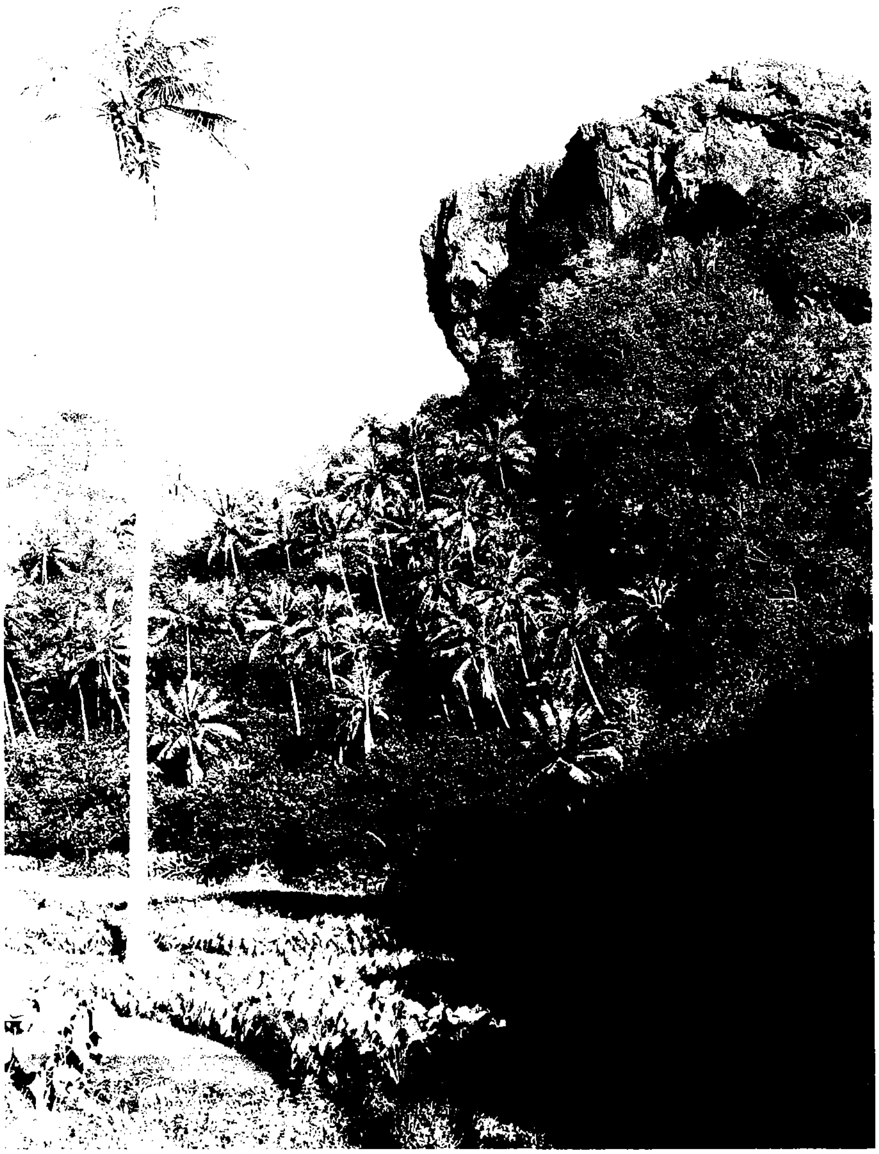

Figure 6. Undercut makatea cliff and swamp depression southwest of Pte Teraipo, Rurutu.

Figure 7. The inner wall of the makatea rim and adjacent swamp depression, Paparai Valley, Rurutu.

behind at least one substantial limestone residual on the west (inland) side of the swamp depression. There is likewise abundant evidence of episodic rejuvenation in the form of raised intertidal notches, horizontal cave horizons, and abandoned drainage conduits in the cliff walls (see Figure 5). The Paparai valley is thus a karst marginal plain identical in origin to those of Mangaia: it owes its existence to the topographically and geologically constrained drainage patterns on the island.

Table 2 gives pH and conductivity measurements on water samples from streams draining the volcanics on Rurutu. Table 3 compares the mean readings for Rurutu streams with those for streams and standing waters on Mangaia, Atiu, Mitiaro and Mauke in the Southern Cooks. Further work on the saturation status of Rurutu waters, to compare with those of the Southern Cooks (Stoddart et al 1985, figure 7) is in progress.

CONCLUSION

We have in this paper outlined the basis for a general theory of erosional development of makatea terrain in Polynesia. We believe that the forms so variably developed on different islands can be readily explained by a consideration of history, geometry and solutional processes, and that we can identify a continuum of forms ranging from low islands of modest relief to the dramatic cliffed terrains of islands like Mangaia.

Marshall was wrong in his diagnosis of Rurutu, and Hoffmeister was right. That the island attracted such controversy more than fifty years ago is perhaps an indication of the critical evidence it affords, most notably in the Paparai valley, of why topography can be so very variable on closely adjacent islands in the south Pacific.

ACKNOWLEDGEMENTS

Our work in Polynesia has been carried out from the start with the staunchest support of Marie-Helene Sachet and F. Raymond Fosberg. Marie-Hélène was with us on Rarotonga when we worked on Mangaia (with T. P. Scoffin) in 1983. We visited Tetiaroa Atoll with her and Dr Fosberg in 1985, and later we went on to Mauke, Mitiaro and Atiu (with C. D. Woodroffe). These studies will be published separately. It was on Tubuai, during our Australs expedition in 1986, that we learned of Marie-Hélène's death. We dedicate this paper to her memory. Fieldwork in the Austral Islands was supported by the Overseas Field Research Grants Board of the Royal Society of London.

Table 2. Water characteristics of streams on Rurutu

Sample number	Location/Stream[1]	pH	Conductivity[2] µ S cm^{-1}
1	Pte Toarutu	8.9	262.3
2	R. Tevaipa	7.2	451.3
3	R. Vaioivi	7.6	139.1
4	R. Aerepau	8.3	251.9
5	R. Teaoa	8.0	466.0
6	Paparai Valley	9.0	212.3
7	Paparai Valley	9.2	172.2
8	Paparai Valley	8.5	184.9
9	Paparai Valley	9.4	146.5
10	R. Topea[3]	8.5	1470.1
11	R. Turiarata	8.0	-
12	Vitaria	8.2	267.7
Mean[4]		8.4	255.4

1. Placenames taken from Rurutu Carte Touristique (Bureau des Affaires Communales, Moerai, 1977).
2. Field measurements corrected for cell constant and standardized to 25°C using tables of Golterman *et al* (1978).
3. Brackish: saltwater intrusion.
4. Excluding sample 10.

Table 3. General physical and chemical characteristics of drainage waters in the Southern Cook and Austral Islands

Island (date)	N	pH	Conductivity[1] $\mu S\ cm^{-1}$	Field temperature °C
Mangaia (2/83)	20	6.8±0.2 (6.4-7.3)	125.7±18.3 (100.7-166.7)	30.6±0.9 (31.8-29.4)
Atiu (6/85)	16	6.7±0.2	430.6±251.9 (139.5±797.3)	
Mitiaro (6/85)	12	7.3±0.7 (6.7-9.0)	24340.3±21154.5 (714.2-44143.9)	
Mauke (6/85)	12	6.4±0.3 (5.8-6.6)	211.3±98.5 (116.8-424.2)	
Rurutu (7/86)	11	8.4±0.7 (7.2-9.4)	255.4±110.6 (139.1-466.0)	

1. Field measurements corrected for cell constant and standardized for 25°C using tables of Golterman *et al* (1978).

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