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BATHYMETRIC AND SEISMIC FEATURES OF
NUKUFETAU LAGOON, TUVALU: AN APPRAISAL
OF SUBMARINE PHOSPHATE POTENTIAL

by

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INTRODUCTION AND BACKGROUND

This report embodies the results and interpretation of a shallow seismic survey made of Nukufetau lagoon in February and March, 1985.

There have been several reported land occurrences of low grade phosphatic soils on islands of Tuvalu atolls (Sollas, 1904; White and Warin, 1964; Flynn and Makin, 1976; Geomarex, 1978; and Sahng-Yup Kim, 1981).

With the recent discovery and development of phosphate deposits in Mataiva Lagoon, Tuamotu Archipelago, French Polynesia, the prospectivity of atoll lagoons has been upgraded for localized high-grade subsurface phosphate deposits. Such deposits appear to originate from guano accumulations which have been modified and concentrated by repeated karstification during drops in sea level that correspond to past glacial episodes. The petrology of lagoon phosphate, and models for these deposits have been documented by Braithwaite (1980). Earlier reconnaissance drilling on the atolls of Tuvalu was based on this genetic concept (Geomarex, 1978) but the survey failed to produce promising results.

Most atolls in Tuvalu have very limited land resources and consideration of competing needs for such limited land influenced our decision to prospect only the submarine areas where such conflicts of interest are, hopefully, not as great.

A re-evaluation of phosphate prospectivity of Tuvalu was conducted prior to coming to the decision to survey Nukufetau lagoon.

A rating of atoll prospectivity in Tuvalu was made by Radke (1985) and Niulakita was ranked as having the highest potential, followed in order by Nukufetau, Nui, Nanumaga, Vaitupu, Funafuti, Nanumea, Niutao, and Nukulaelae. Niulakita is a very small island and its guano? has been previously mined in the nineteenth century (White and Warin, 1964). The extent of remaining deposits there are unknown but the submarine banks and guyots near Niulakita may have comparable potential and require exploration when appropriate cruise vessels are operating in the region.

Nukufetau was selected for the first lagoon survey in Tuvalu because White and Warin (1964) reported a sizeable deposit on uninhabited Coal Islet (Sakalua). Additionally, this atoll has the most favourable attributes a navigable lagoon with good access and anchorage, for development if ever additional phosphate resources are discovered.

OBJECTIVES

1. To delineate the general bathymetry of Nukufetau lagoon.
2. To interpret the subsurface shallow structure and stratigraphy of the lagoon.
3. To delineate areas with potential for phosphate accumulations, to be tested by subsequent drilling and sampling.

EQUIPMENT AND FACILITIES

Equipment and field procedures for the Nukufetau survey are outlined in cruise report 108 (Radke, 1985).

METHODS

BATHYMETRY

Bathymetric soundings were reduced to zero tidal datum of the Funafuti Tide Station, using tide prediction tables for Funafuti lagoon as no tide monitoring was conducted at Nukufetau. Consequently the survey soundings are presented on the assumption that there is amplitude and time - equivalence of tides at Funafuti and Nukufetau. Mean sea level was 1.2m above zero tidal datum in 1982. During parts of the survey, the DE 719B precision fathometer malfunctioned and gaps in soundings were supplemented by depth estimates from the seismic profiles.

SEISMIC INTERPRETATION

Seismic penetration and resolution were best in the deeper areas of the lagoon where the sediment was muddier.

In these areas, significant reflections that generally appeared conformable, were traced laterally. Locally unconformable aspects such as truncation of underlying reflectors and the initiation of patch reef development from such reflectors indicated that they were erosional and indurated surfaces.

These reflectors were traced laterally and extrapolated to all lines using a loop tie-in procedure to check on consistency in this extrapolation. Only two reflectors have been mapped and used for discussion in this report. These are interpreted as the deepest and shallowest continuous unconformities.

Structural contours and isopachs have been used to indicate both sedimentation patterns and possible structural influences on sedimentation.

SAMPLES

Rock samples collected (Radke, 1985) were impregnated with coloured resin and studied in thin sections using a macro-zoom petrographic microscope. Whole rock analyses of phosphorus, calcium, magnesium, manganese and iron in these samples were provided by AMDEL laboratories, Australia. Digestion was in hydrofluoric acid and analysis made by Inductively Coupled Plasma Atomic Emission Spectroscopy.

RESULTS

BATHYMETRY

Figure 1 illustrates the general bathymetry of the lagoon bottom. Many of the scattered near-emergent pinnacle reefs are not shown in this map.

Generally, there is a consistent gentle slope of 6m per kilometre from northwest to southeast where the deepest basin of the lagoon exceeds 40m depth along the entire southeastern side of the lagoon.

On the western side, the lagoon floor is deepest in the southwestern and northern corners while the central zone from north of Te Ava Lasi to north of Te Ava Amua is much shallower. Here a break in slope at 20m depth tends to follow the margins of the reef flat and below this there is a gentle slope eastwards.

Lagoonwards from Te Ava Lasi the lagoon floor drops steeply from 10m to 30m depth, then more gently into a small elongate basin (exceeding 40m depth) that parallels the lagoon margin for its 2.5km length. This basin is paralleled lagoonwards by a rise of similar trend and dimensions. This rise shallows to less than 30m depth and has smaller, isolated undulations of the same relief at its southern end. This feature, comprising proximal basin and distal banks resembles a deep submarine tidal delta.

On its lagoon side, Te Ava Amua has the general features of a tidal delta built up to intertidal level, which has been modified by reef growth along the margins of its distributaries. The main channel is narrow and deep but shallows in steps from 45m at its outer limit, up to 20m at the bifurcation into distributaries. The southern distributary is blind, terminating in intertidal reef flat, with a presumed floor depth of 10 - 20m. The northern distributary of Te Ava Amua, Manga Kifunaota, has an undulatory but shallowing floor from 20 - 10m where it opens into lagoon. A relatively shallow lobe of sand at 15 - 20m depth extends eastwards for almost 1km from the lagoon opening to this distributary.

Within this rectangle-shaped atoll the corners of the lagoon have a more rounded form than the angular outline of the reef flat. In these corners, the lagoon slopes are gentler than elsewhere.

LAGOON FLOOR CHARACTERISTICS

The main variations in lagoon floor types correspond to water depth (Figures 1 and 2). Around the shallow lagoon margin, is a continuous belt of carbonate sand as indicated

by poor seismic penetration, present as shallow subtidal banks abutting the intertidal reef flat and prograding lagoonwards. The scree slopes of these prograding banks are steep and have a distinct basal transition onto the lagoon floor. The lower limit of sand varies locally between 15- 20m on the shallow western side of the lagoon, to 35m adjoining the deepest part of the lagoon on the south eastern side. Along the toe of this sand body there appears to be an erosional depression cut into the muddier and more plastic lagoon sediment.

The remainder of the lagoon floor is covered by muddier carbonate sediment, with better stratification and seismic transmission properties. Excluding the few larger pinnacle reefs which reach to near intertidal levels, low relief mounds and low reef pinnacles have a distribution that can be readily delineated. The densest areas of reef mound cover (Figure 3) lie throughout the southern part of the lagoon that exceeds 40m depth, and in the far northern central deep area (Figures 1 and 2). Reef mounds in sparser distribution tend to rim these denser accumulations and occur in a northeastern area on the deeper lagoon floor, in a band across the lagoonal distributary of Te Ava Amua. On the shallow sand banks and subtidal sand sheets there are scattered patch reefs, of lower relief, which tend to have more of a pinnacle form with steeper sides.

DEPRESSIONS

Throughout the lagoon there are local depressions, commonly around the bases of large pinnacle reefs, which appear to be either erosional moats or channels. In these depressions the frequently accented acoustic reflection character of the surface indicates a harder or denser substrate. Probable

hardgrounds and or dense lag deposits may lie close to the lagoon floor surface in these depressions. The extent of such near surface hardgrounds is seen as occurring predominantly in three main areas (Figures 2):

1. in an east-west tract which extends from the deep basin inside Te Ava Lasi across to Motufetau;
2. in a broad area to the northwest, lying in the centre of the lagoon; and
3. in some erosional zones at the base of the sand slopes along the southern and northern margins of the lagoon.

Many of the depressions throughout the lagoon floor proper are enigmatic without additional data and have at least two probable causes which are discussed below.

Interpretation 1: Blasted Pinnacle Reefs?

Many of the very large pinnacle reefs are unusual in that their upper surfaces are subtidal. These pinnacles (Figure 4) tend to be conical in form and, on the basis of their circumference and corresponding raised seismic substrate, should have easily reached the intertidal zone as has the atoll perimeter, during this latest interglacial period of reef development. Invariably these pinnacles have a moated perimeter on the lagoon floor, a feature which may be purely surficial and cutting into the sediment stratification, or repeat similar relief and character to underlying reflectors down to the deepest unconformity detected (Figure 4).

Johnson (1947) documents reef blasting at Nukufetau and Funafuti by the US Navy during World War 2, to make the lagoons navigable for warships. He described blasting techniques that almost totally obliterated the pinnacles. It can be expected that with such explosions, the shock wave would have created craters about the remnant pinnacle. Gibb and Partners (1984), in surveying the Funafuti lagoon, noted unexplained circular moats and levees around low pinnacles which were detected on side-scan sonar. Consequently, Johnson's record adequately explains both the observed surficial phenomena at Funafuti and Nukufetau.

Most concentric moats around pinnacle reefs in Nukufetau, seen as bilateral symmetry around the pinnacles on seismic charts (Figures 4 and 5), are best explained as blasted reefs. However, some remain questionable with this explanation in that the apparent disturbance into the sediment or indurated substrate has caused disruptions down to 20m.

Interpretation 2: Channels

On seismic sections, depressions appear to have either soft or hard/dense fill. Soft sediment fill is implied where reflectors are continuous but not strong and there is good penetration. Here the reflectors conform to the underlying topography but indicate sequential reduction in relief up to the present lagoon floor. In other depressions, the floor is a very strong reflector with corresponding poor penetration underneath, indicating a hardground or a very dense lag or infill (Figure 7).

Where such depressions do not have an apparent symmetry about a central pinnacle, as to be expected with an explanation by reefblasting, they are interpreted as exposed hardgrounds and lag bottoms in erosional channels.

When crudely mapped out by interpolation between lines, these 'channel features' have a probable radial distributory pattern from Te Ava Lasi to the south and due east for up to 3½km extent (Figure 2). In the north central part of the lagoon these 'channels' have trends normal to the lagoon margin. Collectively these 'channels' indicate erosion by tidal currents that were observed to be very strong on the lagoon surface. Although the seismic lines are not sufficiently close spaced to confirm it, these channels could be conceived to be submarine distributaries of a deep tidal delta originating from Te Ava Lasi. This model is supported by the described bathymetric basin and rise adjacent to Te Ava Lasi (Figure 1) and complements the model of an erosional regime caused by high-velocity water flow in these areas.

Moat around lagoon margins

The best-defined example of this feature is at the southern lagoon margin (Figure 8). The erosional depressions around the scattered patch reefs in the lagoon correspond in acoustic character to this belt. In many areas along this nearly continuous moat around the lagoon margin at 30 - 35m depth, truncation of stratified lagoon sediments indicates an erosional origin. The processes that would form such a feature are unknown, but may approximate deepwater sand transport by storm-generated waves, and may be complemented by tidal bottom currents that might contour such marginal slopes.

SEISMIC INTERPRETATION

Seismic penetration varies with sediment type. Maximum penetration was obtained over the deeper lagoon floor of muddier sediment, on average 35 milliseconds (msecs) two way time (TWT) below the lagoon floor, but as deep as 65 msecs TWT in exceptional circumstances. The marginal, shallower sandy areas prevented comparable penetration and only major unconformities could be detected down to 25 msecs and rarely 35 msecs TWT.

Up to nine good reflectors can be distinguished at any one station in the deeper lagoon. On the evidence of their local truncation of underlying reflectors, these are interpreted as unconformities. The number of reflectors detectable varies across the lagoon and with the quality of the record. Accordingly, only two subsurface reflectors have been mapped out: the uppermost traceable unconformity and the deepest strongest reflector.

Reflector A

Reflector A is the shallowest continuous unconformity, but its identification and traceability is more tenuous in the shallow sand and reef areas. The variation of sediment thickness above reflector A is shown in Figure 9. Seismic velocity in presumed unconsolidated sediment is such that 1 msec TWT is approximately equivalent to 0.8 metres.

Surficial sediment rarely exceeds 20 msecs TWT (~16m) and is less than 10 msecs TWT (~8m) over most of the lagoon. The lagoon perimeter has the thickest sediment, exceeding 10 msecs (TWT) in the peripheral sand belt. The thinnest sequence occurs in:

the northern corner; scattered patches of the north-central lagoon; and in two belts immediately south and east of Te Ava Lasi. The latter eastern belt extends from a thicker apron adjoining Te Av Lasi; to about two-thirds of the width of the lagoon.

Because of the slight thickness, and interpretation difficulties, the reliability of this map is poor. However, it does demonstrate generally lower rates of recent sedimentation on the western side of the lagoon. Lagoonwards from Te Ava Lasi, an immediate thickening of section on the lower sand margin slopes and a contrasting shallower section eastwards across the lagoon indicates a stronger sand influx through the pass but reduced accumulation across the lagoon floor in what appear to be distributary channels that either presently have bathymetric expression, or occur on the unconformity itself. The interpreted channel pattern of an active tidal distributary system is shown in Figure 9. This shows mainly distributary patterns extending into the lagoon from Te Ava Lasi and the north arm of Te Ava Amua. The speculated channel system emerging from Te Ava Lasi corresponds crudely to the previously described active channel system (Figure 2). Consequently the thickness of overburden is much less in this region. In contrast, the interpreted channel system emanating from the north arm of Te Ava Amua tends to follow highs indicating cessation of channel erosion in this area since the time of Reflector A. Some 'channels' extend in from the northeast margin of the lagoon. (It must be reiterated the approximate nature of this interpretation because of the existing line spacing).

Reflector B

This reflector is the most distinctive surface within penetration limits because of its relatively subdued relief and strong reflection character.

Structural contours from zero tidal datum down to Reflector B (Figure 10) indicate a general similarity in the surface to present bathymetry (Figure 1) in its southwest-northwest axis of depression. The significant difference is that this axis is displaced to the northwest, though still not centrally placed in the lagoon. There are several other differences between Reflector B and present bathymetry.

1. On Reflector B the highs around Te Ava Amua and Sakalua are more separate and there is almost complete closure between Luakau Foliki and Te Ava Amua of a northern northwest-southeast trending basin of the same depth (compare Figures 1 and 10).
2. In the main southern basin there is local relief in the deeper area.
3. A narrow linear feature runs through Te Akau Kapuka and may be continuous for over six kilometres in an east-northeast - west-southwest trend. This is not shown as continuous in figure 10. At its implied western end, the feature is a narrow steep-sided depression but this appears to broaden towards the east. This is probably a solution - enhanced joint or fault. It remains speculative whether this feature has any genetic relation to a distinctive step in reef line seaward of Motumua that may indicate an old basement fault with downthrow on the eastern side.

4. On the Reflector B surface, the northern arm of Te Ava Amua was deep and a significant submarine tidal delta for sediment influx into the lagoon at that time.
5. In the area of Te Ava Lasi and the western corner of the lagoon, the Reflector B surface has gentler slopes with fewer local irregularities in relief than present bathymetry.

Locally, Reflector B appears to bifurcate and the structural contour map (Figure 10) is that of the upper surface. The lower surface has comparable characteristics to the upper one. The sequence between these surfaces has been mapped in four areas and is isopached in two way time in figure 10. This interpretation may be erroneous in part but two bodies are significant - these lie lagoonward of Te Ava Lasi and Lafaga in the northeastern corner. These bodies are possible colluvial slope deposits that accumulated from residual material weathering off the reef rims during the low seastand and unconformity development (Reflector B). Although these bodies appear to be ideal for phosphate accumulation, they are at considerable depth below the present lagoon floor, the overburden generally exceeding 24 msec TWT (approximately 20m).

Sedimentation through time

The sediment thickness between Reflectors A and B exceeds 30 msec TWT in places. In this time interval the focus of sedimentation was along a northerly axis that extended from the southern central area to the northern corner of the lagoon (Figure 11). This trend is compatible with atoll subsidence without tilting and where lagoonal sediment has been introduced predominantly from and over the northwestern margin, and through the passes Te Ava Lasi

and Te Ava Amua. This has produced a greater sediment thickness and consequently shallower bathymetry on the northeastern side of the lagoon (Figure 1). Directly in from both passes, sediment buildup since Reflector B time is not as great as would be expected. The northern arm of Te Ava Amua appears to have gradually reduced both in width because of reef wall accretion (Figure 11) and in tidal current velocity since Reflector B time. Distributary channels which transported sediment well into the lagoon, have slowly silted up and are now completely buried. Sedimentation now occurs at the lagoon entrance and within the main pass of Te Ava Amua itself. Te Ava Lasi has long been an area of apparent high water velocities with no or little sedimentation proximally but with distributary channels and distal sedimentation well into the lagoon. There has been a gradual diminution of area with no sedimentation and consequent reduction of the distributary lengths.

PHOSPHATE OCCURRENCES

Phosphatized limestones were observed on Sakalua (White and Warin, 1964) and Savave, and have been reported from the reef flat east of Teafuone, the reef flat north of Motumua, central Motumua (Radke, 1985), and are believed to occur on Lafaga. The Sakalua occurrence is the most accessible where a recent weathering profile (Figure 12) is exposed at an eroded corner of the sand cay which has a slightly raised karstified and indurated foundation (Figure 13). Solution depressions within this limestone are rimmed and partly infilled by dark phosphorites.

Petrographic study (Appendix 1) indicates that phosphatization has been part of the recent weathering process in a

wet climate, caused by the downward filtration of rainwater which has leached phosphoric acid from surface guano. The highest phosphate levels (Figure 12) are in the top part of the profile (61% $\text{Ca}_3(\text{PO}_4)_2$). An underlying mottled and leached zone has patchy phosphatization in loose porous nodules (44% $\text{Ca}_3(\text{PO}_4)_2$) but this becomes more pervasive along the basal lag (41-49% $\text{Ca}_3(\text{PO}_4)_2$) (Figure 14) which overlies an irregular and karstified limestone (Figure 13).

The phosphate content in the uppermost zone may be slightly high in that sample NFT 1 had to be collected close to the centre of the cay where the rocky surface showed solution depressions and evidence of water ponding. Remaining samples were collected from a beach - reef flat profile although sample NFT 4 (Figure 15) is from a comparable horizon on Savave.

Both geomorphologic and petrographic evidence indicate the sampled phosphatization to be Recent, since the last low stand of sea level and above the youngest unconformity found. The upper part of the section has had predominantly vadose diagenesis - vadose solution and meniscus or stalactitic cements. Sample NFT 1 from the centre of the island also has had a subsequent phreatic history (Figure 16) but this is attributed to present day episodic surface ponding of rainwater caused by relatively impervious peat and guano within the uppermost soil horizon.

PHOSPHATIZATION MODEL

Phosphate is presently being introduced to Nukufetau via Avian guano. Although this observed process is at only a modest rate, it is seen as the most probably mechanism that may have been operative throughout the Pleistocene.

Recent annual rainfall in Tuvalu is too high for any significant accumulation of guano compared to the phosphatic islands that predominate in the Doldrums ie Line Islands, Nauru, etc. Based on an exhaustive world wide study of Avian guano, Hutchinson (1950) noted empirically that significant guano does not accumulate where annual rainfall exceeds 1500mm per year. It may be possible, however, that in Pleistocene glacial-interglacial periods, the climate of Tuvalu may have varied dramatically from that of today.

Vegetation on Palmyra shows some differentiation on phosphate content of the soil. Pisonia occurs in wetter acid soils as found over phosphatic hardpan while Pandanus and Cocos prefer drier, more alkaline soil on unphosphatized coral debris (Hutchinson, 1950). On Nukufetau, Pisonia was observed to be relatively prolific on Lafaga. Whether this is due to soil phosphate content or to the introduction of seed by migrating birds, it does indicate an association with Avian guano.

Secondary enrichment of phosphate on Nukufetau is most probably by solution, gravity and submarine sorting processes. Under high rainfall, and with prolific vegetation on islands of bird colonization, the phosphate in guano is readily mobilized under and creating acidic conditions with leaching. This also actively dissolves the host calcareous sand with consequent reprecipitation of phosphorite as carbonatian hydroxy-fluorapatites. Phosphate cements and selective replacement in these sands becomes prevalent down to any impermeable barrier or the freshwater-seawater contact - whichever is higher. Both

vadose and phreatic solution processes in limestone are enhanced - in the enlargement of moldic porosity, joints and caverns. In such conduits, there is localization of colloform crusts of phosphate (hardpan) and phosphatic replacement. Being denser and less soluble than the host limestone or calcareous sands, the phosphate is subject to concentration by subaerial solution of the host as expected during glacial drops in sea level. Once physically released from the rock, phosphate enrichment can continue by gravitational or hydraulic processes to concentrate in lower level cave deposits or on the surface as colluvial fans of phosphatic conglomerates.

Phosphorites occur on Aldabra atoll in the Indian ocean, at a latitude comparable to Tuvalu. On Esprit, Aldabra atoll, the phosphorites occur:

1. as bedded deposits near the summit of the island resting on and in cavities of the karstified surface of the island; and
2. as small outcrops of coarse phosphate - cemented bioclastic limestones and large irregular fans of phosphoritic conglomerate on the lower slopes of the island (Braithwaite, 1980).

With resubmergence during rises of sea level in interglacial periods, such phosphate accumulations can be either buried and diluted by re-establishment of reef and sedimentation, or if in favourable hydrodynamic conditions such as strong currents, could be further sorted and concentrated as lag deposits.

WHERE TO PROSPECT

Submarine occurrences are probably the only areas of prospecting potential as land area on Nukufetau is at a premium for agricultural usage. Anticipated submarine deposits are of a current-sorted lag type derived via fan slope deposits from high-relief primary phosphatic deposits such as at Sakalua.

High phosphatic crusts and pods

Extension of the surface Sakalua-type deposit into the immediate subsurface is probable in several areas of known surface phosphate occurrences. This would be most probable in the Sakalua-Teafuone-Te Ava Amua reef flat area. Such deposits would be expected to be thin but very rich stratiform crusts as well as locally scattered pods in solution cavities below these crusts. Lafaga should also be investigated.

Seismic penetration over reef flats was unsatisfactory and prediction of localized pods is difficult without probing or drilling.

Fan Deposits

Colluvial fans, whether phosphatic or not, are difficult to identify in the shallower sequence as commonly such areas are sand-covered and seismic resolution is unsatisfactory. Two sizeable bodies have been delineated on or just below the deeper unconformity (Reflector B). Although overburden to such features is a major consideration, their dimensions (Figure 10) are encouraging. The larger of these bodies are located:

1. On the lagoonward slope in from Te Ava Lasi where overburden is minimal (body has an area exceeding 3sq km and ranges from 0 to more than 20m thick); and
2. On and below the lagoon slope adjoining the islands Faiava Lasi, Niu'aluka, Lafaga and Oua in the north-eastern corner of the lagoon (approximately 3sq km extent with varying thickness from 0 to more than 10m).

In the latter area, overburden thickness is not as favourable as at Te Ava Lasi.

Channel Lag Deposits

If the channel model for submarine tidal distributaries can be confirmed, then channels with hardground bottoms or channels eroded down to the first unconformity would have the greatest probability of surface lag deposits. Figure 2 shows possible channel systems, the dominant one emanating from Te Ava Lasi. Other possible channels run into the lagoon from the north and northwestern margins.

Channel lags occurring on the first unconformity would have potential. Probable channel systems are shown in Figure 9 indicating major distributary channels to the east of Te Ava Lasi and more questionable ones emanating from the northern channel of Te Ava Amua.

CONCLUSIONS AND RECOMMENDATIONS

1. Accumulations of phosphate exist on Sakalua in a recent weathering profile 1.5 metres thick in which P₂O₅ content varies from 18-27% P₂O₅ (41-61% Ca₃ (PO₄)₂). Traces of phosphate have also been reported from the east end of Savave, the reef flat east of Teafuone, the reef flat north of Motumua, central Motumua, and probably in central Lafaga.
2. Rectangle-shaped Nukufetau has a deep lagoon exceeding 40m depth on its eastern side and shallowing to less than 30m on its central western side between the two reef passes, Te Ava Amua and Te Ava Lasi. There are only limited areas of very shallow prospective lagoon floor.
3. Within the limits of seismic penetration, up to 9 Reflectors interpreted as unconformities, lie within the upper 50 metres of lagoonal sequence. The shallowest unconformity, Reflector A, generally lies between 4 and 12m below lagoon floor but is sometimes exposed around the remnant bases of blasted patch reefs. The deepest unconformity, Reflector B, lies between 10 and 40m below Reflector A.
4. Pleistocene and Recent development of Nukufetau atoll appears to have been on a subsiding basement with the dominant influx of sediment into the lagoon via the western tidal passes and reef flat. This asymmetric sedimentation pattern is considered the prime cause of an eastward-sloping lagoon floor.

5. Potential prospects for phosphate accumulation are as follows:

- a. Below Sakalua, Lafaga and their surrounding reef flats for repeated weathering profiles above unconformities that are phosphatic as at Sakalua.

Exploration would require drilling and sampling with accompanying portable seismic refraction surveys to delineate the unconformity surfaces.

- b. Two very deep colluvial? deposits lie on or just below the marginal slope of Reflector B. These lie lagoonward of Te Ava Lasi and Faiava Lasi-Lafaga-Niuatui. These bodies lie below at least 20m of overburden at considerable and variable water depths.

Exploration requires stratigraphic drilling and sampling at a scale which might be better performed by an additional leg to a deepwater research cruise.

- c. Surface lag deposits may exist in channels on the lagoon bottom and incised into the shallowest unconformity (Reflector A).

Exploration would require initially more detailed bathymetry and shallow seismic to confirm the channel model and to map out the full distributary pattern. Sampling would be by bottom sampling and by drill or vibrocoring into the shallowest unconformity.

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APPENDIX 1

PETROGRAPHIC DESCRIPTIONS

NFT1

Description: This is a foraminiferal grainstone (Dunham (1962) Classification) comprising predominantly Calcarina and Marginoporida foraminifera, minor coralline algae and coral fragments (Figure 16). The grainstone has variable porosity because of stratified cementation (interparticle porosity ranges from 30 to 5%) and associated occlusion of internal pores of the component particles (intraparticle porosity varies from 50 to 20%). Rare mollusc fragments are preserved only as ghost outlines of collophane cement. The shell fragments have been totally dissolved away. Phosphate, present as iron-stained collophane, predominates as meniscus and rim cements. Aragonitic foraminifera, especially Marginoporidas tend to be preferentially replaced and occluded by collophane (Figure 16). Calcarina tests resist replacement on their exterior, largely retaining the fibrous calcitic structure but internal pores are variably occluded with rim (isopach) cements. Collophane (colloform apatite) comprises 61% by weight of this rock.

Interpretation: The grainstone most probably accumulated as a beach sand, being well sorted and with little original lamination. The almost total Calcarina content is comparable to present day sand cay beaches.

As indicated by the porosity varying from 25 to 80% the rock is friable.

Meniscus cements indicate cementation under vadose conditions. However rim cements in other parts of the rock (Figure 16) imply phreatic conditions which may have occurred in

outcrop during the frequent torrential rainstorms. Because of the relative solubility of aragonitic components, phosphatic replacement preferentially follows these particles.

This beach sand could be relatively young, less than 5ka, implying rapid phosphatization which is not improbable considering the rainfall, and humic acidity on a very lush island.

NFT2

Description: NFT 2 is a phosphate limestone from within karstic depressions on the intertidal reef flat (Figure 13). It is laminated with gradational changes between different textural types. One end member is a uniform well sorted foraminiferal coralgall - peloidal grainstone, very porous, but with both clotted and rim cements of collophane. This grades into peloidal-coralgal-foraminiferal packstone which has very patchy phosphatic cement coatings and replacement only on upper surfaces of particles.

Collophane occurs in the grainstone texture as rim cements around particles and as replacement of geopetal pelletal infillings inside gastropod body chambers. In the packstone texture, collophane is restricted to the upper surfaces of large particles where the peloidal matrix is phosphatized - in a 'ponded' distribution.

Interpretation: The textural range of this sample is compatible with a boundstone (reef rock) which would by its organic accretion, comprise grainstone textures in part. Phosphatic replacement fabrics suggest vadose conditions but with impermeable packstone areas, possible short-term phreatic conditions were maintained in the ponding of interstitial water above these barriers.

NFT 3

Description: The sample is an indurated iron-stained phosphatic pebble from within a mixed lag conglomerate within karstic depressions of 0.3-3m diameter and 0.25m deep (Figure 12). Other well-rounded tabuloid pebbles comprise coralgall boundstone and grainstone, and are bound in a semi-indurated matrix of beach sand. The sampled pebble appears to have been derived locally from underlying iron-stained phosphatic crests.

NFT 3 is texturally a Marginoporid-coralgall-coral grainstone with high secondary porosity (Figure 14). This grainstone is almost entirely an orange collophane gel which has replaced the original calcareous particles. It is now 41% $\text{Ca}_3(\text{PO}_4)_2$ by weight. Synaeresis cracks are common. Interparticle areas are solution - modified and partly infilled with unaltered geopetal accumulations of calcareous pellets and small foraminifera.

Interpretation: This clast has been derived from a phosphatized surface which has been subaerially exposed for an extensive period, producing dissolution - enhanced interparticle porosity. Subsequent fine grained calcareous pellets and foraminifera have been washed into and cemented in these pores prior to mechanical erosion and reworking of this clast in a basal lag over a karstic unconformity.

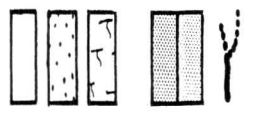
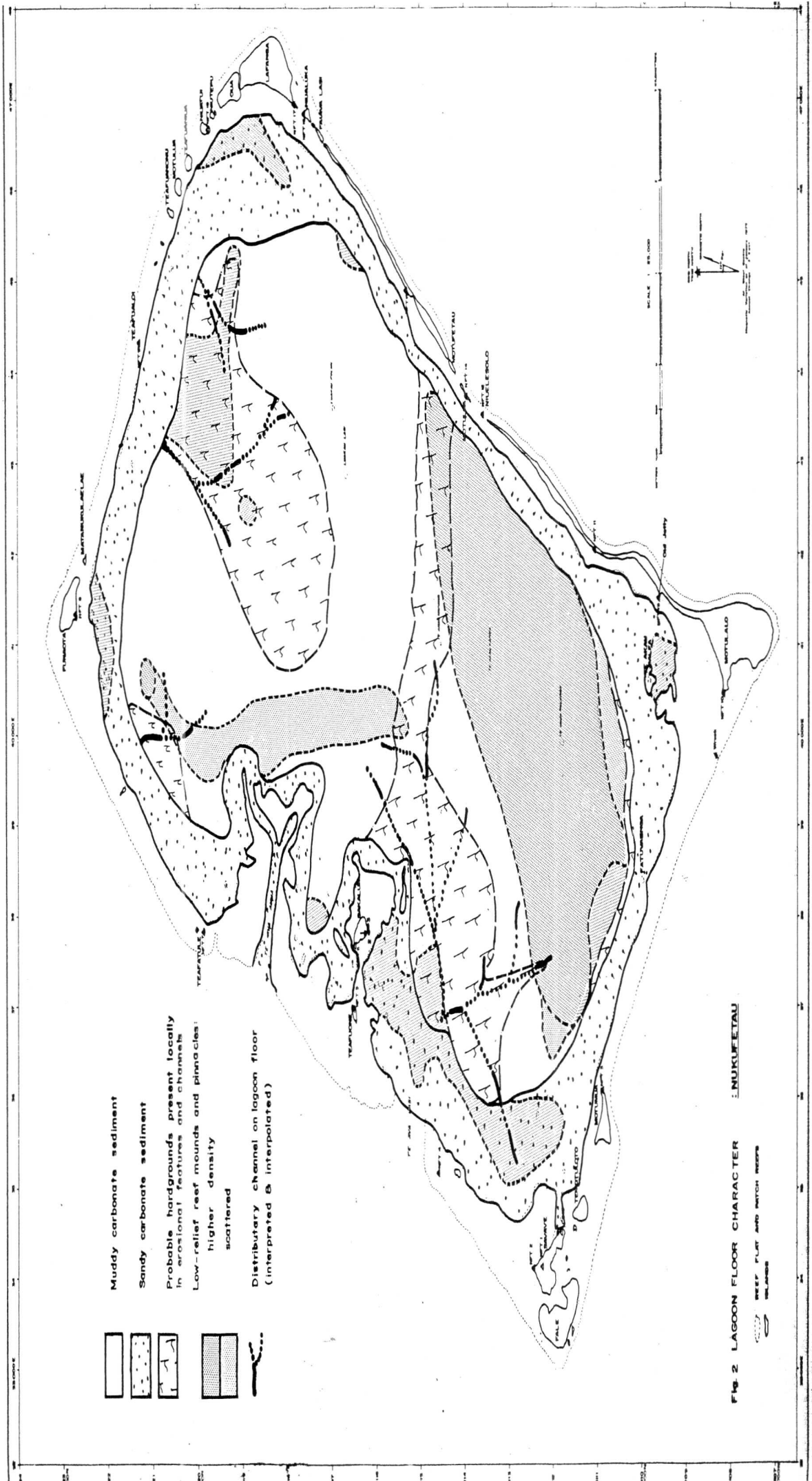
NFT 4

Description: This is a friable foraminiferal grainstone comprising predominantly Calcarina with minor Marginopora, Halimeda, coral fragments and intraclasts (Figure 15).

Intraparticle porosity is approximately 20%. Interparticle porosity is high, approaching 50% and cementation is minimal. The earliest cements are pendant and meniscus accumulations of colourless collophane, overlain by collophane rim cements (Figure 15). These are, in turn, covered by very thin fibrous aragonitic pendant cements.

The phosphate content of 44% $\text{Ca}_3(\text{PO}_4)_2$ by weight is primarily as cements and replacement of particles other than Calcarina.

Interpretation: NFT 4 is representative of patchy phosphatization within a beach sand that now comprises a poorly developed 'B' soil horizon. Most phosphatization has been under vadose conditions, from downward percolation with rich rainwater. A subsequent higher watertable, perhaps as this sediment became the central part of a rapidly accreting cay, caused more uniform phreatic phosphate cementation.



Muddy carbonate sediment

Sandy carbonate sediment

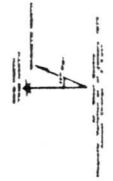
Probable hardgrounds present locally in occasional features and channels

Low-relief reef mounds and pinnacles; higher density scattered

Distributary channel on lagoon floor (interpreted & interpolated)

Fig. 2 LAGOON FLOOR CHARACTER INUKUFETAU ISLAND

REEF FLAT AND WATCH REEF



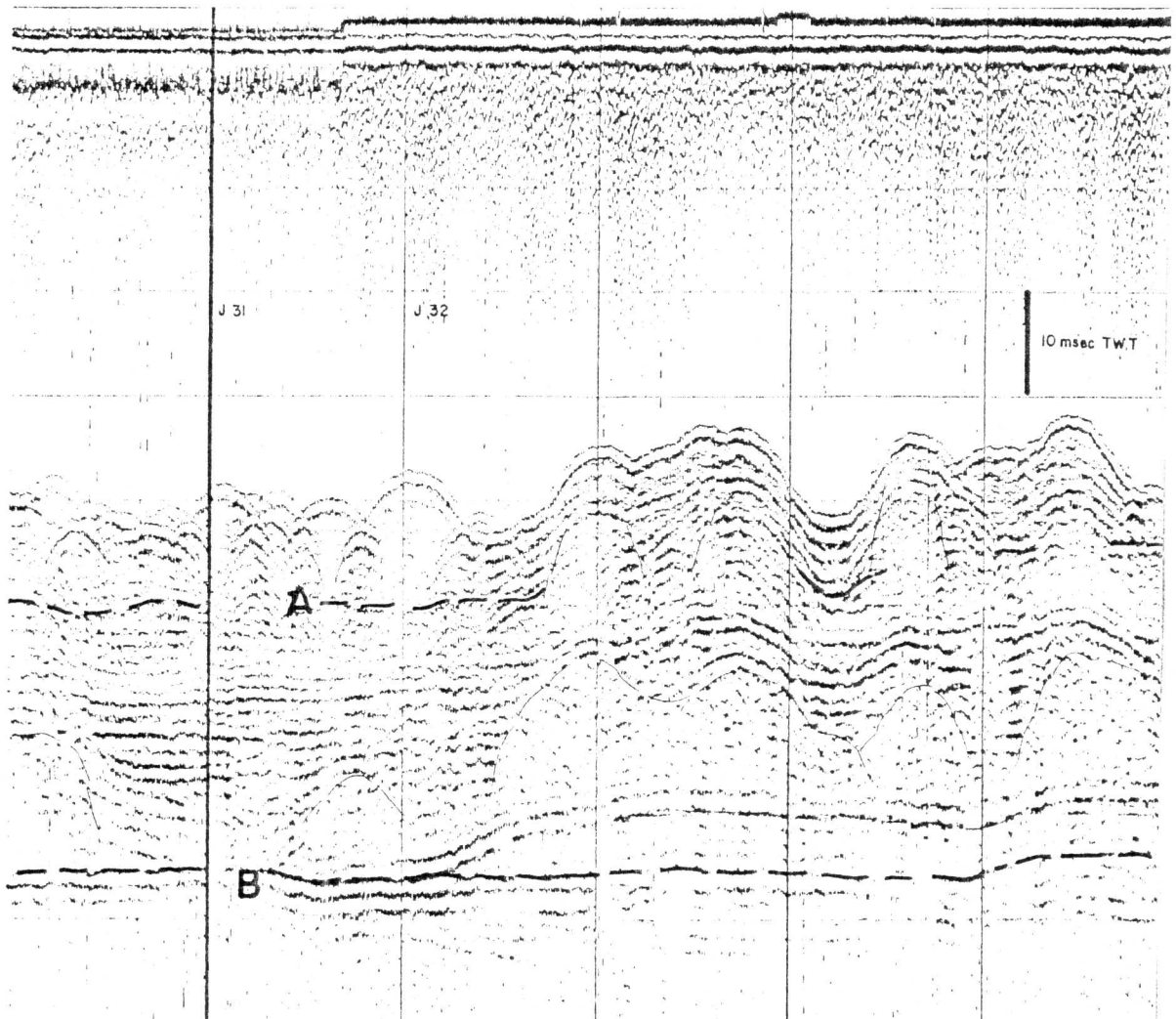


Figure 3 A high density of low reef mounds is apparent throughout the deepest part of the lagoon. While the lagoon reef mounds started development over an old high, the smaller mounds commenced development on the upper unconformity (Reflector A). Line J Stations 30-36

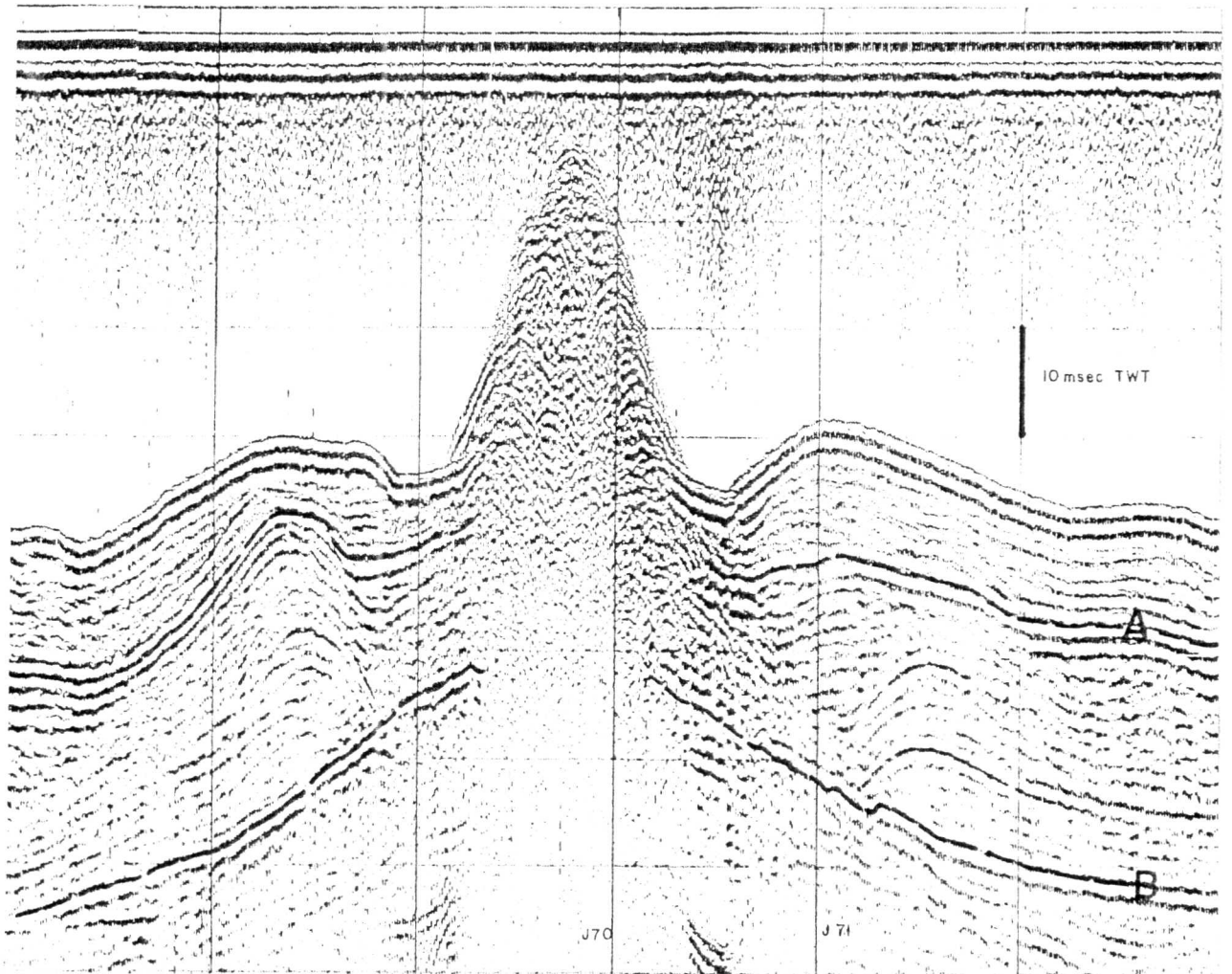


Figure 4 A prominent subtidal pinnacle reef with broad conical form and rounded top. There is an apparent moat and levee system surrounding its base, and which is pervasive down to Reflector A. This base is a much broader simple conical form.

Intersection of Lines J (Station 70) and H (Station 34).

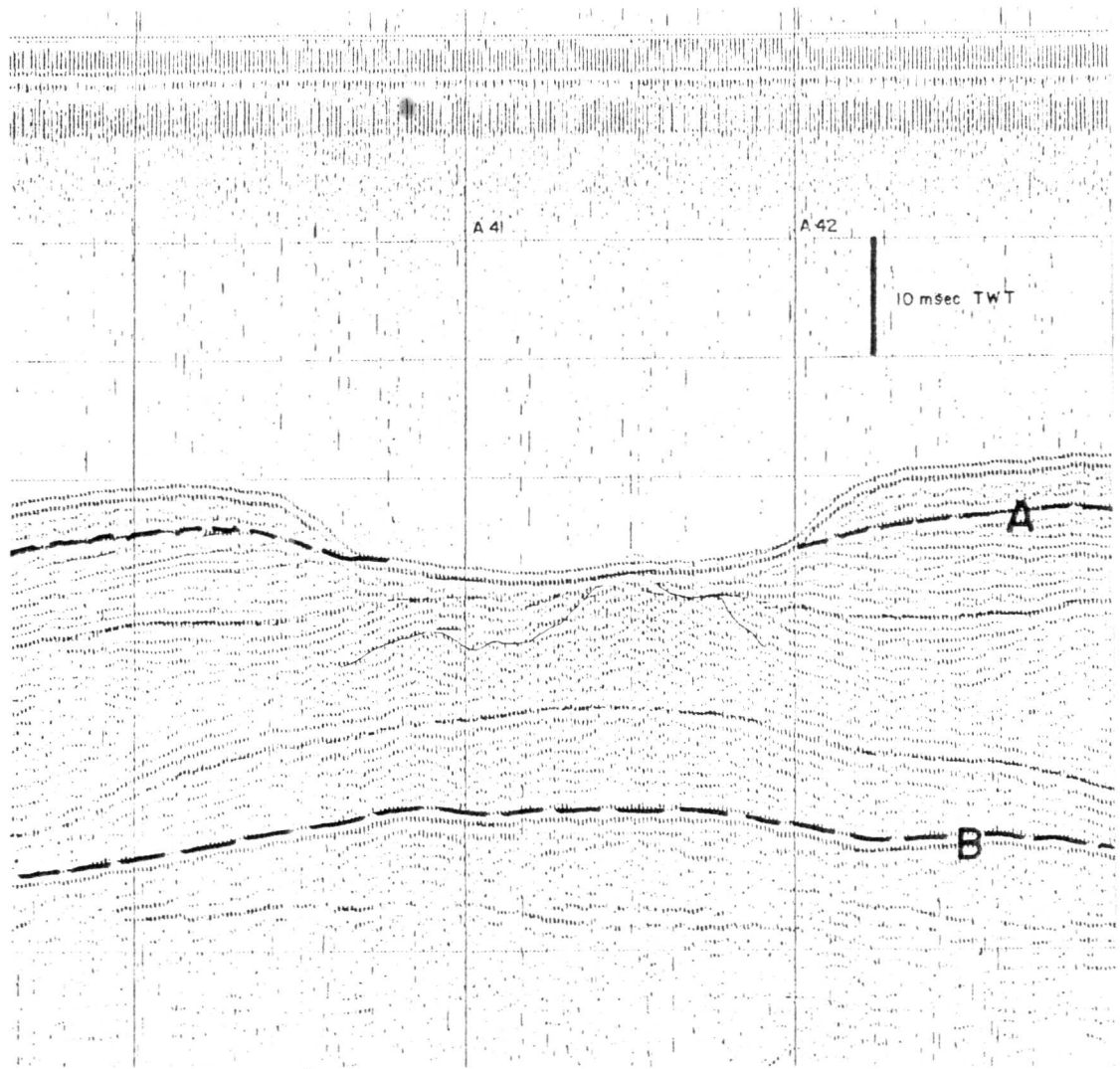


Figure 5 A broad flat-bottomed depression approximately 6m deep with erosional margins and base. An underlying very old reef mound (present below Reflector B) is truncated just below the depression. Line A Stations 40-43.

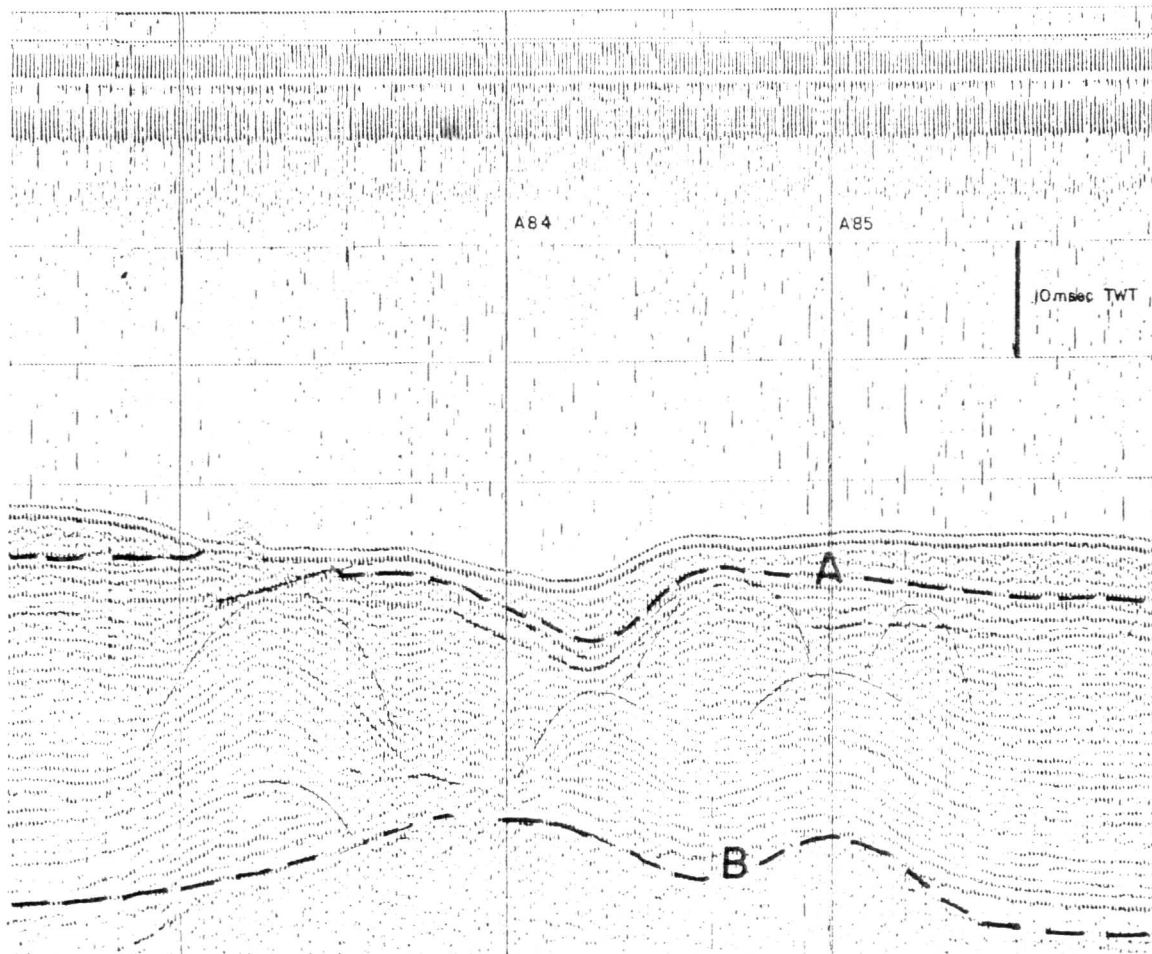


Figure 6 An Asymmetric and shallow surface depression overlies a complex of reef mounds and peripheral moats or channels which in turn overlie a low high on Reflector B. A pinnacle reef may be present offline.

Line A Stations 83-86.

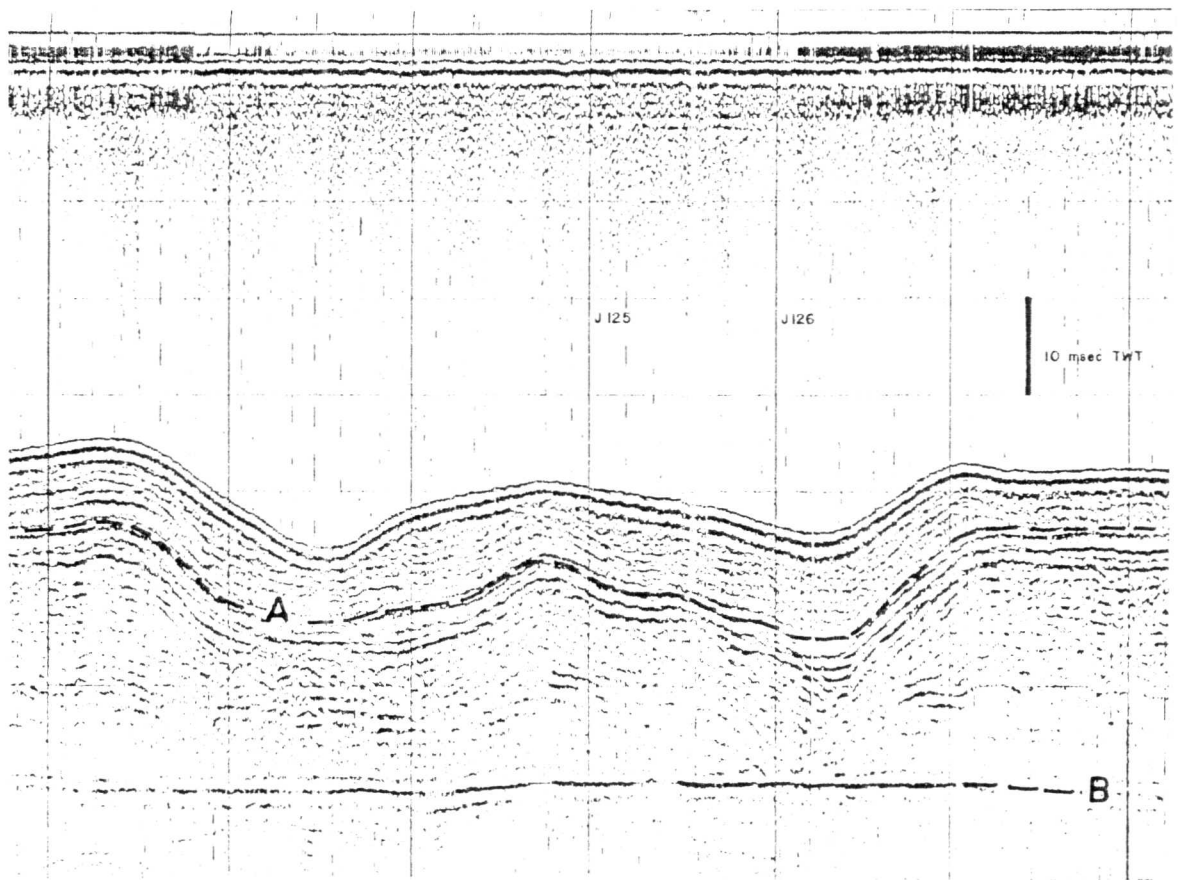


Figure 7 A broad depression with subtle levee-like rims and a gentle central rise. Underlying Reflector B is a flat eroded surface with a reef mound? developed on it. The channel-like depression at J126 has probably lag deposit infill (very strong Reflectors).
 Line J Stations 121-128.

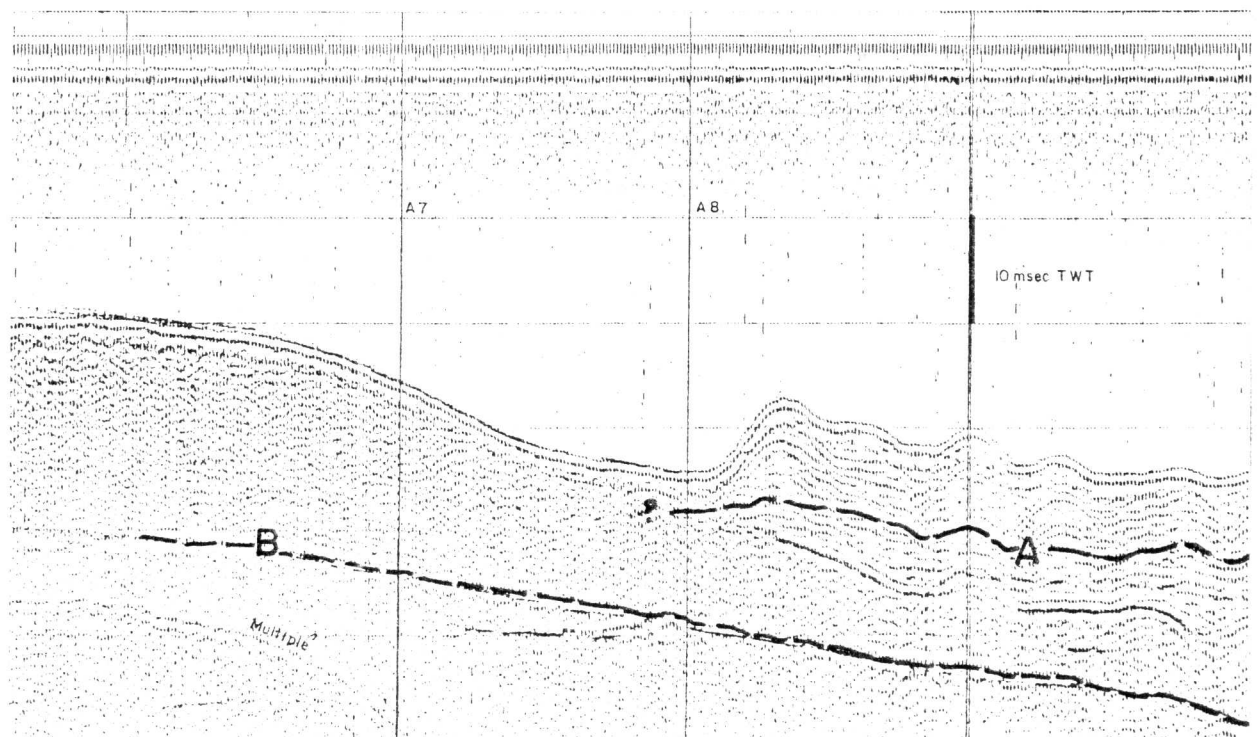
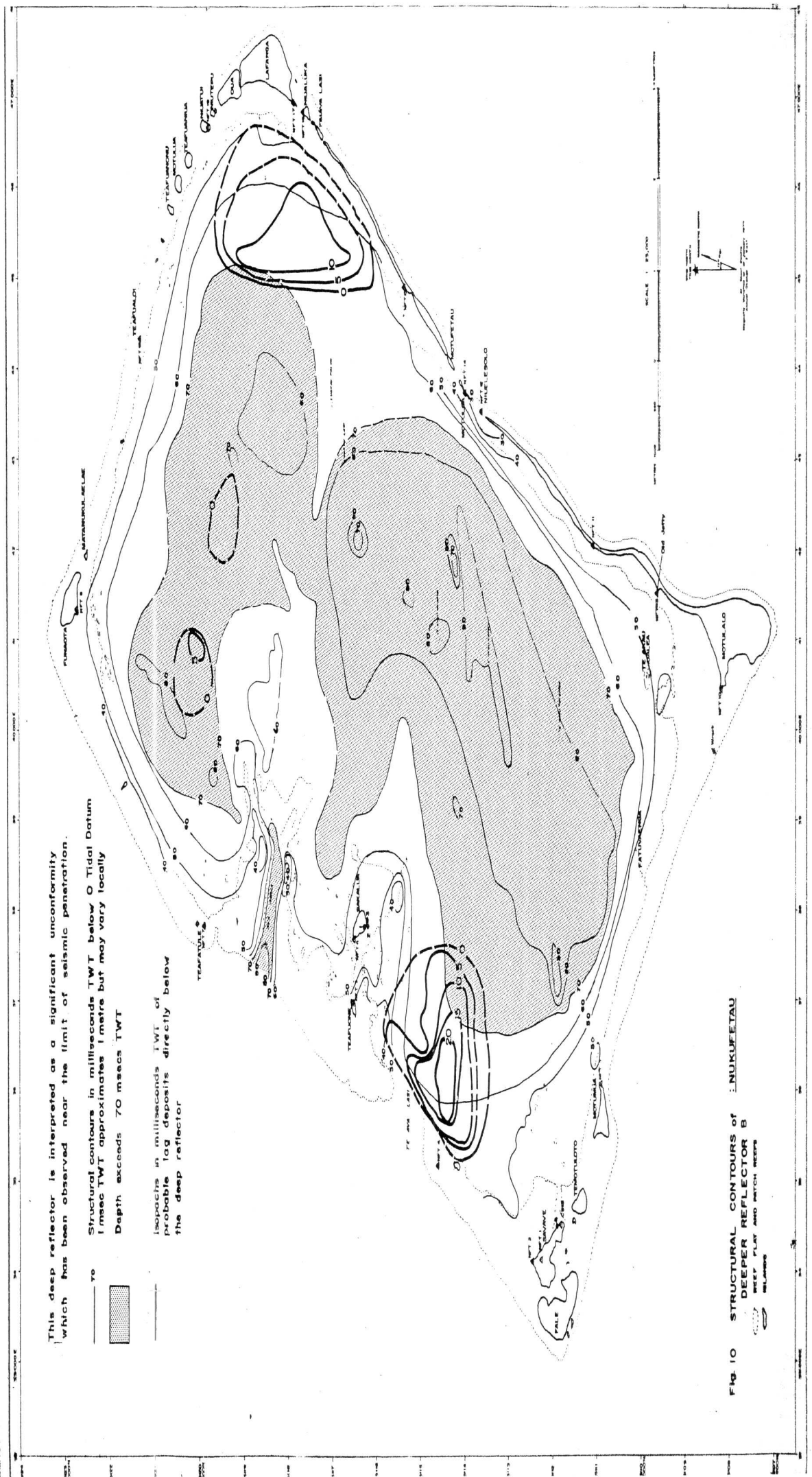


Figure 8 A sand terrace on the southern lagoon margin slopes into the lagoon floor where there is a broad sand-floored depression adjacent to bedded reef mounds and sediment. Deep Reflector B has a very gentle uniform slope. Line A Stations 6-10.



This deep reflector is interpreted as a significant unconformity which has been observed near the limit of seismic penetration.

to

Structural contours in milliseconds TWT below 0 Tidal Datum
 1 msec TWT approximates 1 metre but may vary locally
 Depth exceeds 70 msec TWT

Isopachs in milliseconds TWT of probable lag deposits directly below the deep reflector

Fig. 10 STRUCTURAL CONTOURS OF DEEPER REFLECTOR B
 DEEP PLAY AND MATCH REEF ISLANDS

P	Ca	Mg	Fe	Mn
12.2 (27.9) (61)	35.1	0.92	<0.04	0.01
8.9 (20.4) (44.5)	34.7	<0.69	<0.01	0.01
8.2 (18.9) (41)	34.2	<1.91	<0.01	0.01
9.78 (22.4) (48.9)	33.9	<1.79	<0.01	0.01

{ } Phosphorus as P₂O₅ (PO₄)₂
 { } Phosphorus as Ca₃

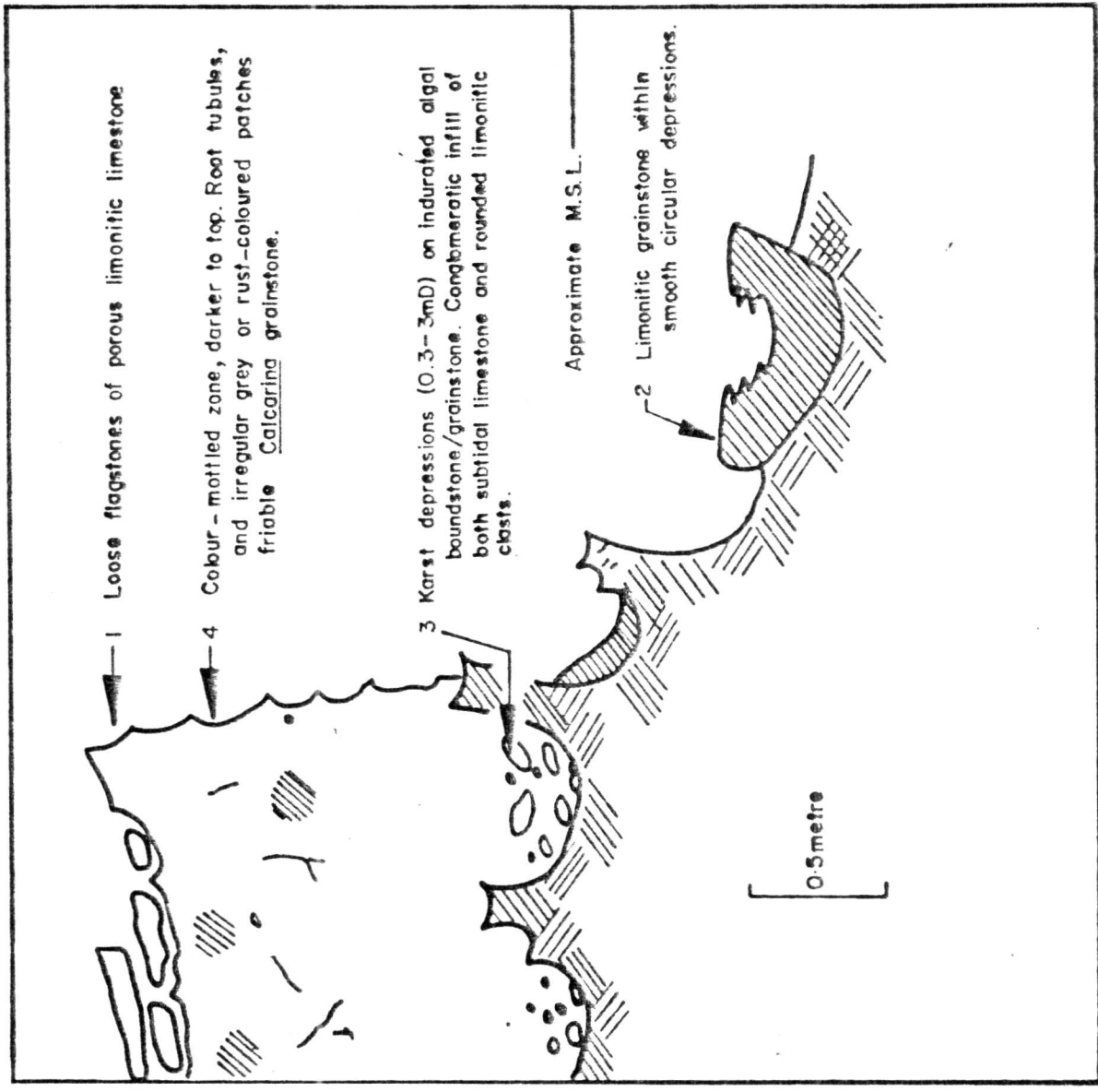


Figure 12 Geochemistry of stratigraphic profile on south-east Sakalua, Nukufetau. Analyses are in weight %



Figure 13

Intertidal 'beachrock', Sakalua, Nukufetau

Black rings of phosphatized limestone (49% $\text{Ca}_3(\text{PO}_4)_2$) outline the distribution of solution depressions in a recent unconformity - the remainder of which is being actively removed by intertidal bioerosion.

Karstic depressions are 0.3-3m diameter.

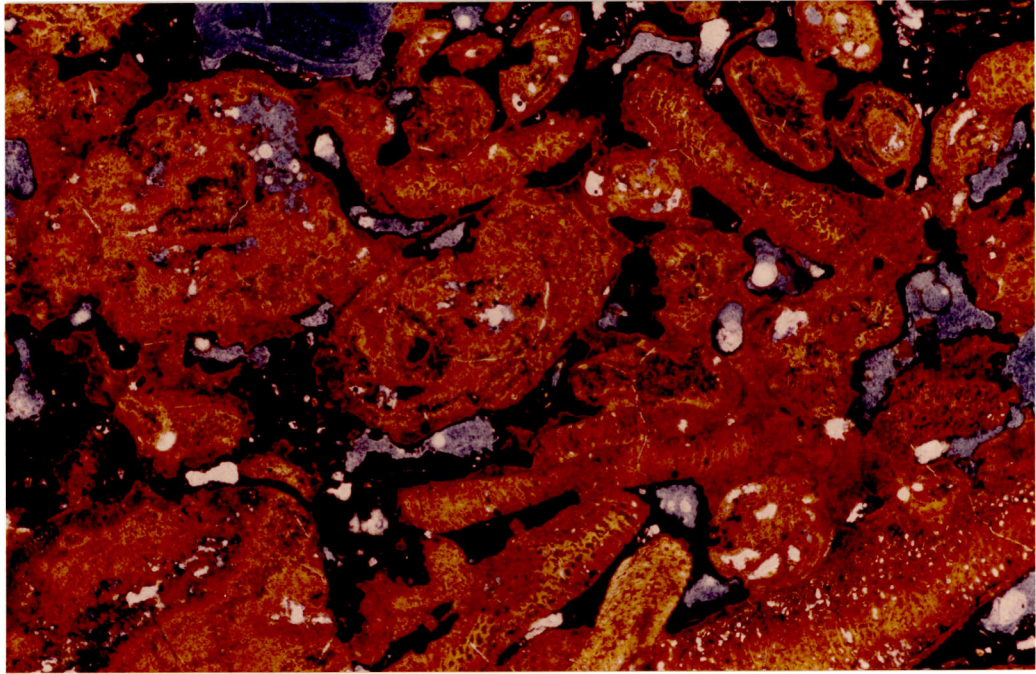


Figure 14

Foraminifera, coral and coralline algae fragments are totally replaced by collophane (orange) which shows fine synaeresis cracks from shrinkage. The rock is very porous (blue) with infiltrated carbonate pellets and fragments (black) forming geopetal deposits between phosphatized particles.

NFT 3, Plane Polarized light, x 20.

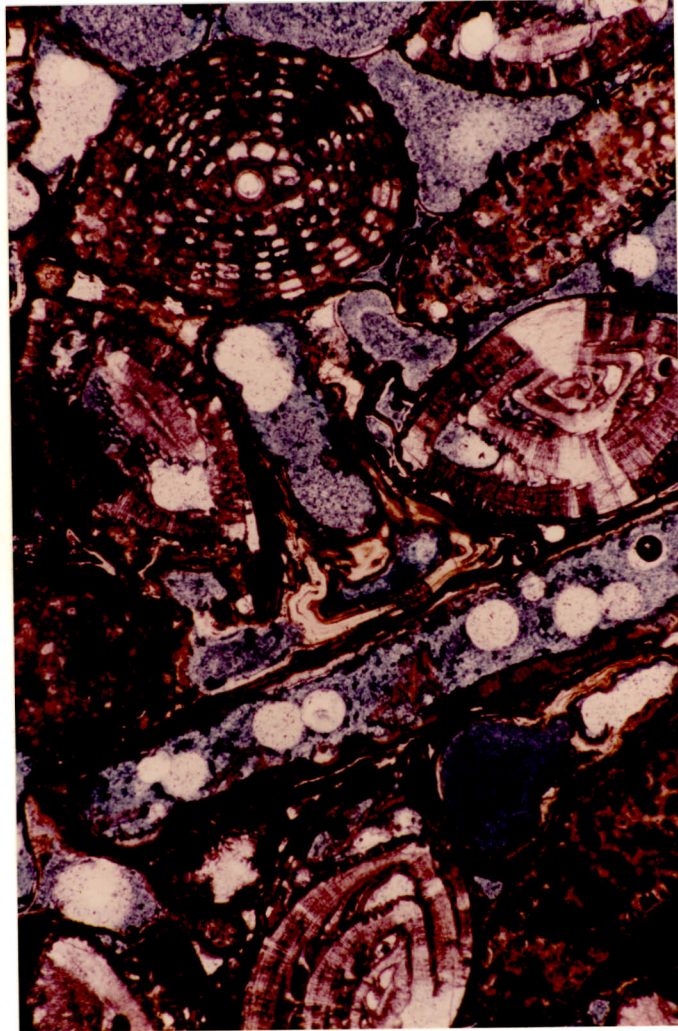


Figure 15 Foraminiferal grainstone, very porous (impregnated with blue resin), with very thin meniscus and isopachous collophane (amber coloured phosphate) cement rims. Marginoporiid foraminifera are partly replaced by phosphate or else totally dissolved away leaving moldic pore spaces. Calcarina foraminifera remain unaltered.

NFT 4, Plane Polarized light, x 45.

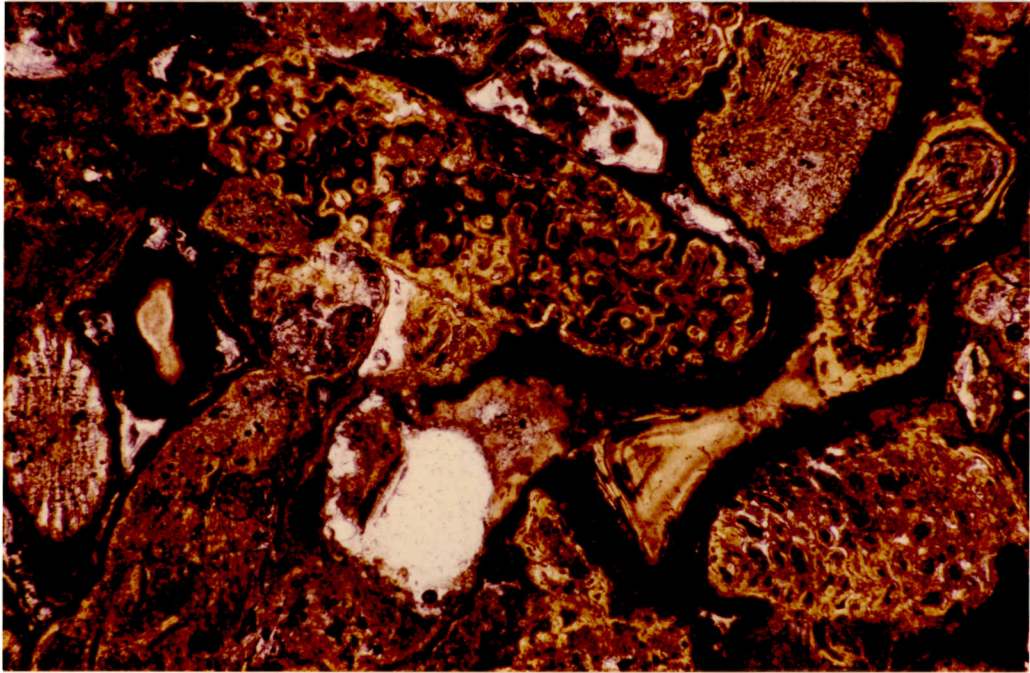


Figure 16 Foraminiferal grainstone almost totally replaced by collophane (amber yellow). Cementation is by very thin isopachous collophane cement, subsequent carbonate micrite (black) and final pore occlusion by collophane (amber yellow).

NFT 1, Plane Polarized light x 40