

Petrology of the phosphates on Tuvuca, F
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Thesis

THESIS



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PETROLOGY OF THE PHOSPHATES

ON TUVUCA, FIJI

A THESIS SUBMITTED TO THE GRADUATE DIVISION OF THE
UNIVERSITY OF HAWAII IN PARTIAL FULFILLMENT
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Abstract

Phosphatic pelletal packstones and grainstones were collected from Tuvuca, Fiji, an island in the northern section of the Lau Islands. The deposits occur within cavities and fractures in the limestone, which is Futuna Limestone of middle Miocene to possibly Pliocene age. The phosphate samples are younger than the limestone, and uranium-thorium age dating studies indicate that they are older than 300,000 years.

The phosphates occur as pisoliths and pebble clasts within the pelletal rock. The pisoliths (1 to 5 mm in diameter) have concentric layers of uneven thickness around nuclei of detrital volcanic fragments, phosphatized carbonate fragments, and phosphatic grains. Electron microprobe analyses indicated a composition of nearly pure apatite in the nuclei, and probably a combination of apatite and crandallite in the layers. Scanning electron microscope studies revealed small tabular apatite crystals and elongate crystals that may be either aragonite or crandallite crystals.

In Nakorovusa, the pisoliths occur in grainstones where the cement is a low-magnesian, coarse-grained bladed calcite, and in fossiliferous pelletal wackestones. Some of the wackestones are geopetal deposits that have a fine-grained phosphate- and manganese-rich layer on the surface. The fossils found within these samples were identified as terrestrial fresh water and arboreal species. The fossil assemblages, textures and compositions of the wackestones suggest that they were deposited in cavities or small

brackish-water pools and cemented in place. The grainstones are non-fossiliferous and have pisolitic layers intercalated with calcite layers. The calcite occurs as bladed crystals oriented perpendicular to the layer surface. The textures suggest a cave origin; phosphate-rich solutions dripping into the caves and forming splash cups and pools would precipitate pisoliths in the splash cups.

The other major deposit lies in Dranoitiri where the pisoliths cover the marshy valley floor and occur as packstones and grainstones on the limestone valley walls. The pisoliths are coated with bluish manganese oxides. Gastropod shells collected from the pisolitic soil on the valley floor were identified as adventive terrestrial species, brought to the island no more than a few hundred years ago. That they have manganese coatings indicates that the coating process occurs very rapidly and that the process is still active today.

Other phosphatic rock occurrences are minor; they are pelletal wackestones that occur on the limestone. By far the greatest volume of phosphatic material is phosphatic clay which floors some of the basins and valleys. The clays probably were formed by the phosphatization of clays by phosphate-rich solutions and by the weathering of phosphatic rocks. Volcanic rocks are additional but minor sources of phosphate.

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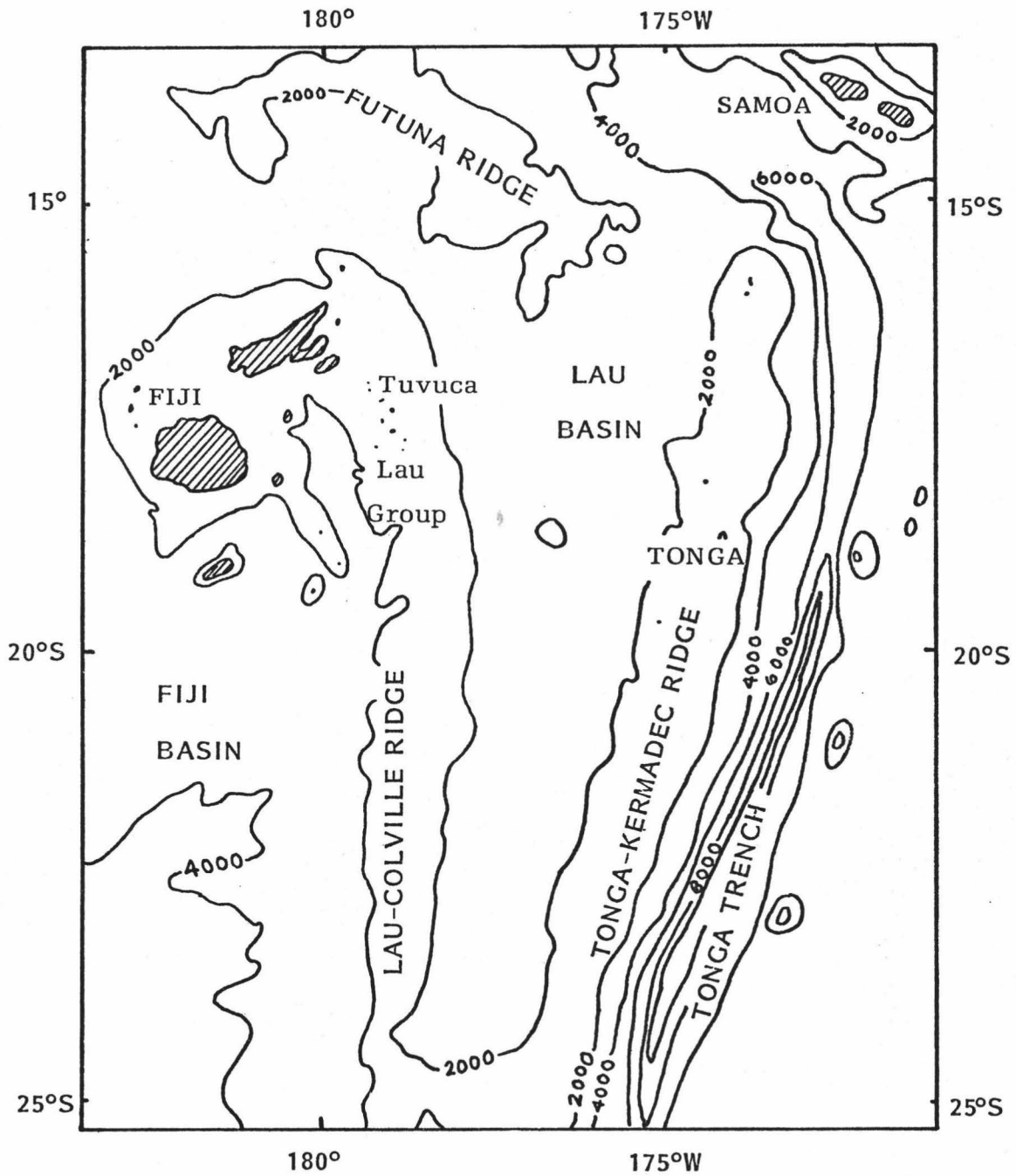
Introduction

The Lau Group is a north-south trending chain of islands that lies 230 km east of Viti Levu, the main island of Fiji (Fig. 1). The islands are the northern subaerial expression of the Lau-Colville Ridge. To the west lies the north end of the South Fiji Basin; to the east, the Lau-Havre Basin. Volcanism began during Miocene time and formed the volcanic edifices of all of the Lau Islands. The Futuna Limestone caps most of the islands and on some islands such as Vanua Vatu and Nayau, there are no exposed volcanics.

Six occurrences of phosphate deposits have been reported on islands in the Lau Group: Tuvuca, Vanua Vatu, Ogea Driki, Vatoa, Marabo, and Vatu Vara.¹ The greatest volume of deposits is on Tuvuca; resources are estimated at 1,837,000 metric tons of clay containing at least 4.5% P₂O₅ (Rodda, 1981). Minor occurrences of phosphate rock have also been reported but those deposits had not been studied previously.

Tuvuca lies in the northern portion of the Lau Group, accessible by chartered boats from the neighboring islands of Lakeba and Vanua Balavu. It is a volcanic island capped by limestone over most of its aerial extent. The volcanics crop out in the southern half of the interior basin as an isolated hill (Maumi) and at several areas along the coast. A series of limestone terraces rim the island. The

¹The names have been spelled using the Fijian alphabet. In the British spelling, "c" would be replaced with "th," "b" with "mb," "d" with "nd," "q" with "ngg," and "g" with "ng." Thus Tuvuca is also spelled as Tuvutha, Ogea Driki as Ongea Ndriki, and Marabo as Marambo, respectively.



contour interval : 1,000 meters (after Green, 1975)

Fig. 1. Location of Lau Islands in relation to regional tectonic features.

seaward edge of these terraces form steep cliffs that drop down into long, narrow valleys. In the interior, the limestone is weathered into a karst topography. The phosphatic clay fills some of the depressions and sinkholes in this terrain. Most of these areas are used as gardens by the Tuvuca islanders. The gardens are accessible by foot paths, though dense foliage obscures the trails to some of the more remote gardens. Phosphate rock is found mainly on the limestone walls in the valleys between terrace cliffs.

This thesis is a study of the phosphate rock occurrences on Tuvuca. A total of five weeks were spent in the field to collect samples of the various rock types on the island, and to examine the field relations of the phosphatic deposits. Transportation was by foot except for a few trips around the island by punt or canoe. The rugged topography added to the difficulty of visiting some of the localities. Though the valley behind Kaova was reported to have "little marbles" (no doubt these are phosphatic pisolites) in the soil, the area was too remote to inspect. For comparative purposes, a few days were spent on Vanua Vatu, an island 44 km southwest of Lakeba. Vanua Vatu is reported to contain 80,000 to 140,000 metric tons of phosphate of at least 30 percent P_2O_5 . Samples were collected from both Tuvuca and Vanua Vatu.

Understanding the petrology and geochemistry of the phosphate rocks will lead to a better understanding of why phosphate accumulated on the island. This thesis includes a petrographic study of the rock samples by examination in thin sections. Mineralogy was determined by X-ray diffraction patterns, and phosphatic pisoliths were viewed under

a scanning electron microscope to examine their structure and crystallinity. Electron microprobe analyses were used to identify the chemical compositions in the different parts of pisoliths. Whole rock geochemical analyses were done on selected phosphatic samples from Tuvuca and Vanua Vatu to compare them to other reported insular phosphate analyses. Information gained from these analyses is used to depict a scenario of how these deposits may have formed.

Previous Work

The first major report on the geology of the Lau Islands was by Ladd and Hoffmeister (1945) who visited the islands as part of a Bishop Museum scientific expedition in 1934. As a result of their studies they described the stratigraphic units listed in Table 1.

TABLE 1.--Stratigraphic relationships in the Lau Islands, as described by Ladd and Hoffmeister (1945)

Group	System	East Indian Stage	Formations
	Quaternary		Mango Odinite
			Fulanga Limestone
Cenozoic	Tertiary	h	Ndalithoni Limestone
		g	Koro Mbasanga Volcanics
			Futuna Limestone
		f	Lau Volcanics

The Lau Volcanics are mainly andesites whereas the Koro Mbasanga Volcanics are mainly olivine basalts. The Futuna Limestone is made up of two parts, a lower unit of bedded limestone made up largely of algae and foraminifera and an upper unit that is coralliferous. The Ndalithoni and Fulanga Limestones are coralline limestones. The type localities of the Tertiary rock units are on Vanua Balavu where the stratigraphic relationships between units are best exhibited.

The tectonics of this region have been studied but controversy still exists over the evolution of the two ridges and intervening basin. The Lau-Colville Ridge has been described as a remnant arc in the island arc system where the Tonga-Kermadec Ridge and the Lau Basin are the frontal arc and interarc basin, respectively (Karig, 1974; Gill, 1976). In this system, the Tonga-Kermadec Ridge is believed to have split from the Lau-Colville Ridge about 5 m.y. B.P., thus forming the intervening Lau Basin (Gill, 1976). Katz (1976) disagreed with this idea and noted that the direction of subsequent volcanism in the Tonga Ridge has been westward, away from the centers of Miocene volcanism. If the Tonga Ridge had been moving away from the Lau Ridge, volcanism should have migrated eastward. Instead, Katz proposed that the Lau Basin is a graben-like structure that downdropped when the Lau and Tonga Ridges were strongly uplifted by block faulting. This activity was likely to have occurred during late Miocene and mainly Plio-Pleistocene times. Further studies on the age and structure of the Lau Basin will help to resolve the relationship between the Lau and Tonga Ridges.

Ladd and Hoffmeister (1945) identified the rocks on Tuvuca as being Lau Volcanics and Futuna and Ndalithoni Limestones. The Ndalithoni Limestone identification was based on a sample collected from Dravuni. The sample contained well-preserved coralline fragments; three of the five species recognized were also found in the type section on Vanua Balavu. The other limestone samples collected from Tuvuca yielded few recognizable fossils because recrystallization obscured the structures and details necessary for identification. However, the rock types and physical stratigraphy suggested that they were Futuna Limestone.

Phosphate was not discovered on Tuvuca until 1958 when J.E. Staargaard of Aluminium Laboratories Ltd. tested the clay deposits for their aluminum content (Rodda, 1981). Although the aluminum contents looked promising, the phosphate content was too high to use the deposits for aluminum manufacture.

Encouraged by this discovery, W.C. White and O.N. Warin of the Australia Bureau of Mineral Resources visited the Lau Islands in 1959 to survey the phosphate deposits. They examined and described the deposits on Vanua Vatu, Tuvuca, Ogea Driki, and Vatoa, and in addition, discovered the small deposits on Vatu Vara and Marabo (White and Warin, 1964). White and Warin extensively traversed Tuvuca and hand-augered drill holes at Qilo, Tavaiwaro, and several other localities in the interior basin. They found the clay to be more than 10 meters thick in some places, and that below the clay was not limestone but weathered volcanic rock. Based on their results from the drill hole samples and their estimates of the volume of clay

deposits on the island, they reported resources to be 2 million tons of phosphatic clay averaging 9.4% P_2O_5 . Unfortunately, the iron and aluminum contents ($\%Fe_2O_3 + \%Al_2O_3 > 40\%$) are too high to utilize the deposits for superphosphate manufacture and thus the deposits were deemed unworkable.

Although the deposits are unsuitable for superphosphate manufacture, investigations have continued on their suitability as direct-application fertilizers. This continued interest prompted the Fiji Mineral Resources Department to conduct a detailed survey of the Tuvuca phosphates. Their report (Rodda, 1981) estimated reserves of 431,000 metric tons averaging 16.4% P_2O_5 , 1,193,000 metric tons averaging 8.8% P_2O_5 , and 213,000 metric tons averaging 4.5% P_2O_5 . The highest average phosphate contents were reported in Qilo (16.7%), Nakorovusa (16.2%), and Ratava (15.6%). The Nakorovusa samples contained phosphatic oolites, but no description of these accretionary grains were given in the report.

Field work during this study revealed the presence of phosphatic pisolites in rock units on the limestone walls in Nakorovusa, Dranoitiri, and other valleys and basins on the island. The discussions in this thesis are focussed on these occurrences as they are likely to be the parent material for some of the phosphatic clay, and their rock form is more suitable for a petrographic study of the phosphates.

Field Relations

Tuvuca is a pear-shaped island that trends northwest-southeast, the slimmer end pointing southeast (Fig. 2). It is 2.5 by 4.0 km in size, with an aerial extent of 12.5 sq km. The island is a volcanic edifice capped by a thick sequence of limestone. The limestone is very weathered and eroded into a karst topography with steep cliffs and numerous solution pits and basins (Fig. 3). Some basins are very large, notably Qilo and Tavaiwaro. These basins are enclosed by steep-sided walls that rise 30-40 meters above the basin floor. Three discontinuous sets of limestone cliffs concentrically rim the island; they are well-exhibited on the southwest portion of the island with the seaward cliffs being lower than the landward cliffs. Taylor (1978) used an altimeter to measure the heights of two of these sets and found them to be 60 m and 135 m. The third set of cliffs are approximately 190 m in height. The highest point on these limestone ramparts is Uluiatavu (>240 m) which is also the highest point on the island.

The cliffs are often referred to as terraces, but they are so heavily eroded that it is difficult to determine if they were formed at sea level or by solution (Taylor, 1978). The cliffs are essentially asymmetrical ridges with the landward sides sloping down to the clay-floored basins and the steep seaward sides descending to the next valley floor at a sharp angle. Their morphology does suggest that the steep seaward walls were formed due to rapid tectonic uplift of the island, the ridges representing still-stands during the uplift.

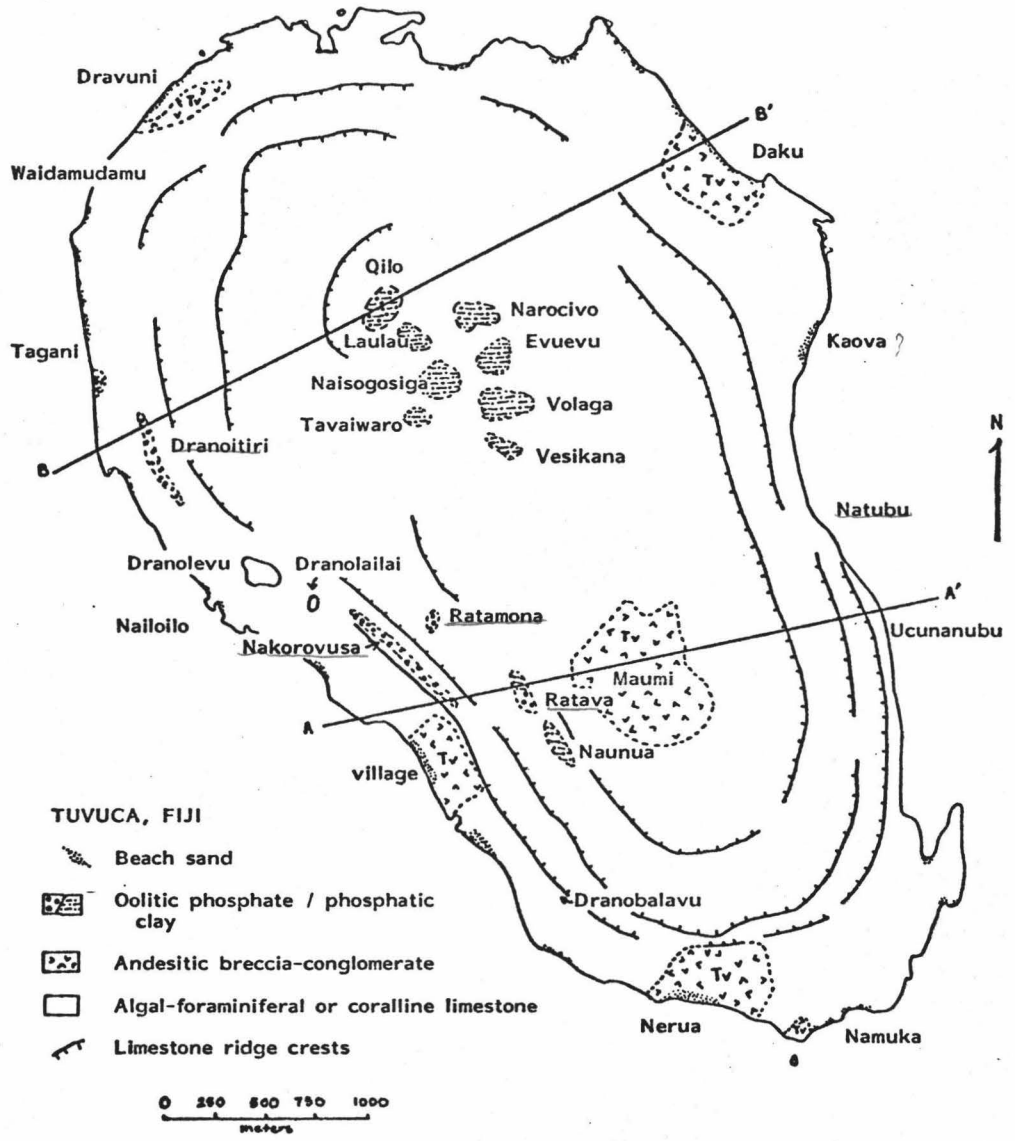
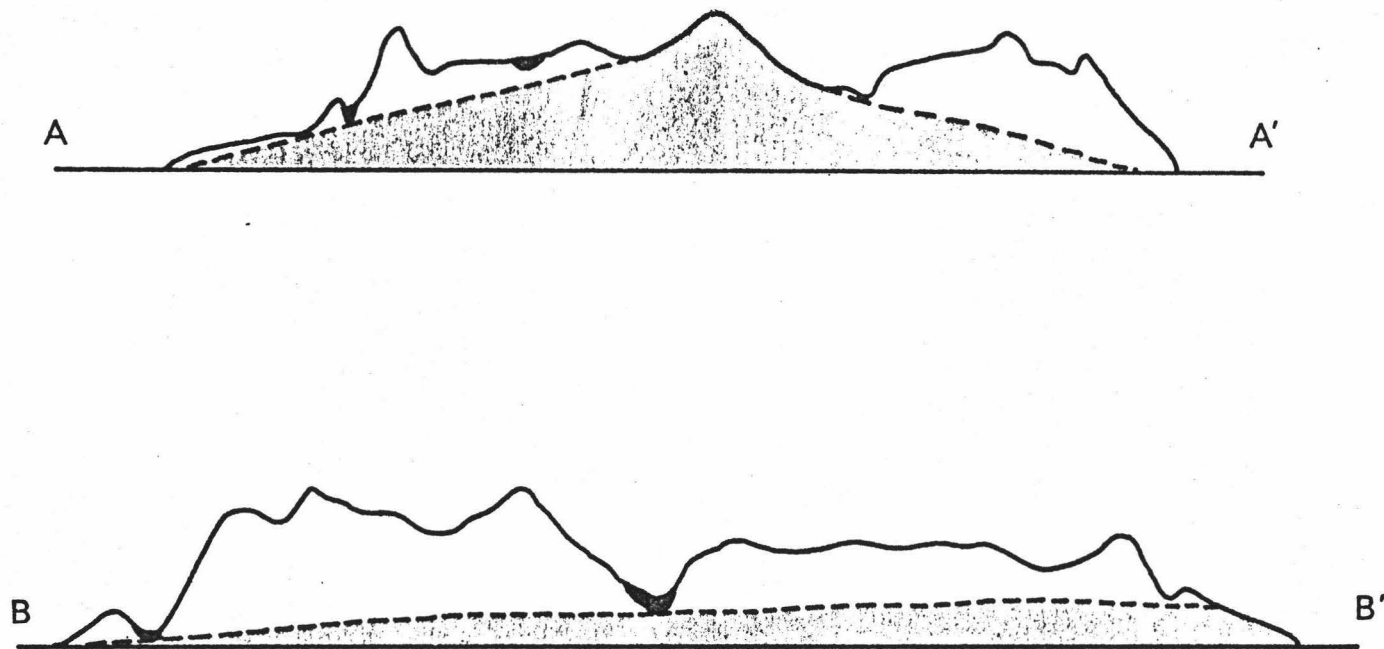


Fig. 2. Geologic map of Tuvuca



- PHOSPHATIC CLAY
- FUTUNA LIMESTONE
- ▨ LAU VOLCANICS
- - - INFERRED BOUNDARIES

VERTICAL EXAGGERATION : 3 X

Fig. 3. Cross-sections A-A' and B-B'

Along the coastline the limestone has a wave-cut nip one to three meters wide. At Natubu, the nip has undercut the limestone such that blocks have broken off the sea cliff and fallen down to the shoreline. Beach rock is present at Dravuni and Waidamudamu.

The limestone is covered with dense jungle growth and in this manner it contrasts sharply with the volcanics which are covered with grasses and low bushes. Most of the clay-floored basins have been cleared for gardens by the villagers and thus contain crops of bananas, kumalas, cassavas, and other food staples. Due to the moderate to high phosphate content in some of the basins, the villagers have been able to enjoy good crop yields from their gardens.

The volcanics, mainly andesitic breccia-conglomerates, crop out at seven places--Maumi where they form an isolated hill, Daku, Nerua, Namuka, Dravuni, Nukumatailelevu, and the village. At Maumi, volcanic boulders dot the gently-sloping grassy hillside. On the southeast slope, a few blocks of limestone overlie the volcanics indicating that this hill was at one time covered with limestone. From Naunua to Maumi, the change from a limestone to volcanic terrain is abrupt though no actual limestone-volcanics contact is visible. Rodda (1981) reports exposed contacts in three caves south of the hill, Soso and Qaraniyau at Soso, and Babau. These caves have eroded such that the floors are andesite but the roofs and walls are limestone.

Along the coast the various volcanic outcrops are indicated by the boulders strewn on the beach and the low grass and brush cover on the sloping terrain. At Namuka the volcanics are exposed in a sea cliff where the reddish-brown color of the lateritic soil cover stains

the cliff face. The outcrop at Nukumatailelevu is very small, being exposed in a large overhang. The floor and a third of the way up the walls of the overhang are volcanic but the remaining walls and ceiling are limestone. The contact between limestone and volcanics is a sharp, horizontal contact. The outcrop at Dravuni is well-exposed inland from the beach. Rodda (1981) describes the andesite as conglomeratic with boulders up to a meter across set in a tuffaceous matrix.

No volcanics crop out at the village but the cliff behind the village and the ridge to the south have exposures of andesitic conglomerate. The village itself sits on a sloping hillside of red clay. Near the stairway leading to Nakorovusa (Naisikasika), andesite is exposed at the base of the cliff. The basal limestone here is massive and appears to have abundant organic debris. South of Naisikasika, Rodda (1981) identified a steeply dipping fault that brings the andesite in near-vertical contact with the limestone cliff. The fault strikes north and dips to the east.

The carbonate rocks which overlie the volcanics are very thick, massive and recrystallized sequences of coralline or algal-foraminiferal limestones. The total thickness of the limestones is greater than 240 meters: they are exposed continually from sea level to Uluiatavu. The limestones have various colors including white, buff, pink, red, and gray. Replacement features are common: at Nailoilo, corals in growth position are replaced by brown ferruginous carbonate. Corals in Nakorovusa are replaced by large secondary

calcite crystals or by black finely crystalline pyrolusite. Notably though, no examples of phosphatized limestone were seen.

Contacts between the limestone and underlying volcanics are usually buried or eroded such that no actual rock-to-rock contact can be seen. The exception to this is the overhang at Waidamudamu mentioned above. The limestone just above the contact there is reddish-brown and friable. It has clasts and grains of volcanic material in its framework. At Dranobalavu, a ten-meter thick basal conglomerate unit is at the base of the east limestone wall. The volcanic clasts are up to two meters in diameter, well-rounded, and oriented parallel to the ground. Pelletal and fossiliferous limestones occur as discrete layers in the valley walls. They appear to be secondary deposits such as cavity fillings or cave deposits on the main limestone unit. The valley floor is covered with a black mud that becomes a marsh towards the south end of the valley. According to the villagers, the marsh dries up during the dry season but refills during the rainy season. At the time of the study (early March), the deepest point of the marsh was approximately one meter. The presence of the marsh and basal conglomerate suggests that the valley is floored by the andesite conglomerate.

A common structure found at the base of the limestone cliffs is an overhang or small cave. These were seen in Nakorovusa, Naunua, Ratava, Natubu, and Waidamudamu. Dripstone, cave popcorn, and pelletal limestones were found lining the cave floors and walls.

Limestone in the interior basin is wholly dolomitized. The dolomite content decreases away from the interior; at some coastline

areas the limestone is mainly low-magnesium calcite with minor dolomite fractions. Ferruginous carbonate deposits are common secondary deposits on the limestone pinnacles along the coast.

The phosphate rock deposits are pelletal packstones and pisolitic grainstones cemented with calcite (classification terminology by Dunham, 1962). Apatite is the main phosphate mineral; minor amounts of crandallite have also been recognized. The major deposits are located in Nakorovusa and Dranoitiri; smaller, less phosphatic deposits are present in Ratava and Ratamona. An important characteristic of phosphatic pisoliths and pellets is that, unlike the ferruginous pelletal carbonates found in the caves and underhangs, they maintain their form when they weather out of the rock. In Rodda's report (1981), he mentioned finding oolites in the clay samples from Nakorovusa. The villagers know of these deposits as "little marbles," and with their guidance, the deposits at Ratamona and Dranoitiri were found and examined. An additional site was mentioned--the valley behind Kaova--but this area was too remote to visit, and thus the reports could not be verified.

In Nakorovusa, the grainstones occur in seams and solution cavities in the limestone. Contacts between the phosphate and limestone are solution contacts; they are sharp and smooth. The richest deposit is a seam, approximately 15 to 20 cm thick and 4 m long, located in the west wall about 300 meters north of Naisikasika. The reddish-brown pisolites are cemented with a white, coarsely crystalline calcite. Although the pisolites are fairly resistant to erosion, the seam did not project out from the limestone because the

calcite cement eroded as much as did the surrounding limestone. Other seams and cavity fillings in the valley are dark brown or gray-brown due to the clay matrix of the deposits. The phosphate grains are sporadically set in these deposits, occurring as one of many other types of clasts in the rock. Some of the deposits are geopetal deposits that have definite layers in the rock: the base is fossiliferous (gastropod shells and other carbonate fragments), becoming more fine-grained upwards until the top layer which is bluish due to the higher manganese content. Though the deposits were dark brown in color, they often appeared blue in outcrop due to the manganese coating on the deposits. The coating is very thin, less than 2 mm, but fairly ubiquitous.

The north end of Nakorovusa slopes down to a small brackish-water pond (Dranolailai). This pond has water year-round and it is not known whether its water level varies with the oceanic tidal cycle. No phosphatic grains were seen near the pond. The clay-floored valley contains pisoliths near the pisolitic grainstone outcrops. Their occurrence in the soil decreases away from the outcrop area.

The valley floor of Dranoitiri is a marsh during the rainy season but dry during the dry season. From near Tagani on the coast up to Dranoitiri, pisoliths occur in the soil and increase in abundance towards Dranoitiri. The ground around the edge of the marsh is richly pisolitic, as are the bases of the limestone cliffs. Patches of pisolitic deposits occur on the limestone walls up to 10 meters above the valley floor. The deposits are grainstones, cemented with a carbonate mud. They are dark brown with a thin, blue manganiferous

coating. No fossils were seen in the rock samples, but freshwater snail shells were found in the pond sediments. The phosphate deposits fill cavities and fractures in the limestone.

The deposits in Ratava and Ratamona are very small in that only one outcrop was seen at each location. In Ratava, the outcrop lies in an overhang in the east wall. The phosphates occurred as pellets in a pelletal limestone on the floor of the overhang. The samples from Ratamona were collected from a deposit on the north wall.

By far, the great bulk of phosphatic material on Tuvuca is in the form of clay. The clay fills sinkholes such as Qilo and Tavaiwaro, ravines such as Nakorovusa, Ratava, and Naunua, and wide basins such as Laulau, Volaga, and Evuevu. The clay varies in color from a yellow-brown (generally found to have a high phosphate content) to reddish-brown. In most areas, limestone is presumed to underlie the clay, but in Qilo, Nakorovusa, and Naunua, auger drilling encountered weathered andesite in the bottom of the holes (Rodda, 1981).

An extensive survey of the phosphatic clay deposits on Tuvuca was conducted by Peter Rodda during 1975-76. The amount and grade of the phosphatic clay in areas he surveyed are listed in Table 2. In all, a total of about 2,050,000 metric tons of at least 4.5% P_2O_5 clay was proved by the survey.

Manganiferous clay was observed in Narocivo, Naunua, and Nakorovusa. Rodda (1981) also reports occurrences in Qilo and Qiloqisoi. The clay is black and powdery, and occurs in the soil or at the base of limestone valley walls.

TABLE 2
 AMOUNTS AND GRADES OF CLAY IN AREAS SURVEYED BY THE FIJI
 MINERAL RESOURCES DEPARTMENT (FROM RODDA, 1981)

Locality	Amount of clay* (in metric tons)	Average grades (in % P ₂ O ₅)
Qilo	299,000	16.7
Laulau	103,000	8.8
Naisogosiga	287,000	9.1
Tavaiwaro	88,000	8.0
Volaga and Volaga East	398,000	8.7
Evuevu	83,000	7.6
Vesikana	19,000	7.1
Nakorovusa (Northwest)	60,000	16.2
Nakorovusa (Southeast)	113,000	7.6
Ratava	72,000	15.6
Naunua	102,000	11.8
Narocivo	213,000	4.5

*Relative density of phosphatic clay assumed to be 2.0.

Stratigraphy and Age Correlation

The exposed volcanic material on Tuvuca is andesitic agglomerates of the Lau Volcanics. The Futuna Limestone which overlies the Lau

Volcanics is made up of two units. In contact with the volcanics is a basal conglomerate and tuffaceous limestone unit. The upper unit is a crystalline limestone. A younger limestone unit, the Ndalithoni Limestone, was reported to occur at Dravuni (Ladd and Hoffmeister, 1945) but was not noted in this study. Rodda (1981) suggests that the Ndalithoni Limestone is merely a facies of the Futuna Limestone and not a separate formation. The phosphate deposits occur on and within fractures and crevices in the limestone. The solution contacts between the phosphates and limestone suggests that the phosphates were deposited after the limestone was formed and subsequently subaerially exposed.

Ladd and Hoffmeister (1945) assigned an age of middle Miocene to the Lau Volcanics and Futuna Limestone. This designation was based on studies of the larger foraminifera and mollusks found in the Futuna Limestone. Though there have been doubts expressed about these age determinations (Gill, 1976; Gill and McDougall, 1973), the middle Miocene age (Tertiary f) was reconfirmed by Adams and others (1979) based on samples they collected from the type section of the Futuna Limestone on Vanua Balavu. The lower tuffaceous limestone unit yielded planktonic foraminifera that they identified as being of N13 and N14 age. They also identified Lepidocyclina (N.) martini (Schlumberger), L. (N.) ruttenei Van der Vlerk, and Cycloclypeus (K.) annulatus Martin. The upper crystalline unit yielded no fossils of restricted age and therefore its age is uncertain. It is possible that the upper unit is much younger than the lower unit. D. Woodhall (pers. comm., 1982), based on stratigraphic relationships observed in

the field, suggested that the upper part of the Futuna Limestone may be as young as Pliocene (Fig. 4). In this study, fossils seen in thin section in the limestone material were vaguely recognizable, but on the whole, too recrystallized and indistinct for age determinations.

The phosphatic mud deposits contain numerous arboreal and fresh-water gastropod shells and shell fragments. The shells are well-preserved and fairly intact. Some are aragonitic, particularly those collected in Nakorovusa. Since all genera recognized are known to exist since the Miocene but are still present today, an age could not be assigned to these deposits. It is possible that these mudstones are of Recent age though the phosphatic pellets and grains are much older.

Samples from Tuvuca (Nakorovusa and Dranoitiri) and Vanua Vatu were used in a uranium-thorium disequilibrium study conducted at the Florida State University by W.C. Burnett. In order that valid age determinations could be made from the results of the study, the following assumptions had to be made: 1) the uranium entered the phosphate mineral(s) at the time of formation, 2) the deposit was either initially free of ^{230}Th or formed with a constant initial $^{230}\text{Th}/^{232}\text{Th}$ activity ratio in all phases, 3) the deposit has remained a closed system with respect to uranium and thorium isotopes, and 4) the deposit was formed during a short period of time relative to the age to be measured (Roe and others, in prep.). Since the Vanua Vatu samples were from the same deposit (Maumi), an isochron plot was used to remove the influence of common ^{230}Th . An age of $111,000 \pm 15,000$ years was determined from the plot, an age that corresponds to a low

LADD & HOFFMEISTER, 1945		
QUATERNARY		MANGO ODINITE
		FULANGA LS.
TERTIARY	H	NDALITHONI LS.
	G	KORO MBASANGA VOLCANICS
		FUTUNA LIMESTONE
	F	LAU VOLCANICS

GILL, 1976	
PLEISTOCENE	MANGO OD. & NDALITHONI LS.
— 1.8 MY —	
PLIOCENE	KORO MBASANGA
— 5 MY —	FUTUNA LS.
LATE MIOCENE	LAU VOLCANICS
— 10.5 MY —	NOT
MIDDLE MIOCENE	EXPOSED

D. WOODHALL (PERS. COMM., 1982)	
PLEISTOCENE	MAGO/KABARA BASALT
— 1.8 MY —	UPLIFT & EROSION
PLIOCENE	KOROBASAGA VOLCANICS
— 5 MY —	
LATE MIOCENE	FUTUNA LIMESTONE GROUP
— 11 MY —	LAU VOLCANIC GROUP
MIDDLE MIOCENE	
EARLY MIOCENE	

Fig. 4. Stratigraphic relationships in the Lau Islands.

eustatic sea level stand (however, high stands occurred before and after this period and are well within the precision of the age measurement). The samples from Tuvuca lacked sufficient variation for a good correlation, but the trend of the plot suggests an age greater than 300,000 years.

Petrography

Volcanics

Two volcanic clasts were collected, one from Dranobalavu (ALT13), and one from Daku (ALT32). The Dranobalavu sample was taken from the northeastern end of the valley, from a tuffaceous limestone conglomerate believed to be the basal conglomerate unit of the Futuna Limestone. The sample is from a boulder that weathers brown. Fresh surfaces show gray groundmass with white feldspar and reddish brown pyroxene phenocrysts. The Daku sample was taken from a boulder on the beach that had weathered out of the conglomeratic unit exposed there. The sample is dark gray, with white feldspar and green pyroxene phenocrysts. The pyroxenes weather to a brown color. Amygdules occur throughout the sample and are filled with light green material.

Both samples are andesites that exhibit pilotaxitic texture. The composition of each rock was estimated by point counting (Table 3). X-ray diffraction was used to identify andesine as the plagioclase feldspar present in the samples. The feldspars are subhedral to

euohedral, have normal and oscillatory zoning, and have albite and pericline twinning (Plate I, Fig. 1). The crystals are 0.25 to 3 mm in size, have cleavages parallel to (001) and commonly are fractured. Some crystals have dusty inclusions and crystallites aligned along zone margins. Apatite microlites are common inclusions in the feldspars in ALT13; they are rare in ALT32. The apatites are clear, light green subhedral needles approximately 0.01 to 0.1 mm in length. Their orientations are random though some tend to be parallel to subparallel to twin planes or zone margins (Plate I, Fig. 2).

TABLE 3
MINERAL COMPOSITIONS OF TWO ANDESITE SAMPLES
(AS ESTIMATED BY POINT COUNTING)

	ALT13	ALT32
plagioclase feldspar	32.9%	29.1%
clinopyroxene	5.9	6.7
orthopyroxene	1.9	1.3
apatite	1.7	0.6
opaques	2.8	1.4
alteration products	- -	8.3
groundmass	54.8	52.6
TOTAL	100.0%	100.0%

The pyroxenes are subhedral to euohedral crystals with well-defined cleavage traces. They occur sparsely as single crystals or are clotted together with other phenocrysts (Plate I, Fig. 3). The

orthopyroxene is distinguished from the clinopyroxene by extinction angle. Simple twinning is rare in the clinopyroxene crystals and absent in the orthopyroxene crystals. Some of the plagioclase feldspars and pyroxenes have reaction rims and resorption edges. The reaction rims are within the crystals as well as in contact with the groundmass, indicating that equilibrium conditions varied during the crystallization history of the rocks. Weathering is more advanced in ALT32, where there is a greater development of amygdules and alteration of the pyroxenes to clay minerals. The alteration products appear as light green microlites that have high birefringence. The amygdules have a narrow rim of cryptocrystalline material, and a thick fringe of microlites directed toward the center of the pore spaces. Opaques are fine-grained and occur sparsely throughout the rock. They are probably magnetite or some type of spinel. The groundmass is made up of plagioclase feldspar microlites, greenish anhedral crystals (probably pyroxene), opaques, and other cryptocrystalline material.

The above-described volcanic rocks are a small sampling of the volcanic rocks on Tuvuca. Rodda (1981) conducted a more general survey of the volcanics on the island and described occurrences of other rock types such as hornblende andesite at Yandrano (Dranobalavu), and gabbro and tonalite at Namoturuarua. The geochemical analyses of some of his samples are listed in Table 4. Despite the different textures and mineral compositions, the chemical compositions are similar, which suggests that the rocks were derived from the same magma body.

TABLE 4.--Geochemical analyses of igneous rocks from Tuvuca (from
Rodda, 1981)

	C 2355	C 2361	C 2390A
SiO ₂	59.34	59.38	59.77
Al ₂ O ₃	17.91	17.60	16.16
Fe ₂ O ₃	4.76	3.09	5.49
FeO	1.75	3.84	2.52
MgO	1.68	2.25	1.71
CaO	5.99	6.21	6.35
Na ₂ O	4.04	3.99	4.01
K ₂ O	1.08	0.72	1.02
TiO ₂	1.03	1.16	0.83
P ₂ O ₅	0.27	0.27	0.24
MnO	0.15	0.20	0.21
LOI	1.58	1.29	1.85
Total	99.58	100.00	99.71
H ₂ O ⁻	1.00	0.52	0.36

C 2355 Pyroxene andesite; just north of Nukumatailelevu

C 2361 Glassy andesite; float piece from east side of ridge east of
village

C 2390A Calcic tonalite; clast from coast opposite Namoturuarua

Limestones

The limestones are predominantly algal-foraminiferal mudstones and wackestones (classification system by Dunham, 1962). Some coralline and algal boundstones are present and there are some limestones that are crystalline carbonate, being that their features are totally obscured by recrystallization. The limestones have been

extensively dolomitized which is characteristic of Tertiary limestones in Lau (Rodda, 1981). Although dolomitization appears to be greater in the interior of the island than at lower altitudes such as in Nakorovusa or along the coast, other factors such as porosity and the mineralogy of the limestone affect the extent to which dolomitization occurs.

Most of the limestones in the interior basins are algal-foraminiferal boundstones or mudstones. Some are crystalline carbonate that have minor amounts of algal fragments. The boundstones contain encrusting algae, disarticulated red algae, and foraminiferal fragments. Dolomite crystals occur within the algal cell spaces and foraminiferal chambers, as well as in the micritic mud matrix. Algal oncolites are prominent circular bodies in ALT60. Their nuclei are made up of algae or sponges. The original wall surfaces are defined by micritic envelopes, and the wall voids are now filled with dolomite crystals. The micrite which filled the sponge canals is partly replaced with dolomite. A coralline boundstone from Ratava has similar dolomite-calcite relationships except that it is the coral walls which are now dolomitic, as well as the micritic mud. The dolomite forms as clear rhombohedral crystals in random orientations. Some have dusty inclusions and some have schizohaline textures, indicating changing conditions during the dolomitization process.

The limestones are mud-supported or algal-bound. Cement textures were not observed, either because the crystals are cryptocrystalline and thus not observable or because dolomite crystals have obscured the original textures. Secondary calcite as anhedral crystals fill

fractures and large voids in the rocks. The algal and coralline boundstones are probably from the reef-wall facies (facies classification system by Schlanger, 1964), and the mudstones are probably from the lagoonal facies.

Limestones on the coast vary in their composition and degree of dolomitization. A sample collected from the limestone wall south of the beach at Kaova has abundant dolomite rhombs throughout the matrix. The rock is an algal mudstone (ALT86). Sample ALT84 from Ucunanubu has very little dolomite. The rock contains abundant red algal fragments, foraminifera, echinoid spines, and encrusting algae. Micritic envelopes demarcate previous bioclastics that are now dissolved away. The voids are filled with equant calcite. The cement is interlocking anhedral medium- to coarse-grained calcite. There is an outcrop of coralline limestone at Nailoilo where the coral calices have been replaced by iron-rich carbonates. The corals appear to be in growth position and in situ. The coral calices were filled with micrite, then the coral walls were dissolved and the voids filled with the ferruginous material. Just north of Nailoilo, a clastic packstone (ALT107) was collected from the base of the solution notch. Unlike the surrounding limestone, the packstone weathered into smooth surfaces. The sample resembles a stream or beach deposit that contains well-rounded volcanic pebbles, large shell fragments, and carbonate sand grains. X-ray diffraction analyses indicate the presence of calcite, dolomite, aragonite, and kutnahorite, a manganoan calcite (Fig. 5). [Chemical analyses were not done on this sample and so it was not confirmed if indeed the sample had substantial amounts

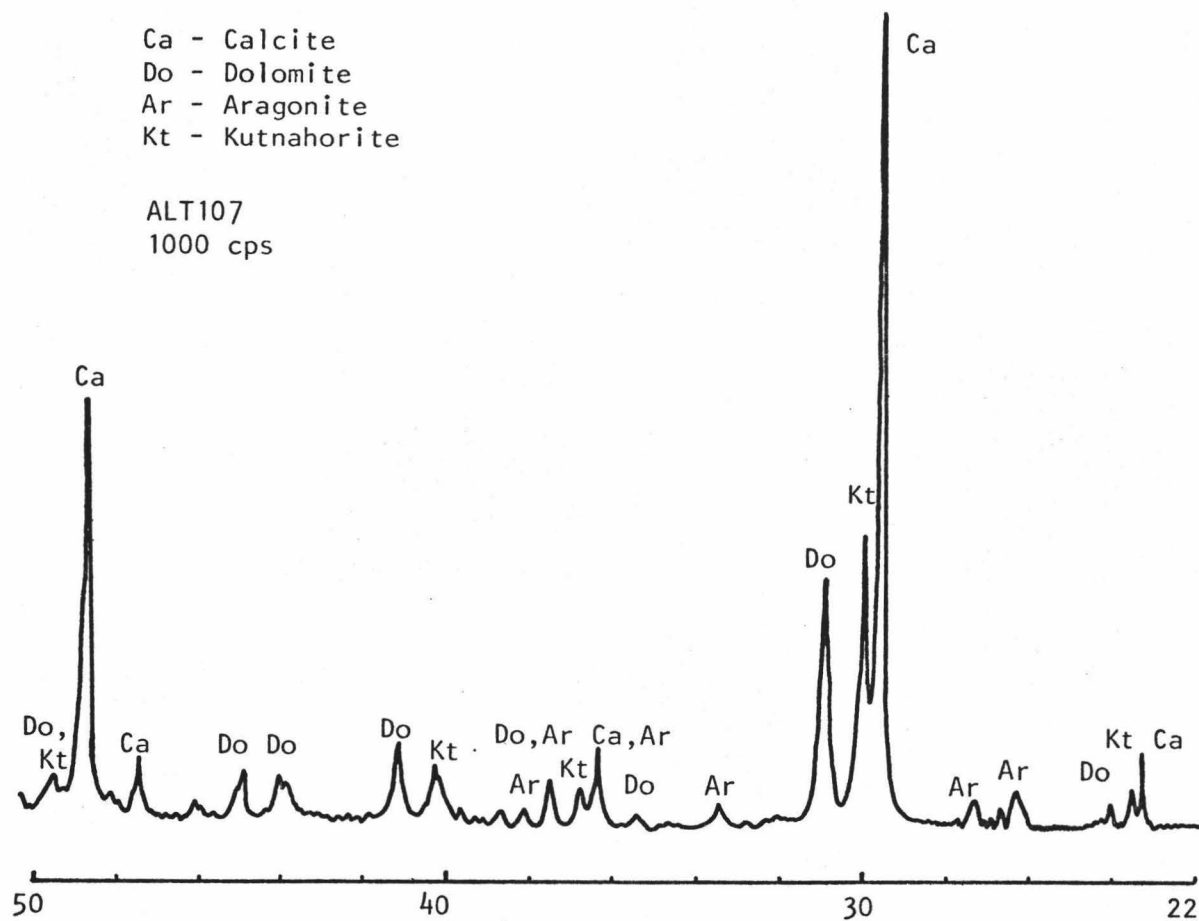
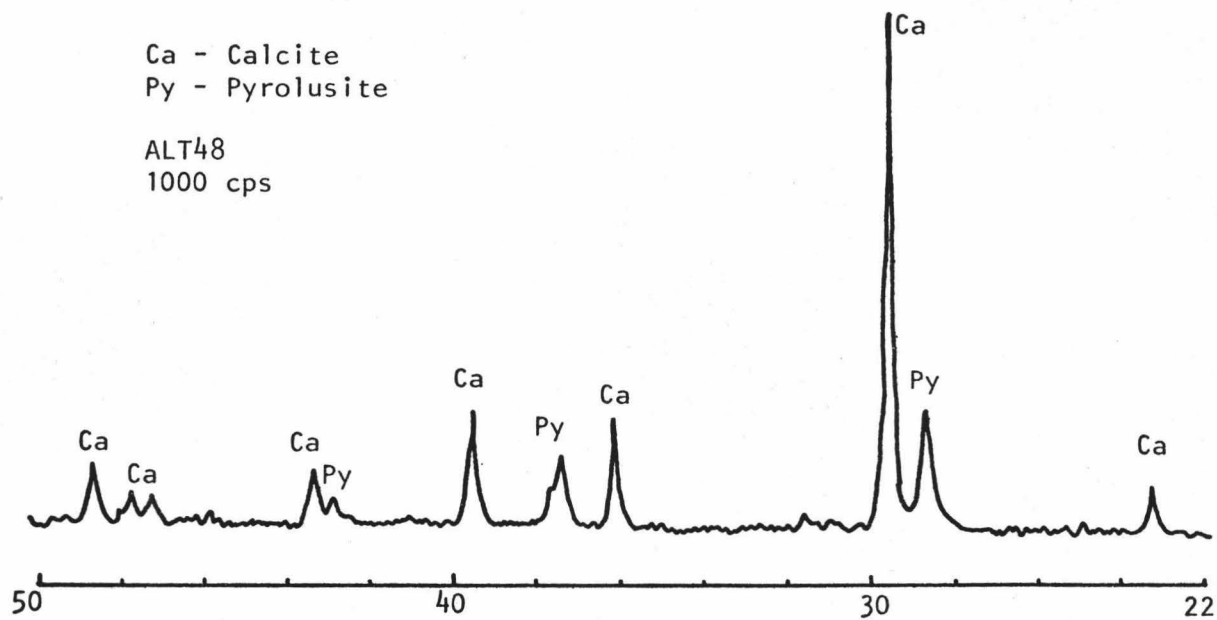


Fig. 5. X-ray diffraction pattern of sample ALT107.

Fig. 6. X-ray diffraction pattern of sample ALT48.



of manganese. The rock color does not indicate the presence of manganese. Jorgensen (1976) reports a similar diffraction pattern for recent beach sediments. He suggests that the mineral is not kutnahorite but an exceptionally magnesium-enriched magnesium calcite.]

Nakorovusa limestones are predominantly coralline limestones and are probably of the reef-wall facies. The coral walls are defined by micritic envelopes (except in one case where the internal chambers were defined by micritic envelopes, the coral walls themselves having been replaced by micrite). The internal chambers are filled with micritic mud that is partly recrystallized into sparry calcite. Dolomite rhombs occur sporadically throughout the micritic mud matrix. A striking outcrop of black coralline limestone occurs near Naisikasika. X-ray diffraction analyses indicate the presence of pyrolusite and calcite in the rock sample (Fig. 6). The pyrolusite replaced the coral walls and some micritic mud. The interior chambers are filled with dusty subhedral coarse-grained calcite and micrite. Micritic envelopes outline former wall surfaces. Dolomite crystals are present within the calcitic cement.

Chemical analyses of some Tuvuca limestone samples have been reported in Rodda, 1981 (Table 5). The analyses shows a similar dolomite relationship, that is, limestones from the interior of the island tend to have higher magnesium contents than limestones on or near the coast. This assumes that most if not all of the magnesium oxide is in the form of dolomite. The samples from Maumi have higher R_2O_3 (Fe + Al = R), SiO_2 , and P_2O_5 contents than the other limestones

TABLE 5
 CHEMICAL COMPOSITIONS OF SOME LIMESTONES FROM TUVUCA
 (FROM RODDA, 1981)

Sample no.	CaO	MgO	SiO ₂	R ₂ O ₃	P ₂ O ₅	LOI
C 1849	34.98	18.07	0.01	0.45	0.05	44.47
C 1851A	33.58	18.49	1.19	1.56	0.34	41.33
C 1851B	34.42	18.32	0.85	1.30	0.08	43.68
C 2119	54.76	0.41	0.01	0.24	0.002	42.36
C 2125	48.12	5.62	0.01	0.91	0.11	43.11
C 2132	43.09	11.36	0.02	0.24	0.09	43.32
C 2138	53.73	0.96	0.18	0.37	0.01	43.05
C 2325	36.90	15.44	0.08	0.60	0.04	45.22
C 2326	33.23	18.10	0.06	0.22	0.03	43.33

C 1849 from Baubau; C 1851A and 1851B from Maumi; C 2119 from northeast of the village; C 2125 from Tubalevu; C 2132 from Narocivo; C 2138 from Daku; C 2325 from Veinumu; and C 2326 from Vatoa.

in the table. This is probably due to the inclusion of volcanic material in the limestones at Maumi.

Another limestone type on Tuvuca is pelletal non-phosphatic wackestone that occur on the limestone bedrock. The wackestones occur on the walls in most of the basins and valleys, and in joints and fractures in the limestones on the coast. They are composed of mollusk shell, algal, bone?, and foraminiferal fragments, ferruginous pellets, and phosphatic pellets. The phosphatic pellets are 0.1 to 1.3 mm in diameter and are structureless. The ferruginous pellets (1 to 15 mm in diameter) have inclusions of algal and shell fragments as well as other unrecognizable grains. The pellets have vague

concentric structure, defined by grain orientations within the pellet. Some pellets have well-defined walls whereas others seem to dissipate into the micritic mud matrix or cement. Dolomite crystals are common within the pellets as well as in the matrix. Some pellets enclose the dolomite crystals and some dolomite crystals have grown around the pellets.

Several gastropod shells were found intact within the mud matrices and were removed for identification. Omphalotropis sp. was recovered from sample ALT18 from Ratava, and Taheitia sp. was recovered from sample ALT92 from Ratamona (identifications by C.C. Christensen, pers. comm., 1982). Both species are terrestrial; Omphalotropis is a leaf-and-mould dweller.

Sample (ALT15) from Dranobalavu is an extremely fossiliferous pelletal packstone. The fossils are coated with ferruginous material and though recrystallized to low-Mg calcite, the wall structures are well preserved. Gastropods were identified as Sturanyella cf. tectiformis, Gonatorhaphe sp., Omphalotropis sp., Endodontidae (sharp periphery), Taheitia? (large cylindrical snail), and Diplommatinidae or Achatinellidae? (small cylindrical snail) (identifications made by C.C. Christensen, pers. comm., 1982). These fossils are all terrestrial species.

In samples from Tavaiwaro, Ratamona, and Qilo, volcanic fragments are also enclosed within pellets. These fragments are recognized by their lower birefringence and apatite inclusions. Spherulitic needles were also observed in the samples from Tavaiwaro and Ratamona. These

spherulitic bundles may be siliceous material that crystallized within the pelletal limestone.

The cement textures in the pelletal limestones varies from outcrop to outcrop. In samples from Tavaiwaro, cryptocrystalline calcite around the pellets coarsen into blocky calcite toward pore spaces. This suggests that cementation occurred in the freshwater phreatic zone (Longman, 1980). Samples from Ratamona have micritic rims that become more coarse-grained toward pore spaces. Some elongate needles similar to aragonite needles were observed oriented away from the pellets toward the pore spaces. This cement may have formed in the marine phreatic zone (Longman, 1980). It is more likely though that the cement formed in the freshwater phreatic zone (Halley, 1979). Sample ALT18 from Ratava has pendant and meniscus cements, and spherulitic calcite bundles (flower spar, as described by James, 1972). These textures may indicate cementation in the vadose zone (Assereto and Folk, 1980; James, 1972). Sample ALT15 from Dranobalavu also has textures that indicate a vadose zone environment for cementation.

These pelletal deposits may have formed in a shallow, quiet-water lagoon or as vadose deposits on the limestone. Dunham (1969) suggests that these textures and composition are characteristics of oversized marine ooliths that formed in a lagoon. James (1972) describes caliche that formed on Pleistocene reefs in Barbados that seem similar to the pelletal deposits on Tuvuca. In light of the terrestrial fossils, flower spar, and pellet structures, this vadose origin seems more likely than a marine origin. The brownish color of the

ferruginous pellets is probably insoluble residue of brown amorphous pigment containing iron (Read, 1976).

Phosphatic Deposits

Phosphatic rocks occur in Nakorovusa and Dranoitiri, and less phosphatic rocks occur in Ratava, Ratamona, and Tavaiwaro.

Substantial phosphatic clay deposits occur in Qilo, Tavaiwaro, Ratava, Nakorovusa, and other basins (Fig. 2). The following discussion focusses mainly on the phosphatic rocks though phosphatic clays are discussed briefly. The classification scheme used for the rocks is by Dunham (1962).

Mineralogy.--X-ray diffraction studies indicated the presence of apatite, calcite, dolomite, and a crandallite-like mineral (Fig. 7). The apatite has a low carbonate content and PIXE (Proton Induced X-Ray Emmissions) analyses by W.C. Burnett (pers. comm., 1981) indicate a low fluorine content. The apatite is probably better termed dahlite. The calcite is low-magnesian calcite (less than 5 molar percent magnesium). The pattern for the crandallite-like mineral did not match the reported peaks for crandallite. Similar patterns were obtained from pisolith samples from Vanua Vatu and Vatoa.

Crandallite is one of seven minerals in the plumbogummite group. Minerals in the group are isostructural, with the simple cations held in large open sites with twelve-fold coordination (the minerals have hexagonal symmetry). Thus crandallite can pick up a wide variety of cations in its structure. The diffraction pattern more closely corresponds to waylandite, another plumbogummite group mineral, but no

C - Calcite
 A - Apatite
 Cr - Crandallite
 K - Kutnahorite?

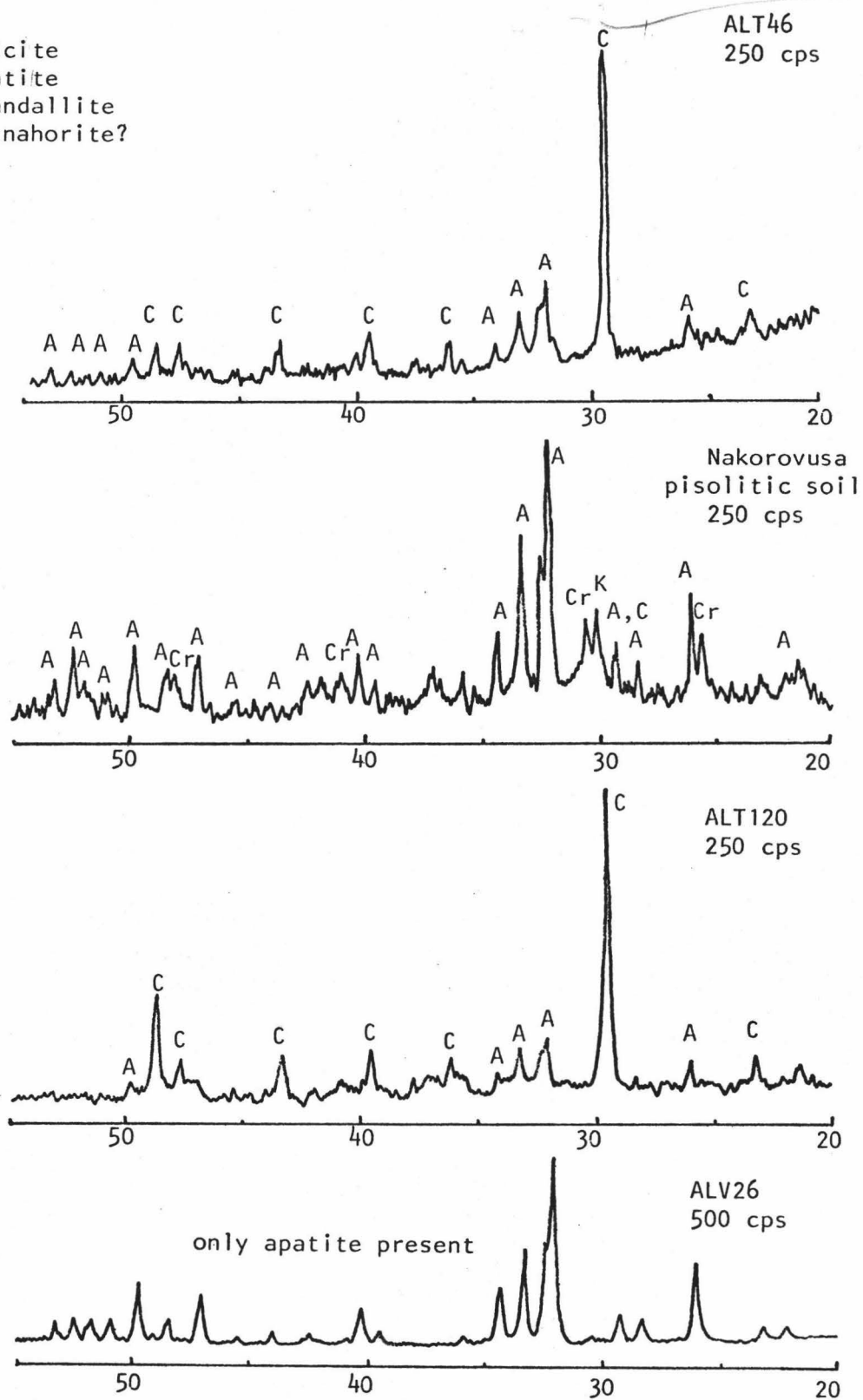


Fig. 7. X-ray diffraction patterns of phosphatic samples

bismuth is present in the samples to make this mineral. In light of the relative ease for substitutions of the large cations in these minerals, it is possible that the mineral present is crandallite, but that substitutions by iron, magnesium or manganese ions have distorted the structure such that the crystal dimensions are more like waylandite.

Rock descriptions.--The Nakorovusa and Dranoitiri deposits are mainly pisolitic grainstones and wackestones cemented with low-magnesian calcite. The textures, fabrics and cements of the rocks vary from outcrop to outcrop; the deposits are not continuous but rather are small localized deposits on and within the limestone walls. The colors of these deposits vary from brown to blue-black. The blue-black color reflects the high manganese content of the rock surface.

Most of the deposits in Nakorovusa are composed of phosphatic pisoliths, ferruginous pellets, and ferruginous oxides-coated bioclastics in a dark brown mud matrix. The rocks are cemented by finely crystalline calcite. Some outcrops are ungraded and sorting is mixed--there are pellets of nearly uniform size (1 to 3 mm), fossil shells whose sizes are biologically controlled (3 to 1.3 mm), and phosphate pebble clasts and carbonate fragments (up to 1.7 mm in diameter). The fossil shells are fairly intact, and a few have retained some of their original color markings. Bedding planes are suggested by coarse and fine pellet layers, and preferred orientations of fossil shells. The geopetal deposits have large fossil shells (3 to 10 mm) in the lower layers in the rock intermixed with ferruginous

and phosphatic pellets, and grade upward to finer-grained pelletal layers (In ALT77, this cycle repeats once.). The final layer is a manganiferous mudstone. The rocks have bedding, defined by layers of pelletal and bioclastic material alternating with fine-grained carbonate mudstone. In one sample (ALT65) (Plate II, Fig. 1), the layers are thin laminations of light and dark carbonates. These laminations may represent alternating wet and dry periods where the dark laminations represent the dry periods.

The fossil shells associated with the pelletal deposits are terrestrial, found near fresh or brackish-water areas. The species are listed in Table 6 (see also Plate III, Figs. 1-5). The fossils are unnamed species, a common situation for terrestrial fauna since species diversity is high and terrestrial mollusks in general have not been well-studied. The genera range in age from early Miocene to late Pleistocene or Recent so the fossils are not useful for age determination.

Endodontids, helicinids, and Sturanyella are arboreal species, while zonitids and Omphalotropis are leaf-and-mould dwellers (Baker, 1938; Solem, 1976; Solem, 1978). Although endodontids have been found in assemblages of shallow-water marine mollusks (presumably the endodont was transported from a forest environment and deposited on the beach or in the lagoon) (Ladd, 1958), the land snail assemblages in the Nakorovusa samples suggest that the environment was terrestrial, and that the depositional environment was a brackish-water pond. In addition, the shells are unabraded and aragonitic. Their good preservation suggests that they were deposited and then cemented in place.

TABLE 6.--Species names of gastropod fossils from Nakorovusa
(identifications by C.C. Christensen of the B.P. Bishop Museum in
Honolulu, Hawaii, 1982)

Sample ALT5

?Omphalotropis sp. (Assimineidae); Sturanyella cf. tectiformis;
Endodontidae (medium size, sharp periphery)

Sample ALT6

Diplommatinidae or Achatinellidae? (minute tall snail);
Omphalotropis sp.; Endodontidae (rounded periphery); Trochomorpha
cf. corallina (Zonitidae)

Sample ALT7

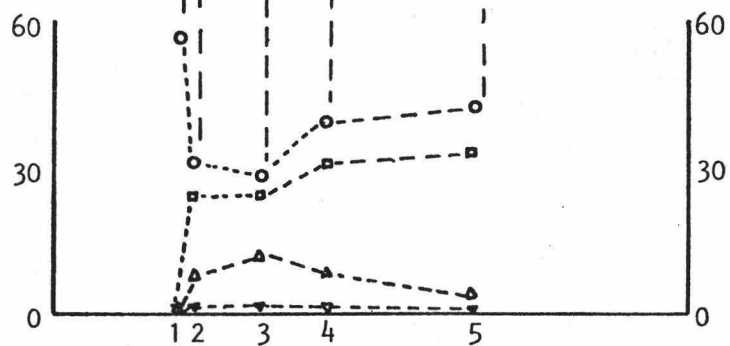
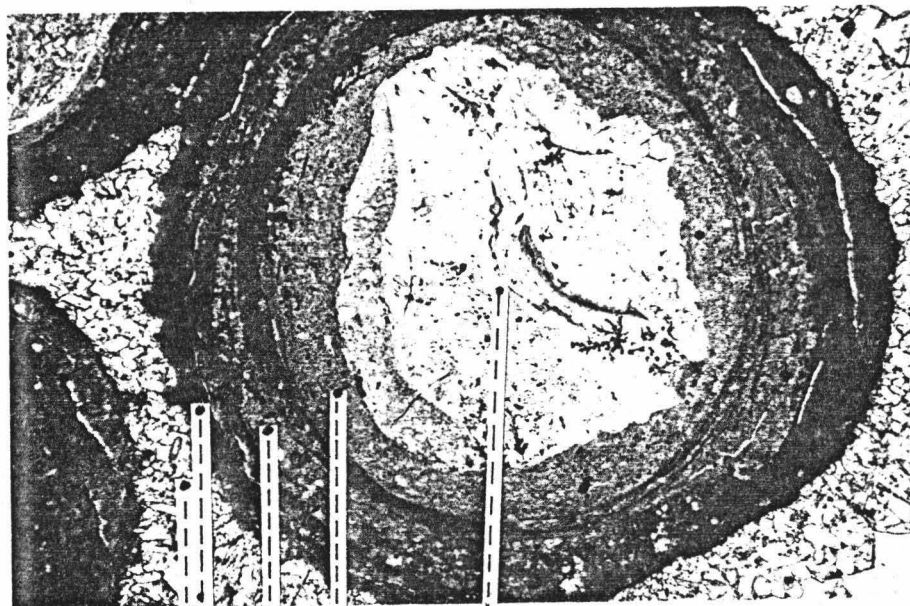
Sturanyella cf. tectiformis; Helicinidae (rounded periphery--not
Sturanyella); Omphalotropis spp.; Gonatorhaphe sp. (Poteriidae);
Taheitia sp. (Truncatellidae)

One particular outcrop on the west wall of Nakorovusa, approximately midway from Naisikasika to Dranolailai, is richly phosphatic. The rock is a pisolitic grainstone. The pisoliths weather out from the carbonate cement and eventually fall out of the rock. When weathered, they vary in color from red-brown to gray to light brown to white (carbonate coated). Cross-sections through the rock reveal the dark brown to red-brown color of the pisolith layers. The pisoliths are intermixed with phosphatic and carbonate pebbles. The clasts have no bedding directions although thick (4 to 10 mm) layers of coarsely crystalline calcite are intercalated with the pisoliths (Plate II, Fig. 2 and 3). The calcite layers do not continue through the seam; they are irregular blankets over the pisoliths. The calcite crystals grow perpendicular to the surface of the layers. The top surfaces of the layers are thin brown layers of

the same color as the pisolith coatings. In some places, pisoliths are included in the calcite layers.

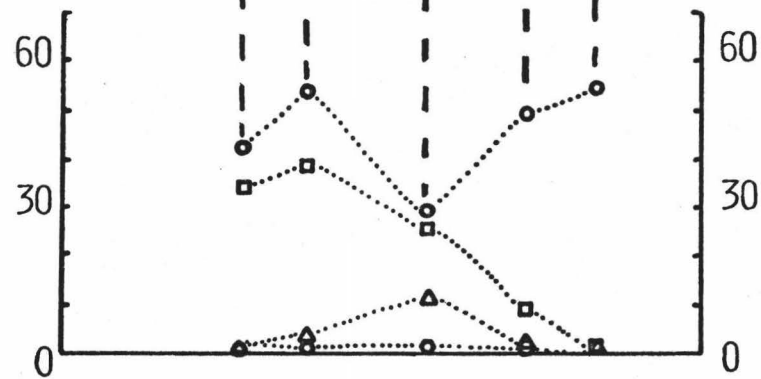
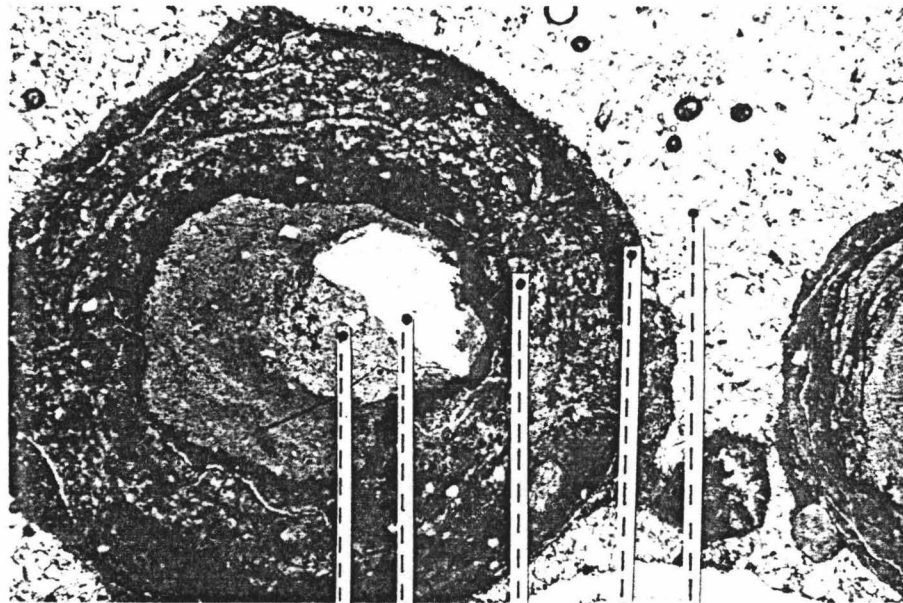
The contact surfaces between the grainstone and limestone walls is a thick (5 to 6 mm), coarsely crystalline calcite layer. In some places, a yellowish-brown mudstone overlies this layer. The mudstone includes small phosphatic pellets and other detrital grains.

The pisoliths have good concentric banding and vary in size from 1.2 to 5 mm in diameter. Most have good sphericity but some are elongate or ovule-shaped, depending on the shape of their nuclei (Plate II, Fig. 4). The nuclei are phosphatized shell fragments, lithic fragments, and other detrital grains. That the nuclei are no longer carbonate but are now phosphate was confirmed by electron microprobe analysis. Figures 8 and 9 illustrate the pisoliths that were analyzed and the results of those analyses. An apatite standard was also analyzed for comparison. The composition of the colorless nuclei correlates well with apatite and suggests that the nuclei are almost pure apatite. In the colored concentric layers about the nuclei, the phosphate and carbonate fractions decrease and the aluminum fraction increases. The phosphate:calcium ratio is much higher than is needed for apatite, and it was suggested that crandallite may be the other phosphate mineral present in the layers (W.C. Burnett, pers. comm.). In thin section, some layers appear to be altered to a mineral that forms aggregates and has a birefringence of .025 to .035. The birefringence is too high to be crandallite, and instead, this may be wavellite or pseudowavellite(?).



- CaO, in weight percent
- P₂O₅, in weight percent
- △ Al₂O₃, in weight percent
- ▽ F, in weight percent

Fig. 8. Microprobe analysis of pisolith (ALT71b) (analyses conducted at the U.S. Geological Survey in Denver, Colorado, 1982).



- CaO, in weight percent
- P₂O₅, in weight percent
- △ Al₂O₅, in weight percent
- ◇ F, in weight percent

Fig. 9. Microprobe analysis of pisolith (ALT71a) (analyses conducted at the U.S. Geological Survey in Denver, Colorado, 1982).

In some nuclei, solution cavities or void spaces are filled with elongate crystals that have low birefringence. The crystals have square terminations and hexagonal habits (Plate IV, Figs. 1 and 2). The crystals are possibly apatite that formed during a phosphatization period. Most pisoliths have two or three concentric layers but some have up to six layers. The yellow-brown color of the layers partially stain some nuclei. The outer surface of the pisoliths are abraded and the reddish-brown color of the pisoliths suggests that the pisoliths were subaerially exposed or in well-oxygenated waters to oxidize the iron pigments.

Like the thick calcite "blanket" layers, the cement is coarsely crystalline, elongate prismatic and bladed calcite. The crystals are oriented perpendicular to the pisoliths surfaces (Plate IV, Fig. 3). They have a hexagonal habit and exhibit growth rings (Plate IV, Fig. 4). Some of the pisoliths have been fractured and cemented by the calcite. The fracturing was probably enhanced by the calcite cement formation.

Though only one outcrop was observed during this field study, there must have been at some time many more similar outcrops that have since weathered and released their pisoliths to the valley floor. There is a high concentration of pisoliths in the soil near the pisolite outcrop, and the occurrences extend over 50 meters away from the outcrop locality. The phosphatic pellets and pisoids included in the other phosphatic deposits in Nakorovusa probably formed in the same environment as the pisoliths in the grainstone, but their environment of deposition is different. Perhaps the pisoids and

pellets were derived from the weathering of grainstone deposits similar to the one described above.

The Dranoitiri deposits are manganiferous pisolitic grainstones, packstones, and wackestones cemented with low-Mg calcite. The manganese-rich coatings cover phosphatic pellets and ooliths (Plate V, Fig. 1), and carbonate detrital fragments. The weathered surface is a blue color due to the manganese oxides. Fresh surfaces of the coatings are brownish-black; the phosphatic grains are orange-brown and the carbonate fragments are white or pink in color. The deposits have a layered fabric, defined by varying proportions of cement versus pellets. The layers are moderately sorted, with a fining upwards trend. Large pore spaces are lined with crystalline calcite.

The pisoliths have concentric layers. Some layers are alternately phosphatic and manganoan. The layers are of uneven thickness, tending to round off elongate and irregularly shaped nuclei. Cement textures vary throughout the rock. Some areas have clear coarse-grained calcite cement. The calcite have high concentrations of dusty inclusions around the pisoliths, suggesting that this is neomorphosed micritic cement. Fine-grained calcite rims around pisoliths are of uneven thickness. Some pore spaces have calcitic needles oriented towards the center of the pore. The variety of cement textures and types suggests cementation in the fresh water phreatic zone.

Gastropod shells were found in pisolitic soil samples from the valley floor. Some have a thin manganese-rich coating that adheres

well to the shell. Others have a clay coating that is easily removed by gentle scraping. The subfossils have been tentatively identified as Pseudopeas tuckeri and Thiara (Melanoides) tuberculata (Plate III, Figs. 6 and 7) (C.C. Christensen, pers. comm., 1982). P. tuckeri is an adventive species, that is, it was introduced to the island by man. The snail probably came to the island on the roots of taro plants or other food crops. Both snail types are found in brackish-water or fresh water habitats. Their presence in the soil demonstrates that the process of adding manganese-rich coatings on detritus in the marsh is still active, and that the process can occur during a short period of time.

In a further study of the pisolith structures, several pisoliths from Nakorovusa and Dranoitiri were examined under a scanning electron microscope. The apatite crystals showed up as tabular and stubby crystals, .1 to .2 microns in size (Plate V, Fig. 2). These crystals are ubiquitous in the nuclei and layers. Elongate crystals were seen in fractures and bore holes (Plate V, Figs. 3 and 4). These may have been aragonite needles that have since been replaced by low-Mg calcite or crandallite needles. (The needles did not resemble the elongate crystals mentioned earlier as apatite void fillings. They did not have a distinct hexagonal habit.) Dranoitiri pisoliths contain platy material on the outer surface of the pisoliths as well as within the concentric layers (Plate VI, Figs. 1 and 2). This material is probably manganese oxides. One pisolith in a Nakorovusa sample (ALT7) had a layer of particularly well-formed hexagonal calcite crystals (Plate VI, Figs. 3 and 4). The crystals are oriented tangential to

the pisolith surface and appear to have formed as a distinct layer around the pisolith.

In all the examinations under the scanning electron microscope, no examples were seen of phosphate minerals as pseudomorphs of other minerals to suggest replacement textures. The apatite crystals appeared as aggregates and seemed to have primary textures.

Other phosphatic deposits on the island are phosphatic deposits in the sense that they contain phosphatic pellets. But the percentage of phosphate is less than five percent and so, they are discussed in the limestone section as pelletal wackestones. More significant in their phosphate content are the phosphatic clays that fill the interior basins. Table 7 lists the phosphate, iron and aluminum oxides compositions of some clay samples.

TABLE 7.--Phosphate, iron and aluminum oxides compositions of selected clay samples from Tuvuca (from Rodda, 1981)

Locality	Sample no.	% P ₂ O ₅	% Fe ₂ O ₃	% Al ₂ O ₃
Qilo	50.5/20-1	20.01	12.58	29.48
Qilo	50/20-A	22.18	10.87	27.59
Qilo	50/20-F	15.85	15.33	31.06
Qilo	50/20-K	10.52	14.30	35.18
Narocivo ^a	47/22.5-1	1.70	7.78	11.56
Volaga	43.5/21-2	12.01	18.01	32.50
Beraseukai	42.5/22.5-2	6.34	19.87	41.57
Nakorovusa	N10-6	1.53	38.60	13.79
Nakorovusa ^b	N13-3	27.01	11.15	11.34
Ratava	R3-4	15.88	20.30	33.07

^aThis sample contains 61.7% MnO₂.

^bThis sample contains phosphatic oolites.

An earlier study by Staargaard (1962) indicated an average titanium oxide (TiO_2) content of 1.5 percent. Silica (SiO_2) contents averaged less than 10 percent. X-ray diffraction studies by Staargaard indicated the presence of crandallite or pseudowavellite, with accessory goethite and possibly hematite. X-ray diffraction analyses in this study indicated the presence of apatite and a crandallite-like mineral in a Nakorovusa soil sample. Crandallite is commonly recognized as a weathering product of phosphatic material (Altschuler, 1973; Lucas and others, 1980).

Over twenty basins were augered during Rodda's survey but only Qilo results showed any variation of phosphate content with depth (Rodda, 1981). The upper 2 meters averaged 21.9% P_2O_5 , the next 4 meters averaged 17.6% P_2O_5 , and the next 6 meters averaged 11% P_2O_5 (Fig. 10). No explanation is given for this layering. Perhaps successively richer phosphatic deposits were being weathered and added to the basin, resulting in the layering observed.

Geochemistry.--Various methods were used to analyse the chemical composition of the phosphatic rocks. In the field, a simple kit of ammonium molybdate solution and standards was used to test for phosphate content (method described by Shapiro, 1952). Of those samples that were phosphatic but indicated contents of less than five percent phosphate, several were chosen for a semiquantitative emission spectrographic analysis. The results are reported in Table 8. All analyses are whole rock analyses with the exception of ALT65 (only the blue layer was analyzed).

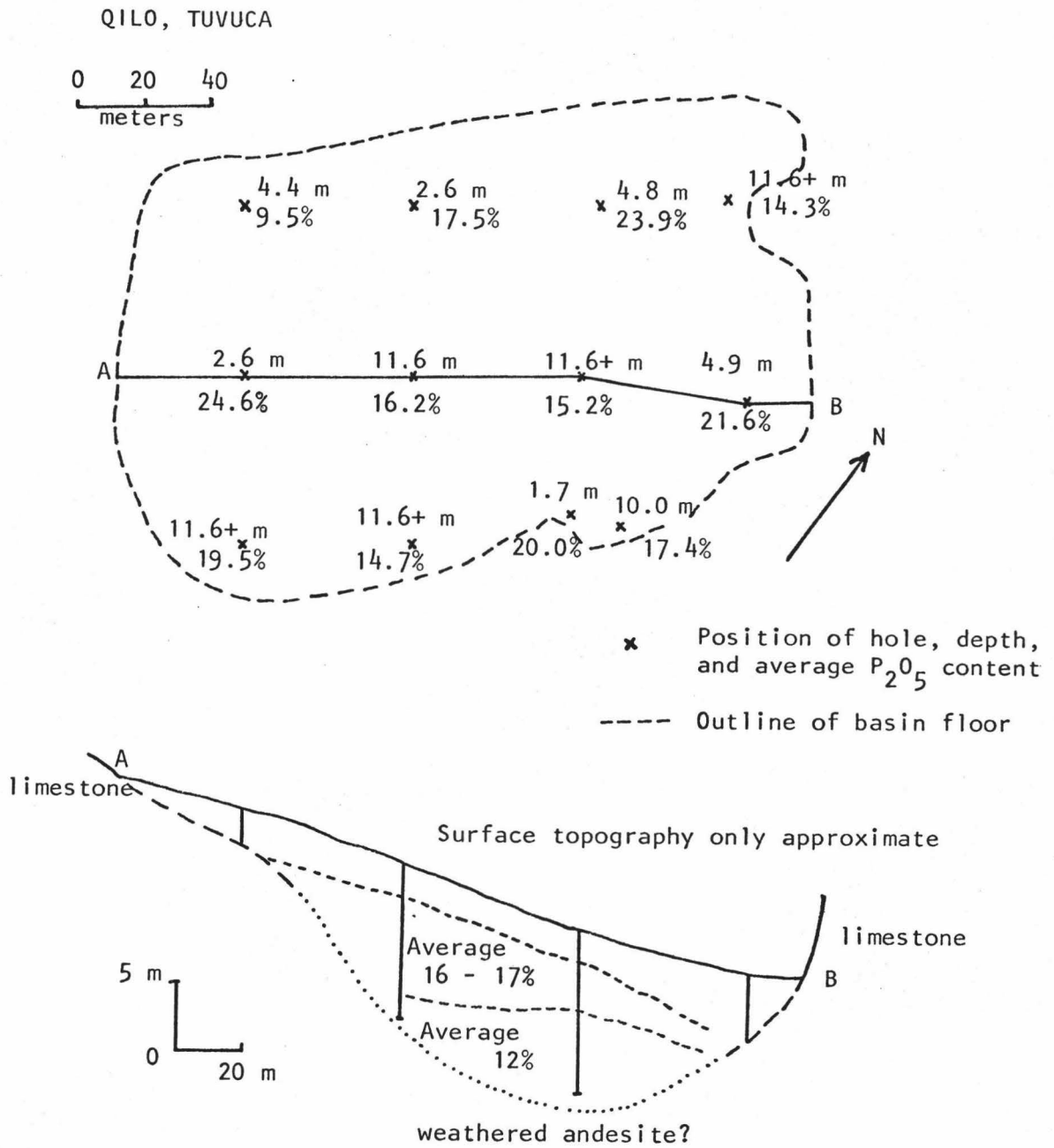


Fig. 10. Map of Qilo with cross-section showing variation of phosphate content with increasing depth in the basin (after Rodda, 1981).

TABLE 8.--Chemical composition* of the less phosphatic rocks by emission spectrographic analysis (analyses done at the U.S. Geological Survey's Branch of Analytical Laboratories, J.L. Harris, analyst)

	ALT21	ALT42	ALT65	ALT93
	Ratava	Tavaiwaro	Nakorovusa	Ratamona
SiO ₂	0.086	1.2	0.28	0.060
Al ₂ O ₃	7.6	6.1	1.5	2.5
Fe ₂ O ₃	7.2	3.2	2.3	1.7
MgO	1.3	2.2	2.3	2.7
CaO	21	27	29	31
Na ₂ O	0.0093	0.020	0.26	0.019
K ₂ O	< 0.082	0.15	0.21	< 0.082
TiO ₂	0.30	0.22	0.057	0.098
P ₂ O ₅	4.4	0.48	3.4	1.6
MnO	0.75	0.94	7.6	0.098

*The compositions were analyzed as chemical elements and later recalculated as oxides.

The samples are mainly calcium carbonate, and aluminum and iron oxides. The Tavaiwaro sample has a comparatively high silica content, perhaps due to volcanic material included in the rock. The sample is only slightly phosphatic and should not be considered a phosphatic rock. Rather it is a pelletal wackestone where some of the pellets are phosphatic. ALT65 is a geopetal deposit and the blue layer in ALT65 was the last sediment to be deposited in the stratigraphic sequence. In thin section the layer shows up as thin hummocky laminations of fine-grained carbonate. The solutions in which the layer formed was enriched in manganese and phosphorus.

The more phosphatic rocks from Nakorovusa and Dranoitiri, and from Vanua Vatu were analyzed by atomic absorption spectroscopy, using the method described in Shapiro, 1975. Two pisolitic soil samples, one from Dranoitiri on Tuvuca and one from Vanua Vatu were also analyzed. Table 9 is a list of the major element compositions of the samples. For comparison, two samples from other islands have been included in the list.

The Lau samples have high aluminum and iron contents and higher titanium contents compared to the Esprit (Indian Ocean) and Curacao (Caribbean Sea) phosphates. Correspondingly, the Lau deposits have less calcium (except for ALT7 and ALT121 which have high calcite contents) than the other insular deposits. These differences are due mainly to the volcanic input in the sediments on the Lau Islands. Even Vanua Vatu which has no exposed volcanics has some detritus from volcanic emanations as evident by the titanium, aluminum and iron contents of the samples. Quaternary volcanism in northern Lau may have been the source for these elements.

TABLE 9
GEOCHEMICAL ANALYSES OF SELECTED INSULAR PHOSPHATES

	ALT7 ^a Nakorovusa	ALT121 ^a Dranoitiri	ALT130 ^a Dranoitiri	ALV17 ^a Vanua Vatu	ALV60 ^a Vanua Vatu	Curacao 2 ^b	10A4 ^c Esprit
SiO ₂	<0.1	0.30	0.60	0.10	0.20	0.39	0.15
Al ₂ O ₃	3.9	5.6	7.2	10.9	10.1	0.40	5.54
Fe ₂ O ₃	2.8	12.6	20.9	6.2	5.2	0.61	0.11
FeO	-	-	-	0.12	0.08	-	-
HgO	0.62	1.5	1.3	0.15	0.15	1.23	0.67
CaO	48.9	36.1	17.7	37.7	38.6	49.96	44.84
Na ₂ O	0.25	0.04	0.24	0.07	0.14	0.88	0.65
K ₂ O	0.27	0.12	0.26	0.14	0.03	0.09	0.11
H ₂ O ⁺	2.8	5.6	10.0	7.4	6.4	2.47	4.85
H ₂ O ⁻	1.1	1.9	8.7	1.5	1.6	-	-
TiO ₂	0.18	0.36	0.45	0.48	0.43	0.024	0.02
P ₂ O ₅	12.5	11.5	12.4	32.6	33.6	38.59	37.10
MnO	0.5	6.2	17.6	0.08	0.06	<0.003	-
CO ₂	27.1	18.2	3.5	2.0	1.7	3.90	3.96
Total	101	100	101	100	99	99.7	101.28
Total S	<0.01	0.07	0.05	0.01	0.01	0.61	-
LOI	31.6	25.6	21.6	10.4	9.7	-	-
F	0.51 ^d	0.67 ^d	-	2.11 ^d	-	0.70	2.9

^aAnalyses by U.S. Geological Survey, Branch of Analytical Laboratories, D. Kobilis, analyst, July 1981.

^bFrom Jacobs and others, 1933, reported in Altschuler, 1973.

^cFrom Braithwaite, 1980, p. 534.

^dFluorine content by Burnett, written comm., 1981.

Origin of the Phosphate Deposits

Introduction

It is generally accepted that phosphate deposits on oceanic islands are directly or indirectly due to guano accumulations, although minor contributions may come from volcanic sources (Cook, 1982). Today, guano deposits are commonly found on semi-arid to arid islands or coasts that support or at one time supported large bird populations. These deposits are generally small (several thousand tons) but may be fairly substantial; for example, the Chincha Islands off the coast of Peru have had accumulations over 40 meters thick (Hutchinson, 1950). In his very thorough study of guano deposits, Hutchinson discussed the conditions necessary for guano accumulation:

Guano deposits are formed only when the organisms producing excreta are relatively large, feed over a wide trophic field, and return to a limited site for rest and reproduction.... [In addition] the substratum must be of a suitable form to retain the deposit and the rainfall must not be so great that the deposit is entirely washed away. [These] biological and geophysical conditions are, however, not entirely independent for in the case of guano produced by marine birds, the same factors that make the regions of the richest guaneras arid also provide that the adjacent seas be unusually fertile, permitting an extraordinary quantitative development of the marine biota and extraordinary populations of marine birds (Hutchinson, 1950, p. 4).

The guano accumulations are believed to be the phosphorus source for insular phosphate deposits. The deposits occur in many forms; for simplicity, they are categorized as phosphatic guano, and coherent and incoherent phosphates (Owens, 1923; White and Warin, 1964).

Phosphatic guano are differentiated from fresh guano in that they are deposits formed by the decomposition of guano. They occur as mixtures of phosphatized calcareous debris, cemented by both precipitated and residual calcium phosphate. Coherent and incoherent phosphate have no evidence that they were formerly guano. They are believed to have formed as the result of phosphate-rich solutions percolating down through the substrate. Incoherent phosphate may be of three types: fragmental, oolitic or clay. The clay results when terra rossa or volcanic clays become phosphatized. Coherent phosphate may be phosphatized bedrock (limestone or volcanics), accretionary phosphate (phosphatic clasts and grains cemented by phosphate) or a colloidal-type phosphate rock. The colloidal-type rock is commonly found as fracture and cavity fillings and is formed by the gelation of phosphate-saturated solutions. The large deposits of Makatea (in the Tuamotu Archipelago), Banaba (formerly Ocean Island), Nauru, and other high-elevated islands are mostly coherent and incoherent phosphates.

In considering the mode of formation of insular phosphate, the deposits can also be categorized by the type of island on which the deposits occur. White and Warin (1964) distinguished three island types: low-lying islands or atolls, elevated islands that have an unbroken rim encircling a well-defined central depression, and elevated islands that have flat tops or are slightly saucer-shaped.

The low-lying islands and atolls have guano and/or phosphatic guano deposits. These deposits are generally small and many were mined out during the early 1900s. The deposits are very young; recent studies by H.H. Veeh and W.C. Burnett (cited in Tracey, 1980) report uranium-series age dates of between 3000 and 5000 years B.P. for the apatite in the phosphatic crusts and cements. The elevated islands have deposits that are older and much larger. The islands with the well-defined central depressions have deposits that are usually ferruginous-aluminous phosphatic clay. White and Warin (1964) believed that the unbroken rim helped to contain the terra rossa clay (formed by limestone dissolution) within the central depression. Phosphate solutions leached from extensive guano deposits flowed into the central depression and phosphatized the clay and whatever lagoonal sediments were present. This accounts for the high iron and aluminum contents of the deposits. The Lau Islands, Bellona (Solomon Islands), Nauna (Papua New Guinea), and several other Pacific islands are islands in this category (White and Warin, 1964, p. 159).

Most of the major insular deposits (Banaba, Nauru, Makatea) occur on flat-topped or saucer-shaped islands. Instead of a central depression, a karrenfeld with tall limestone pinnacles is developed on the island. White (1964, in White and Warin, 1964, p. 163-165) suggested that subaerial weathering forms this topography. Reefal material fills in the spaces between the pinnacles and when guano is deposited, phosphate-rich solutions are added to the reefal debris, phosphatizing the deposits. With continued guano deposition, the spaces between the pinnacles eventually fill up and a thick cap of

incoherent phosphates forms over the landscape. However, based on examinations of the deposits on Christmas Island (Indian Ocean) and Nauru, R.P. Sheldon (pers. comm., 1982) suggested that limestone solution and phosphate deposition was a continual process that occurred in the vadose zone. The unphosphatized limestone bedrock also supports this latter interpretation.

The above descriptions are very general, and will need to be modified as each island is examined. A variety of environments exist on an island and since the phosphate deposits are very localized, their origin should be discussed separately. The timing of events, such as when the island emerged, when the limestone was dolomitized, and when the climate was arid, would be the same for each deposit. But the sequence of events for phosphatization such as when the guano was deposited and leached, when the pisoliths formed or when material was phosphatized, and the conditions under which the phosphate formed may be different for each deposit.

Present Work

The phosphate deposits on Tuvuca (Fig. 2) are incoherent phosphates only. Most of the deposits are clays in the interior basins. Though the phosphate rock deposits in Nakorovusa, Ratava, Ratamona, and Dranoitiri are well-cemented, they are termed incoherent phosphates since the cementing matrix is not phosphate. The deposits could have formed by primary phosphate precipitation or they could be phosphatized by replacement. Some grains have obvious replacement

features--phosphatic gastropod shell fragments and phosphatic crystals that display twinkling under crossed-nicols. But other features such as the pisolith concentric layers, phosphatic pellets and grains look like primary precipitates. In the following discussions, the mode of phosphate formation is assumed to be primary precipitation unless otherwise stated.

Dranoitiri.--The ubiquitous bluish manganese-coated clasts and grains in Dranoitiri and the seasonal nature of the marsh suggests that the brackish-water may have been significant in the formation of the pisoliths and pebble clasts. Presently no phosphate is being formed and no exposed phosphate is seen in outcrops. Instead the phosphatic deposits are coated with manganese oxides. The manganese was probably dissolved from older rocks by meteoric water containing large amounts of carbonic acid. Upon mixing with the marsh waters (which are in contact with limestone), the solution would become neutralized. Evaporation of the marsh would concentrate the manganese such that manganese precipitates. This precipitation process can be accelerated by bacteria or by the catalytic action of MnO_2 (Krauskopf, 1957). The process of dissolution and reprecipitation probably occurred many times and thus concentrated the manganese precipitates.

The phosphate grains may have formed when the marsh had a higher water level, that is, when it was a brackish-water pond like Dranolevu. The patches of manganiferous phosphatic material high up on the limestone walls are evidence of a higher water level in the valley. Saline lakes which are much deeper than ponds may also be the sites of phosphate formation though this has yet to be demonstrated.

Assuming that guano-derived phosphates were being added to the pond or lake in Dranoitiri, phosphatic grains could have formed in the bottom sediments. Evidence of whitlockite $[(Ca, Mg, Sr, Na)_3(PO_4, CO_3)_2]$ forming in a saline pond has been reported on Enderbury Island (Gulbrandsen, 1975). The pond occurs in the lowest part of a small pit though it at one time covered the entire pit floor. A fresh guano pile in the pit is contributing material to the sediments. The brownish-black sediments are composed predominantly of whitlockite with some amounts of apatite, sodium chloride, brushite, and organic matter. Experimental work by Rowles (1968, as cited in Gulbrandsen, 1975) showed that whitlockite forms in solutions that contain significant amounts of magnesium and that nearly all the whitlockite precipitates contained apatite. With continued weathering, the phosphatic sediments would accumulate and the whitlockite would change to apatite. Altschuler (1973) points out that calcic phosphates of cave and insular origins have a progressive recrystallization to apatite. "With more intensive or prolonged leaching, deposits would be transformed from brushite-monetite to whitlockite to apatite--a sequence accompanied by a parallel decline in organic, nitrogenous, and ammoniacal compounds" (p. 74).

Nakorovusa.--The deposits in Nakorovusa differ from the Dranoitiri deposits in that the phosphatic pisoliths have more concentric banding and the rock textures suggest deposition in solution cavities and caves. Although the pisolites are no longer in a cave environment, certain features in samples ALT7 and ALT70 indicate that they may have formed in a cave or solution cavity. The contact between the

limestone and phosphatic pisolites is an uneven surface of calcite layers similar to those lining solution cavities. The pisolith structures are similar to calcareous cave pisoliths, and the calcite layers intercalated with the phosphatic pisoliths resemble "coconut-meat" calcite, a term used by Assereto and Folk (1980) to refer to coarsely crystalline, parallel-fibrous calcite commonly formed in fractures or cavities in caves. Finally, the rocks are mainly grainstones, and the grains are all phosphatic pisolites or pellets. The grains are not sorted or graded, and the matrix is mud-free. These textures may have been produced by periodic overflows from splash cups and pools where the pisoliths formed.

An excellent description of calcareous cave pisoliths is given by Baker and Frostick (1947) in their study of caves located in Victoria, Australia. In Angel Cave, located on the Mornington Peninsula, a ledge halfway up the northwest wall has a series of pools that contain pisoliths and ooliths.

A few dozen of these pools occur in the cave. They vary in size from 2 inches to 2 feet or so across, and 3/4 inch to 4 inches deep; they contain from as few as 3 to as many as 2000 and more pisoliths and ooliths, the larger ones (around 20 mm. long) occur at the top, flush with the edge of the pool, the smaller ones (down to 1 mm.) occur at the bottom of the pool. It is not known how many pisoliths and ooliths have been generated in any particular pool, because the top ones in overcrowded pools become pushed out with continued growths.... Pisoliths which have rolled out of overcrowded

pools and now rest on a sloping (and therefore well-drained) surface, commonly become cemented in place (p. 43-44).

The bicarbonate-rich waters which feed these pools seeped out of joints and planes of separation in the rock that formed the cave walls, ceiling and floor. A fast flow of water into the pool did result in agitation or rolling about of the pisoliths, but agitation was not necessary for the spherical shape of the pisoliths. Cross-sections through the accretionary grains displayed three to five layers about nuclei composed of foreign matter (basalt or shell fragments), calcite crystals or no nuclei at all. The layers are commonly of uneven thickness; the thinner sides are assumed to have been the bottom sides of pisoliths as they were forming. The layers are made up of low-Mg calcite and some aragonite, and though they may form radial structures, interruptions during their formation or the inclusion of other minerals may result in concentric banding.

Many similarities are observed between these cave pisoliths and the pisoliths in Nakorovusa. The concentric layers about the nuclei are well-defined but of uneven thickness. They have concentric banding; this is assumed to be due to the inclusion of phosphate in the structure. The nuclei are apatitic crystals, phosphatized shells, and lithic fragments. The pisoliths attain maximum diameters of 3 mm though pellets included in the deposits (and having similar phosphatic coatings) are larger. The rock fabric looks like pisoliths were periodically added to the deposits. Interruptions are represented by the thick parallel-fibrous calcite layers, the surfaces of which are brownish--possibly terra rossa input. This fabric could have been

formed by spillover from splash cups or pools, in situ cementation, and thick calcite layers developing during interruptions in the pisolith formations.

The pisoliths were possibly low-Mg calcite and aragonite pisoliths that were replaced by apatite. On Curacao, phosphatization preferentially occurred in coralline limestone pockets (Ten Have and others, 1982), leaving the surrounding high-Mg calcite micritic limestone unphosphatized. The phosphatization is believed to have occurred due to the carbonate mineralogy (predominantly aragonite, but some dolomite and low-Mg calcite) and higher porosity in the pockets. According to Baker and Frostick (1947), the pisoliths have higher porosity than calcite crystals (specific density of 2.47-2.59 versus 2.71 for calcite), and this may have made them more susceptible to phosphatization than the crystalline cement. The only difficulty with this hypothesis is the lack of replacement textures in the pisoliths. Except for replacement features, the present deposits could have formed by primary precipitation or by replacement of pre-existing carbonates.

Other phosphatic deposits in Nakorovusa include fossiliferous deposits in limestone cavities, phosphatic pisoliths in the soil, and phosphatic clay. The fossiliferous deposits are either pelletal mudstones or geopetal deposits; they contain phosphatic pellets and grains intermixed with nonmarine mollusk shells and shell fragments. The shells are fairly intact and are still aragonitic. Most clasts are coated with a ferruginous layer. A smooth bluish top layer on the geopetal deposits indicate a high manganese content; this blue layer

is approximately 1 mm thick. The rest of the rock is well-graded, coarsening downward. Cementation occurred in the freshwater vadose or phreatic zone. These features indicate that the deposits formed as cavity fillings and have not been in the marine environment. The phosphatic pellets and grains were probably eroded from former phosphate deposits or moved from splash cups, and added to the cavities. The geopetal deposits probably settled out of a pool, the manganiferous layer indicating evaporative final conditions. The other, loosely packed, unsorted and ungraded fossiliferous deposits were cavity fillings. Cementation probably occurred in the fresh water vadose or phreatic zone. The fossil shells indicate that a tropical forest near a brackish-water body was present in the valley at the time the mollusks were living.

The phosphatic pisoliths in the soil are derived from the pisolites in the valley walls. This is indicated by the distribution of the pisoliths in the valley: the heaviest concentration is near the pisolites, with virtually no pisoliths in the soil approximately 100 meters away from the pisolites locality. The phosphatic clay is a further weathering product of the phosphatic material in the valley. A substantial contribution was probably directly from guano deposits, perhaps with minor additions from the volcanics underlying the clay floor.

Other deposits.--The deposits in the interior are mostly phosphatic clay (The Ratava and Ratamona samples were too sparse and weathered to be properly considered rock units.). Their origin could be either by primary precipitation as described by Gulbrandsen (1975) for the

Enderbury Island deposits, or by replacement of the terra rossa clay and volcanic rock-derived clays, or by both mechanisms. Weathering of the andesites that that underlie the limestones may be another minor source of phosphate. Chemical analyses of some of the igneous rocks on Tuvuca show a phosphate content of 0.24 to 0.27 weight percent (Rodda, 1981). The phosphate is present as apatite crystals (approximately 0.55 mm long though some near Maumi were larger). The volcanic material may have contributed a significant amount to the phosphate accumulations in basins such as Qilo, Tavaiwaro, and Nakorovusa. Auger drilling in these basins reached material that resembled weathered andesite. If the clay in these basins is a mixture of terra rossa and weathered andesite, then some phosphate would have been added from the andesite. As shown in Fig. 11, phosphatic clay is the product of phosphatization of limestone- or volcanic rock-derived clays, or of weathering of phosphatic deposits.

Geologic History

There have been various interpretations of the geologic history of Tuvuca. Agassiz (1899) who made a brief stop on the island, described the topography as one of subaerial solution; he found no basis for suggesting that the limestone rims were atolls. He also (erroneously) assumed that the volcanics intruded into the limestone and therefore were younger than the limestone. Foye (1918) cited Tuvuca as an example of an island that was submerged, overlain by limestone, and uplifted.

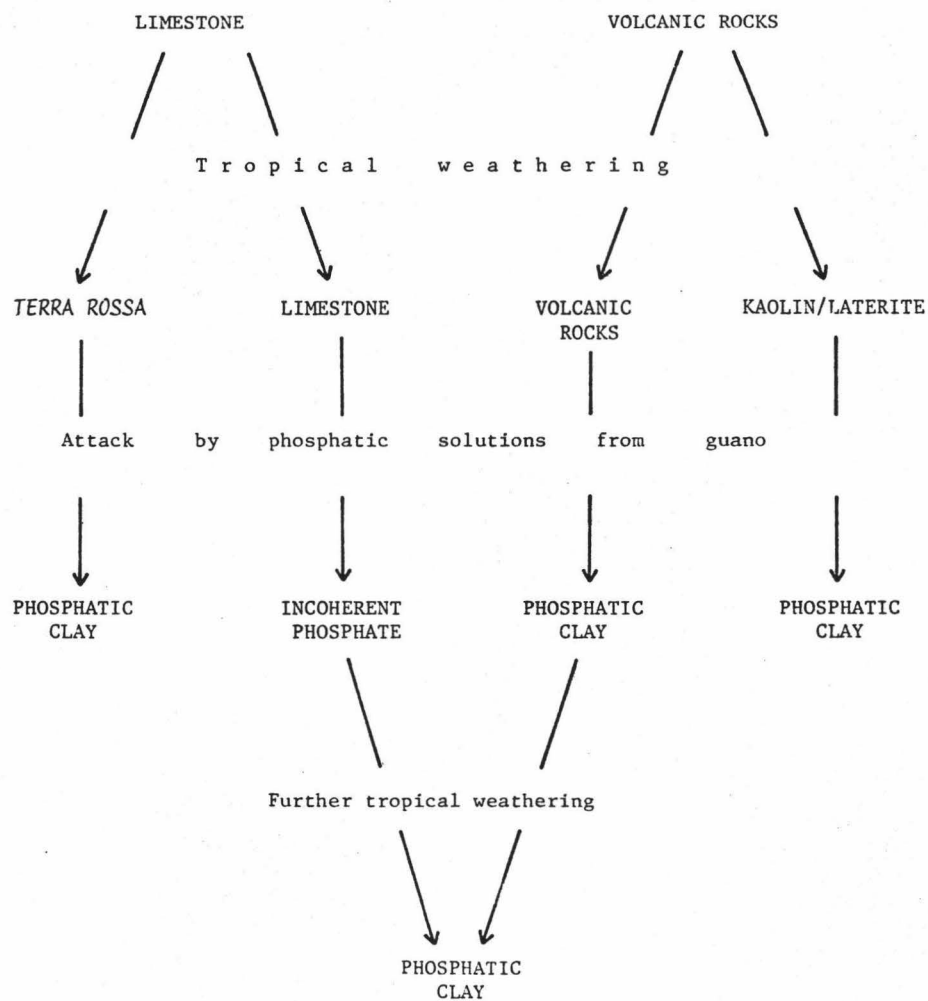


Fig. 11. Weathering relationship between limestone, volcanic rocks and phosphatic deposits (after Warin, 1968)

He saw the morphology as one of "a nearly dissected, ring-like limestone crest, 800 feet in altitude, enclosing a 'circular moat,' inside of which an eroded central mass of volcanic rock rises from beneath the limestones to an altitude of 540 feet" (Foye in Davis, 1927). The shape of the limestone rim and the orientation of coral heads that he saw on the island suggested that the island was at one time an atoll.

Ladd and Hoffmeister's study (1945) of the geology of the Lau Islands during 1934 led to the interpretation that the geomorphology is of a volcanic mound overlain by limestones. The limestone topography is due to subaerial solution and though the limestone may at one time have been an atoll, those remnants are no longer present. More specifically, Ladd and Hoffmeister used the following scenario to depict the geological history of the island:

1. A mound or a series of mounds composed of andesitic agglomerates and lavas was built up from the ocean floor. This mass came near but did not reach sea level.
2. Calcareous biogenic material was deposited on the mound. Where the depth range was suitable for growth, corals and other animals lived on the mounds and thus were deposited in place. In some areas the basal limestone included volcanic fragments that eroded off the mound, thus forming a sequence of basal conglomerates.
3. The limestone increased in thickness (>700 feet) and may have been at or above sea level. The highest point on Tuvuca, Uluiatavu, does not contain reefal material and so, if a reef developed, it was above Uluiatavu and has since eroded away.

4. The island was then uplifted in stages such that three sets of terraces were developed around the island. Flat areas and depressions in the limestone developed solution pits and formed basins. A younger limestone, the Ndalithoni Formation, was deposited as veneers on the older limestone.

Schlanger (1965) modified step 4 by stating that prior to uplift, the island could have been an atoll or flat-topped bank. As the island emerged, dissolution deepened the pre-existing lagoon or formed a central depression. The island was then resubmerged and the Ndalithoni Limestone was deposited. During this period, the central depression would have formed a restricted lagoon. Under the proper climatic conditions, this would have served as an evaporation basin suitable for dolomitization of the limestone bedrock.

If the Ndalithoni Limestone is just a facies of the Futuna Limestone, then there may not have been a period of resubmergence. Instead the formation of restricted lagoons may have occurred as the island emerged (assuming depressions were already present on the limestone surface) and dolomitization would have been active then. Alternately, the island may have been resubmerged without the concomitant limestone deposition but with the restricted lagoons formation and dolomitization of the limestone bedrock.

Step 5 is the continued emergence of the island, with the lagoons becoming saline lakes or brackish-water ponds. Presently Tuvuca has two brackish-water ponds, Dranolevu and Dranolailai, and several marshy areas, including Dranoitiri and Dranobalavu, that dry up during the dry

season. Phosphate deposits occur in Dranoitiri and uphill from Dranolailai in Nakorovusa. The relationship between phosphate deposits and restricted lagoons or ponds has been described in a previous section. Assuming that these restricted lagoons and ponds contained phosphate-rich solutions, phosphatization and phosphate formation may have occurred concurrently with or soon after dolomitization of the limestone bedrock. The variety of phosphate deposits are due to the varying degrees of weathering.

A recent paper by Sibley (1980) proposes an alternate hypothesis for the formation of dolomite on an island.

Dolomitization begins at high sea level when orographic rainfall is low causing an arid climate on the island. The groundwater will be predominantly brackish and low in P_{CO_2} due to the lack of vegetation. The low P_{CO_2} in the groundwater allows dilution of the seawater with rainwater without rapid conversion of aragonite and high Mg-calcite. Therefore, the metastable carbonates are present in waters with a Mg^{2+}/Ca^{2+} ratio close to one and may be dolomitized. If regression follows this high sea-level stand, the freshwater lens will descend and for a period will continue to effect dolomitization until the P_{CO_2} in the groundwater will have increased enough to cause dolomitization to cease. If the regression continues, aragonite and high Mg-calcite would be converted to low Mg-calcite limestone rather than dolomite. The resultant geometry would be dolomitization of the up-dip beds and limestone formation down-dip (Sibley, 1980, p. 256).

On Tuvuca this type of geometry is suggested by the higher dolomite/calcite ratio of limestones in the interior of the island compared to limestones on the coast.

The scenario for dolomitization as described by Sibley fits in well with the scenario for insular phosphate formation as described by Braithwaite (1980). On Esprit in the Indian Ocean, Braithwaite found the upper phosphate deposits on floors of small caves and on solution-eroded limestone surfaces. He proposed that when sea level was higher (relative to the island), guano was deposited on the island and caves began forming in the limestone bedrock. As the island rose (or sea level dropped), phosphate was leached from the guano deposits and was deposited in caves and solution cavities. In these cavities, they formed pisoliths, phosphatic cements, and colloidal-type phosphates. Limestone solution continued and eventually the phosphate deposits were also eroded. The material derived from the erosion of the higher phosphate rock was deposited at lower elevations where it was reworked and recemented. If the phosphate deposits on Tuvuca formed according to this model, then deposits such as those in Nakorovusa (samples ALT7 and ALT70) would be the original cave deposits and the other deposits would be the reworked and recemented deposits. The clay deposits would be those deposits that were more weathered such that no rock textures remain. Dolomitization likely occurred during the sea-level drop such that it was concurrent with the phosphate mobilization.

It is difficult to determine which steps 4 and 5 in our scenario is more appropriate to the conditions presently found on Tuvuca. Although the mechanisms are different, the environmental conditions and resultant

deposits are similar. In both models, an arid climate and high sea-level stand followed by a marine regression are necessary conditions for dolomitization and phosphate formation. In the evaporation basin model, the phosphate forms as brackish-water lagoon or saline lake deposits. The caves model has the phosphate forming in caves and solution cavities. Pisolites can form in both environments though their morphology will differ. The field relations are also appropriate for either model. On the one hand, the presence of phosphate in the interior basins and near the brackish-water ponds suggests a close association between phosphate accumulation and evaporation basins. In Dranoitiri, the manganese oxide coating on the sediments indicates a brackish-water origin. On the other hand, the rock textures and geopetal deposits in Nakorovusa suggests that the deposits were formed in a series of caves. Also it is not clear if the the interior basins and pond areas formed as the island emerged or are wholly the products of subaerial solution. In the latter case, they would have formed too recently to have played a major role in the phosphate formation.

It may be that both scenarios are appropriate to different areas of Tuvuca. A combination of reflux-seepage from an evaporative lake or inland lagoon and the interaction of meteoric water and seawater may have been conducive to dolomitization. Phosphate formation was probably dependent on whether saline lakes or ponds formed or caves formed. Phosphatization and dolomitization may also have occurred during several periods during the emergence of the island. As indicated by the limestone terraces, the island was uplifted in several stages. If the conditions were right, dolomitization could have occurred during each

successive period of uplift. The second set of terraces lies between 400 and 500 feet in altitude. A map of the contour intervals above 300 feet is a representation of how the island might have looked if sea level were 300 feet higher or the island were 300 feet lower, a time when the sea level was falling from a high sea level stand (or in this case, when the island was in a period of emergence). The phosphate deposits enclosed by those contour lines (Fig. 12), are located in areas of what would have been restricted basins or inland lakes. If guano were deposited on areas near these lakes, the waters would have been enriched in phosphate and phosphatic sediments could have formed in the lake bottom. The Nakorovusa and Dranoitiri deposits would have formed later when those areas became emergent.

Economic Importance of the Phosphate Deposits

Fiji imports an estimated 10,000 metric tons of phosphate fertilizer per year for its sugar industry (Table 10). In efforts to meet those needs through domestic production, studies have been conducted on the Lau phosphates to determine if there are sufficient resources available for anticipated future consumption, and if those resources will be suitable as fertilizer raw materials.

The phosphate resources are estimated (Plummer, 1980) to be the following:

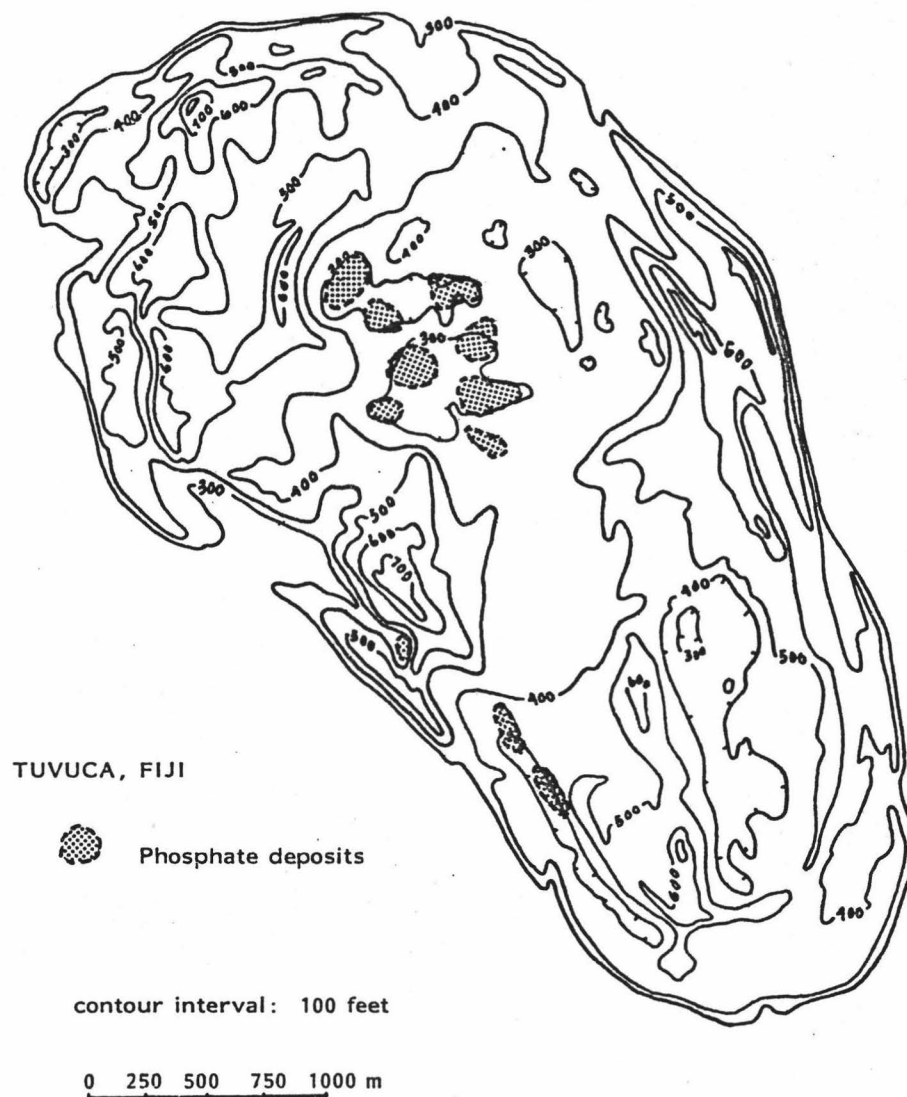


Fig. 12. Relationship between contour intervals above 300 feet and phosphatic deposits.

TABLE 10

CONSUMPTION OF PHOSPHATE FERTILIZER IN FIJI (FAO, 1980)

Year	Consumption	
	(in metric tons of P ₂ O ₅)	(in metric tons of fertilizers ^a)
1974	2,220	12,300
1975	2,500 ^b	13,900
1976	1,400 ^b	7,800
1977	1,800 ^b	10,000
1978	2,200 ^b	12,200

^aAssuming an average of 18% P₂O₅ content in the single superphosphate consumed.

^bEstimated

Tuvuca, phosphatic clay--430,000 metric tons averaging 16.7 percent P₂O₅, 1,193,000 metric tons averaging 8.8 percent P₂O₅, and 213,000 metric tons averaging 4.5 percent P₂O₅;

Vanua Vatu, oolitic phosphate--80,000 to 14,000 metric tons averaging 30 percent P₂O₅; and

Ogea Driki, oolitic phosphate and phosphatic clay--77,000 metric tons of 25 to 30 percent P₂O₅.

By volume alone, the Tuvuca phosphates will be sufficient to meet Fiji's domestic needs for many years to come. But the ore is medium to low grade, and so mixing with the higher grade Vanua Vatu or Ogea Driki ores would help to upgrade the phosphate. The resources are probably insufficient to develop for export marketing.

The question of suitability for fertilizer use is a problem that can be addressed in a variety of ways. If the intention is to produce a highly soluble product such as the commercial fertilizers available today, then the resources would be unsuitable. The high aluminum and iron oxides present in the phosphatic clays would cause precipitation problems during the wet-acid process for manufacturing the fertilizer (McClellan, 1980). A less soluble but still useful fertilizer is direct application fertilizer, that is, phosphate rock that, with minimum beneficiation, can be used directly on the fields. The Lau phosphates can be used in this form. Tests by the Overseas Geological Survey showed that the citric acid solubility (used to measure the suitability of phosphate rock as direct application fertilizer) increased three-fold when Lau phosphate samples were calcined (heated) to 500-550°C. This is true of the deposits composed mainly of crandallite. Apatite is unaffected by the calcining and it "...acts essentially as a diluent, its P₂O₅ content remaining in the 'unavailable' state and therefore of little immediate value as a fertilizer" (Overseas Geological Survey, 1960, p. 6). Apatite has long-term effects on the soil though, as it eventually dissolves and becomes available to plants.

Assuming that direct application fertilizers are effective substitutes for the commercial fertilizers presently used in Fiji, then the Lau phosphates are sufficient available resources and they will be suitable for fertilizer use. The next step is to conduct a feasibility study on the mining and production of the Lau deposits. Questions that need to be considered include:

- o Who will mine the deposits and manufacture the fertilizer? Will the islanders form a cooperative and mine the deposits, will the government subsidize the project, or will the total operation be handled by a private company?
- o How will the deposits be mined and what kind of infrastructure will be needed to support the mining operation?
- o How will the ore be transported to the calcining plant? Where will the calcining plant be located?
- o What is the current land use of the ore area and what will be the effect of mining on the lifestyles of the Lau Islanders?
- o How will markets be developed for the phosphate fertilizer?
Having just the sugar industry as a single consumer will make the phosphate mining operation vulnerable to fluctuations in sugar industry.

The road to development of these phosphate deposits is not an easy one. The technical questions of the physical characteristics of the deposits are soon answered by careful surveys and research. But the question of, "Should the deposits be developed and at what cost?" needs to be addressed before development can occur.

Summary Remarks

Although there currently are no guano deposits accumulating on the island, it is assumed that guano deposits were the source of phosphorus for the phosphatic rocks and clays. The guano deposits

probably accumulated during an arid climate when the island was less elevated (either because eustatic sea level was higher or because the island was emerging and was at a still-stand position before uplift). As sea level dropped (or the island emerged) dissolution of the limestone bedrock would result in solution cavity or cave formations in the vadose zone just above the water table. Dolomitization would also be occurring during this period. Periodic rainfall would leach the guano deposits and form phosphate-rich solutions that would either percolate down through the limestone and concentrate in the solution cavities or caves, or flow into restricted lagoons or ponds where, by evaporation and changing chemical conditions, the phosphates would precipitate out of solution.

Unlike the deposits on Vanua Vatu and Nauru which are single contiguous bodies, the Tuvuca phosphates occur as localized deposits in discrete basins and valleys. The textures and compositions differ between deposits. It is unlikely that the same mechanism was in effect to concentrate the phosphates in each locality. It is proposed here that the dominant mechanism for forming phosphatic pisoliths in Nakorovusa was precipitation in a spelean environment. The Dranoitiri deposits probably formed in the bottom sediments of a restricted lagoon or pond. Phosphatic pellets and pisoids in the rock deposits in the interior basins probably formed via the same mechanisms. Due to weathering, the deposits are too sparse and small for a careful study of their origin. The large volumes of phosphatic clay in the basins and the karst topography of the limestone also attest to the high degree of weathering on the island.

Tuvuca is one of six islands in the Lau Group that have phosphatic deposits. Studies of the other islands may contribute to a better understanding of the time of phosphate formation on the islands, and the relationship of the phosphate deposits to the underlying limestones and island geomorphology.

PLATES

PLATE I

PHOTOMICROGRAPHS OF IGNEOUS ROCK SAMPLES

- Figure 1. Feldspar phenocryst that has marked concentric zoning. An apatite crystal is aligned parallel to a zone margin. (Sample ALT13, photomicrograph is 0.3 mm across; crossed nicols)
- Figure 2. Feldspar phenocrysts with inclusions aligned along growth rings. Feldspar microlaths in groundmass exhibit flow texture. (Sample ALT13, photomicrograph is 3.2 mm across; plane polarized light)
- Figure 3. Mafic clot of feldspar and pyroxene crystals. A clear rim of feldspar has grown around the older crystal that had reacted with the melt. In the upper left corner, an amygdule with fibrous crystals is present. (Sample ALT32, photomicrograph is 3.2 mm across; plane polarized light)

Plate I

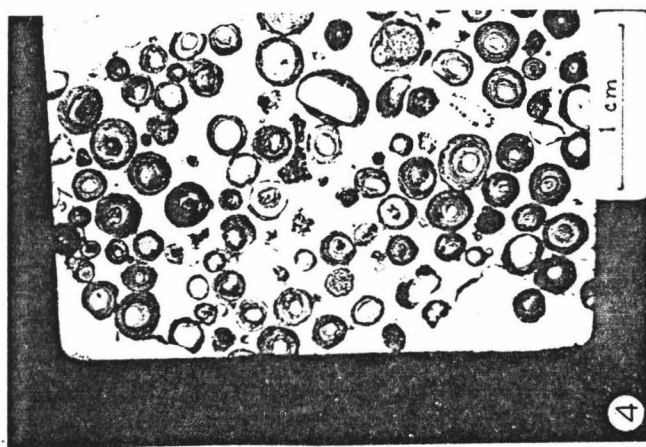
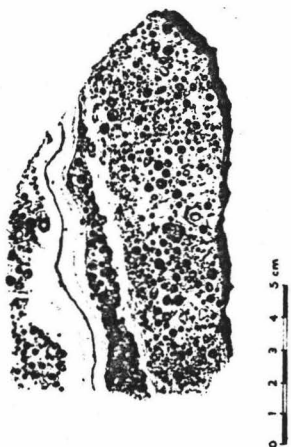
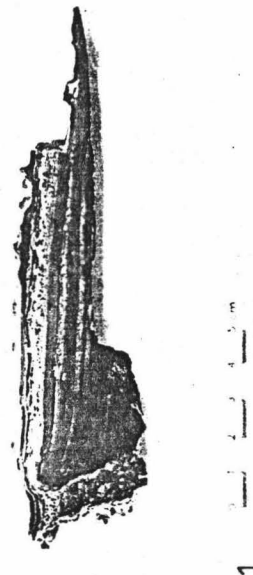
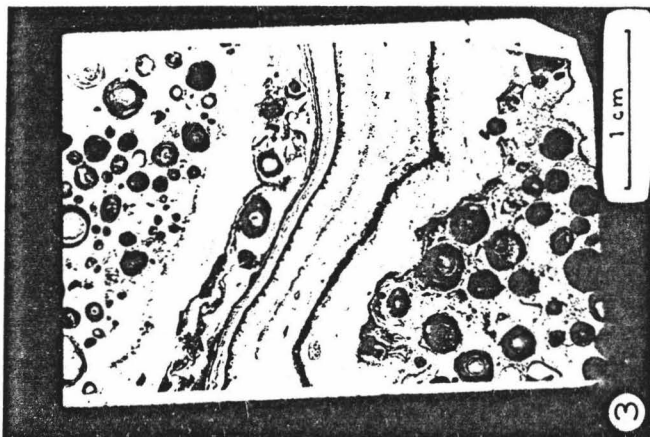


PLATE II

ROCK SLABS AND THIN SECTIONS OF NAKOROVUSA SAMPLES

- Figure 1. Sample ALT65, showing the relationship between the layering of light and dark fine-grained carbonate and the pelletal layers (pocket on left side of rock slab). The uppermost dark layer is a phosphate- and manganese-rich sediment.
- Figure 2. Sample ALT7, showing the relationship between the pelletal, pisolitic layers and the intercalated calcite layers.
- Figure 3. Thin section of ALT7. The calcite layers are extremely coarse-grained, parallel-bladed calcite crystals. Some pisoliths included in the calcite layers were auto fractured.
- Figure 4. Thin section of ALT71. Despite irregular shapes of the nuclei, the layers have rounded off the forms to make the pisoliths more spherical.

Plate II



2

3

4

PLATE III

GASTROPOD FOSSILS AND SUBFOSSILS

1. Taheitia sp. (Ratamona, from ALT92), shell is 1.1 cm long
2. Omphalotropis sp. (Ratava, from ALT18), shell is 1.3 cm long
3. Omphalotropis sp. (Nakorovusa, from ALT77), shell is 1.3 cm long
4. Sturanyella cf. tectiformis (Nakorovusa, from ALT77), shell is
1.0 cm wide
5. Sturanyella cf. tectiformis (Nakorovusa, from ALT5), shell is
1.1 cm wide
6. Thiara (Melanoides) tuberculata (Dranoitiri), shell is 1.0 cm long
7. Pseudopeas tuckeri (Dranoitiri), shell is 0.7 cm long

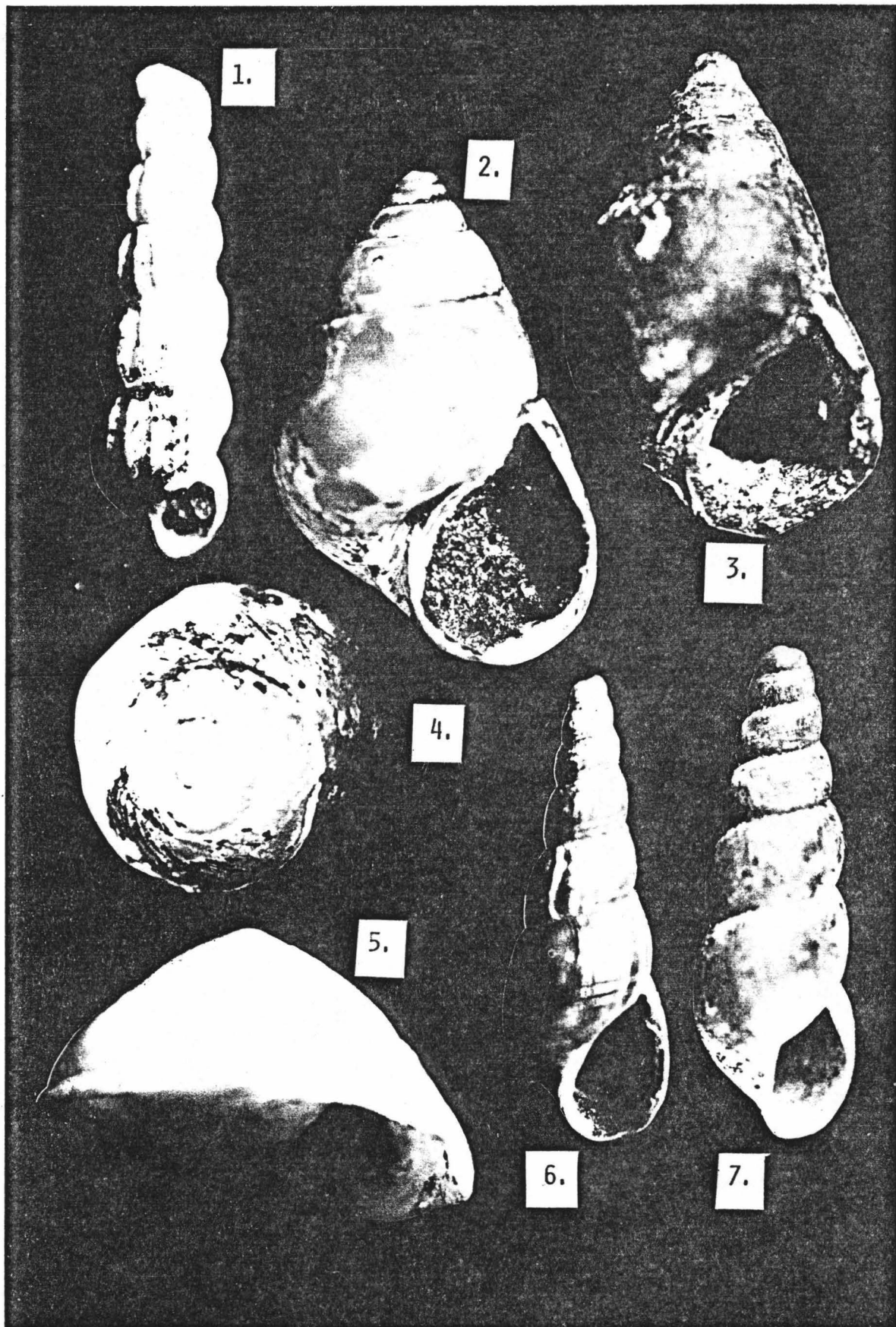


PLATE IV

NAKOROVUSA PISOLITH STRUCTURES AND CEMENTS

- Figure 1. A void within the nucleus of a pisolith is filled with elongate crystals that have grown perpendicular to the void walls. (Sample ALT7, photomicrograph is 0.3 mm across; plane polarized light)
- Figure 2. Same void as in Figure 1 magnified to show hexagonal habit of the crystals. (photomicrograph is .08 mm across)
- Figure 3. The pisoliths are cemented with coarse-grained bladed calcite. The calcite crystals grow perpendicular from the pisolith surfaces. (Sample ALT7, photomicrograph is 3.2 mm across; crossed nicols)
- Figure 4. Some of the crystals in the calcite layers have hexagonal habits. Note the growth rings exhibited in the crystal in the lower right corner. (Sample ALT7, photomicrograph is 3.2 mm across; plane polarized light)

Plate IV

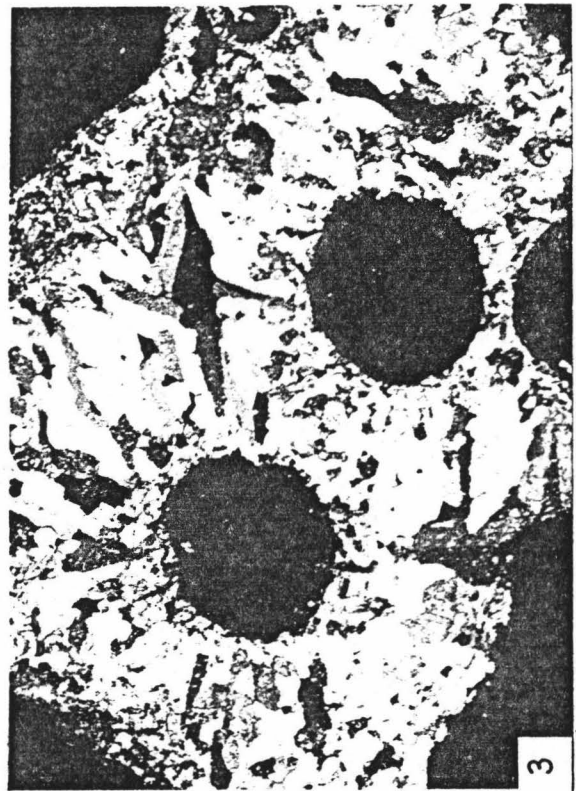
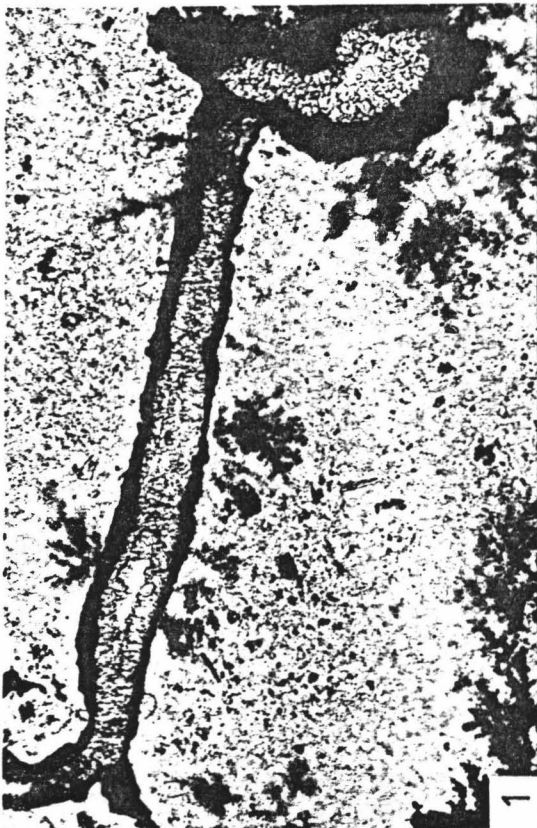
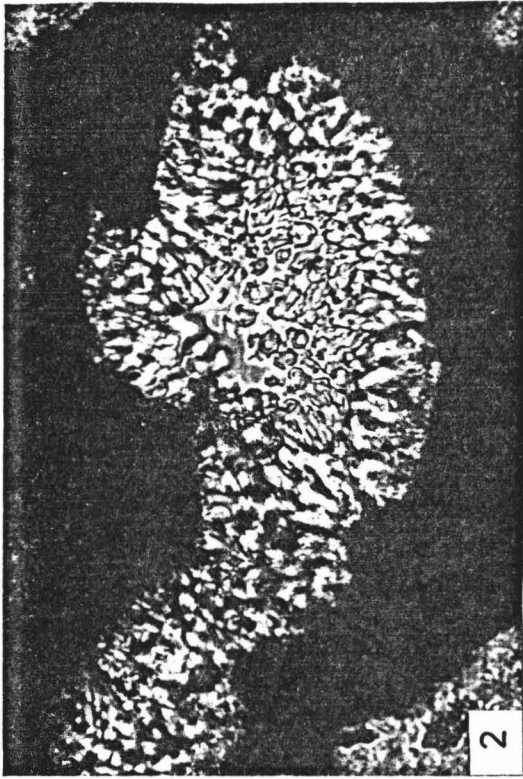


PLATE V

SCANNING ELECTRON PHOTOMICROGRAPHS OF PISOLITH STRUCTURES

- Figure 1. Dranoitiri pisoliths are coated with manganese oxides (opaques in the photomicrograph). The nucleus in this pisolith is phosphatic. (Sample ALT117, photomicrograph is 3.2 mm across; plane polarized light)
- Figure 2. Apatite crystals in a pisolith layer (Scanning electron photomicrograph)
- Figure 3. Elongate crystals with needle-like terminations formed in this algal bore hole. These crystals are probably aragonite. (Scanning electron photomicrograph)
- Figure 4. Elongate crystals formed within fractures and voids in the pisolith layers. These crystals may be crandallite; they differ from the crystals in Figure 3 by having blunt terminations, and from Figure 2 in Plate IV by not having a hexagonal habit. (Scanning electron photomicrograph)

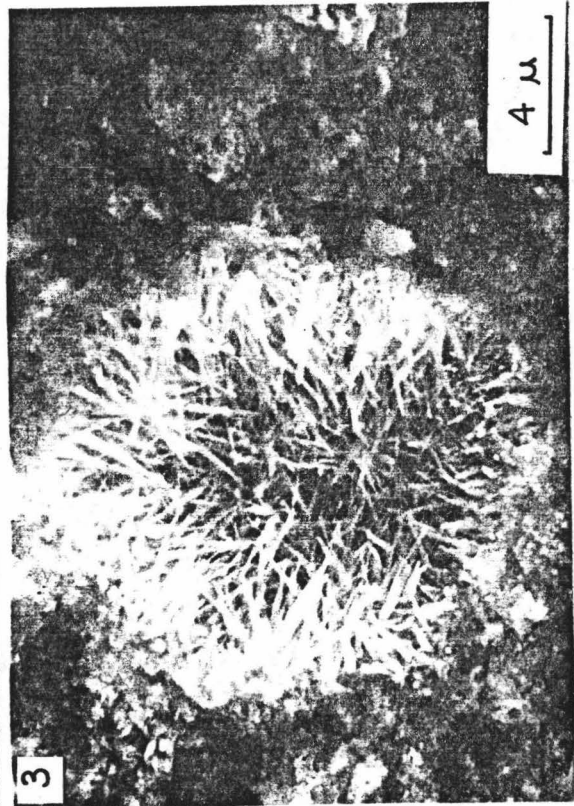
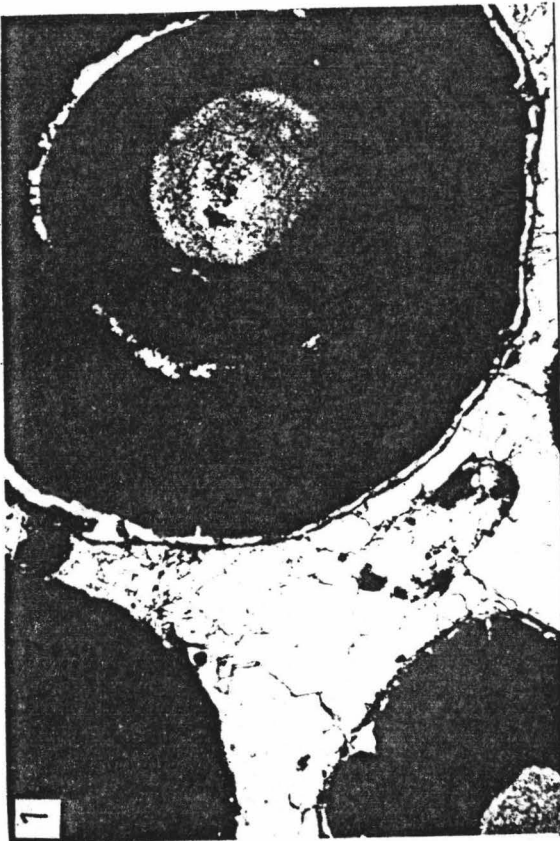
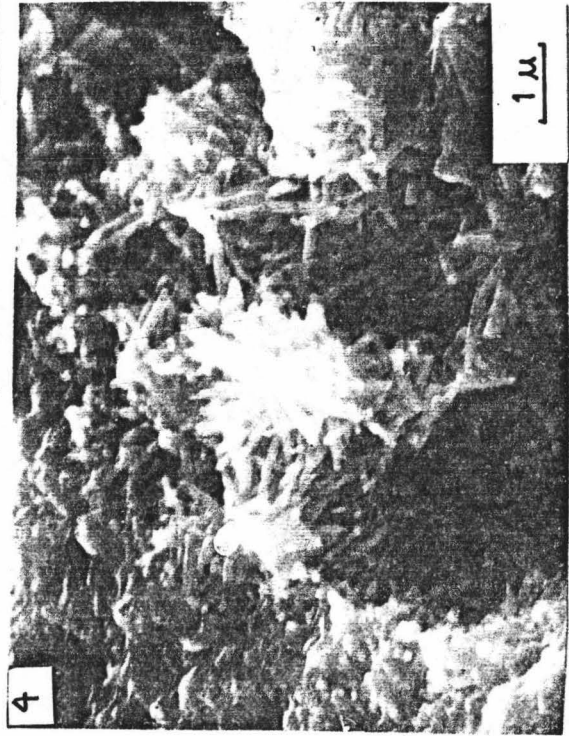
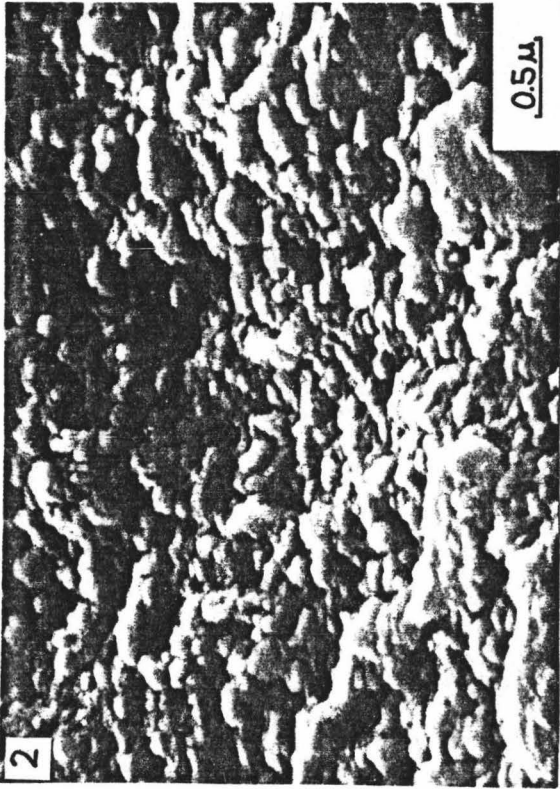
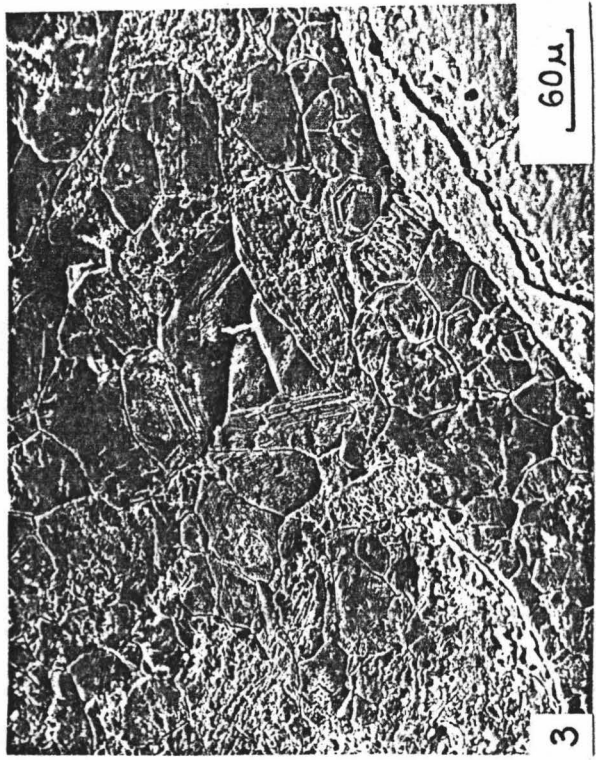
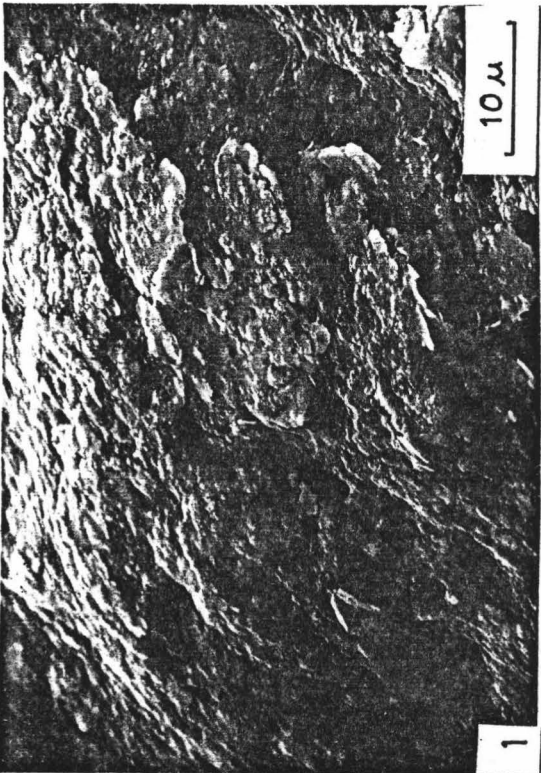
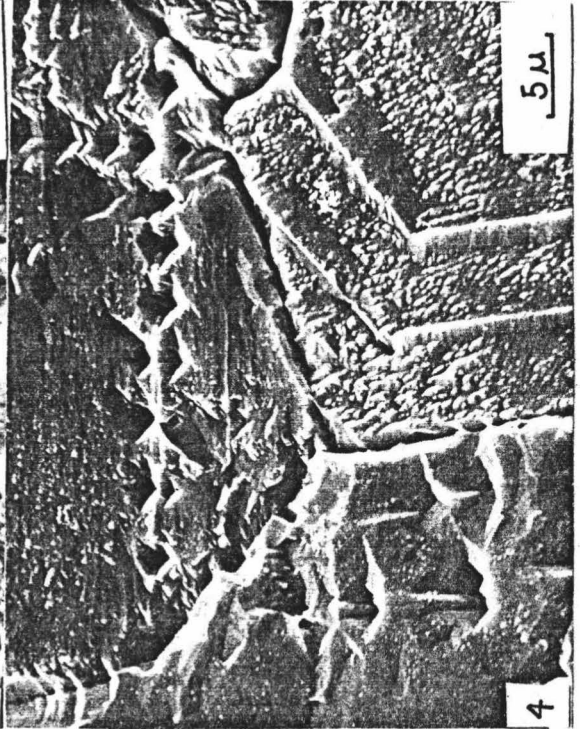
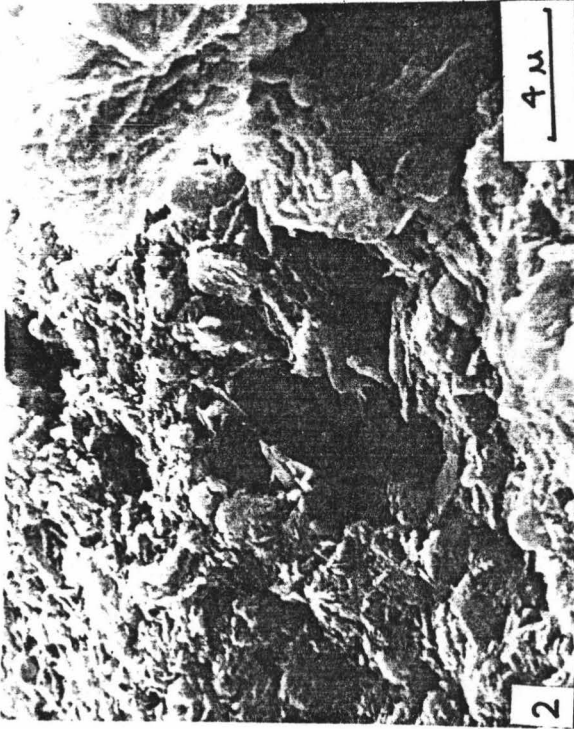


PLATE VI

SCANNING ELECTRON PHOTOMICROGRAPHS OF PISOLITH STRUCTURES

- Figure 1. Platy minerals on the surface of a Dranoitiri pisolith. These are probably manganese oxides.
- Figure 2. Some of the platy minerals form rosettes within the pisolith layers.
- Figure 3. Hexagonal calcite crystals formed tangential to the pisolith surface. The crystals have marked growth rings (compare to Plate IV, Figure 4).
- Figure 4. Same crystals as in Figure 3 but with higher magnification.



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