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Distribution and Morphology of Chatham Rise Phosphorites

by

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ABSTRACT

This study is based on an extensive programme of sampling for phosphorite nodules, undertaken by Global Marine Inc., on the Chatham Rise during 1967 and 1968.

The data resulting from this survey substantially increase knowledge of the general geology and geomorphology of Chatham Rise, and reconstructions are presented of the structure, stratigraphy and geological history of the region in the light of the new evidence.

The nature of the phosphorite nodules has been studied in considerable detail, and fresh information on the distribution and on the complex mineralogy and geochemistry of the phosphorite is discussed. Glauconite commonly accompanies the phosphorite on the Chatham Rise as discrete sandsize grains and as thin coatings on nodules, and this association is described in some detail.

Finally, an interpretation is given of the evolution of the Chatham Rise phosphorite nodules by phosphatisation of late Miocene foraminiferal oozes, followed by uplift, fragmentation and weathering under subaerial conditions before resubmergence.

INTRODUCTION

During 1967 and 1968, Global Marine Inc. conducted an extensive exploration programme on the Chatham Rise. The work was undertaken in order to determine whether phosphorites, known to occur on the Rise, represented a potential phosphate ore deposit. Approximately 329 bottom samples were taken during the course of this investigation.

The primary purpose of this study is to describe the phosphorites of the Chatham Rise and determine their origin. A secondary objective is to discuss the geology of the Rise in the light of the new data contributed by the sampling.

Previous Work

The occurrence of phosphorite nodules in a sample taken on the Chatham Rise was reported by Reed & Hornibrook (1952) who attributed their presence to erosional removal of material except for that "preserved by phosphatisation". Norris (1964) describes nodules from various regions of the Rise and takes exception to the erosional theory of Reed & Hornibrook, although not specifying an alternative. Two papers have shown the nodules to have possible economic value (Summerhayes 1967; Watters 1968) and a third, while dealing

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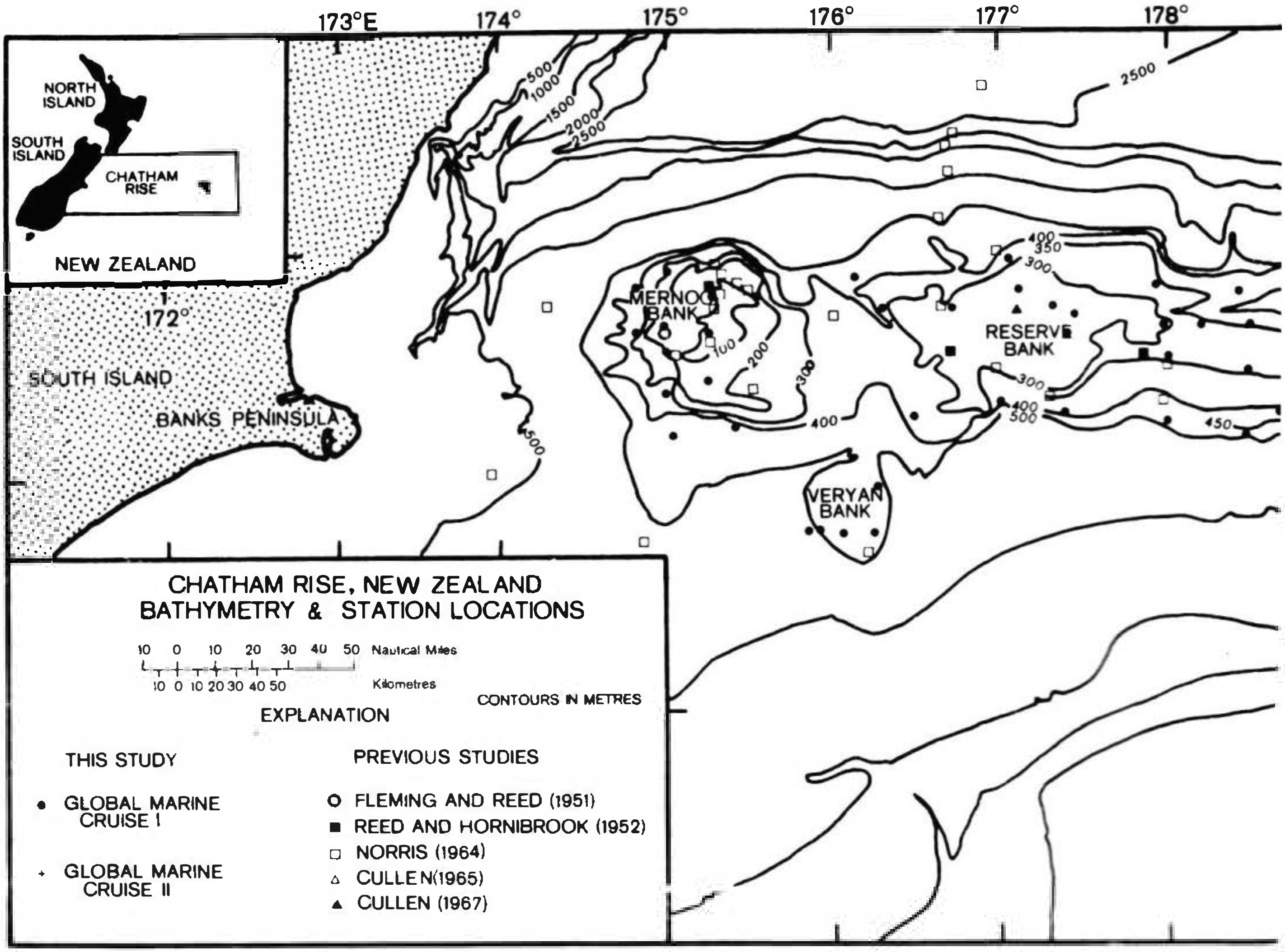


Fig. 1. Chatham Rise, New Zealand : bathymetry and station locations.

with the same theme, adds new data resulting from exploration of the deposits by Global Marine Inc. (Buckenham *et al.* 1971).

Techniques

Bottom Sampling: All the samples were taken with a 45cm diameter pipe dredge. As the Chatham Rise nodules did not approach the dredge diameter in size, the samples are considered to be representative with respect to size, unlike those reported by Glasby & Singleton (1975) who used a smaller diameter pipe dredge. Positions were obtained by celestial navigation. Sample stations are listed in Appendix I and II, and plotted on Fig. 1.

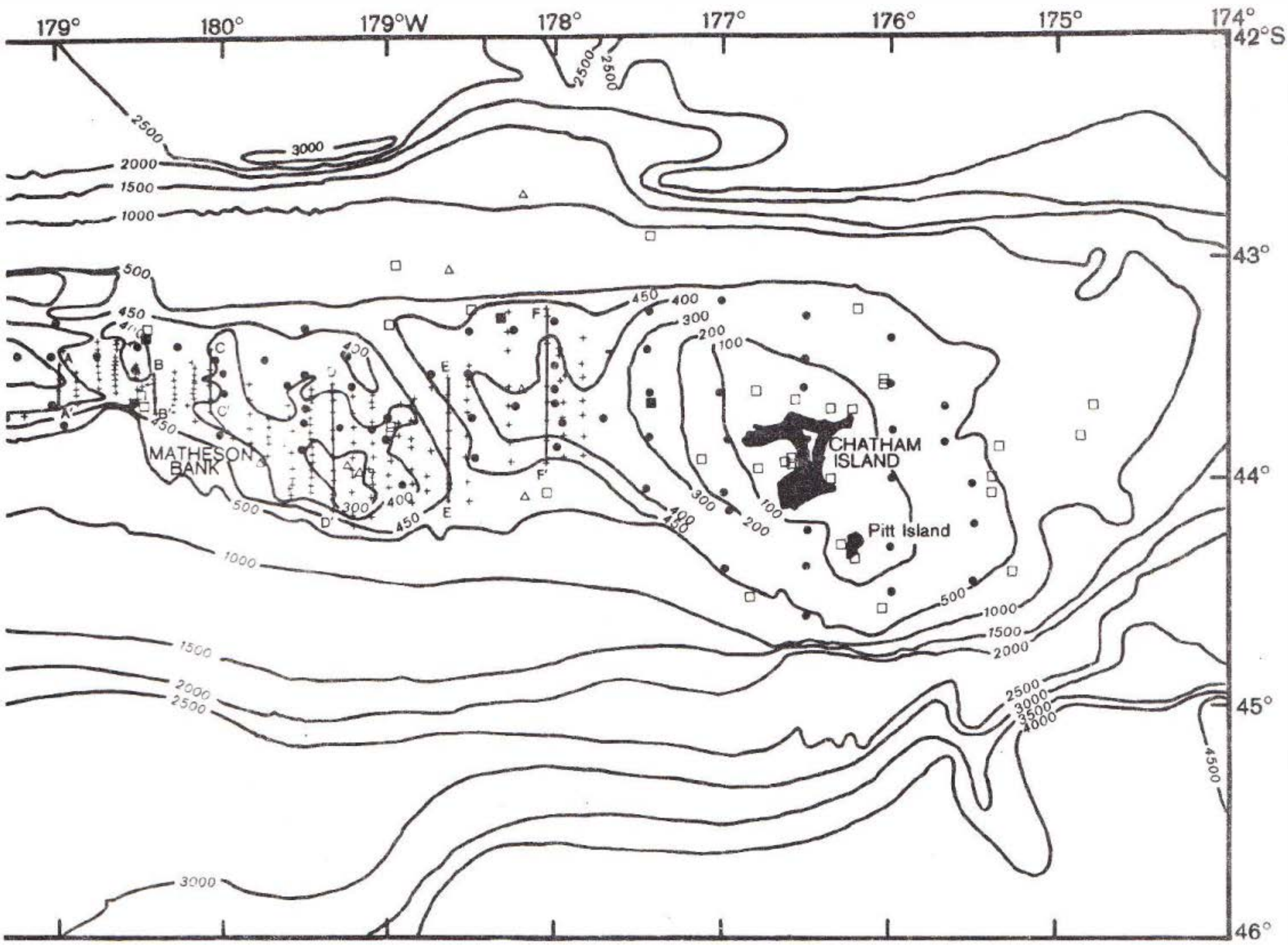
Sample Treatment: Duplicates of all samples taken on the Chatham Rise were given to the author by Global Marine Incorporated. Sediments and rocks from each station were logged and described.

Cross-sections of 2 or 3 nodules from each of 20 different sample stations that yielded phosphorite were prepared and studied. Approximately 43 thin sections were made from 40 nodules. At least one nodule was taken from each of the stations.

Phosphate Analyses: Quantitative analyses for P_2O_5 were performed on 20 samples from the Chatham Rise. Unless a specific region of the interior was selected, analyses were performed on splits of crushed whole nodule cross-sections. These were ground to minus 120 mesh and oven dried for 24 hours at 110°C. Samples were prepared by fusing the powder with La_2O_3 and $Li_2B_4O_7$, and pressing the ground mixture into sample wafers. Analyses were performed on a Norelco X-ray fluorescence unit.

Microscopic Techniques: The mineralogy of clastics in Chatham Rise phosphorites was ascertained by digesting the nodules in HCl and performing a grain count on the clastics in the residue.

Relative percentages of various constituents in the nodules were determined by modal analyses of thin sections. Grain size distributions were arrived at by point-counting grains within sieve intervals.



GEOLOGIC SETTING

TOPOGRAPHY

The Chatham Rise is a broad submarine high extending over 500 nautical miles from Banks Peninsula on the South Island of New Zealand to a short distance beyond the Chatham Islands (Fig. 1). Averaging approximately 60 nautical miles in width, the Rise crest covers over 40,000 square miles or two-thirds the area of the South Island. Outlined by the 500 m contour, the crest of the Rise is separated from the shelf off Banks Peninsula by a narrow saddle just over 570 m deep. The northern slope of the Rise extends to 2,500 m and is notably steeper than slopes bounding it on the south and east which deepen gradually to approximately 4,000 m. Four banks and the Chatham Islands form the major topographical features atop the Rise.

Mernoo Bank, described by Fleming & Reed (1951), is the westernmost bank and comes to within 56 m of the surface. It is roughly dome-shaped, being somewhat elongated along a north-east/south-west axis. The 200 m contour approximately marks the transition from a relatively flat summit to steep slopes on the north, south and west. Fleming & Reed (1951) suggest that the valley-like channels, dissected plateaus, and cliff structures found on the bank result from subaerial processes. Notably, the valley-like channels with branching sinuous courses radiating from the summit region can be traced down slope to about 100 m, a depth consistent with the maximum reduction in sea level during the Pleistocene (Curray 1969). The gentle side slopes of the valleys, which contrast with the very steep slopes often found in true submarine canyons do not point to formation by submarine processes.

Protruding from the southern slope of the Rise is Veryan Bank, a relatively small steep-sided feature with a flat summit at 40 m (Brodie 1964). Flat summit, shape and recoveries of volcanic rocks lead Brodie to suggest it is a truncated volcanic cone.

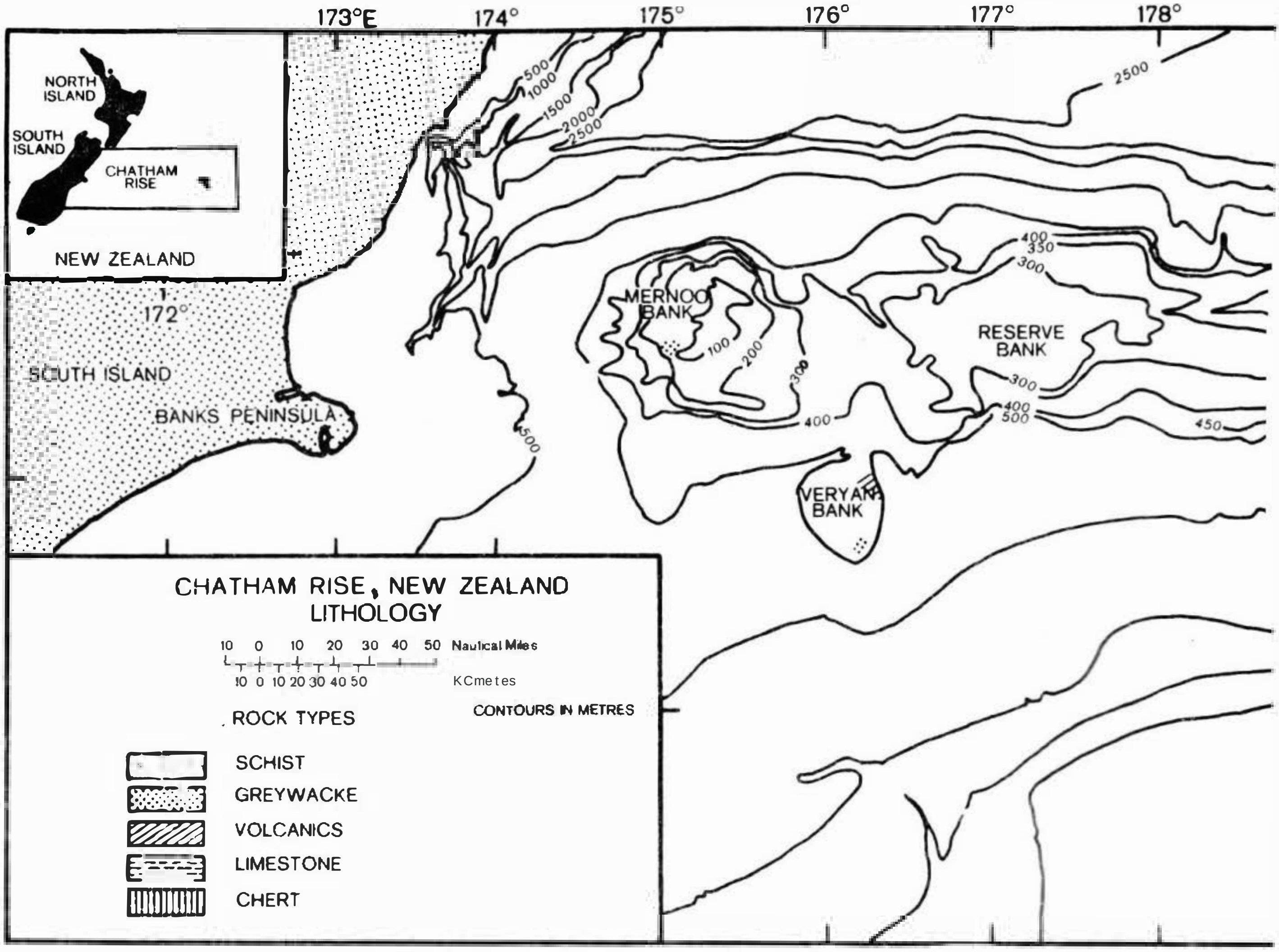


Fig. 2. The Chatham Rise, New Zealand : lithology.

Reserve Bank is elongated east-west, parallel to the axis of the Rise. Separated from Mernoo Bank on the west by a north-south saddle up to 385 m deep, it shallows to the east reaching a depth of under 200 m. Further east it narrows and deepens.

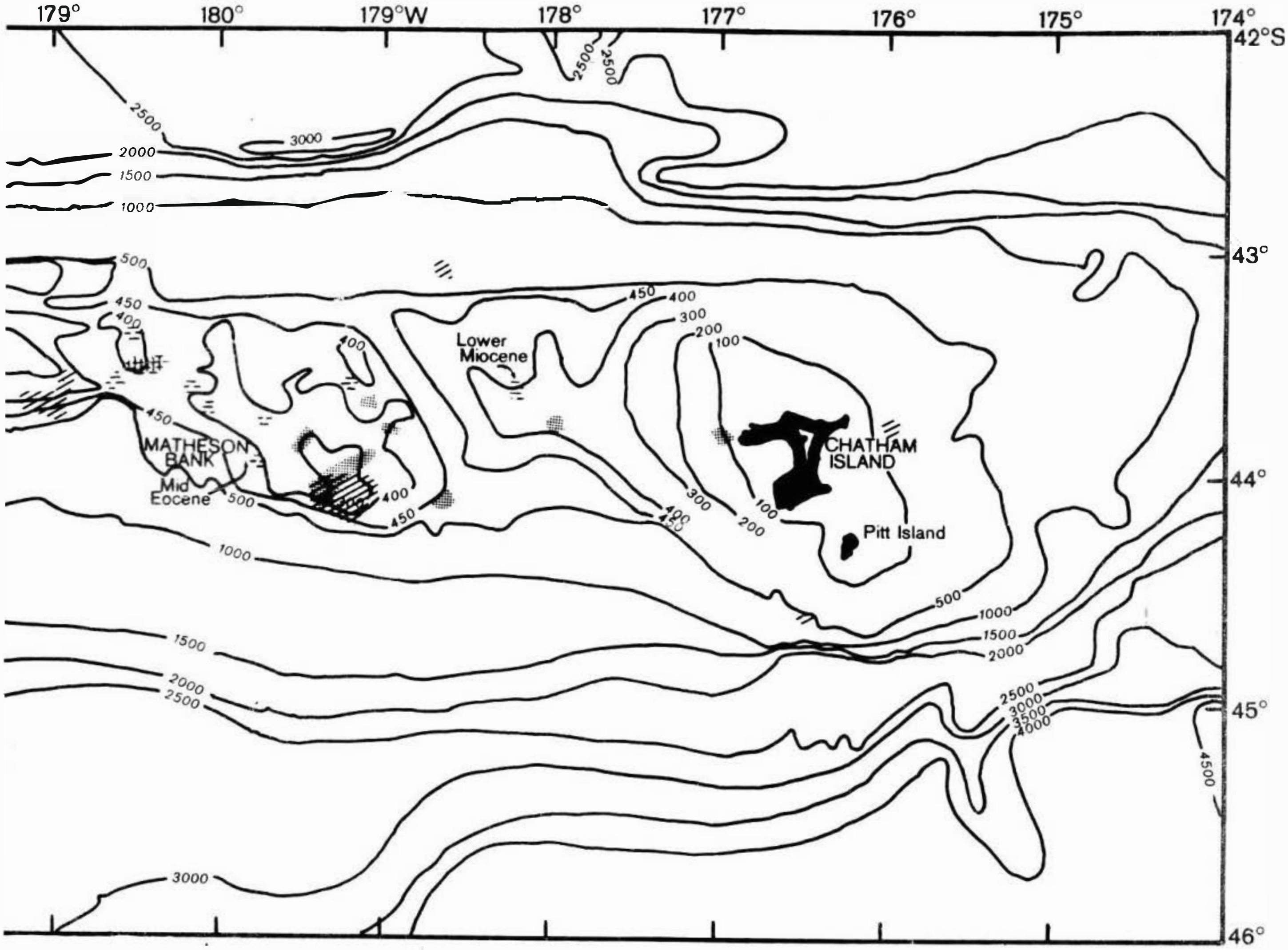
Reserve and Matheson Banks are separated by a broad deep saddle averaging over 400 m in depth. From a regional depth of 400 m, Matheson Bank rises abruptly from the north and south in a succession of levels to depths under 200 m (Fig. 4B in Cullen 1965). The Bank trends in a north-west/south-east direction, terminating somewhat abruptly on the east and deepening into a ridge on the west.

The Chatham Islands are emergent portions of a broad east-west trending arch beginning about 179°W and extending eastward past the Islands. Chatham Island is the largest land mass of the group. The second largest island is Pitt Island to the south-east of Chatham Island. Several submarine benches have been reported around the Chatham Islands (Brodie *in* Knox 1957). The two deepest are at 293 m and 119 m. The former is believed by Brodie to be early Pleistocene while the latter is a result of the lowest glacial sea level stand.

LITHOLOGY

The lithology of Chatham Rise is poorly known and can only in part be pieced together from rocks exposed on Chatham Island and those taken in bottom samples.

Many of the rock fragments from the Chatham Rise are believed to be locally derived (Fig. 2). This is based upon generally accepted criteria for autochthonous occurrence : large size, abundant rocks of similar lithology, fresh fracture or angularity, and fragile or poorly consolidated rocks (Emery 1960). In certain areas of the Rise, however, mixed assemblages of exotic rock types have been recovered that include red feldspathic sandstone, garnetiferous granite and granite gneiss, dioritic gneiss, dark greywacke, schist and andesite (Cullen 1962). The red sandstone, in particular, shows undoubted evidence of glacial transport, and it is considered that the assemblages in which this rock occurs have been ice-rafted, presumably from Antarctica.



The oldest rock type recovered from the Rise is from the Chatham Islands, and is a light grey, medium-grained, well-laminated schist which is correlated on petrographic and lithologic grounds with the Otago Schist on South Island (Allan 1929; Hay *et al.* 1970). Westward, along the strike of the schist on Chatham Island, similar schists have been dredged (Reed & Hornibrook 1952; Cullen 1965). These, and samples taken during this study, indicate extensive exposures on Matheson Bank, and to a lesser degree on the arch extending to the west from the Chatham Islands. While the lack of schist in samples west of 180° suggests it is not exposed, Houtz *et al.* (1967) believe the base reflector in seismic profiles over Reserve Bank represents the westward extension of the schist. Otago Schist, although exposed only on the eastern portion, may then extend beneath younger formations along the remainder of the length of the Rise.

On the South Island, Otago Schist has been interpreted as a metamorphosed basal section of a thick sequence of greywackes which conformably overlies it (Houtz *et al.* 1967; Brown *et al.* 1968). Greywackes, which grade into schist on Chatham Island and appear equivalent to these Triassic and Jurassic greywackes, are dredged from widely scattered localities on the Rise (Fig. 2). Some of these greywackes may be derived from a greywacke conglomerate, such as the Cretaceous Headland Conglomerate found on Pitt Island. Whether eroded from primary or secondary deposits, their presence on Reserve Bank, Mernoo Bank, Pitt Island, and Chatham Island indicates their original extent. The presence of schist on Matheson Bank suggests erosional removal of greywacke cover from that feature.

Late Lower to early Upper Cretaceous deposits are represented by a series of conformable conglomerates, sandstones and calcareous tuffs, which constitutes the Waihere Formation of Pitt Island. The basal Headland Conglomerate (composed of rounded schist and greywacke clasts) probably indicates a major unconformity between it and underlying beds (Hay *et al.* 1970). The microflora from lignitic lenses within the sandstones suggests non-marine conditions which gave way to marine conditions in which the tuff was deposited.

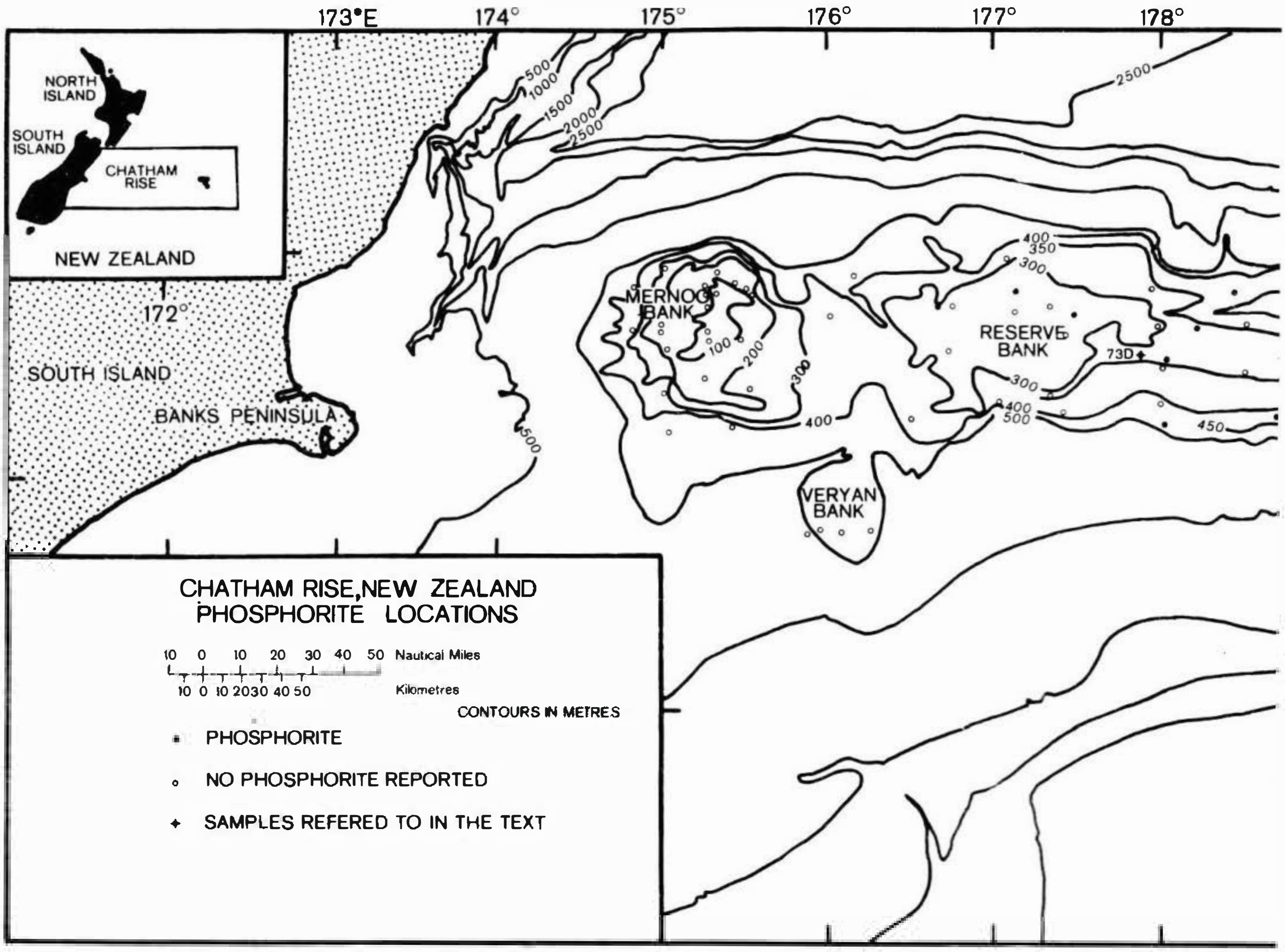


Fig. 3. The Chatham Rise, New Zealand : phosphorite locations.

Paleocene to Lower Eocene grits, greensands, phosphatic nodules and limestones make up the Tioriori Group which disconformably overlies Otago Schist on Chatham Island. Shallow marine conditions are indicated.

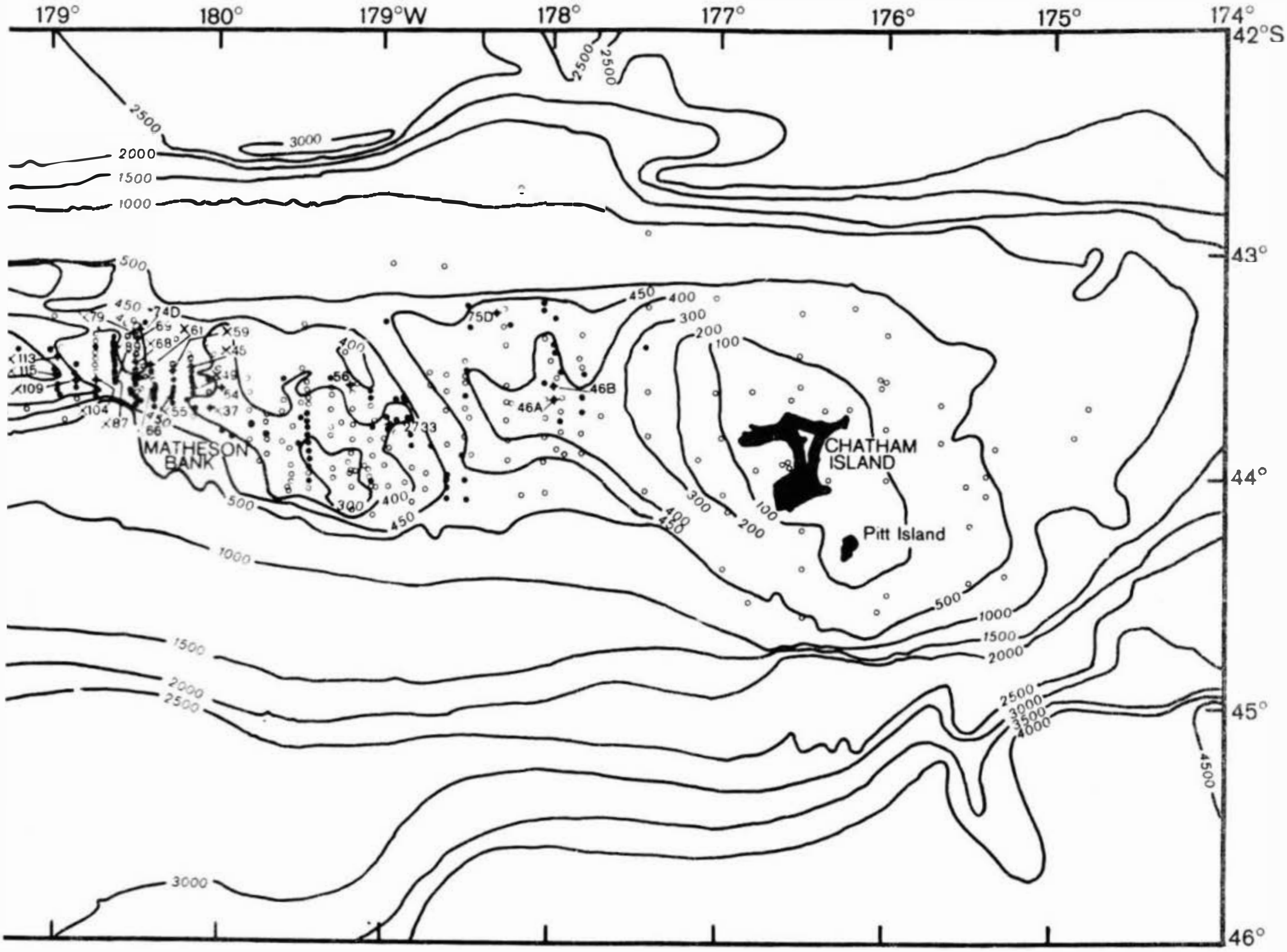
Volcanics and limestones from upper Middle to lower Middle Eocene strata constitute the Kekerione Group on the Chatham Islands. The volcanics comprise basaltic lavas, calcareous fossiliferous tuff, and pillow lavas with lenses of limestone. Hard crystalline limestone (Te Whanga Limestone) containing angular schist fragments and a few phosphatic nodules is overlain by a soft limestone composed of polyzoa and foraminifera, which also contains phosphatic nodules (Te One Limestone). Some of the Eocene limestones are similar to Bortonian (Middle Eocene) cross-bedded foraminiferal limestone from Matheson Bank (Cullen 1965) (Fig. 2). These limestones from Chatham Island and Matheson Bank indicate shallow water conditions in both regions during the Middle Eocene.

Miocene argillaceous limestones have been reported from a station between Chatham Island and Matheson Bank by Cullen (1965) and phosphatised Upper Miocene foraminiferal ooze fragments (the phosphorites of this study, Fig. 3) are abundant in many areas between Reserve Bank and Chatham Island. These are the youngest dated consolidated rocks known from submerged portions of the Rise. Similar rocks of Miocene age have not been reported from the Chatham Islands.

Unconformably overlying Te One Limestone (Eocene) is a series of lava flows and interbedded calcareous tuffs of Upper Miocene to Lower Pliocene age. They were, in part, extruded under water, as evidenced by pillow structures.

Upper Pliocene to lower Pleistocene shallow water limestones and tuffs rest disconformably upon the Te Whanga Limestone of Eocene age.

Although volcanic rocks are found on many areas of the Rise, it is not now possible to date them, nor to correlate them with volcanics on the Chatham Islands or the South Island.



Cherts have been recovered from the saddle between Matheson and Reserve Banks. Except for suggesting a Tertiary age by reason of their association with Miocene phosphatised oozes, it cannot be said when they were deposited.

Sediments

Sediment distribution on the Chatham Rise has been treated in some detail by Norris (1964), from whose work this discussion has largely been taken. Norris has categorised the sediments as allochthonous rock fragments, authigenic minerals, organic remains, faecal pellets, and monomineralic grains. While allochthonous rocks have been reported (Cullen 1962), they are quantitatively unimportant.

Of the authigenic minerals found, glauconite is the most common and to some extent forms a part of most sediments. Very high concentrations, sometimes over 50 per cent, are centred over Reserve Bank and to a lesser extent north of Chatham Island. Glauconite occurs mainly as dark green rounded grains, internal casts of foraminifera, and as replacements of faecal pellets. Cullen (1967) demonstrates that the age of rounded grains from one location on Reserve Bank is between 5 and 10 million years. Based upon the age, rounding, sorting, concentration in the upper portion of cores, and extreme degree of concentration on shallows, Cullen proposes they have been derived from pre-existing rocks by winnowing and erosion. Several sediment samples from shallow areas containing mixed and reworked microfossil assemblages tend to support this idea. Kennett & Casey (1969) report three samples from Matheson Bank which contain glauconite casts of Eocene foraminifera mixed with Recent foraminifera. They suggest that a limestone such as the Eocene glauconitic-foraminiferal rocks from Matheson Bank would be an adequate source of glauconite. A similar mixture of late Eocene to early Miocene coccoliths and discoasters with Recent coccolithophores and foraminifera is found on Matheson Bank (Norris 1964).

Calcareous organic remains such as shell fragments and foraminiferal tests form a major portion of the Chatham Rise sediments. Regions shallower than 150 m and removed from sources of terrigenous material are covered with shell gravels. Shell fragments include few if any extinct forms and thus point to a recent origin.

Below 150 m the calcareous fraction of the sediment consists mostly of foraminifera. Foraminiferal remains are often sufficiently abundant to class the deposits as foraminiferal oozes. Foraminifera may be exclusively Recent although, as previously noted, assemblages of Eocene and Recent age are reported from Matheson Bank.

While detrital sediments are found around Chatham Island, land-derived material is largely excluded from the Rise because of topographic isolation from the mainland, and thus forms only minor portions of sediments in deeper areas of Rise crest. Norris (1964) suggests that the assemblage of minerals found in some Chatham Rise sediments (glass shards, feldspars, hypersthene, augite, and quartz) can be accounted for by wind transport of Taupo ash showers from the North Island.

Structure

Subsurface structure of the Chatham Rise is known from a series of seismic reflection profiles taken over the Rise by scientists from the Lamont-Doherty Geological Observatory (Houtz *et al.* 1967). The profiles show the Rise to be anticlinal along an east-west axis. Truncation of tilted Upper Eocene strata on the crest of the Rise indicates post-Eocene emergence.

Bathymetric cross-sections suggest normal faulting may have been important in forming the Banks. Around Matheson Bank, vertical offsets up to 50 m can be seen (Fig. 4). On the Chatham Rise, the majority of traceable faults strike west-north-west but are discontinuous and may be offset in some instances by north-south trending faults.

Several structural trends and periods of deformation are distinguished on the Chatham Islands (Hay *et al.* 1970). East-west trends marked by faults, strike of schistosity, and linear distribution of intrusives are present in the northern section of Chatham Island and may reflect pre-Cretaceous tectonic activity. Cretaceous structures, consisting of north-east trending folds cut by later north-east trending tensional faults with throws of less than 6 m, are found on Pitt Island (Austin *et al.* 1972). Post-Eocene normal faults, oriented north-east and north-west are inferred on Chatham and Pitt Islands, respectively, and gentle late Tertiary - early Pleistocene folding about an east-west axis is found on Pitt Island.

During late Paleozoic and early Mesozoic times, the area occupied by the Chatham Rise was an eastward extension of the New Zealand Geosyncline (Fleming 1962; Hay *et al.* 1970). Beginning in mid-

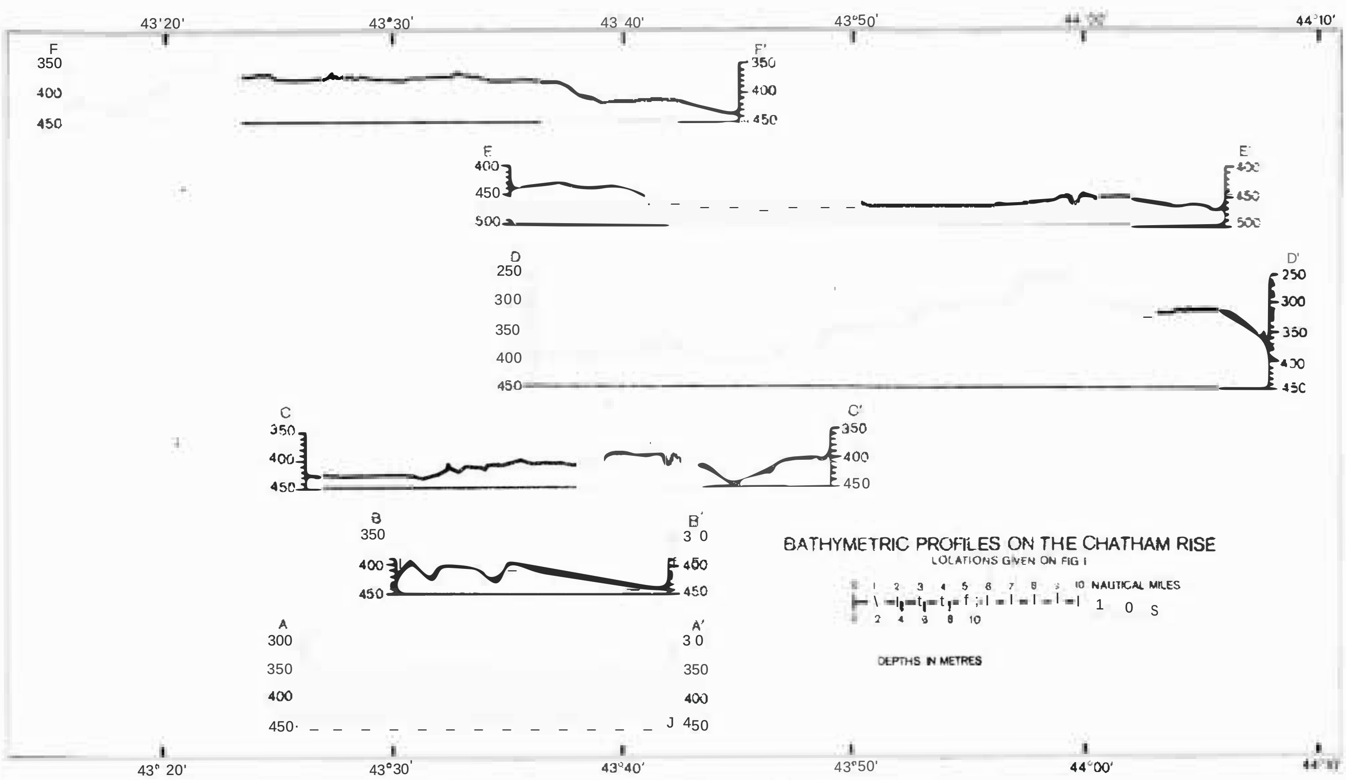


Fig. 4. Bathymetric profiles on the Chatham Rise.

Jurassic, the thick sequence of greywackes and interbedded basalts which formed the geosynclinal axial facies was elevated during the Rangitata Orogeny (Brown *et al.* 1968). Emergence of the eastern portion of the Rise prior to the Lower Cretaceous is indicated by Lower Cretaceous greywacke conglomerates and lignitic sandstones containing microflora on Pitt Island, as well as Paleozoic-Lower Eocene beds overlying Otago Schist on Chatham Island. It may also be possible to infer a similar unconformity on Matheson Bank from the absence of all but schists and Eocene limestones in samples collected in a rather dense pattern.

The rocks suggest that, by early Tertiary time, shallow marine to estuarine conditions prevailed on the eastern part of the Rise. The lack of detritals in these sediments (Hay *et al.* 1970) indicates the absence of an elevated land mass. The conditions were similar to those which existed on the eastern coast of the South Island and Campbell Island (Brown *et al.* 1968). Apparently the region was at that time characterised by land areas of low relief and transgressive seas.

As indicated by the widespread occurrence of phosphatic foraminiferal oozes, much of the Rise was submerged during the Miocene. Although the Chatham Islands may have been emergent (Hay *et al.* 1970), high land masses were still absent and thus rocks are very low in clastics. The Rise probably existed as a relatively shallow, isolated feature. The environment of deposition was similar to seamounts, ridges and banks, where foraminiferal oozes are now accumulating (Emery 1960; Karig *et al.* 1970).

On the South Island, Pliocene-Pleistocene time was dominated by the Kaikoura Orogeny (Brown *et al.* 1968). Common unconformities and disconformities between strata of Eocene and early Pleistocene age on Chatham Island probably reflect these tectonic movements. The occurrence of Miocene foraminiferal rocks on portions of the Rise where Eocene strata are truncated indicates post-Miocene emergence which is also probably related to the Kaikoura Orogeny. Shallow water conditions since the late Miocene could also explain the occurrence of winnowed glauconite (from 5 to 10 million years old) and mixed fossil assemblages. Some indication of the degree of vertical movement on the eastern part of the Rise is given by a late Pleistocene terrace around Chatham Island which is as much as 293 m below present-day sea level.

After early Pleistocene times, Chatham Island was largely submerged by a marine transgression which was followed by emergence during the glacial lowering of sea level.

DESCRIPTION OF THE PHOSPHORITES

External Character

Phosphorite nodules from the Chatham Rise are hard, dense, and many have a smooth black glauconitised exterior surface which is rarely glazed or shiny. Encrusting organisms are not uncommon (Fig. 5).

The size of phosphatic nodules is variable. A majority of the larger nodules are less than 5 cm in length although some reach 15 cm. Microscopic examination of sieved samples reveals that phosphorite particles are very common in fractions with grain-sizes ranging down to a few millimetres, and less common in finer-grained fractions.

On the basis of available specimens, the amount of variation and average specific gravity of phosphorite appears to decrease with increasing size (Fig. 6). Nodules less than 2 cm have densities that vary between 2.5 and 3.0 $g\,cm^{-3}$, while nodules over 5 cm vary between 2.4 and 2.5 $g\,cm^{-3}$.

Because they have sustained several periods of fracturing, rounding, and boring by organisms, nodules are extremely variable in shape. They may be well-rounded, blocky, angular or highly perforated by borings. In many nodules several ages of fracturing can be distinguished by variations in colour and degree of glauconitisation, as well as the angularity of corners formed by fracture intersection. In some instances, more than three periods of fracturing can be identified on the same nodule. Typically, the oldest surfaces are well rounded and have a black glauconite coating. Younger fracturing is characterised by surfaces that are not so well rounded, lighter in colour (mostly green) and less thoroughly glauconitised. Most recent fractures have no glauconite coating and very angular edges. In some instances, unglauconitised surfaces are attributable to breakage

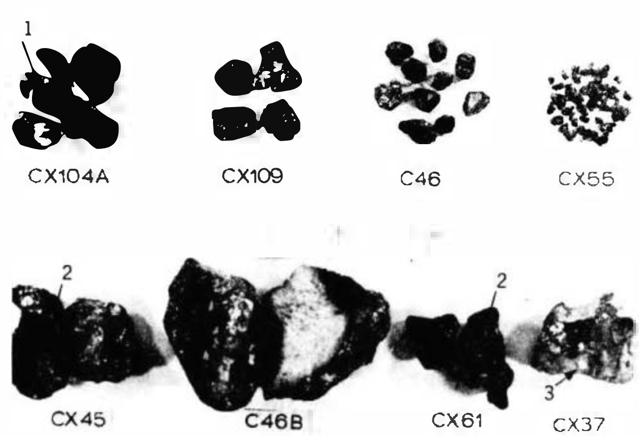


Fig. 5. Typical Chatham Rise phosphorite nodules. 1 "small" burrow; 2 "large" burrow; 3 coral attached to unglauconitised fracture surface.

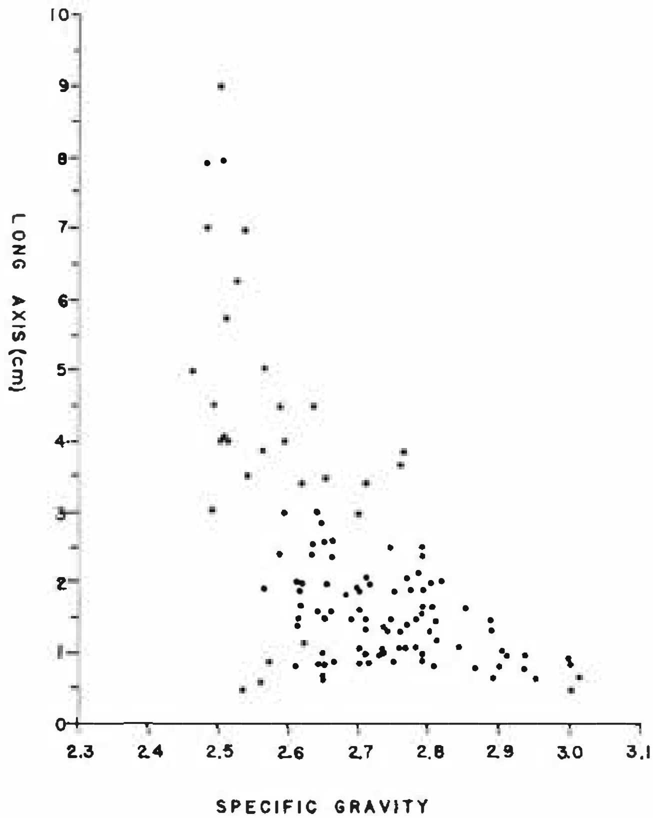


Fig. 6. Relationship of specific gravity and size (given as long axis length) in phosphorite nodules from Chatham Rise. Data taken on nodules from eight stations.

during sampling. These are distinguished by their extremely fresh, unweathered appearance in contrast to the older unglauconitised surfaces which are characterised by pitting and by the adherence of organisms (Sample CX37, Fig. 5). In a general way, the age of fracturing is related to the degree of rounding; more angular nodules tend to have more recent fractures.

Considering the density, size, and coherence of the nodules, it is doubtful whether any deep water mechanism could account for the fracturing. Reworking and abrasion in a shallow high-energy environment are required. Several such periods of reworking were apparently separated by times of deeper submergence when nodule surfaces were glauconitised.

Well preserved mollusc or worm burrows are not uncommon in nodules. They are typically tube-like, less than 1 cm in diameter, and generally extend completely through the nodules. Fractures commonly cross-cut the tubes both perpendicularly and longitudinally (Fig. 5). Their interior surfaces are glauconitised and appear comparable to the "oldest" fractured surfaces on the nodule, indicating that the burrows were made prior to the oldest discernible period of glauconitisation. The lack of infilling indicates that the burrows are post-lithification features.

Macroscopic Examination of Nodule Interior

In cross-section (Fig. 7), nodules are composed of tan to grey indurated foraminiferal ooze enclosed by a rind of dark green glauconite. Texturally, the material is rather uniform. Primary depositional structures such as bedding or accretionary zonation are not present.

In many nodules the irregular distribution of brown and grey areas gives the nodules a mottled appearance. Where small brownish patches are densely and evenly scattered throughout, an argillaceous appearance results. Most tan and light brown areas are randomly distributed and appear unrelated to nodule geometry. In some nodules, however, the brown region tends to be of rather uniform thickness, leaving an inner grey zone (Fig. 7).

Darker brown or yellow brown areas occur within and adjacent to glauconitised surfaces. The regions are rather narrow and are not more than 2 or 3 mm thick.

The glauconite rind covers all naturally-formed external surfaces with the exception of "young" fractures. Glauconite on older surfaces penetrates up to 2 mm into the interior while penetration on recent surfaces is noticeably less.

Burrows are not uncommon within the nodules. In addition to those previously mentioned, smaller burrows are revealed in sections. While somewhat uniform in size (all less than 2 mm in diameter), they vary in terms of infilling, presence of a light "alteration zone", and glauconitisation of the wall (Fig. 7).

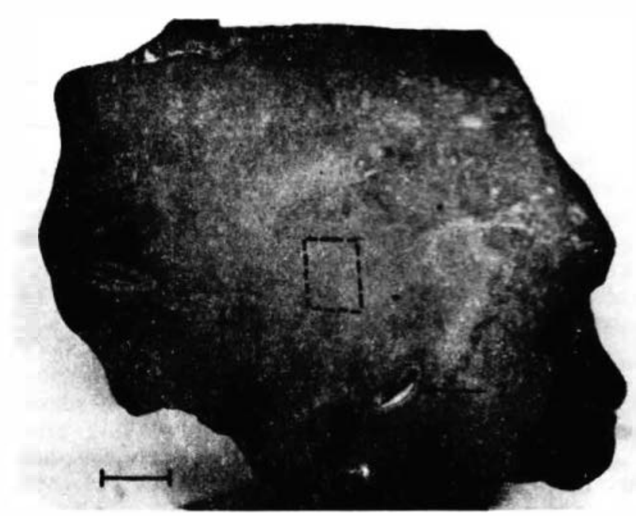


Fig. 7. Cross-section of Chatham Rise phosphorite nodule : 1 unfilled glauconitised burrow; 2 unfilled unglauconitised burrow with alteration zone; 3 filled burrow. Note : Mottled appearance and dark material near external surface. Dotted area indicates portion analysed separately for P_2O_5 (*see* text in section on "Chemical Composition"). Scale line is 1.0 cm.

Polished sections of nodules were etched in formic acid to distinguish less soluble phosphatic material from more soluble calcium carbonate. Microscopic examination showed foraminifera tests within light regions to be most susceptible to solution. Almost all were totally dissolved, leaving well-defined moulds and casts. Within brown or yellowish regions, foraminifera were less soluble and thus probably phosphatic. Brown to yellowish material is found both in the outer part of the zone inside the glauconite rind and as small randomly scattered patches which were less soluble than the light coloured, apparently less intensely phosphatised ooze.

In several sections, etching revealed small brassy crystals (pyrite ?) within foraminifera tests throughout the nodules.

Microscopic Examination of Nodule Interior

Microscopic examination of thin sections reveals that Chatham Rise phosphorites are composed of well-lithified partially-phosphatised foraminiferal limestones or chalks. A majority of the nodules are more than 30% (Fig. 8) foraminifera; some contain 10% or less (Fig. 9). The variation in foraminifera percentage is rather distinct, gradational types between 30 and 10 being rare. Tests in both are distributed randomly throughout a crypto-crystalline matrix. Foraminifera are commonly whole and do not appear to have been abraded. The tests range in size from 0.2 to 0.6 mm.

Partial dissolution of the nodules in HCl released foraminiferal moulds which could be identified. All samples examined yielded Late Miocene dates (O.L. Bandy & R.L. Fleischer, pers. comm.).

Collophane appears light brownish yellow to dark reddish brown. It replaces foraminifera and matrix material, usually without obliterating the foraminifera tests (Fig. 10). Dark brown collophane is common as a pseudomorphic replacement or test filling. Where both are phosphatic, the matrix collophane is usually a lighter colour than that replacing the tests. Selective replacement is common but variable. Tests alone may be replaced, or sometimes the matrix and material within the test may be replaced, leaving the test untouched. Most intense replacement of foraminifera and matrix generally occurs in regions, or occasionally two distinct regions, on the outer edge of the zone inside the glauconite rim. Within the rest of the nodule replacement is random, although in some (Fig. 7) a central zone of less intense replacement is found.

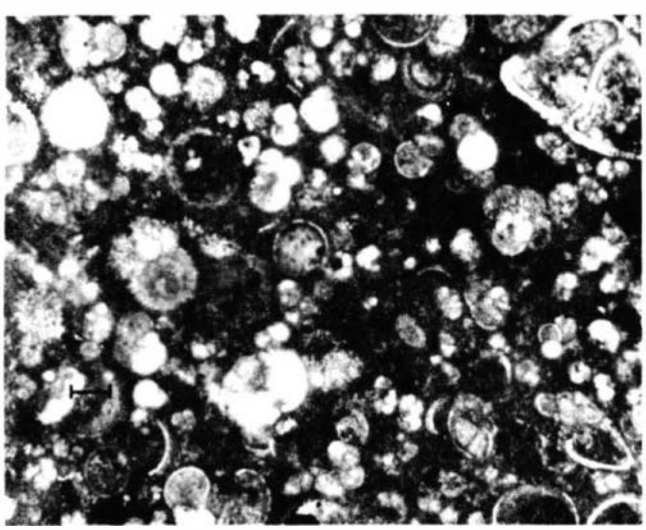


Fig. 8. Photomicrograph of phosphorite nodule composed of foraminifera tests (C56B). Scale line is 0.1 mm.

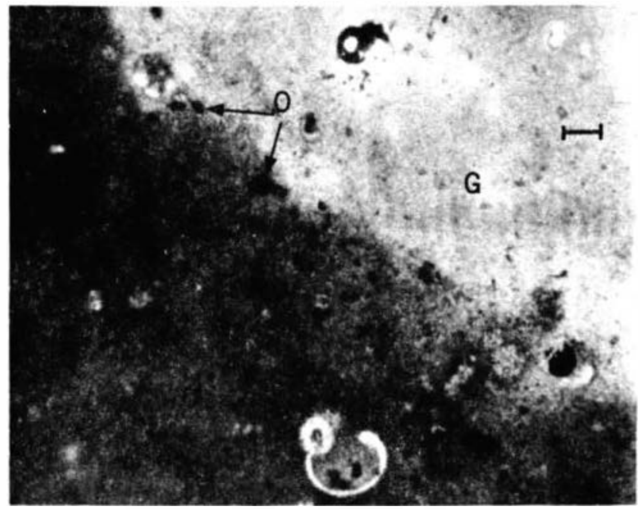


Fig. 9. Photomicrograph of phosphorite nodule containing few foraminifera tests (CX66B). Note opaque material (O) concentrated at the boundary of the glauconitised rim (G) and the collophane replaced area (C). Scale line is 0.1 mm.

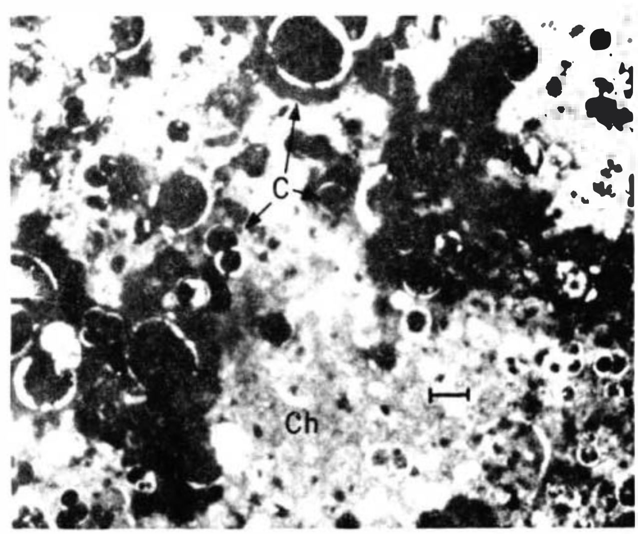


Fig. 10. Photomicrograph of phosphorite nodule illustrating collophane (C) replacing chalk (Ch) (CX69A). Note the occasional, selective infilling of the foraminifera tests by collophane. Scale line is 0.1 mm.

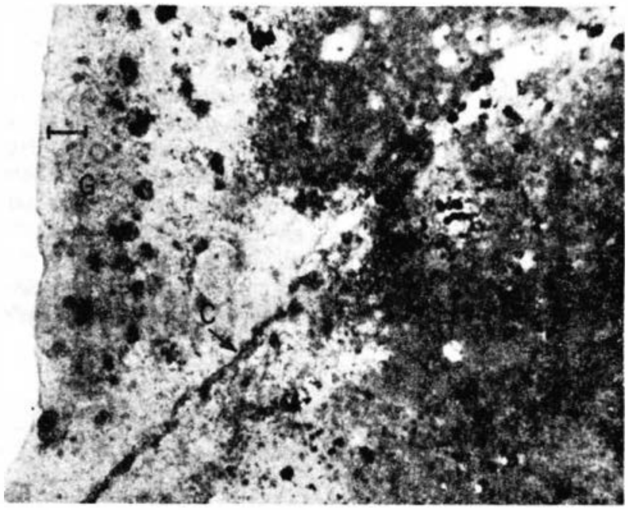


Fig. 11. Photomicrograph of phosphorite nodule illustrating collophane infilled fracture (C) cross-cutting the glauconite replacement rim (G) (CX79B). Scale line is 0.1 mm.

Collophane is found to replace glauconite that occurs as scattered foraminifera test fillings. Replacement is most intense on the exterior portions of the glauconite and may on occasions totally or partially replace the enclosing test. Collophane may also occur as crack fillings which cross-cut glauconite replacement rims and foraminifera replaced by an earlier generation of collophane (Fig. 11). Foraminifera tests within the glauconite rim are occasionally replaced by collophane.

Glauconite occurs within the nodules as (1) a rim replacement; (2) foraminifera filling; (3) crack fillings; and (4) rounded clastic grains.

Exterior surfaces on the nodules have been replaced by glauconite (Fig. 12). The thickness of the rim is variable but shows no relationship to surface irregularities. That the glauconite is not a coating but represents true replacement of foraminiferal ooze is indicated by the continuity of texture across the replacement boundary. Partially obliterated foraminiferal tests are common within the glauconite (Fig. 12). Where the leading replacement edge is distinct, a foraminifer may lie partially within the glauconite, leaving the remainder of the test unreplaced. The nature of the transition from glauconite rim to unreplaced matrix is variable. Usually grass green glauconite grades to a light green or yellow glauconite which terminates at a boundary marked by a concentration of small disseminated opaque particles. A grey or brown layer containing coarser opaque matter may be present. Further in, a layer or two of matrix, and foraminifera replaced by collophane are found. Glauconite rims also grade directly into an evenly replaced collophane interior which may or may not have a disseminated opaque layer.

The concentration of collophane in a layer beneath the glauconite rinds may be a result of inward phosphate migration during replacement by glauconite resulting in regions of secondary collophane concentration. Throughout the replacement rind, scattered foraminifera may contain a darker glauconite than that replacing the matrix. While this may indicate that the interior of the foraminifera is more favourable to formation of dark glauconite, it is inconsistent with the observation that not all foraminifera contain the darker variety, even when adjacent. More probably the foraminifera with darker glauconite represent those infilled with glauconite prior to replacement. This would be consistent with Pratt's (1971) observation that darker glauconites tend to be older than light forms.

Grass-green glauconite occasionally occurs as foraminiferal test fillings. Such glauconite-filled tests make up as much as 5% of all tests. They are randomly distributed throughout the nodules and are adjacent to foraminifera that are not filled. Their distribution among unfilled tests and the definite confinement of glauconite within the test suggests either that this glauconite formed prior to lithification and is not a post-depositional replacement feature, or that the glauconite-filled tests represent reworked material from a glauconitic ooze. The latter idea is not supported by the lack of abrasion of the tests.

Darker green varieties of glauconite fill cracks that cross-cut glauconitised rims indicating later periods of glauconitisation (Fig. 12). This glauconite may represent material deposited during glauconitisation of the successively younger angular exterior surfaces.

Opaque Minerals. Most nodules contain a noticeable amount of opaque material which is present as disseminated particles, foraminifera test replacements or test fillings. The material may at least in part be pyrite which was noted in foraminifera on etched interior sections.

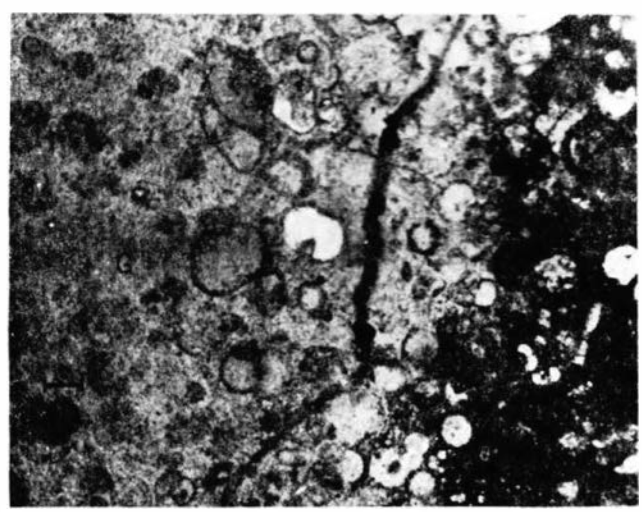


Fig. 12. Photomicrograph of phosphorite nodule showing the transition from the glauconitised rim (G) to the collophane replacement zone (C) (C6-D). Note ghosts of replaced foraminifera tests and late glauconite vein filling. Scale line is 0.1 mm.

Disseminated opaque particles up to 0.2 mm are found scattered throughout unphosphatised material or concentrated at collophane-non-collophane boundaries (Fig. 9). Secondary origin is indicated by their delicate dendritic edges and replacement relationships with foraminifera. The scarcity of opaque particles in phosphatised areas, as compared to their abundance in adjacent unreplaced regions, might be interpreted as the result of obliteration of opaques during replacement. However, where opaque particles are found in collophane, they have the same delicate dendritic edges and cross-cut foraminifera replaced by collophane, and are thus of post-replacement origin. It would appear that non-phosphate material is more susceptible to replacement by the opaques.

Concentrations of particles are found at boundaries of the glauconite rim with the collophane and unreplaced chalk (Fig. 13).

Opaque material may selectively replace foraminifera tests, even those previously replaced by collophane or glauconite; such replacement occurs anywhere in the nodule. Infilling of foraminifera by opaque material is common and not necessarily accompanied by test replacement (Fig. 14).

Opaque particles were apparently the most recently formed material. The concentration at boundaries, especially those of glauconite replacement, may indicate that the opaque material also was remobilised during the replacement process, and was either concentrated at the replacement front, or formed preferentially in unreplaced foraminiferal ooze.

Detrital Grains. A small number of detrital mineral grains were noted in thin sections. To facilitate their identification, nine phosphorite nodules from different stations were dissolved in hydrochloric acid. The insoluble residue was screened, and the plus 200 mesh fraction retained for petrographic analysis. This portion of the insoluble residue was always less than 1% by weight of the whole nodule sample.

Most of the grains measure between 0.62 and 0.125mm. With few exceptions, the grains are quite angular showing no indication of abrasion on sharp corners. Glass shards, quartz and feldspar are common or even dominant in many of the assemblages, and are associated with subordinate epidote, sphene, zircon and hornblende (Table 1).

Glass shards are present in all residues examined and abundant in many of these. They are clear, very angular and less than 0.125 mm in size. A majority are curved and many contain fine dark-coloured inclusions.

Quartz is similarly common and occurs as small angular fragments less than 0.125mm or as slightly larger rounded grains. All are clear and lack inclusions.

Feldspars are found in many samples. Most are untwinned plagioclases which were distinguished from minor quantities of orthoclase by their higher index of refraction. The grains are angular, small and often exhibit good cleavage.

Epidote grains are clear, equant, angular and of high birefringence.

Zircon is present as chipped or fragmented crystals. Fragments are clear and, although broken, show no other signs of mechanical abrasion.

Sphene and hornblende, when present, are represented by only a few grains. Sphene is clear and angular. Hornblende fragments are tabular and exhibit green-yellow/green pleochroism.

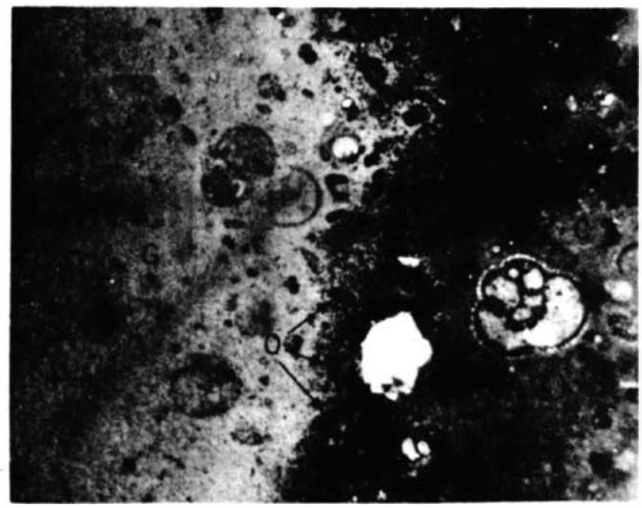


Fig. 13. Photomicrograph of phosphorite nodule showing a concentration of opaque material (O) at the boundary of the glauconite rim (G) and collophane zone (C) (CX37A).

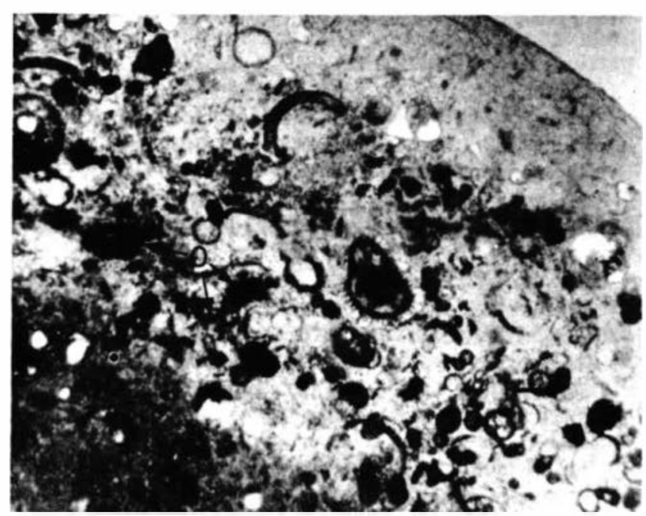


Fig. 14. Photomicrograph of phosphorite nodule showing opaque material (O) (CX66B). Note selective infilling of foraminifera tests.

Mineral	CX59A	C64A	CX109B	C56A	C46A-D	C68A	C69A	C46B-B	C46
Glass shards	X	C	C	X	C	C	C	X	X
Quartz	X	C	C	X	C	C	C	X	X
Feldspars	-	C	C	-	C	C	C	X	X
Epidote	-	-	U	-	R	R	R	-	X
Sphene	-	-	R	-	R	-	R	X	-
Zircon	-	U	U	-	R	U	M	-	-
Hornblende	-	R	R	-	R	R	R	-	-
Glaucophane	-	-	-	-	-	R	-	-	-

C = common (25-50%) M = moderately common (5-25%)
U = uncommon (1-5%) R = rare (less than 1%)
X = present, but insufficient number of total grains to be meaningful

TABLE 1. Relative frequency of mineral grains in the insoluble residue of Chatham Rise phosphorite nodules.

Aeolian transport of the grains is suggested by their small size, good sorting and their unabraded character. Experiments suggest that grains of this size, 0.62 to 0.125 mm, can be transported by strong winds only a few miles (Udden 1898), and it is assumed, therefore, that the detrital grains in the phosphorite nodules have been derived from land masses that existed nearby.

Chemical Composition

Available analyses of phosphorite nodules (Table 2) show that CaO, P_2O_5 and CO_2 make up over 70% of the nodules. Lesser amounts of Fe_2O_3, F, SiO_2 and insolubles account for nearly all of the remainder. Most of the P_2O_5 and F, and part of the CaO and CO_2 make up the collophane within the nodules. Some CaO and CO_2 most probably exist as calcite. Silica, iron and insolubles are attributed to detritals, opaque particles and glauconite.

The phosphate content of samples from the Chatham Rise, representing 51 station averages, ranges between 16 and 25% and averages 20.5% P_2O_5 (Appendix III). A histogram of the frequency of P_2O_5 percentages shows a definite peak between 20 and 22% (Fig. 15).

A selection of nodules of different sizes from the same stations, and nodules with different percentages of foraminifera were analysed to discover if the variability of P_2O_5 (collophane) content could be attributed to either of these variables.

Based upon the analyses of three size groups from three stations, no definite pattern relating P_2O_5 and size was found. The only generalisation made here is that the P_2O_5 content of the 0.5 to 1.0 cm nodules is higher than the 2.5 to 3.5 cm nodules at the same station (Table 3).

A comparison of the P_2O_5 content of nodules high (30%) and low (10%) in foraminifera shows no significant variation in either range or average (Table 4).

Analyses of various regions within several nodules showed virtually no variation in P_2O_5. Even analyses from the brownish outer and light tan inner areas of a distinctly zoned nodule (CX61A, Fig. 7) both indicated 16% P_2O_5. These results are consistent with an electron microprobe analysis of a cross-section of a nodule, which did not detect any major difference in the composition across the surface of the nodule section (Buckenham *et al.* 1971). These data are significant in that they indicate that the colour zonation noted in some nodules is not a result of differential phosphate replacement as originally suspected by the author (Pasho 1972).

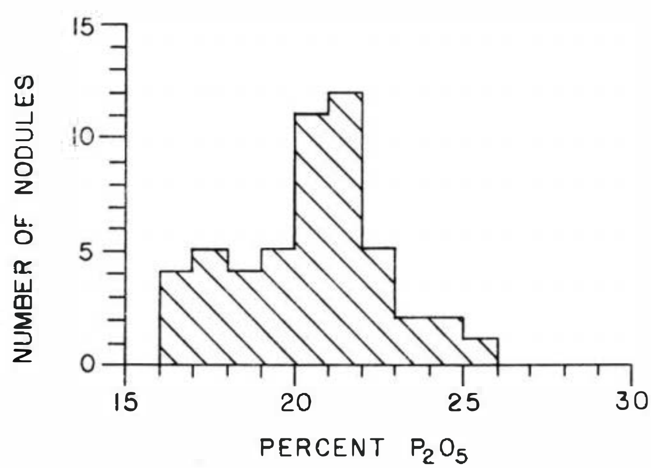


Fig. 15. Histogram of the P_2O_5 content in phosphorite nodules representing 51 stations on the Chatham Rise (Appendix III).

	1	2	3	4	5	6	7	8
P_2O_5	25.4	19.18	18.10	19*	21.8	19.51	20.43	20.74
CaO	42.70	47.50	44.00	49*	37.5	53.31	51.25	40.04
Al_2O_3	T	T	0.30	-	-	-	-	-
Fe_2O_3	1.43	2.50	4.27	-	-	1.48	2.18	2.37
MgO	T	T	T	-	-	0.50	0.49	-
Insolubles	4.00	0.10	5.12	-	-	-	-	-
Organic	N	N	N	-	-	-	-	-
CO_2	12.40	20.92	19.11	14.1	9.3	-	-	15.3
F	1.50	1.30	1.60	2.4	2.56	2.28	2.65	2.04
R_2O_3	-	-	-	4.2	-	-	-	-
SiO_2	-	-	-	4.5	6.9	0.45	1.15	-
CaO/P_2O_5	1.68	2.48	2.37	2.58	1.68	2.73	2.51	2.29
CO_3/P_2O_5	0.49	1.09	1.06	0.74	0.43	-	-	0.74
F/P_2O_5	0.059	0.066	0.086	0.126	0.117	0.117	0.130	0.100

1. Monsoon 73 Analyst Smith-Emery, Los Angeles
2. Monsoon 74 Analyst Smith-Emery, Los Angeles
3. Monsoon 75 Analyst Smith-Emery, Los Angeles
4. Global Marine CX59 (Rouse 1969)
5. Discovery II-2733 (Reed and Hornibrook 1952)
6. Global Marine CX45 (Burnett 1974)
7. Global Marine CX79 (Burnett 1974)
8. Average

* = Not averaged
\- = No analysis
T = Trace
N = Nil

TABLE 2. Collected partial chemical analyses of Chatham Rise phosphorite nodules.

CHARACTERISTICS OF DISTRIBUTION AND ASSOCIATIONS

With few exceptions, phosphorite nodules are recovered on the Chatham Rise only in the area between Reserve Bank and the western shelf of Chatham Island (Fig. 3). Phosphorite appears to be absent from Mernoo and Veryan Banks and the shallower areas of the Chatham Island shelf. Over most of the region, phosphatic samples are scattered, and separated by non-nodular samples. A significant concentration of phosphorite nodules occurs in the saddle between Matheson and Mernoo Banks. The great majority of nodules were recovered from between 400 and 500m. No nodules are found shallower than 200m. Lack of samples from a depth greater than 500m prevents generalisation on the maximum depth at which they occur.

Station	0.5-1.0cm	1.5-2.0cm	2.5-3.5cm
C66	24.7	20.2	20.1
CX55	22.3	18.8	21.2
C56	22.2	27.7	18.8

TABLE 3. P_2O_5 content of various size phosphorite nodules from three stations on Chatham Rise.

Percent foraminifera	10%	30%
Number of nodules	4	5
P_2O_5 range (%)	17.2-21.4	18.6-20.2
P_2O_5 average (%)	18.8	19.5

TABLE 4. Comparison of P_2O_5 content in nodules with different percentages of foraminifera.

A variety of lithologic types and sediments are associated with phosphorite nodules. Limestones, chert, schist and volcanics accompany nodules. Green mud, foraminiferal ooze and glauconitic silts are the common sediment types associated with nodules. The type of associated material depends entirely upon what is present in that region; in other words, there appears to be no relationship between phosphorite distribution and the distribution of associated lithologic or sediment type. Phosphorite nodules may be entirely absent or make up the total of fragments larger than 2.4cm. Most commonly nodules make up less than 50% of the large grain sizes, averaging 10 to 15%. Comparison of the size distribution of the minus 3.8cm sediment and the distribution of phosphorite grains within individual size fractions indicates phosphorite is basically confined to the plus 0.599mm fractions irrespective of the total sediment distribution pattern (Fig. 16).

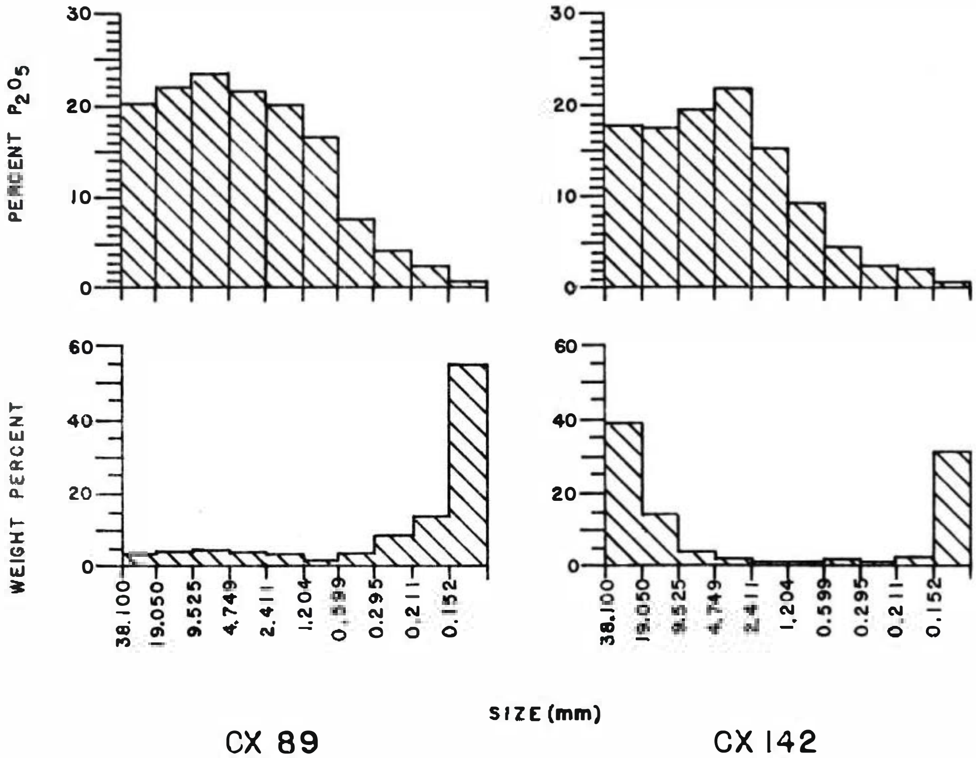


Fig. 16. Diagrammatic representation of two total sediment samples from the Chatham Rise illustrating the distribution of P_2O_5 in various size fractions. (Data from Global Marine Inc.). Class intervals are British Standard mesh size.

DISCUSSION AND CONCLUSIONS

Depositional Setting

During the late Miocene, foraminiferal oozes and chalks were deposited over much of the area now occupied by the Chatham Rise. The accumulation of such oozes and chalks, which contain rather insignificant amounts of detritals, suggests that the region was a submarine bank or ridge, isolated from detrital sedimentation, in an area of high or moderate planktonic surface productivity. In such a situation, relatively coarse skeletal debris is deposited, whereas only the finest detrital sediment from shore can reach the bank. Further separation of fines may have resulted from winnowing by bottom currents.

The relatively minor amounts of glauconite, which occur mainly as test fillings, might be attributed to the existence of reducing micro-environments within the individual tests. Such a condition may lead to the alteration of clays filling the test to glauconite (Emery 1960; Ehlmann *et al.* 1963). Other conditions which are believed necessary for glauconite formation are not inconsistent with a bank top environment. They include a depth of formation between 10 and 1800m; temperature as "probably not favoured by markedly warm waters" (Cloud 1955); and a low sedimentary influx (Cloud 1955; Bell & Goodell 1967).

Absence of Miocene deposits on the far western and far eastern stretches of the Chatham Rise could be explained by the emergence of these areas during that time. If these areas were exposed, they were probably of low relief.

The setting, as described here, is quite similar to the situation existing on the Santa Rosa-Cortez Ridge of the Southern California Borderland (Uchupi 1954, 1961).

Phosphatisation

The sporadic and irregular distribution of first-generation collophane-replacement features, and the lack of significant variations in P_2O_5 content within individual nodules are consistent with phosphatisation of the chalk during diagenesis. A possibly similar modern example of the phosphatisation of foraminifera in an unconsolidated sediment from the western shelf of Baja California has been described by d'Anglejan (1967, 1968).

Subsequent History

Following diagenesis the deposit was uplifted, perhaps during the Plio-Pleistocene Kaikoura Orogeny. Subaerial erosion resulted in the initial fragmentation of the phosphatised ooze. Weathering of fragments during subaerial exposure may have produced the penetrating brown zones noted in some nodules. Subsequent periods of submergence, with glauconitisation of fracture surfaces, and re-emergence are indicated by the numerous relative ages of glauconitised and unglauconitised fractures. That post-Pleistocene glauconitisation has occurred is independently supported by the occurrence of glacial erratics with a glauconite coating (Cullen 1962). Later fracturing with no glauconitisation was apparently the last stage leading to the present form of the phosphorite nodules.

As indicated by the extent of phosphatised ooze fragments, much of the Chatham Rise must have been above sea level at various times since the late Miocene. Significant reworking has occurred on Reserve and Matheson Banks where phosphorites are mixed with Mesozoic greywackes and pre-Mesozoic schists respectively. Whether phosphatised oozes ever existed on Mernoo Bank or the Chatham Islands is open to question. If so, the deposits have been either extensively eroded or are blanketed by younger sediment.

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APPENDIX I

CHATHAM RISE STATIONS
GMI Cruise I

Roman numerals indicate a resampling of the same station. Capital letters indicate a unique station, but one which was not in the original cruise plan.
Depth uncorrected for regional variation of sound velocity.

Station (C)	Latitude (°S) ° '	Longitude ° '	Depth (m)
1	43 48	175 01 E	437
2	43 46	175 25 E	360
3	43 43	176 00 E	346
4	43 44	176 29 E	400
5	43 40	177 00 E	455
6	43 43	177 23 E	375
7	43 45	178 00 E	432
8	43 50	178 29 E	412
9	43 45	179 02 E	433
10	43 37	179 29.5 E	412
11	43 47	179 59.0 W	400
12	43 57	179 30 W	318
13	44 02	178 54 W	369
14	44 54	178 30 W	409
15	43 52	178 00 W	409
16	44 03	177 28 W	391
17	44 24	177 00 W	500
18	44 09	176 57 W	282
19	44 04	177 00 W	164
20	44 13	176 32 W	120
21	44 23	176 32 W	164
22	44 36	176 32 W	
23	44 30	176 00 W	
24	44 18	176 00 W	73
25	44 27	175 30 W	437
26	44 12	175 30 W	182
27	44 02	175 30 W	127
28	43 50	175 40 W	231
29	43 40	175 40 W	292
30	44 00	176 00 W	91
31	43 46	176 00 W	127
32	43 34	176 00 W	229
33	43 22	176 00 W	400
34	43 16	176 32 W	270
35	43 27	176 32 W	109
36	43 35	176 32 W	55
37	43 48	176 57 W	104
38	43 36	177 00 W	106
39	43 24	177 00 W	91
40	43 12	177 00 W	391
41	43 15	177 27 W	354
42	43 25	177 27 W	258
43	43 36	177 27 W	258
44	43 48	177 27 W	292
45	43 44	177 42 W	376
46 }	43 45	178 00 W	364
46 I }			
46 A }	43 39	178 00 W	364
46 A I }			
46 B }	43 35	178 00 W	364
46 B I }			
47	43 28	178 00 W	364
48	43 17	178 00 W	354
49	43 19	178 15 W	392
50	43 20	178 30 W	405
51	43 32	178 30 W	400
52	43 40	178 15 W	377
53	43 43	178 30 W	445
54	43 31	178 45 W	437
55	43 25	179 13 W	437
56 }	43 35	179 10 W	400
56 I }			
56 A	43 38	179 05 W	400
57	43 43	179 00 W	386
58	43 49	179 00 W	391
59	43 45	179 17 W	356
60	43 44	179 30 W	324
60 A	43 40	179 30 W	345
61	43 32	179 30 W	394
62	43 20	179 30 W	482
63	43 28	179 45 W	430
64 }	43 36	180 00 W	390
64 I }			
64 A	43 31	180 00 W	393
65	43 27	179 58 E	393
66	43 18	179 59 E	455
67	43 24	179 44 E	432
68 }	43 30	179 30 E	391
68 I }			
69 }	43 23	179 30 E	394
69 I }			
70	43 26	179 15 E	382
71	43 37	179 00 E	382
72	43 26	178 58 E	386
73	43 18	179 00 E	400
74	43 26	178 46 E	340
74 A	43 43	178 42 E	332
75	43 32	178 30 E	338
76	43 20	178 30 E	364
77	43 11	178 27 E	386
78	43 20	178 12 E	318
79	43 29	178 01 E	332
80	43 20	178 00 E	286
81	43 10	177 58 E	364
82	44 14	175 52 E	410
83	44 14	175 55.6 E	131
84	44 14	176 05.5 E	104
85	44 14	176 16 E	146
86	44 02	176 16 E	418
87	44 20	175 00 E	278
88	43 21	174 50 E	338
89	43 10	174 50 E	328
90	43 06	175 02 E	120
91	43 15	175 02 E	157
92	43 26	175 02 E	373
93	43 38	175 02 E	
94	43 34	175 16 E	200
95	43 22	175 17 E	100
96	43 12	175 17 E	140
98	43 12	175 33 E	100
99	43 23	175 29 E	118
100	43 07	176 10 E	455
101	43 15	176 21 E	342
102	43 15	176 45 E	284
103	43 05	176 45 E	391
104	43 03	177 05 E	355
105	43 11	177 08 E	226
106	43 17	177 28 E	280
107	43 22	177 25 E	273
108	43 15	177 20 E	222

APPENDIX II

CHATHAM RISE STATIONS
GMI Cruise II

Roman numerals indicate a resampling of the same station. Capital letters indicate a unique station, but one which was not in the original cruise plan. Depth uncorrected for regional variation of sound velocity.

Station (CX)	Latitude (°S) ° '	Longitude ° '	Depth (m)
1	43 35	179 28 W	417
2	43 37	179 28 W	373
3	43 39	179 28 W	373
4	43 41	179 28 W	365
5	43 43	179 28 W	365
6	43 45	179 28 W	
7	43 47	179 28 W	314
8	43 49	179 28 W	299
9	43 51	179 28 W	289
10	43 53	179 28 W	292
11	43 55	179 28 W	289
12	43 57	179 28 W	303
13	43 59	179 28 W	321
14	44 01	179 28 W	343
15	44 03	179 28 W	406
16	44 04	179 36 W	
17	44 03	179 36 W	347
18	44 01	179 35 W	343
19	44 00	179 35 W	376
20	43 57	179 35 W	380
21	43 53	179 35 W	380
22	43 51	179 38 W	369
23	43 47	179 35 W	365
24	43 44	179 36 W	395
25	43 40	179 36 W	413
26	43 42	179 44 W	402
27	43 46	179 44 W	376
28	43 48	179 44 W	365
29	43 50	179 44 W	376
30	43 54	179 44 W	395
31	43 50	179 50 W	402
32	43 46	179 50 W	365
33	43 42	179 50 W	384
34	43 38	179 50 W	406
35	43 34	179 50 W	424
36	43 49	179 56 W	402
37 } 37 II }	43 42	179 56 E	398
38	43 38	179 56 E	413
39	43 34	179 56 E	409
40	43 30	179 56 E	424
41	43 26	179 56 E	
42			457
43	43 28	179 49.5 E	442
44	43 29	179 50 E	409
45 } 45 II }	43 32	179 50 E	395
46	43 33	179 50 E	402
47	43 34	179 50 E	395
48	43 35	179 50 E	402
49 } 49 II }	43 37	179 50 E	395
50	43 38	179 50 E	402
51	43 40	179 48 E	406
52	43 42	179 50 E	395
53	43 44	179 50 E	420
54	43 41	179 43 E	418
55 } 55 II }	43 39	179 43 E	402
56	43 38	179 43 E	402
57	43 37	179 43 E	406
58	43 35	179 43 E	402

Station (CX)	Latitude (°S) ° '	Longitude ° '	Depth (m)
59 } 59 II }	43 33	179 43 E	402
60	43 31	179 43 E	420
61 } 61 II }	43 31	179 36 E	413
62	43 32	179 36 E	413
63	43 34	179 36 E	431
64	43 35	179 36 E	398
65	43 36	179 36 E	409
66 } 66 II }	43 37	179 36 E	409
67	43 38	179 36 E	409
68	43 39	179 36 E	413
69	43 40	179 36 E	420
70	43 42	179 36 E	431
71	43 39	179 29 E	420
72	43 38	179 28 E	417
73	43 36	179 30 E	413
74	43 35	179 31 E	411
75	43 34	179 33 E	409
76	43 32	179 34 E	396
77	43 31	179 29 E	431
78	43 20	179 29 E	431
79 } 79 II }	43 23	179 29 E	395
80	43 23	179 27 E	393
81	43 29	179 29 E	396
82	43 32	179 29 E	393
83	43 35	179 29 E	417
84	43 39	179 29 E	424
85	43 41	179 30 E	442
86	43 36	179 22 E	424
87 } 87 II }	43 34	179 22 E	402
88	43 33	179 22 E	415
89 } 89 II }	43 32	179 22 E	398
90	43 31	179 22 E	395
91	43 30	179 22 E	438
92	43 28	179 22 E	402
93	43 27.5	179 22 E	395
94	43 27	179 22 E	409
95	43 25	179 22 E	398
96	43 23	179 22 E	409
97	43 22	179 22 E	424
98	43 23	179 15 E	442
99	43 25	179 15 E	442
100	43 27	179 15 E	435
101	43 29	179 15 E	418
102	43 31	179 15 E	424
103	43 32.5	179 15 E	411
104 } 104 A II }	43 35	179 15 E	413
105	43 38	179 15 E	395
106	43 40	179 15 E	409
107	43 39	179 07 E	426
108	43 37	179 07 E	395
109 } 109 II }	43 35	179 07 E	369
110	43 33	179 07 E	398
111	43 31	179 07 E	413
112	43 26	179 01 E	420

Station (CX)	Latitude (°S) ° '	Longitude ° '	Depth (m)
113	43 30	179 01 E	380
113 II			
114	43 32	179 01 E	347
115	43 38	179 01 E	369
115 II			
116	43 36	179 01 E	356
117	43 38	179 01 E	369
118	43 40	179 01 E	329
119	43 42	178 48 E	400
120	43 34	179 20 W	417
121	43 36	179 20 W	395
122	43 38	179 20 W	387
123	43 42	179 20 W	380
124	32 47	179 20 W	380
125	43 49	179 20 W	347
126	43 54	179 20 W	309
127	43 58	179 20 W	248
128	44 00	179 20 W	318
129	44 04	179 20 W	318
130	44 08	179 20 W	402
131	44 11	179 13 W	402
132	44 07	179 13 W	
133	44 03	179 13 W	299
134	43 59	179 13 W	270
135	43 58	179 13 W	219
136	43 54	179 13 W	230
137	43 50	179 13 W	369
138	43 46	179 13 W	380
139	43 42	179 13 W	406
140	43 38	179 13 W	424
141	43 37	179 06 W	409
142	43 39	179 06 W	424
143	43 41	179 06 W	417
144	43 45	179 06 W	402
145	43 50	179 06 W	393
146	43 54	179 06 W	340
147	43 57	179 05 W	376
148	43 58	179 06 W	409
149	44 00	179 06 W	380
150	44 01	179 06 W	358
151	44 02	179 06 W	256
152	44 05	179 06 W	303
153	44 10	179 06 W	438
154	44 06	179 00 W	420
155	44 02	179 00 W	336
156	43 58	179 00 W	318
157	43 54	178 59 W	398
158	43 48	178 57 W	424
159	43 44	178 56 W	417
160	43 39	178 56 W	395
161	43 52	178 45 W	438
162	43 59	178 46 W	438
163	44 03	178 46 W	431
164	44 06	178 52 W	409
165	44 02	178 52 W	395
167	43 52	178 52 W	420
168	43 48	178 52 W	407
169	43 44	178 52 W	396
170	43 40	178 52 W	438
171	43 39	178 52 W	468
172	43 35	178 45 W	466
173	43 32	178 38 W	431
174	43 37	178 38 W	438
175	43 42	178 38 W	449
176	43 47	178 38 W	464
177	43 51	178 38 W	459
178	44 00	178 38 W	438
179	44 01	178 38 W	438
180	44 02	178 38 W	446
181	44 06	178 38 W	464
182	44 07	178 32 W	446
183	44 01	178 32 W	468
184	43 54	178 32 W	468
185	43 48	178 32 W	449
186	43 42	178 32 W	438
187	43 38	178 32 W	420
188	43 34	178 32 W	420
189	43 34	178 32 W	420
190	43 28	178 32 W	438
191	43 22	177 50 W	438
192	43 27	177 50 W	438
193	43 32	177 50 W	427
194	43 33	177 50 W	387
195	43 38	177 50 W	385
196	43 43	177 50 W	384
197	43 48	177 50 W	380
198	43 53	177 50 W	438
199	43 53	177 57 W	438
200	43 48	177 57 W	406
201	43 43	177 58 W	382
202	43 38	177 58 W	380
203	43 33	177 59 W	365
204	43 32	177 58 W	376
205	43 27	177 57 W	402
206	43 25	177 57 W	438
207	43 14	178 03 W	420
208	43 16	178 03 W	409
209	43 23	178 03 W	365
210	43 35	178 03 W	384
211	43 39	178 03 W	384
212	43 44	178 03 W	380
213	43 49	178 03 W	424
214	43 55	178 04 W	453
215	43 55	178 17 W	421
216	43 50	178 17 W	402
217	43 45	178 17 W	380
218	43 45	178 17 W	380
219	43 35	178 17 W	411
220	43 25	178 17 W	420
221	43 20	178 17 W	424
222	43 15	178 17 W	409

APPENDIX III

Listing of available P_2O_5 analyses on phosphorite nodules from Chatham Rise.

No.	Station	Analysed Portion	$\%P_2O_5$	Reference
1	Monsoon 73	Whole nodule	25.4	Global Marine +
2	Monsoon 74	Whole nodule	19.2	Global Marine +
3	Monsoon 75	Whole nodule	18.1	Global Marine +
4	Discovery II - 2733	Analyses of six nodules	21.8	Reed and Hornibrook (1959)
5	C46	Average of three analyses on various portions of the same nodule	17.2	This work
6	C46A-D	Whole nodule	17.7	This work
7	C46B-B	Whole nodule	19.9	This work
8	C56	Average of three size fraction analyses	22.9	This work
9	C56A	Whole nodule	19.2	This work
10	C64A	Whole nodule	20.2	This work
11	C66	Average of three size fraction analyses (*See* Table 3)	21.7	This work
12	C68A	Whole nodule	18.9	This work
13	C69A	Average of two analyses on exterior and interior portions of the same nodule	21.4	This work
14	CX37	Bulk sample	16.5	Global Marine *
15	CX39	Bulk sample	21.7	Global Marine *
16	CX45		19.5	Burnett (1974)
17	CX46	Bulk sample	18.5	Global Marine *
18	CX47	Bulk sample	16.9	Global Marine *
19	CX54	Bulk sample	20.3	Global Marine *
20	CX55	Average of three size fraction analyses (*See* Table 3) 20.8)	20.0	This work
	55	Bulk sample 21.2)		Global Marine *
21	CX56	Bulk sample	21.4	Global Marine *
22	CX57	Bulk sample	23.3	Global Marine *
23	CX59A	Whole nodule	19.9	This work
	59		19 †	Rouse (1969)
24	CX61	Bulk sample	17.8	Global Marine *
25	CX61A	Average of two analyses on exterior and interior portions of the same nodule	16.5	This work
26	CX62	Bulk sample	21.3	Global Marine *
27	CX65	Bulk sample	20.7	Global Marine *
28	CX66	Bulk sample	21.8	Global Marine *
29	CX67	Bulk sample	21.9	Global Marine *
30	CX69	Bulk sample	20.4	Global Marine *
31	CX71	Bulk sample	24.9	Global Marine *
32	CX73	Bulk sample	22.4	Global Marine *
33	CX77	Bulk sample	21.0	Global Marine *
34	CX79	Bulk sample 20.0)	20.2	Global Marine *
	CX79	20.4)		Burnett (1974)
35	CX91	Whole nodule	21.5	This work
36	CX93	Bulk sample	20.5	Global Marine *
37	CX94	Bulk sample	21.3	Global Marine *
38	CX104A	Whole nodule	20.2	This work
39	CX105	Bulk sample	21.5	Global Marine *

No.	Station	Analysed Portion	$\%P_2O_5$	Reference
40	CX106	Bulk sample	23.1	Global Marine *
41	CX109B	Whole nodule	18.8	This work
42	CX114	Bulk sample	20.6	Global Marine *
43	CX115	Bulk sample	22.4	Global Marine *
44	CX141	Bulk sample	17.6	Global Marine *
45	CX142	+ 3/4 in Bulk sample	17.8	Global Marine *
46	CX159	Bulk sample	22.6	Global Marine *
47	CX178	Bulk sample	24.4	Global Marine *
48	CX183	Bulk sample	23.0	Global Marine *
49	CX188	Bulk sample	20.0	Global Marine *
50	CX196	Bulk sample	20.7	Global Marine *
51	CX203	Bulk sample	16.6	Global Marine *
		Average	20.45	

\+ Analysed by Smith-Emery, Los Angeles
* Analysed by M.H. Buckenham, University of Otago, New Zealand
† Value not included in average

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