BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

RECORD

BMR RECORD 1988/36

RESEARCH CRUISE PROPOSAL

ORGANIC CARBON CYCLING AND QUATERNARY PHOSPHORITE FORMATION:- EAST AUSTRALIAN CONTINENTAL MARGIN (28-32°S)

Project 9131.03

Principal Investigators:- G.W.O'Brien & D.T.Heggie

Schedule:- May, 1987

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TABLE OF CONTENTS

FIGURES

Figure 8. Variation in the nitrate ($umole l^{-1}$) concentrations of surface waters at the CSIRO 50m station (lat. 29° 07'S., long. 153° 38'E) for the three year period from July 1966 to June 1969. "Spikes" represent individual upwelling events. Redrawn from Rochford (1972).

Figure 9. Calculated profiles of longshore velocity versus depth off Evans Head, showing a northward flowing counter-current (stipled) moving along the continental shelf and upper slope. Redrawn from Godfrey et al. (1980b).

Figure 10. Line drawing of a seismic reflection profile across the continental shelf and upper continental slope off Eastern Australia. Redrawn from Marshall (1979).

Figure 11. Proposed high-resolution seismic tracklines and sampling programme.

EXECUTIVE SUMMARY

Organic carbon cycling and Quaternary phosphorite formation: East Australian continental margin (28-32 S).

The East Australian continental margin between 29-32°S is one of only three areas in the world where modern phosphorite formation has been documented. Holocene and late Pleistocene phosphate nodules occur within organic-poor, glauconitic, foraminiferal sands on the upper slope, generally at water depths ranging from 350-450m. Extensive deposits of ferruginous Neogene phosphorite also occur in the same general area, but in shallower water (200-300m), on the outer shelf. There are also systematic variations in both the sedimentary facies and in the concentrations of organic carbon (TOC) across the continental shelf and upper slope. The inner and outer shelf (50-300m) sediments are characterized by low TOC concentrations. TOC increases systematically at depths below 300 m, averaging 0.4-0.8% between 300-500 m. The deep basin (>500m) sediments contain significant (>0.8%) TOC, and may be anoxic. The TOC distribution appears to be principally controlled by variations in the strength East Australian Current.

It is planned to use "Rig Seismic" for 17 days during May 1987 to investigate the Quaternary to Neogene phosphorites and also organic carbon cycling processes on the East Australian continental margin. Three days of the cruise will be devoted to high resolution seismic acquisition, approximately 12 days to geological sampling, and 2 1/2 days for transiting. The collection of high resolution seismic data will allow:

i. An understanding of the spatial and temporal relationships within (and between) the Neogene and Quaternary phosphorites.

ii. To determine if large, as yet undiscovered, phosphorite resources are present on the outer shelf or upper slope.

iii. An understanding of possible structural and/or topographic controls on the distribution of the Neogene and Quaternary phosphates.

iv. To define sea-level history from the mid-Miocene to the present day.

The geological programme will primarily utilize box, piston, gravity and vibro-coring, though some dredging, underwater photography, and side-scan sonar work will also be carried out. Specific objectives of the geological programme include:

i. Understanding the sedimentology and distribution of phosphatic and non-phosphatic sediments from inner shelf to abyssal environments.

ii. Documentation of the pore water chemistry of sediments, particularly those associated with Quaternary phosphorites, in order to test two models of phosphorite formation, namely:- a), that the nodules form via the interfacial cycling and fixation of phosphorus within bacterial mats at the sediment-water interface, or b), that the nodules form via the bacterial degradation of organic matter deeper within the sediments, with phosphorus diffusing to, and precipitating at, the sediment-seawater interface.

iii. To determine the rates at which aerobic, sub-oxic, and anaerobic microbial respiration are occurring within the sediments, and hence determine the rates of phosphorus remineralisation.

iv. Understand the principal factors controlling organic carbon accumulation and preservation in shelf and slope environments, and to determine how these have varied through time.

v. Estimate the relative degree of saturation of the pore fluids with respect to carbonate fluorapatite (CARFAP).

vi. To determine phosphorite and microbial growth rates.

Project Timetable

Late 1986 - early May 1987	:	evaluation of existing geophysical, geological, and geochemical data.
8 May - 25 May 1987	:	R/V Rig Seismic cruise commencing in Sydney and ending in Brisbane.
Before May 1989	:	public release of all geophysical, geological and geochemical data from the cruise.

Project Leaders

G.W. O'Brien

D.T. Heggie.

Consultation with Industry and Other Organizations

This project proposal has been developed in consultation with: BMR Division of Continental Geology; CSIRO Baas-Becking Laboratories; CSIRO Marine Laboratories; CSIRO Division of Oceanography; Florida State University;

University College, London; Scripps Institute of Oceanography; East Carolina University; Lake Illawarra Management Committee; Flinders University. Copies of the project proposal will be forwarded to the relevant State and Federal authorities, and to interested companies and universities, by April 1987.

1. INTRODUCTION

Marine sedimentary phosphate deposits occur throughout most of the geologic record from the Late Proterozoic to the Holocene. They are found on many modern continental shelves, and are usually spatially associated with centres of present day coastal upwelling. As a consequence, many of the models proposed to explain the origin of these deposits invoke upwelling as an essential link in the phosphogenic cycle. The discovery of Holocene phosphorites within organic-rich sediments on the continental margins off Peru-Chile and Namibia, regions characterized by an eastern boundary current with strong coastal upwelling and associated high organic productivity, seemed to provide additional evidence of a genetic association between upwelling and phosphorite formation. It has been proposed that upwelling provides a continued supply of nutrients to the surface water, leading to a high biological productivity, and hence a high flux of organic matter to the sediments. Apatite is thought to form diagenetically within the sediment from phosphate released by bacterial decomposition of organic matter (Baturin, 1971a; 1971b; Atlas, 1975; Burnett, 1977). However, several phosphorite deposits in the geologic record do not easily fit this "Upwelling Model" (Bushinski, 1964; Cook, 1976; Bentor, 1980) when paleogeographic reconstructions are applied. Furthermore, the sediments associated with phosphorites deposits often have low contents of both organic carbon and diatomaceous silica, in contrast to the sediments of modern day "Eastern Boundary Current" upwelling areas.

The discovery of late Pleistocene and Holocene phosphate formation on the East Australian continental margin, an area of only limited seasonal upwelling and low organic productivity, has aroused much interest among phosphate researchers throughout the world. The Quaternary phosphorites occur as nodules lying in unconsolidated foraminiferal sands on the upper continental slope between latitudes 29-32°S, generally at water depths ranging from 350-450 m (Fig. 1). This phosphogenic province may provide the first modern analogue for phosphate deposits whose origin is not easily related to either coastal upwelling or high organic productivity. In addition, ferruginous middle Miocene phosphorites occur in the same general area as the Quaternary phosphates, but in shallower water. The ferruginous phosphorites appear to cover a moderately large area, and are similar in age to extensive mid-Miocene phosphorite deposits in other parts of the world.

Because of the significance of this area, it is planned that the R.V. "Rig Seismic" spend 17 days at sea off northern New South Wales in May 1987. Outstanding problems relating to the formation of the Quaternary phosphorites will be addressed, as will the closely related problem of the controls on organic cycling on starved passive continental margins. During the cruise, sampling procedures will include dredging, piston coring, gravity coring, box coring and water sampling on the continental slope and vibro-coring on the continental shelf. High resolution single-channel seismic reflection profiling will be conducted along transects within the area of interest. The cruise and post-cruise work will attack the related problems of phosphorite genesis and organic carbon cycling by integrating physical oceanographic, sedimentological, geochemical, and microbiological data.

2. STUDY AREA

2.1. OCEANOGRAPHY

2.1.1. Hydrography

The hydrography of the area is dominated by the East Australian Current (EAC), a strong southward-flowing western boundary current that scours much of the shelf and upper slope, thereby restricting sediment accumulation. In this region, surface currents of 200 cm/sec have been reported, while further south (33°S) velocities of 150 cm/sec are common (Hamon, 1965). However, the current strength decreases to approximately half its surface value at a depth of 250 m (Hamon, 1965), though there is evidence of some continuity of the current regime from the surface to a depth of at least 2300 m (Boland & Hamon, 1970).

While the East Australian Current usually follows the shelf edge between 27 - 32°S (Boland & Hamon, 1970) it periodically meanders up onto the shelf and then back into deeper water again (Pearce, 1980). In addition to these periodic meanders, northward-flowing counter currents have been reported inshore from the main body of the southward-flowing East Australian Current (Reed et al., 1968; Godfrey et al., 1980a). These counter currents do not appear to be permanent features but nevertheless can be of considerable magnitude.

2.1.2. Current Velocities

There are pronounced north-south and east-west variations in current velocity on the East Australian continental margin. The East Australian

Current tends to separate from the coast between Smoky Cape and Sugarloaf Point (see Fig. 2) and, as a consequence, current velocities drop sharply (Fig. 3) south of 31 -32°S (Godfrey et al., 1980a). This decrease in velocity has a major effect on sedimentation patterns, with major accumulations of fine sediment absent north of 32°S, but common south of 32°S (Davies, 1979). The current is much stronger in summer than winter (Figs. 3 & 4), and is strongest approximately 30 km from shore (Fig. 4).

2.1.3. General Character Of East Australian Continental Margin Waters

2.1.2.1. Chemical parameters

In considering the oceanographic regime of the East Australian continental margin, particularly in regard to phosphogenesis and organic carbon budgets, four important chemical parameters are the dissolved oxygen concentration, and the inorganic phosphate, nitrate nitrogen, and silicate concentration of the ocean waters. The nutrient concentrations and distributions indirectly limit the potential maximum biological productivities of the surface waters, while the oxygen concentration has a significant effect on the preservation of organic matter. The distributions of phosphate, nitrate, and dissolved oxygen in the Tasman and Coral Sea has been discussed in detail by Rochford (1969a, b, c; 1968a, b; 1969) and a great deal of unpublished data is available from CSIRO Division of Oceanography, Hobart.

A. Dissolved oxygen

The dissolved oxygen concentration of surface waters off Eastern Australia between latitudes 29 - 34°S is typically high, averaging between 4.80 - 5.20

ml/l. There is usually a steady, but slow decrease in oxygen concentration with increasing depth; at 1000m, values average 4.20 ml/l. Fig. 5 shows the oxygen distribution of Evans Head (lat. 29° 07'S; long. 153° 50'E) versus depth. The profile was drawn from unpublished CSIRO data, and presents data from 15 separate stations at this location. Fig. 6 represents the vertical oxygen distribution of four stations along a traverse on latitude 29° 07'S off Evans Head, drawn together with the bottom topography.

B. Phosphate, nitrate, silicate

The surface waters of the Tasman Sea are characteristically poor in nutrients (Rochford, 1969), primarily due to the fact that the source waters of the Tasman Sea, and hence the EAC, are also poor in nutrients (Rochford, 1969 a-c; Godfrey, 1973). Fig. 7 shows phosphate, nitrate, and silicate profiles for stations between 29 - 32° S. Surface phosphate concentrations average 0.16 umolel^{-1} , surface nitrate 0.39 umolel^{-1} , while surface silicate is usually less than 0.9 umolel^{-1} . All three nutrients show increases in concentration with increasing depth, as expected; at 1000m phosphate averages approximately 1.8 umolel^{-1} , nitrate 28 umolel^{-1} , while silicate reaches 25-30 umolel^{-1} .

2.1.4. **Upwelling And Nutrient Enrichments**

The surface waters along the East Australian continental margin are typically poorly productive, with productivity averaging only about 0.10 gCm^{-2} day^{-1} (Jitts, 1965; Scott pers. comm., 1980). This is presumably due to the paucity of nutrients within the photic zone. However, there have been reports of upwellings and associated nutrient enrichments (Rochford, 1972; 1975) at various points off Eastern Australia (Fig. 2). The upwellings are sporadic, are of short duration (usually lasting a total of less than 10 days), and occur only during the summer months (see Fig. 8). The upwellings occur when the East Australian Current moves close to the coast; the strong, southward-flowing current interacts with the continental slope, producing an Ekman layer in which the mass transport is directed up into shallower water. The upwelling waters usually originate from depths of 150 to 200m. Studies conducted using current meters moored at, or above, the seafloor have shown that upwelling periods coincide with periods of high bottom current velocities, with bottom current velocities of 70 cm/sec common at the 200 m isobath.

Because the surface waters between 28-32°S are typically poor in nutrients, these localized upwelling events can have a significant effect on the nutrient budget of the coastal areas. For example, surface nitrate values off Evans Head (see Fig. 2) are usually less than 0.5 umole l^{-1} for much of the year; ocasionally nitrate cannot even be detected. During upwelling events, however, surface nitrate values rise to, but do not exceed, 5 umole l^{-1}, and are usually in the range 3-5 umole l^{-1}. Surface phosphate concentrations are also higher during upwelling events, and exceed 0.3 umole l^{-1}, compared with an average of 0.1-0.2 umole l^{-1}.

2.1.5. Bottom Current Velocities

Various aspects of the oceanography of Eastern Australia highlight the fact that the East Australian Current <u>interacts with both the continental slope and shelf</u>, and the extent of this interaction is critical to any understanding of the sedimentological controls in the area. Between latitudes 28 - 29°S, the surface velocities of the East Australian Current are highest, and measured bottom current velocities on the continental shelf average 15 - 30cm/sec, with peaks of 100cm/sec (Godfrey et al. 1980a). These currents are mostly directed southward.

Pearce (1980) summarised current meter data obtained from two moorings located off Cape Hawke (lat. 32°13'S) at the 200m isobath at depths of 5m and 60m above the sea-floor. These data demonstrated that at times when the EAC meandered onto the continental shelf, current velocities 60m above the sea-bed peaked at 150cm/sec, while speeds of up to 70cm/sec were recorded 5m above the sea-bed. The currents generally parallel the bathymetry, although there may be a small cross-shelf component in either direction (A.F. Pearce pers. comm. 1980). Subsurface current directions off Cape Hawke are variable, and can shift from southerly, to northerly, and back to southerly within a few days. Theoretical calculations by Godfrey et al. (1980b) have indicated that a northward, subsurface countercurrent with velocities of up to 50cm/sec can intersect the continental slope at depths of 200-400m off Evans Head (Fig. 9). Currents 10m above the sea-floor at the edge of the shelf (180m isobath) off Port Hacking were variable in direction and strength, averaging 10-20cm/sec with maximum velocities of 30m/sec (Cresswell, 1974). It therefore appears that the highest bottom current velocities on the continental shelf and upper slope are off Evans Head and tend to decrease to the south, along with the overall strength of the East Australian Current.

2.1.6. Organic Productivity

Unfortunately, there has been little work done on primary production on the East Australian continental margin. Jitts (1965) described the summer characteristics of primary production in the Tasman and Coral Seas, and found that the source waters of the East Australian Current (i.e. the waters of the northern Coral Sea and west central South Pacific Ocean) were typically only poorly to moderately productive. Between 20-35°S, productivity values are characteristically low, averaging approximately 0.10 gCm^{-2} day^{-1}. Productivity increases markedly south of 35°S, where they average about 0.20 gCm^{-2} day^{-1}. South of approximately 40°S, productivity values rise sharply to about 0.30 gCm^{-2} day^{-1}. Scott (pers. comm. 1980) considers that primary production values at Evans Head and Laurieton would be likely to peak at about 1.0 gCm^{-2} day^{-1} during the height of upwelling events, though throughout the rest of the year, values of 0.1 gCm^{-2} day^{-1} would be typical. The seasonal upwelling events are restricted to within 10-15 km of the coast and the associated enhanced productivities are similarly restricted.

2.2. GEOLOGY, SEDIMENTS, AND PHOSPHORITES

2.2.1. Geology

The continental shelf between 28-32°S is fairly narrow (25-40 km) and consists of a flat plain extending out to about the 100m isobath. Marshall (1979) has attributed this flatness to the development of broad terraces, particularly at depths between 50-100m. The boundary between the inner and outer shelf is marked by a nick-point and prominent terrace at 105m depth. Beyond this point the outer shelf has slopes of 1-3°. The major shelf break occurs at depths between 210-450m, and the continental slope is unusually steep, with typical gradients of 8-12°, though occasionally as steep as 20°.

Several seismic studies have been undertaken on the continental shelf and upper continental slope regions off northern New South Wales and southern Queensland. Davies (1975, 1979) reported the results of 3000 km of seismic reflection profiles obtained across the shelf and upper slope between Sugarloaf Point (32°30'S) and Gabo Island (37°40'S), an area to the south of the present study area. He showed that two seismic reflectors, named S1 and S2, were present in most seismic sections. The deeper S2, a strong reflector, could be followed westwards into the coastal cliffs and was considered to represent the basement rock upon which the shelf sediment sequence was built. Overlying S2 was a sequence of unconsolidated sediments within which S1 represents a major unconformity. S1 is present in nearly all sections between Sugarloaf Point and latitude 35°10'S, and because of its characteristics, was considered by Davies (1975, 1979) to have arisen from a single event.

Marshall (1979) described seismic reflection profiles between latitudes 28-30°S, and noted that between 28-31°S, the S2 reflector forms a broad, sub-horizontal surface beneath the inner shelf region, whereas further south it is slightly more inclined. Over the inner shelf region basement is usually within 50m of the sea-floor and the sediment cover is thin. Jones & Davies (1979) stated that bedrock often crops out on the sea-floor when water depths are less than approximately 60m. The depth of the present day shelf break shows considerable variation from one locality to the next, and these variations are related to the depth to basement.

An unconformity of regional extent, designated S1 by Marshall (1979), also occurs between latitudes 28-32°S. He described it as having the characteristics of a previous sea-floor (e.g. prominent shelf break beneath the existing shelf break) and considered it to be northward extension of the unconformity designated S1 by Davies (1975, 1979). Marshall (1979) observed contrasts in sediment thicknesses above the S1 unconformity at different locations on the outer shelf and upper slope. For example, between latitudes 28 - 29° S, a thick sediment sequence is developed on the upper slope, whereas the outer shelf possesses only a thin sediment cover (see Fig. 10). In contrast, south of 29° S the upper slope exhibits only a thin sediment sequence, whereas sediment cover on the outer shelf is relatively thick. Marshall (1979) invoked the actions of the East Australian Current (EAC) to explain the apparent slow rate of sediment accumulation in this area, and suggested that sedimentation rate would be minimal where the velocity of the EAC is maximal. This appears to be the case between latitudes 28 - 29° S, and is consistent with the observations of Jones et al. (1975), who noted, in relation to a rapid decrease in the velocity of the East Australian Current south of 32° S, a definite increase in the thickness of the sedimentary sequence south of 32.5° S, while at 35.8° S outbuilding of the shelf was obvious.

The suggestion from seismic sections is that the East Australian continental margin between latitudes 28-32° S is a region of thin sedimentary cover, implying a low rate of sedimentation. South of 32° S, the sedimentary section is somewhat thicker but the rate of sedimentation is also apparently low. An estimate of sedimentation rate was made by Davies (1975, 1979) for the region between 32° 30' - 35° 10'S, based on a comparison of the S1 unconformity with early to middle Pliocene unconformities occurring at similar depths to S1, off east Gippsland. He proposed that the S1 and the Gippsland unconformities were of similar age, and as the sediment thickness above S1 on the present day continental margin is 120-212 m, the average rate of sediment accumulation since the early to middle Pliocene might have been 2.0 - 2.5cm kyr^{-1}.

2.2.2. Sediments

The first descriptions of sediments from off northern New South Wales were by Loughnan & Craig (1962). These workers described "siderite" and "ferruginous" nodules recovered from the outer shelf off Coffs Harbour and Port Macquarie. Subsequently, in 1966 Global Marine Inc. (von der Borch, 1970) conducted a limited dredging operation, specifically for phosphorite, in water depths ranging from 90 - 385 m. In 1970, the marine geology group of the Bureau of Mineral Resources (BMR) occupied sediment sample stations on a 10 mile grid, while during 1971 closer spaced (1-5 km) stations were occupied on several transects across the shelf (Marshall, 1980). Most sediment samples were recovered with a small pipe dredge, whereas conventional rock dredges were used to sample the outer shelf and upper slope. Single channel seismic reflection profiling was run across the shelf in conjunction with the sampling programme (Marshall, 1979). Flinders University undertook sampling in the area in May 1979 during a cruise of the R.V. "Sprightly", during which 16 sample sites were occupied in water depths of 105-465 m between 29° 12' and 29° 30'S using a large Smith-MacIntyre grab. Additional samples were collected by Flinders University in December 1979 from the R.V. "Tangaroa", using piston and box corers, as well as dredge sampling. Some 74 stations were occupied between 29 - 31° S in water depths of 93 - 655 m (O'Brien, 1983). The sea floor of the inner and mid-shelf is mantled by quartz-rich sands that gradually increase in carbonate content seaward (Facies I). The carbonate component consists of either whole or fragmented skeletons of foraminifera, molluscs, articulated and crustose coralline algae, bryozoans and echinoderms (Marshall & Davies, 1978; Marshall, 1980). On the outer shelf the carbonate content of the sediment decreases, and the glauconite content increases. The glauconite is typically strongly oxidized, and the sands have a distinctive dark yellowish-brown colour that is a result of a relatively high abundance of hydrated iron oxides (Facies II). On the upper slope, particularly in water depths greater than 350 m, the sediments consist of reasonably well-sorted fine to medium sands (Facies III). Glauconite and the remains of planktonic foraminifera dominate; the glauconite is a dark green in colour, in contrast to its oxidised nature on the outer shelf. The organic carbon flux to the outer shelf sediments is very low, as is the sedimentation rate (O'Brien et al., 1981), and consequently the organic carbon concentrations in the sediment are low, averaging less than 0.5%. In deeper water (>500m), the sediments are finer grained foraminiferal sands and silts (Facies IV), and also appear to have significantly higher organic carbon concentrations (>0.8 wt%).

2.2.3. Phosphorites

Phosphate nodules, ranging from pebble to boulder size, are present on both the outer shelf and upper slope. The Quaternary phosphorite occurs as non-ferruginous nodules (Type 1 of O'Brien and Veeh, 1980) on the upper slope, generally between water depths of 350-455 m. These nodules, which are earthy, friable and range in colour from near white to yellowish-brown to dark grey, are similar in appearance to the surrounding sediment, except for their degree of induration. The cementing material is cryptocrystalline apatite. These Quaternary nodules invariably occur associated with foraminiferal (Facies III) sands, and typically range from 1-5 cm in diameter. The Quaternary nodules occur approximately 35-40 km offshore, and are thus far removed from the zones of coastal upwelling, which are restricted to within 10-15 km of the coast.

Ferruginous nodules (which contain significant amounts of iron oxy-hydroxides, mostly goethite) also occur on the upper slope and outer shelf, though they typically occur in shallower water (<350 m) than do the Quaternary non-ferruginous nodules. These iron-rich nodules invariably have ages which are beyond the dating limit of the uranium-series method (>800kyr). The ferruginous nodules contain greatly varying amounts of goethite, and their total iron concentrations (expressed as Fe_2O_3) can vary from 10% to >50% Fe_2O_3. In contrast, the Fe_2O_3 concentration of the non-ferruginous nodules typically ranges between 2-5%. The megascopic characteristics of the ferruginous nodules varies with the abundance of goethite, which in turn appears to be controlled by the relative location of the nodules on the outer shelf and upper slope. Ferruginous nodules which are associated with Quaternary non-ferruginous nodules, and Facies III sediments, at water depths between 350-455 m on the upper slope, are typically moderately indurated and resemble the associated Quaternary nodules, except for their more abundant goethite content. These nodules typically contain 10-12% Fe_2O_3. In shallower water (250 - 350m), ferruginous nodules commonly occur within unconsolidated goethite - rich, Facies II sediments. These nodules are typically well-indurated, and have a thin, "glazed" goethite coating around the nodule exterior. Such nodules typically contain 10-20% Fe_2O_3, which is similar to, or in excess of, the Fe_2O_3 concentrations of the associated sediments. In still shallower water (150-250m), highly ferruginous phosphate nodules occur on relict, current-swept areas of the outer shelf in some places, particularly off Coffs Harbour and Port Macquarie (von der Borch, 1970). These nodules occur on the seafloor either as a nodular lag deposit or as outcrops of older shelf sediments. These nodules are very well-indurated, often conglomeratic, and have a thick goethite "glaze" and high goethite concentrations in their matrix. Total iron concentrations in these nodules typically range from 30-50% Fe_2O_3.

Palaeontological evidence suggests that many of these nodules are as old as middle Miocene. These very iron-rich nodules range from 1-5 cm in diameter to boulder size, though nodules larger than 5 cm in diameter are usually conglomeratic. These areas of highly ferruginous phosphatic "lag", whether they occur as gravel, pavement, or outcrop, are defined as "Facies V". Ferruginous nodules do not occur associated with Facies I sediments in very shallow water.

Recent studies (O'Brien et al., 1987a) have shown that the Quaternary non-ferruginous nodules progressively gain iron oxy-hydroxides with time, and it appears that a continuous spectrum of Fe_2O_3 concentrations exists between non-ferruginous Quaternary and highly ferruginous middle Miocene "end-members" (O'Brien et al., 1987b). The amount of goethite present within the nodules thus appears to be related primarily to nodule age: -

i. Quaternary non-ferruginous nodules are the youngest, and occur in an area of active (but slow) sedimentation on the upper slope. Slightly ferruginous nodules (containing 10-12% Fe_2O_3) associated with the Quaternary nodules are probably only slightly older than the Quaternary nodules.

ii. Moderately ferruginous nodules (10-20% Fe_2O_3) and associated Facies II goethite-rich glauconite-foraminiferal sands probably represent an older phosphate-depositing system which was active in pre-Quaternary times. As these nodules and sediments are found in shallower (250-350m) water than the Facies III sediments (which appear to represent their modern equivalents), it may be that they were deposited during a higher sea-level stand. A subsequent lowering of sea-level would be accompanied by an increase in the strength of the East Australian Current, inducing sediment non-deposition over the area presently occupied by Facies II sediments, and shifting the depocentre of the phosphate nodules and glauconite-foraminiferal sands (Facies III) seaward. This increase in current velocities could possibly reduce the flux of fine grained organic matter to the Facies II sediments, resulting in strongly oxic conditions within the sediments. Glauconite would begin to breakdown under oxic, non-depositional conditions, liberating the iron oxy-hydroxides now found within the Facies II sediments. Continued high bottom current velocities would winnow the foraminiferal fraction from the sediment, thereby concentrating both glauconite and phosphate nodules. Glauconite oxidation could also provide the iron oxy-hydroxides now found in the ferruginous nodules.

iii. The highly ferruginous non-conglomeratic and conglomeratic nodules which occur on relict, current-swept areas of the outer shelf are probably of middle Miocene age. They were probably originally deposited during a Miocene sea-level high, and have undergone multiple periods sea-floor erosion, reworking, and redeposition. If the depositional environment of the Quaternary nodules is a guide, these highly ferruginous nodules probably occur as a nodular lag, rather than within eroding Miocene strata.

2.2.4. Organic Carbon Distribution

The organic carbon concentration (TOC) in the sediments shows systematic variations from the inner shelf to the upper slope, and these variations are possibly related to variations in the strength of the EAC. The TOC concentration is very low on the inner shelf (Facies I), and generally in the range 0.05 - 0.15%. TOC occurs in similar concentration further offshore in Facies II sediments, but then increases steadily to 0.4 - 1.0% (average 0.5%) in Facies III (350-450 m water depth). Facies IV sediments appear to contain the most organic carbon, with average TOC values increasing to >0.8% (O'Brien et al., 1987b). Facies I sediments are relict quartz-carbonate sands and gravels, and hence TOC would not be expected to occur in high concentraton. Facies II sediments are also relict, but probably originally contained similar TOC to Facies III sediments; glauconite oxidation/goethite precipitation, sea-floor exposure, and winnowing processes have probably significantly reduced TOC in this Facies (O'Brien et al., 1987 a,b). The higher TOC concentrations in Facies III and IV may be related to a higher organic carbon rain rate (predominantly planktonic foraminifera and coccoliths) to the sediment, and a higher sedimentation rate, which has removed the organic carbon from oxidative processes at the sediment-water interface.

Reduction of iron oxy-hydroxides apparently occurs within Facies III sediments (O'Brien et al., 1987a), indicating that the sediments are sub-oxic to anoxic at depth. Sediment accumulation rates in Facies IV average 4-5 cm/kyr, compared with 0.5-1.0 cm/kyr in Facies III (O'Brien et al., 1987c). The higher sedimentation rate (higher organic carbon burial rate) could, by itself, explain the higher TOC in Facies IV, even if the carbon rain-rate to Facies III and IV were identical (see Muller & Suess, 1979).

2.2.5. Relationship of oceanography to phosphogenesis.

The Quaternary phosphates on the East Australian margin are located approximately 35-40 km offshore. In contrast, the localized coastal upwelling centres occur within 10-15 km of the coast, and are thus spatially unrelated to the zone of active phosphate formation. Moreover, coastal upwelling occurs when the East Australian Current moves closer to the coast, and bottom current velocities intensify. In fact, bottom current velocities probably reach 100 cm/sec on the upper slope during coastal upwelling periods, and thus the Quaternary phosphorites and Facies III sediments actually undergo active reworking/erosion during coastal upwelling events, rather than deposition (O'Brien, 1982; O'Brien *et al*., 1987a). It thus appears that the origin of the Quaternary phosphorites is unrelated to coastal upwelling. In addition, the high level of oxygen saturation in the waters off East Australia contrast sharply with the oxygen minimum zones that are associated with the Quaternary phosphorites off Peru-Chile and Namibia.

Fundamental differences thus exist between the Quaternary phosphate province off East Australia and the Quaternary provinces off Peru-Chile and Namibia. The differences are so great with respect to oceanography, biological productivity and sedimentary associations, that there may be fundamental differences in the origins of the East Australian phosphorites, compared with the other areas.

3. FUNDAMENTAL PROBLEMS AND SCIENTIFIC OBJECTIVES

There are several fundamental scientific problems concerning our understanding of biogenic (including organic matter) and authigenic sedimentation on the East Australian continental margin. These problems can be loosely sub-divided into two inter-related sub-groups:-

i. Phosphorites and sediments

and ii. Organic carbon cycling.

3.1. PHOSPHORITES AND SEDIMENTS

Phosphorites on the East Australian continental margin range in age from mid-Miocene to Quaternary. The mid-Miocene ferruginous phosphorites are of similar age to phosphorites from many other continental margins, and probably correspond to a well-documented, major phosphogenic episode in the world ocean. The Quaternary East Australian phosphates are anomalous in that they are presently forming in a low organic carbon-flux environment, within relatively organic-poor, slowly accumulating glauconitic, foraminiferal sands on the upper slope. The estimated organic productivity (0.10 $gC/M^2/yr$) and carbon flux ($4g/C/m^2/yr$; O'Brien & Veeh, 1983) to the sediments appear to be insufficient to produce, via bacterial degradation of organic matter, high phosphate concentrations in the interstitial waters of the sediments. It thus seems unlikely that carbonate fluorapatite (CARFAP) could precipitate inorganically from the pore waters in the East Australian sediments.

In recent years (O'Brien et al., 1981; O'Brien & Veeh, 1983), scanning electron microscopic (SEM) evidence has been presented which suggests that bacteria are intimately involved in the formation of the Quaternary East Australian phosphate nodules. O'Brien and his co-workers have shown that all the detectable phosphorus in the Quaternary nodules is present within 1.5-2.0 micron long botuliform structures which appear to be bacterial cells calcified with CARFAP. It has been proposed (O'Brien et al., 1981; O'Brien & Veeh, 1983) that a slow-growing bacterial population proliferates on the sea-floor, forming a semi-lithified bacterial "mat". Because of their very slow growth rates, these chemolithotrophic bacteria can accumulate elevated concentrations of nucleic acids, phospholipids, and polyphosphates from seawater of normal composition. The assimilated phosphorus is then converted to CARFAP during *post-mortem* alteration of the bacterial cells. Sedimentological evidence (O'Brien *et al.*, 1981) suggest that the phosphorites form during periods of relatively low current activity on the sea-floor, and that the phosphatic "mat" is subsequently dissaggrated to form individual nodules, possibly when current velocities increase (O'Brien *et al.*, 1986).

If O'Brien *et al.*'s model is correct, and the botuliform structures are bacterial, then phosphorite formation is not necessarily restricted to areas of high biological productivity. As a consequence, the rates of phosphorite (CARFAP) formation may possibly outstrip the input of phosphorus (via organic matter) to the sediments. If the botuliform structures are not bacterial, then they must represent inorganically precipitated carbonate fluorapatite. In this case, the phosphate concentrations of the interstitial waters must have reached sufficiently high levels to allow appatite precipitation. How this could occur, considering the low organic carbon-flux, is unclear. Two primary objectives of cruise 1A.09 are to determine if bacteria do control the precipitation of CARFAP off Eastern Australia, and also to determine the degree of saturation of the pore fluids with CARFAP.

CARFAP in the ferruginous middle Miocene nodules is present as large, euhedral crystals, which appear to have formed via the recrystallization of an original "bacterial" apatite. It thus appears that the Quaternary and middle Miocene nodules formed by similar processes, and that the present-day differences are attributable to diagenetic alteration in the ferruginous nodules.

3.2. ORGANIC CARBON CYCLING

The East Australian continental margin between 28-32°S is basically a sediment-starved passive margin which is swept by a strong western boundary current. In addition, the biological productivity throughout the area appears to be relatively constant. Because dilution of the sediment with terrigenous material is minimal and because the biological productivity appears to be largely constant, variations in the total organic carbon concentrations of the sediments must be principally related to either:-

i. Variations in the organic carbon rain-rate to the sediments and/or ii. Variations in the rates of organic carbon preservation/ destruction in the sediments.

One important aim of cruise 1A.09 is to constrain the fundamental controls on organic carbon accumulation on the East Australian continental margin. This study will hopefully also have implications for petroleum geoscience, in that it will provide a better understanding of petroleum source rock preservation on the upper continental slope. In addition, since the Quaternary phosphorites occur on the "hinge-line" between the oxic, shallow water Facies II sediments and the deep water, more organic-rich (?reducing) Facies IV sediments, the origin of the phosphorites are almost certainly intimately linked to organic carbon cycling processes.

4. PROPOSED SHIP-BOARD PROGRAMME

Research problems will be investigated under four sub-programmes, namely:

4.1 Geophysical

4.2 Sedimentological

4.3 Geochemical

4.4 Microbiological

4.1. GEOPHYSICAL PROGRAMME

The primary aim of the geophysical programme will be to collect high resolution, single-channel seismic reflection data in transects from deep-water (>2000m) up onto the inner shelf (50-100m). Approximately 3 days (72 hours) of the cruise will be devoted to seismic acquisition, and about 600-750 km of data should be acquired. The data will be acquired using 5 and 10 cubic inch air-guns, and will provide detailed information on the upper 100-300m of the sedimentary column. The seismic will be acquired in 15-17, 40-50 km long transects, as shown in Fig. 11. The seismic lines will be located to intersect all of the previously described Facies (I-V). In particular, the seismic data should assist with:-

i. Understanding the spatial (and temporal) relationships between the highly ferruginous, middle Miocene phosphorite (Facies V) and the younger Facies II and Facies III (Quaternary) phosphate and determining if large, as yet undiscovered, phosphorite resources may be present on the outer continental shelf or upper slope.

ii. Understanding possible structural or topographic controls on the distribution of the mid-Miocene and Quaternary phosphorite. In particular, to determine if dynamically-induced upwelling could be responsible for the origin of the Neogene to modern phosphates.

iii. Defining the sea-level history from the mid-Miocene to the present day, and determining the relationship of sea-level history to both phosphorite formation and organic carbon preservation in the sediment.

4.2. SEDIMENTOLOGICAL PROGRAMME

Geological sampling will be predominantly along several selected high resolution seismic lines. Two or more cores will be collected from the abyssal plain, to provide sedimentological and geochemical information about the deep basin sediments. In particular, these deep cores may provide data on the effects that large scale, anti-cyclonic eddies have on biological productivity. Thereafter, a series of piston, gravity, box, and vibro-cores will be collected from deep water (>2000m) to the inner shelf (50-100m).

It is hoped to obtain up to 6 m cores on the sandy sediments of the shelf using the vibrocorer. Previous cores on the inner shelf of this area (Colwell and Roy, pers. comm.) penetrated a series of depositional environments ranging from a weathered late Pleistocene marine sandy unit, through a transgressive estuarine to bay barrier sequence and an uppermost Holocene nearshore, shelly sandy unit. It is considered that cores from the mid to outer shelf areas will provide information on the earlier phases of the post-glacial marine transgression, as well as evidence of earlier, more short lived transgressions/regressions related to interstadial fluctuations in sea level. In addition, an attempt will be made to vibrocore sediments associated with the coastal upwelling centres off Evans Head (Rochford, 1975). These cores may provide data on the history of upwelling in this area throughout the Quaternary.

On the outer shelf and upper slope (Facies II & III), box, piston and gravity cores will provide the opportunity for detailed sedimentological analysis of phosphorites and associated sediments. In particular, the undisturbed samples collected by the box corer should enable many of the sedimentologic models proposed for these phosphorites to be critically evaluated. Cores of Facies IV sediments will also be recovered, and will provide information on the nature of sediments in the deep basin and also perhaps on sea-level history.

The high resolution seismic data will be used to locate suitable dredge sites for recovering highly ferruginous, middle Miocene phosphorites (Facies V). The seismic sequences may thereby be accurately related to the geology and it may be possible to trace Facies V sediments in the subsurface. This will be particularly important if the Facies V phosphorites are found to be weathering out of Miocene strata, rather than being a simple nodular Miocene lag deposit. In addition, pipe dredging will be conducted within both Facies II & III sediments, so that large amounts of phosphorite and sediment can be recovered, and the distribution and abundance of phosphorite throughout the area can be evaluated.

Underwater photography will be carried out within Facies II, III, IV, & V sediments at various points during the sampling leg of the expedition, and will provide information on both the distribution of the phosphorite on the sea-floor, and also on local sedimentary bedforms. In addition, side scan sonar data will be acquired in conjunction with underwater photography and geologic sampling to determine if the large scale bedforms have a significant effect on the sedimentology of the phosphorites and associated sediments.

4.3. GEOCHEMICAL PROGRAMME

The documentation of the pore water chemistry of the sediments, particularly those associated with Quaternary phosphorites (Facies III), is an important facet of the cruise. Box, piston, gravity, and vibro-cores will be collected concurrently with the sedimentological programme along resolution seismic transects, at water depths ranging from >2000m to 50m. It is anticipated that, although many cores will be used for both geochemical and sedimentological analyses, it will necessary to "twin" numerous cores to provide sufficient pore water for all of the analyses. Pore water determinations will be carried out on:-

1. Facies IV:- relatively organic-rich sediments upper slope sediments in water depths between >2000 to 450m.

2. Facies III:- uppermost slope (350-450 m) glauconitic, foraminiferal sands which contain Quaternary, and preferably modern, phosphorites.

3. Facies II:- outer shelf (150-350m) relict, iron-stained sediments which contain ferruginous nodules.

4. Facies I:- inner shelf sands associated with coastal upwelling centres.

Analyses that will be performed on the pore fluids include:-

A. NO_3, NH_3, Mn&Fe:- to document the redox of the sediments, and to provide semi-quantitative estimates of carbon rain rates to the sediments.

B. Inorganic and organic phosphate, pH, fluoride, calcium, magnesium, chlorinity, dissolved inorganic and organic carbon.

C. Uranium concentration and isotopes, and oxygen, carbon, and sulphur stable isotopes.

All analyses will be carried out at sea following extraction of pore fluids from the sediments by centrifuging.

Objectives of the pore water program include:-

(I) To determine if carbonate fluorapatite is precipitating from pore water during early post-depositional degradation of organic matter.

(II) To test if the phosphorus source for nodule growth is from older (perhaps mid-Miocene) buried phosphate deposits which are dissolving at depth, with subsequent phosphate transport through pore waters to surface sediments.

(III) To test if nodule growth may be an interfacial process with rapid cycling of organic carbon, nutrients, and metals between interfacial pore water and sediments.

(IV) To test the amount of ferric iron reduction and remobilization within the sediments, and determine how this relates to the ferruginization rates calculated for the older nodules.

(V) To determine the pore water phosphate flux, and relate this to (radio-metrically determined) nodule growth rates in order to estimate phosphorus accumulation rates.

In addition to the above geochemical programme, Dr Clare Riemers (Scripps Institute of Oceanography, U.S.A.) will measure oxygen fluxes into the sediments using oxygen microelectrode techniques on undisturbed box cores.

The pore water analyses will be combined with subsequent total organic carbon determinations and sedimentation rate studies on the sediments to construct an overall organic carbon budget for the East Australian continental margin.

4.4. MICROBIOLOGICAL PROGRAMME

The microbiological programme will be carried out by Dr Graham Skyring (BBL) and Dr David Moriarty (CSIRO), in conjunction with the geochemical programme. This programme will attempt to provide additional constraints on the carbon and phosphorus mass balance for the outer shelf and upper slope sediments (Facies I-IV). The specific aims include:-

1. To collect and confirm that the botuliform structures are bacterial. If this is confirmed, then identify the type of benthic mats considered to be colonizing the most recent phosphorite sediments (Facies III) and, if possible, to determine whether or not the component organisms are autotrophic.

2. To determine the rates at which the following microbial processes occur in the sedimentary column:

(I) oxygen reduction (aerobic respiration).

(II) nitrate reduction and Fe and Mn oxyhydroxide reduction (sub-oxic respiration).

(III) sulfate reduction (anaerobic respiration).

(IV) methanogenesis (anaerobic respiration).

(V) hydrogen metabolism (couped to anerobic and aerobic processes).

3. To determine the effects of microbial metabolism on the physiochemical properties of the porewaters and sediments, and, in particular, determine the rates of microbial activity important in the solubilization and precipitation of phosphate.

4. Count and measure sizes of bacteria in sediment.

5. Determine growth rates of bacteria in sediment samples from the continental shelf and attempt to determine at least minimum values for growth of bacteria in abyssal sediments.

6. Measure rates of phospholipid and protein synthesis.

7. Determine biomass and community structure of microbes by lipid analysis (in conjunction with P. Nicolls; CSIRO, Hobart).

5. CRUISE PLAN

The cruise is predominantly a sampling cruise, but will include 3 days (72 hours) of high resolution seismic acquisition. The ship will leave Sydney (probably late afternoon, May 8) and transit northwards for approximately 18-20 hours to 30°25'S. Geological sampling (box, gravity, piston coring) will then commmence, and continue for approximately 36-48 hours. Cores will be collected in deep (>2000 m) to shallow (200m) water environments between 31°30' and 30°25'. Holocene phosphates have been recovered from this area (locations G16, P852; O'Brien et al., 1986), and this initial coring programme will allow the geochemists/microbiologists refine their analytical techniques.

Following this initial sampling, the streamer will be run out, and seismic acquisition will begin. Data will be acquired in approximately 40 km transects from approximately 31°30'S to 29°S, as shown on Fig. 11. Assuming 72 hours acquisition at 5-5.5 knots, about 700 km (17-18 transects) of data should be collected.

Sampling (coring) of Facies II, III, & IV sediments will begin off Evans Head and move slowly south, finishing off Coffs Harbour seven days later. Dredging of ferruginous phosphorite (and perhaps bedrock) will then be carried out in shallow water (200-500m) for approximately 48 hours. The principal purpose is to sample critical reflectors visible on the high resolution seismic data. Following this, another 48 hours will be available for coring, dredging, underwater photography and side scan sonar work to to 28°S. The ship will then transit for approximately 12 hours to Brisbane.

6. PERSONNEL AND EQUIPMENT

6.1 PERSONNEL

Chief scientists

G.W. O'Brien

D.T. Heggie

Geochemists

W.C. Burnett (FSU)

J.M. McArthur (UCL)

C. Riemers (Scripps I.O.)

Microbiologists

D. Moriarty

G. Skyring

Sedimentologists

P.J. Cook (Cont. Geol.)

S. Riggs (ECU)

Geochemical assistant

A. Banks

Geophysicists

P. Hill

C. Penney

Technical officers

K. Revill	J. Pittar
C. Tindall	J. Mowatt
I. Roach	G. Burran
P. Walker	P. Davis

J. Stratton   R. Schuler

J. Kossacs

6.2. EQUIPMENT

6.2.1. Geophysical

6.2.1.2. Seismic System

6.2.1.1.

- 300m GBR Teledyne hydrophone streamer
- 2 x Teledyne 28420 single channel hydrophone streamers
- 2 x Bolt 5,10,20 cubic inch airguns
- 3 x Price A-300 compressors, each rated at 300 scfm at 2000 psi
- 1 x Price AGM W-2 compressor, rated at 200 scfm at 2000 psi
- BMR designed and built seismic acquisition system based on Hewlett-Packard minicomputers and 96-channel digitally controlled preamp/filters.
- Side scan sonar

6.2.1.2. Bathymetric Systems

- Raytheon deep-sea echo-sounder; 2 kW maximum output at 3.5 kHz
- Raytheon deep-sea echo-sounder; 2 kW maximum output at 12 kHz.

6.2.1.3 Magnetometer System

- 2 x Geometrics G801/803 proton precession magnetometers; may be as standard single-sensor cable or in horizontal gradiometer - configuration.

6.2.1.4 Navigation Systems

Hi-Fix radionavigation system

Prime System

- Magnavox MX1107RS dual channel satellite receiver
- Magnavox MX6100 dual-axis sonar doppler speed log
- Robertson gyro-compass

Secondary System

- Magnavox MX1142 single channel satellite receiver
- Raytheon DSN450 dual-axis sonal doppler speed log
- Robertson gyro-compass

GPS Navigation System

- Magnavox T-Set GPS navigator

Radio navigation

- Decca HIFIX-6

6.2.1.5. Data Acquisition System

- data acquisition system built around Hewlett-Packard 2113 E-Series minicomputer, with tape drives, disc drives, 12" and 36" plotters, line printers, and interactive terminals.

6.2.2. Geological

Rock dredges for up to 30 stations.

Large pipe dredges (25cm x 75 cm) with detachable back plates

Piston and gravity corers for up to 80 stations (predominantly gravity cores).

Box corer for up to 60 stations.

Grab for up to 20 stations.

Vibrocorer for up to 10 stations.

Flow injection analyser.

UV-VIS spectrophotometer.

Underwater camera for up to 30 stations.

Deep-sea geological winch with 10000 m of 18 mm wire.

Hydrographic winch with 4000 m of 6 mm wire.

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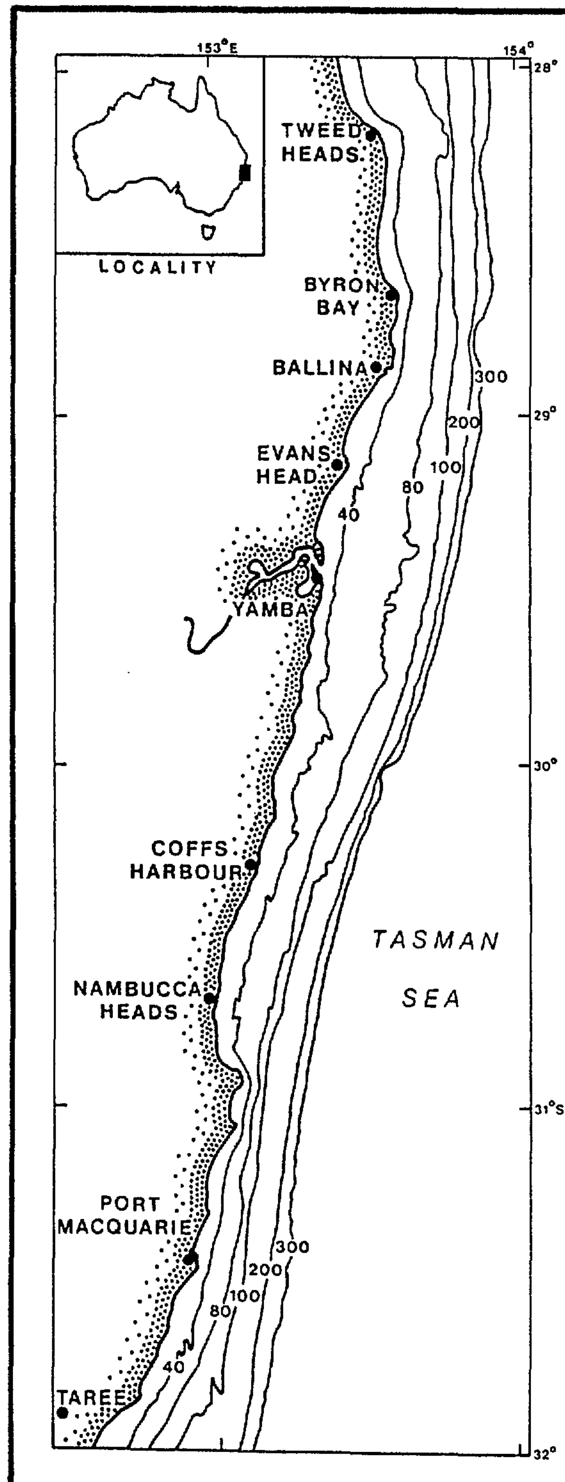

Figure 1. Location map of the East Australian continental margin. Bathymetric contours (in metres) redrawn from Marshall (1979).

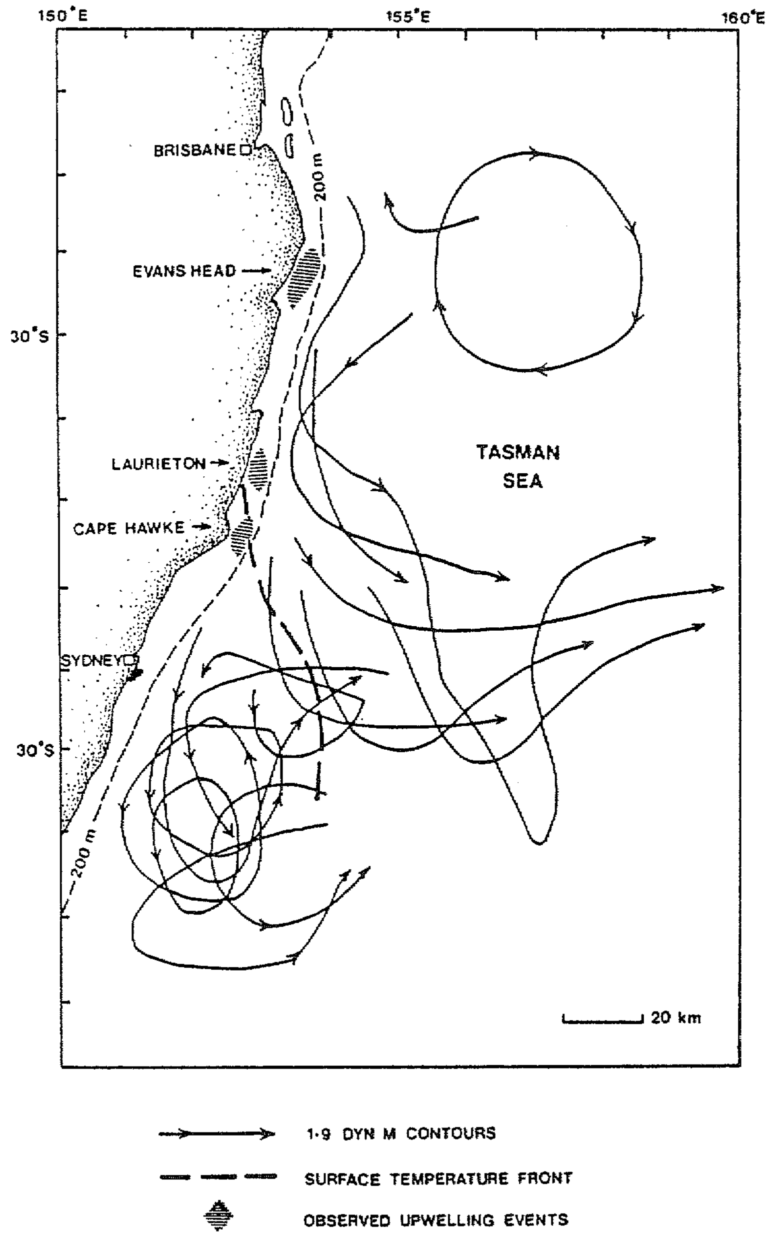

Figure 2. General circulation patterns of the East Australian Current in the summer half year, when the tendency of the current to separate from the coast at Sugarloaf Point is strongest. Locations of reported upwelling events are also marked. Redrawn from Godfrey et al. (1980a)

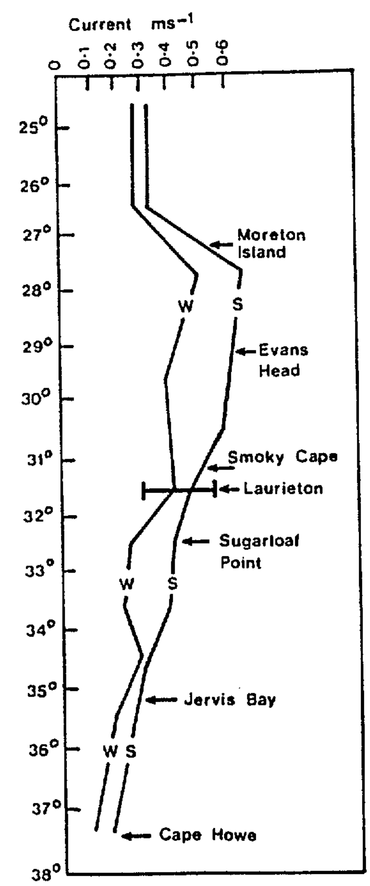

Figure 3. Average longshore components of surface current in the 1^o square covering the 200 m isobath along the East Australian coast for the summer (S) and (W) half years. Positive currents flow southward. Note the distinct increase in current velocities at 27^oS, caused by the East Australian Current approaching the edge of the continental shelf in this region. Falling velocities south of 31^oS reflect the strong separation of the current from the coast in this region. Redrawn from Godfrey et al. (1980a).

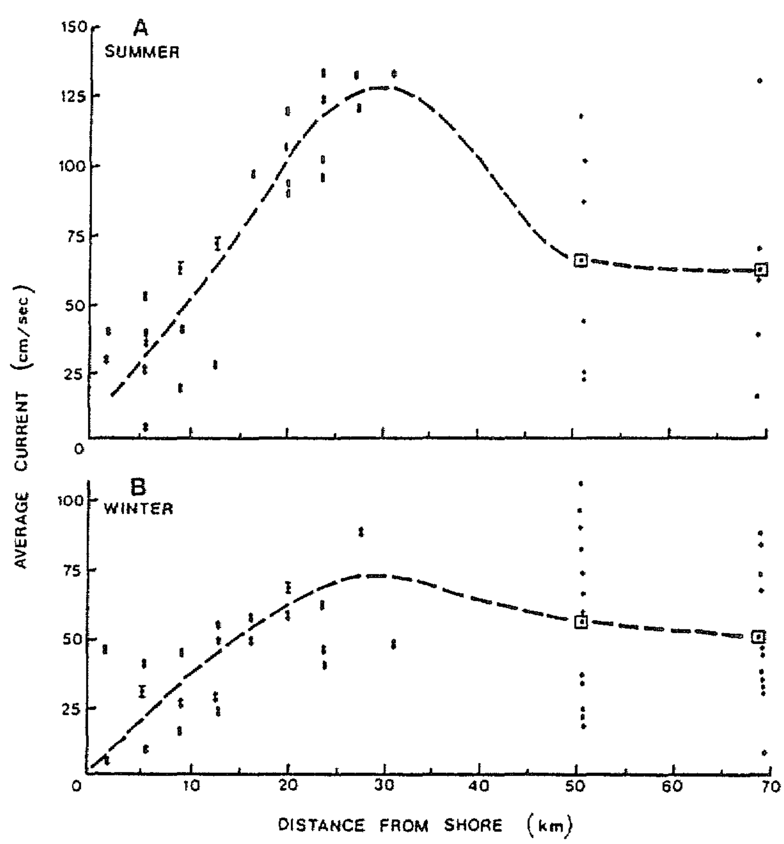

Figure 4. Average current velocities as a function of distance offshore near Evans Head for summer (A) and winter (B). Note that the current is considerably stronger in summer than in winter. Summer average velocities peak some 30 km offshore at over 125 cm/sec, while in winter peak velocities average less than 75 cm/sec. Redrawn from Godfrey (1973).

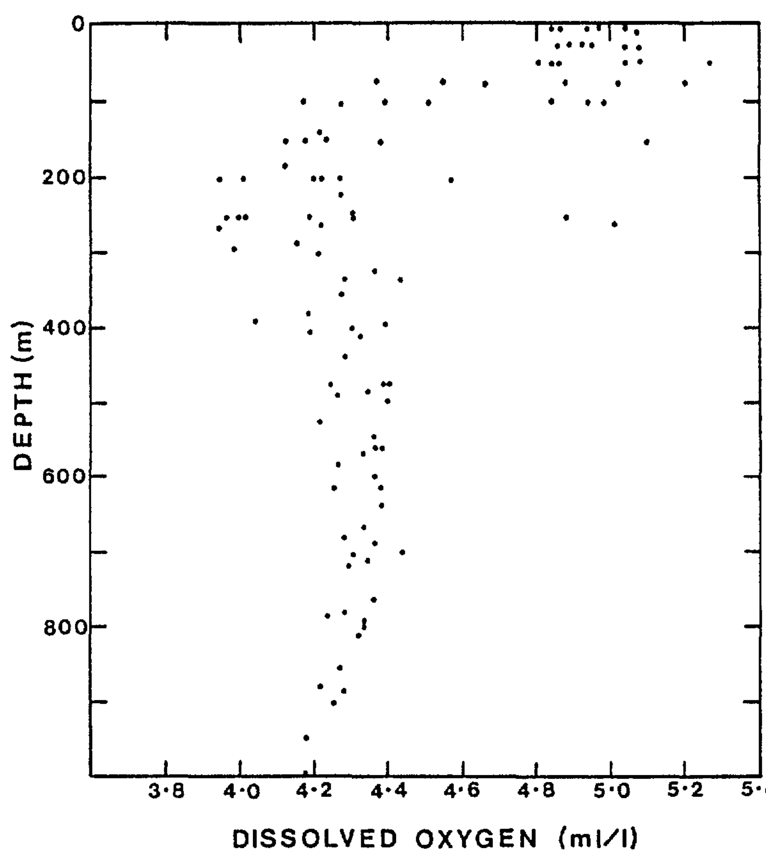

Figure 5 . Dissolved oxygen (ml/l) versus depth profile drawn from unpublished CSIRO data from 15 stations off Evans Head. Note that the dissolved oxygen concentration is high, and here does not fall below 4.20 ml/l.

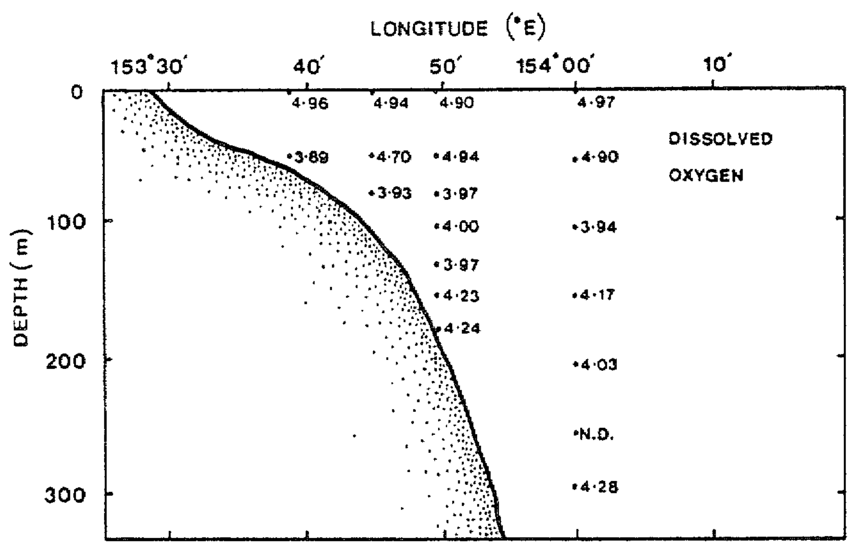

Figure 6 . Dissolved oxygen versus depth profiles for four stations off Evans Head, drawn along with bottom topography. Note the oxygenated nature of the seawater in contact with the continental shelf and upper continental slope. Diagram constructed using unpublished CSIRO data.

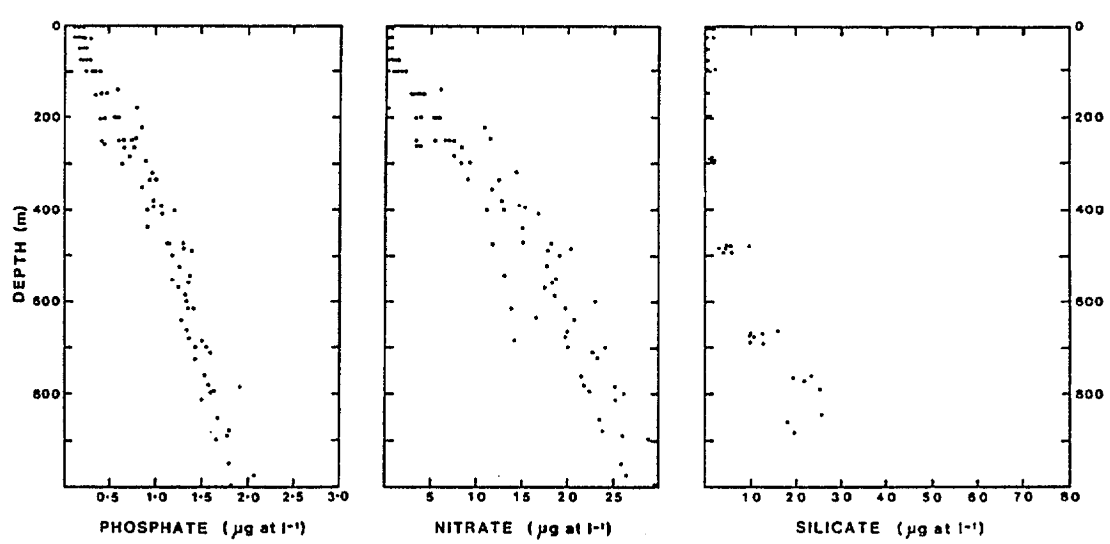

Figure 7 . Phosphate, nitrate, and silicate profiles of East Australian continental margin waters between latitudes 29-32^{o}S. Drawn using unpublished CSIRO data.

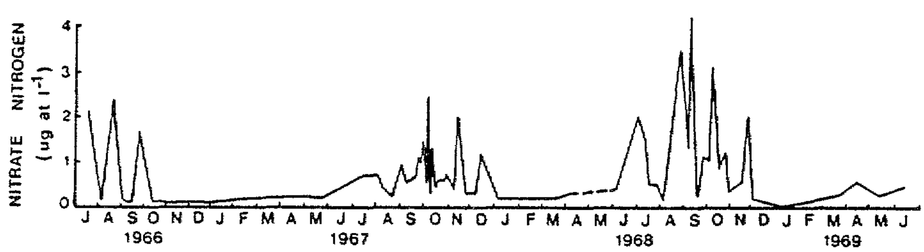

Figure 8. Variation in the nitrate (ugatl^{-1}) concentrations of surface waters at the CSIRO 50m station (lat. 29°07'S., long. 153° 38'E) for the three year period from July 1966 to June 1969. "Spikes" represent individual upwelling events. Note that events vary in duration from a few days to several weeks. Redrawn from Rochford (1972).

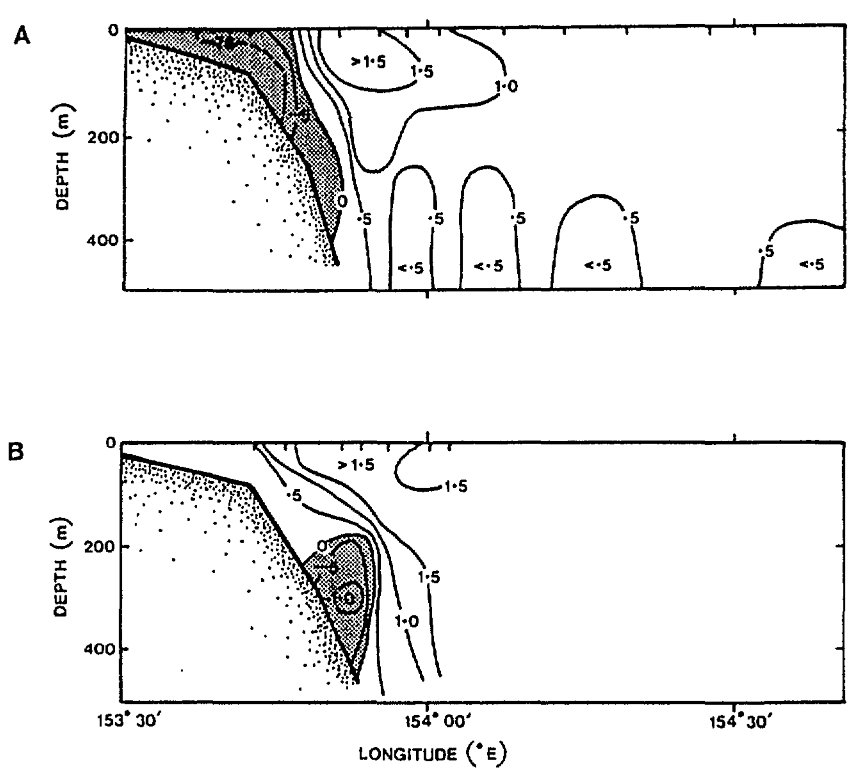

Figure 9. Calculated profiles of longshore velocity versus depth off Evans Head, showing a northward flowing counter-current (stipled) moving along the continental shelf and upper slope. Numbers are velocities in m/sec, southward currents are positive, northerly currents negative. Profiles are approximately E-W, at about latitude 29°15'S. Redrawn from Godfrey et al. (1980b).

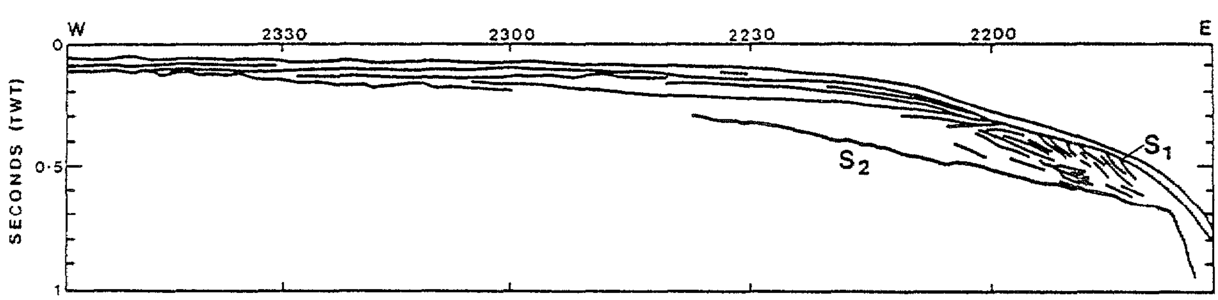

Figure 10. Line drawing of a seismic reflection profile across the continental shelf and upper continental slope off Eastern Australia, showing the thin veneer of sediment present over the upper slope. Traverse runs approximately east-west off Yamba. Redrawn from Marshall (1979).

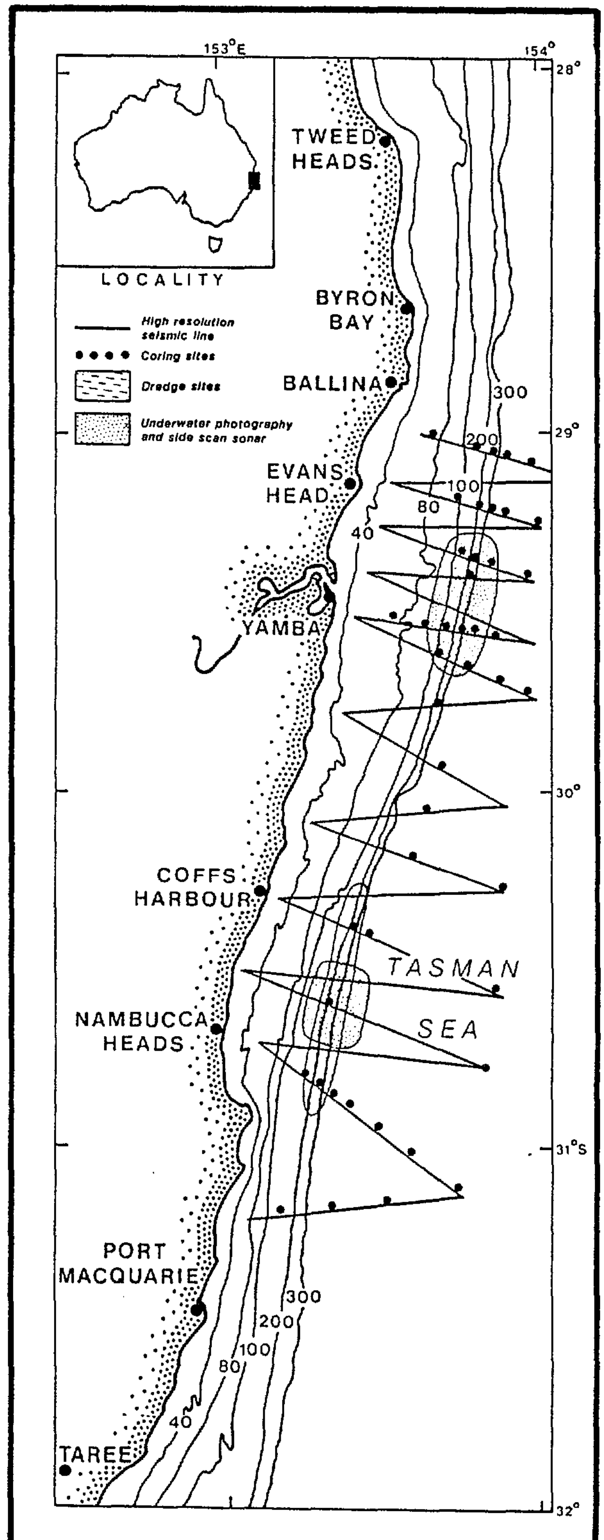

Figure 11 Location map of the East Australian continental margin. Bathymetric contours (in metres) redrawn from Marshall (1979).