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Dahllite and whitlockite from Amatuku islet, Tuvalu

PHOSPHATIC limestones and a related soil were described from collections made by the first Royal Society coral-reef-boring expedition to Funafuti in 1896 (Cooksey, 1896; David and Sweet, 1904, Judd, 1904; Sollas, 1904; cf. Cullis, 1904). Although there is some geographic uncertainty about the source of some of Judd's samples, the specimens came from three localities on Funafuti, the largest being on Amatuku.

Occurrence. Amatuku is a small (550 × 180 m) arcuate islet in the north of Funafuti atoll (lat: 8° 31′ S; long: 179° 12′ E). Apart from the phosphatic rocks, the entire islet consists of bioclastic Quaternary calcareous sediments and limestones. The main occurrence of phosphatic rock is 80 m from the westernmost tip of the islet. From here, Sollas (1904, p. 24–5) described phosphatic limestone forming a low cliff reaching almost two metres above sea level on the lagoon coast. This cliff is now eroded but phosphatic limestones are exposed beneath low tide and extend to the top of the islet's terrace with small residual phosbergs (cf. Stoddart and Scoffin, 1983) jutting out within a gravel-strewn beach. Above the intertidal zone a jumble of broken phosphatic blocks extend across the 20 m width of the island in a 25 m wide band. On the ocean coast the phosphatic horizon is less than half a metre thick and confined to the supratidal terrace with a thin, indurated phosphatic layer coating the storm wave platform. In addition to this main locality, small knobs of brown, phosphatic limestone outcrop throughout central and western Amatuku.

Petrography. The 3–4° WNW dip which Sollas recorded for the lagoon coast beds is that of phosphatic biocalcarenties and biocalcirudites forming the phosbergs. Texturally the rocks are grainstones with sorting being moderate to good within any one layer. In the rudites, rounded clasts commonly vary up to 12.5 cm but the main range is between 20 and 60 mm. Arenites are well rounded, medium to coarse sands in which granules consisting of entire tests of calcarinid and soritinid foraminifera are frequent (Fig. 1*a*). Fines are rare to absent.

In a typical, highly porous, fine biocalcirudite, the granule- and pebble-sized clasts are cemented by a thin (0.02–0.05 mm), microlaminated, botyroidal phosphatic crust which evenly coats grains and intraskeletal cavities (Figs 1*a*, *b*). At high magnifications the crust often appears as globular clusters coated in a reticulated web of ill-defined crystallites. In thin section the crust shows from five to fifteen layers of extremely fine-grained, translucent collophane, tinted pale yellow to brown, weakly anisotropic and with r.i. greater than balsam (Fig. 1*c*). Individual laminae forming the layers are about 0.005 mm thick and rarely show microfibrous texture. Bioclasts show no replacement by phosphate nor is there evidence of pre-existing carbonate cement(s) nor of replacement of such cement(s). The textural relationships of the Amatuku rocks conform to those of Stoddart and Scoffin's (1983, p. 386) Group I: 'Phosphates cementing unaltered carbonate grains.'

The colour of the cement ranges from tan to dark brown, the darkest colours occurring amongst sub-aerial samples. One rock from the intertidal zone was bright pink when first collected. Within twenty-four hours the dry specimen had

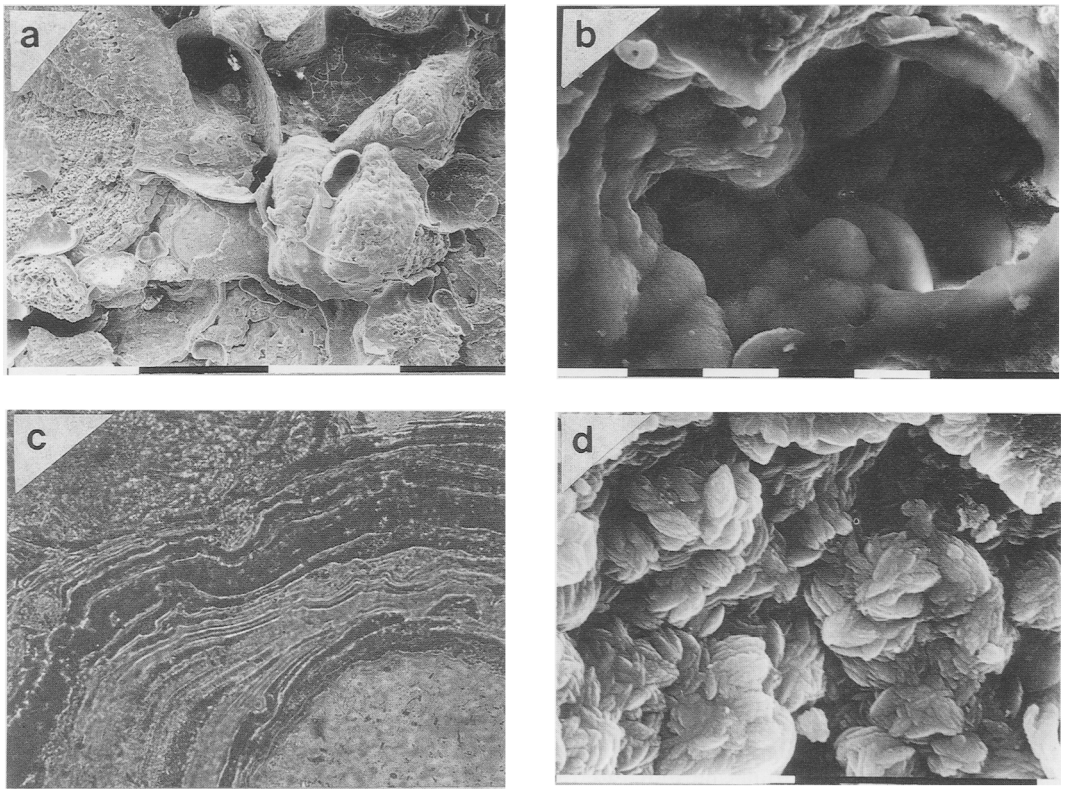

FIG. 1 (*a*). Phosphate cement 'coats round the pebbles as a thin layer formed of many concentric lamellae, and extends from them into the interstices in tubular processes and irregular minute nodules which form a lose spongy aggregate' (Sollas, 1904, p. 25). Scale bars 1 mm. (*b*) Botryoidal phosphate lining intraparticle cavity. Scale bars 10 μm. (*c*) Photomicrograph of thin section showing multiple concentric layers of fine grained collophane about algal clast. Plane polarised light. Base of photo 0.4 mm. (*d*) Drusy clusters of flattened rhombs of whitlockite growing poreward of dahllite cement crust. Scale bars 10 μm.

become orange, deepening to medium tan over the following week. This colouring is believed due to organic matter which Sollas (1904) reported as incorporated in the cement. No coloured metal ions were detected in any samples. In particular iron and manganese were absent.

In samples from below high tide the cement seldom fills pore spaces totally, but in those taken from above the tidal zone pores have become infilled with a silt of fine phosphate, carbonate, humus and animal droppings with outcrops often appearing somewhat indurated.

Mineralogy. Carbonate-free separates of the cement were obtained by controlled digestion of the limestone in 'acetate soup' (Lennart *et al.*, 1985). The X-ray powder diffraction pattern of this cement shows the signatures of carbonate-hydroxy apatite and/or whitlockite. An unambiguous interpretation of the apatite pattern is made difficult by the broad line width of most reflections, with some exhibiting ill-defined maximum intensities. Rodgers (1987) considered the dominant phosphate mineral of a single, unlocated sample from the Amatuku was probably dahllite and the essential characters of the apatite X-ray diffraction signatures of the present samples are of that species (cf. McConnell, 1973). Braithwaite (1968) regarded

TABLE 1. Spot microprobe partial analyses of phosphatic crustose cement, Amatuku

	1	2	3	4	5	6	7
CaO	47.62	48.76	50.53	47.28	49.38	47.77	49.50
P_2O_5	33.71	33.16	37.76	34.60	35.69	33.15	36.50
F	<0.10	<0.10	1.76	1.63	<0.10	<0.10	<0.10
Total	81.33	81.92	90.05	83.51	85.07	80.92	86.00

1,2 AU 39352; 3,4,5 AU 39353; 6,7 AU 37469

lack of definition of X-ray patterns of similar insular collophanes as resulting from low grain size and poor crystallinity. The effect may also arise from compositional variation amongst different generations of cement crystallites. While spot EDAX analyses for Ca, P and F showed a range of values (Table 1), in part this range reflects the varying amounts of organic mucilage intimately admixed with the cement and regarded as an integral part of the paragentic association. Only analysis 3 in Table 1 is close to that of a stoichiometric, reasonably pure, carbonate hydroxyapatite. Apart from traces of Na and Cl, no significant amounts of other elements were detected in the EDAX spectrum. It can be noted that in only two cases was fluorine in excess of 0.1%.

In most samples from above the tidal range whitlockite is present although always subordinate to dahllite. The mineral occurs as drusy clusters of flattened rhomb-shaped crystals growing porewards of the main crustose cement (Fig. 1*d*). For samples from within the intertidal zone and below, whitlockite is at best a minor component although identification of small amounts of this mineral in X-ray diffraction traces is made difficult by the diffuse nature of the apatite pattern.

No other minerals which have been recorded from comparable insular phosphate occurrences (e.g. Hutchinson, 1950; McConnell, 1950) have been identified at Amatuku. Notable in some subaerial samples were implanted spheres *c.* 30 μ dia, partly buried in the cement crust. Whether these were organic or inorganic could not be determined.

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Low-temperature, hydrothermal garnet associated with zeolites, from basalt lavas near Beith, Ayrshire

A WORKING quarry, at Loanhead (NS363557) within the Clyde Plateau Carboniferous lavas, is traversed by a tholeiitic Tertiary dyke some 25–30 m wide. Throughout the quarry the lavas