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Oceanography and Reefs of Recent and Paleozoic Tropical Epeiric Seas

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Contents

SUMMARY

The Java Sea, one of the few modern tropical epeiric seas, is used as an analogue to examine oceanography, stratigraphy, and reefs of Devonian strata in the Appalachian and Michigan Basins. Nearshore patch reefs and offshore "pinnacle" reefs occur in both the Java Sea and the Emsian-Eifelian Onondaga Formation in the Appalachian Basin. Nearshore patch reefs also occur in the Eifelian Formosa Reef Limestone in the Michigan Basin.

The Java Sea is characterized by quasi-estuarine circulation, in which runoff and rainfall exceed evaporation. Nutrient and organic matter influx from land and from estuarine upwelling contribute to organic rich facies during transgressions and sea level highstands. Similarly, we propose that high runoff from the Appalachian Mountains and from the Laurentian craton contributed to slightly reduced salinity in the Appalachian basin, including possible density stratification during Middle Devonian highstands. By contrast, the Michigan Basin was characterized by anti-estuarine circulation, in which evaporation exceeded combined runoff and rainfall. Contemporaneous Emsian-Eifelian strata in the Michigan Basin are dolomite and dolomitic limestone, rather than cherty and muddy limestone typical of the Appalachian basin.

Reef composition generally reflects oceanographic circulation regime within the epicontinental seas we examine. Nearshore reefs of the modern Java Sea and the Onondaga Formation (Appalachian Basin) are dominated by multilobate submassive, dendroid, and phaceloid corals, and virtually no platy corals or tabular stromatoporoids. Multilobate and phaceloid corals are better able to accommodate muddy sedimentation. By contrast, offshore pinnacle reefs of the Java Sea and nearshore reefs of the Formosa Reef Limestone are dominated by platy *Acropora* (modern) or tabular and laminar stromatoporoids (Devonian). The scarcity of tabular stromatoporoids, and the dominance of phaceloid corals and dendritic branching corals, in the Onondaga Formation (Appalachian Basin) are herein explained by localized high productivity conditions driven by quasi-estuarine circulation, rather than cool water. Quasi-estuarine circulation or localized topographic upwelling leading to highly productive coastal environments may be responsible for other Paleozoic examples of apparent cool-water carbonate deposition within the tropics, including the Ordovician of Eastern Canada.

1 INTRODUCTION

Broad, shallow epeiric seas covered much of the continents during early and middle Paleozoic and Cretaceous times. Because even modern interglacial sea levels are relatively low, compared to most of the Phanerozoic greenhouse, very few epicontinental seas exist today. Consequently, the special oceanographic conditions of broad, shallow continental seas, though of paleontological and sedimentological interest (Droste and Shaver, 1987; Feldman, 1987; Murphy et al., 2000b), have received relatively little attention from modern

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oceanographers (Wyrtki, 1961; Volpio, 1981, Wolanski, et al. 1988; Stansfield and Garrett, 1997). Modern examples of epicontinental seas can be divided into warm-water and cold-water seas. Modern tropical epicontinental seas include the waters covering the Sunda shelf, specifically the Java Sea, shallow portions of the South China Sea, and the Gulf of Thailand (Tjia, 1980; Stansfield and Garrett, 1997; Edinger and Browne, 2000), the Arafura Sea (between Australia, New Guinea, and Timor; Wolanski et al., 1988), and the subtropical Persian Gulf. Modern temperate or polar epicontinental seas in siliciclastic settings include examples such as the Baltic Sea, Black Sea, North Sea, and Hudson Bay.

The Laurentian craton was most extensively flooded from mid-Ordovician through Late Devonian (Frasnian) time, with seas covering as much as 70-80% of the present continental area, at a time of global greenhouse climates. The next most extensive flooding occurred through most of the Cretaceous. Prominent mid-Paleozoic epeiric sea basins include the Appalachian, Michigan, Illinois, Williston, Hudson Bay, and Western Canada Sedimentary Basins (Johnson, 1987). These basins experienced global synchronous transgressive-regressive cycles (Ross and Ross, 1985), while having individual subsidence histories and variable environmental conditions. The variable environmental conditions were most important for the fossil communities developed in those basins.

As continents moved through various latitudes during the assembly of Pangaea in the middle and late Paleozoic, climatic and oceanographic conditions varied considerably among the Laurentian intracratonic and pericratonic basins as the continent crossed the equator. Paleogeographic reconstructions use climatically sensitive sediments, such as redbeds, carbonates, evaporites, and coral reefs, to help indicate the positions of continents at various times (e.g. Witzke and Heckel, 1989; Scotese, 1997). These reconstructions are sometimes complicated by oceanographic conditions in the tropics that simulate deposition under temperate-water type conditions (e.g. Wood, 1993; Lavoie, 1995, many others). Shelly fossils, corals, sponges, and the carbonate sediments they produce are particularly sensitive to this type of mixed climatic/oceanographic signal. In this paper, we examine the roles that quasi-estuarine circulation may have played in producing false cold-water indicators in tropical epeiric sea sediments. We describe circulation, reef sediments, and reef composition in a modern epeiric sea, the Java Sea, and compare these with examples of carbonates, reef sediments, and reefs during Devonian sealevel highstands in the Appalachian and Michigan Basins.

1.2 Epeiric sea circulation models

Circulation in broad shallow continental seas differs from circulation in open ocean environments in several ways. (1) Shallow depth over vast distances causes high bottom friction; this friction frequently ensures that shallow seas are well mixed (Hallam, 1981). (2) Tidal amplitudes are increased on broad shallow shelves, despite the high bottom friction (Klein and Ryer, 1978). (3) Shallow depth allows only shallow wind-driven currents whose speeds rapidly attenuate with depth. (4) Waves are short-period wind-driven waves, rather than long-period oceanic swell (Beer, 1997). (5) Hurricanes and typhoons can be expected to have even greater force in the 10-40° latitudes. Depending on their geographic location, epeiric seas may also have these further characteristics: (6) Input of fresh water is significant in relation to the volume of very large shallow basins. (7) Large shallow basins proportionally increase evaporation rates, especially in the sub-tropics. (8) Large shallow seas may have proportionally reduced siliciclastic input, depending on locally adjacent terrain.

Early models of epeiric sea circulation emphasized high bottom friction and focused on clear water environments (Irwin, 1965). These attempted to explain broad belts of nearshore laminites, dolomites, and evaporites. These models could not adequately explain the widespread black shale deposits in cratonic interior seaways and other epeiric sea environments (Hallam, 1981). More recent models have attempted to relate mid-latitude arid environments (e.g. Irwin 1965) to a broader spectrum of climatic and sedimentary environments (Heckel, 1977; Schopf, 1980). Circulation systems for epeiric seas based on salt balance have been divided into quasi-estuarine (QEC), applying to regions where freshwater influx from rainfall and runoff exceeds evaporation, and anti-estuarine (AEC) where evaporation exceeds input of freshwater (Schopf, 1980; Witzke, 1987; Fig. 1).

Under quasi-estuarine (QEC) conditions, less-dense water flows out of epeiric seas at the surface, and is replaced by deep, nutrient rich, oxygen-depleted water from the oxygen minimum zone of open ocean basins (fig 1A). Anoxic black shale facies can form under QEC conditions with or without a sill separating the embayment from the ocean basin (Fig. 1C; Witzke, 1987). Black shale deposition need not require anoxic conditions in the water column or on the substrate, but only requires that flux of organic matter to the sediment exceeds the oxidative capacity of those sediments, as observed in the Black Sea and Eastern Pacific equatorial divergence zone (Pedersen and Calvert, 1990). Both high productivity and low oxygen availability within sediments are promoted under QEC conditions. A sharp slope break at the edge of such shelves can lead to upwelling at the shelf edge, promoting zones of high productivity, including possible phosphorite deposition (Fig. 1E; Riggs, 1984; Witzke, 1987; Hiatt, 1997, 1998; Rancourt and von Bitter, 1998). Because high runoff under QEC conditions usually carries terrigenous sediments, QEC promotes deposition of siliciclastic silts and clays if a source area is available, or limestones with high clay content and dissolved silica content in the form of chert or silicified fossils (Witzke, 1987). Under icehouse conditions (e.g. Modern), the tropics almost invariably have high rainfall, and QEC conditions should generally be most common within 20 degrees of the equator, while AEC conditions should be most common in sub-tropical latitudes. Under greenhouse conditions, however, this pattern may be reversed, with AEC conditions in the core tropics and QEC in subtropical latitudes.

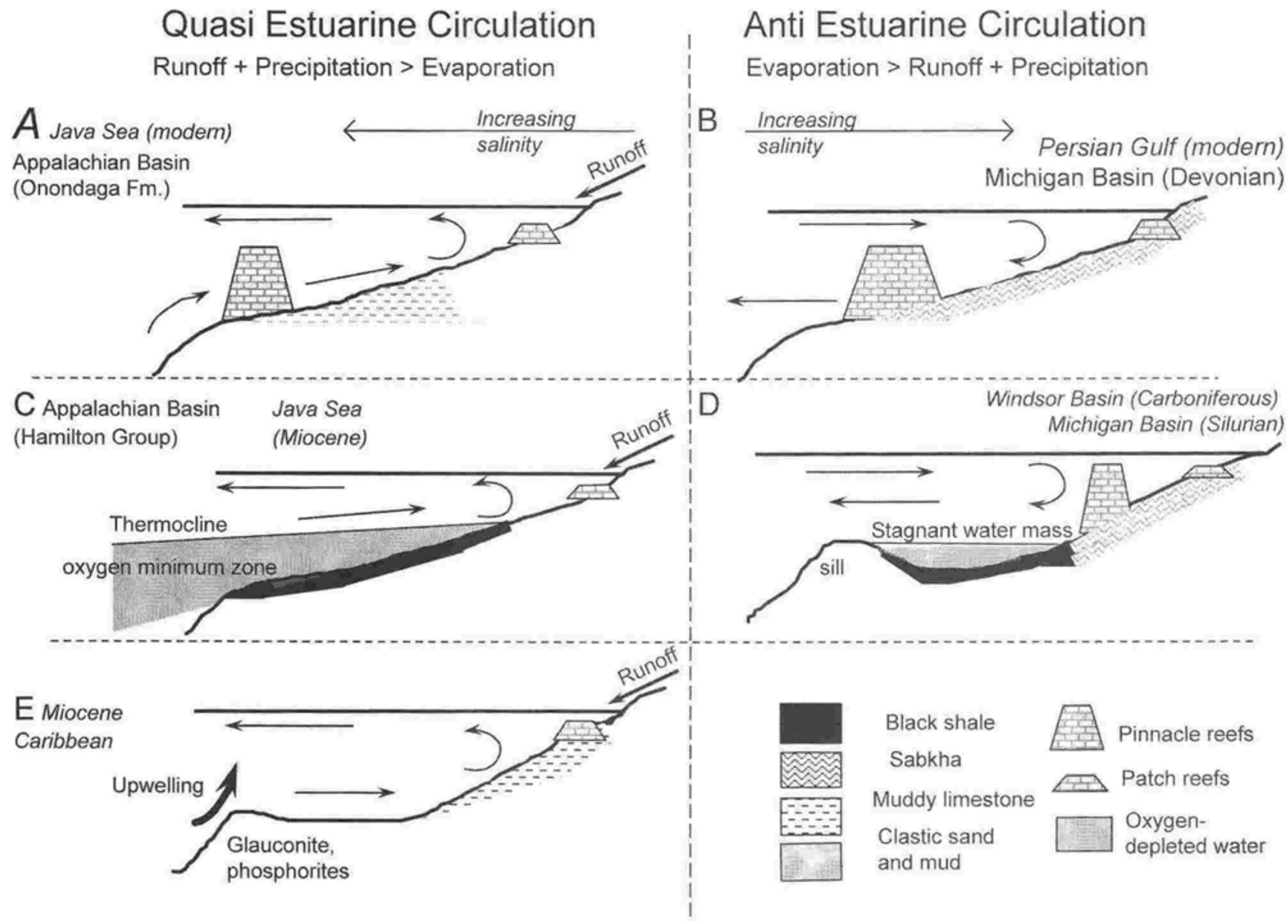

Fig. 1. Quasi-Estuarine and Anti-Estuarine circulation models (general). A, C, E: Quasi-estuarine circulation. A: Circulation in modern Java Sea and Appalachian Basin during Onondaga time. Runoff and precipitation greatly exceed evaporation, and estuarine outflow draws some marine nutrients into the basin. Both offshore pinnacle reefs and nearshore patch reefs occur. Non-reef sediments are dominantly siliciclastic sand and mud in the Java Sea, or siliciclastic sand and mud in nearshore areas of the Onondaga Fmn., and muddy limestone in offshore areas of the Onondaga. C: Quasiestuarine circulation under sea-level highstand. At higher sea levels, influx of bottom water through quasi-estuarine circulation draws water from the oxygen-minimum zone onto the shelf, causing deposition of black shales. This model can explain abundant Miocene oil and gas on the Sunda Shelf, and the deposition of black shale facies throughout the Appalachian Basin during Hamilton Group time. E: Upwelling in the Caribbean during the Miocene contributed to the demise of offshore reef systems, and a regional extinction of coral taxa living on offshore reefs (Edinger and Risk, 1994). B, D: Anti-estuarine circulation. B: Evaporation exceeds combined runoff and precipitation, causing anti-estuarine circulation. Water is well-oxygenated throughout the basin, as long as no sills are present. Reef development occurs as both patch reefs and pinnacle reefs. D: Anti-estuarine circulation with a sill allows development of a stagnant water mass below the sill. This type of circulation contributed to formation of extensive evaporites in both shallow and deep water, and black shales or black limestones below the sill depth.

Under anti-estuarine (AEC) conditions such as the Mediterranean Sea and Persian Gulf today, evaporation exceeds freshwater influx, surface waters become hypersaline and dense, and sink (Fig. 1B).

The surface waters are replenished by nutrient poor, fully oxygenated surface water from open ocean basins (Schopf, 1980; Witzke, 1987), supplemented by nutrient-rich fresh water runoff (in the modern Mediterranean). Under such conditions, black shale facies will not form except in the presence of a large sill separating the marginal sea from the open ocean basin (Fig. 1D). Because evaporation exceeds runoff, AEC promotes deposition of dolomites and evaporites at low latitudes, rather than siliciclastic sediments (Witzke, 1987).

1.3 Sedimentologic and paleontologic signatures of eutrophication

Nutrients have been suggested to simulate cold-water conditions in carbonate depositional environments (Hallock et al., 1988; Lavoie and Asselin, 1998; reviewed by Wood, 1993, 1995). Increased nutrient availability generally favours planktic and fleshy benthic algae and fast-growing heterotrophic organisms such as sponges, bryozoans, and molluscs over slower-growing mixotrophs such as corals (Hallock and Schlager, 1986; Birkeland, 1987; Wood, 1993). Higher green algal abundance contributes higher proportions of lime mud to nutrient-rich carbonate facies, either through the breakdown of calcareous green algae into lime mud, or through baffling of detrital lime mud by fleshy algae (Littler and Littler, 1985). These factors may contribute to a shift

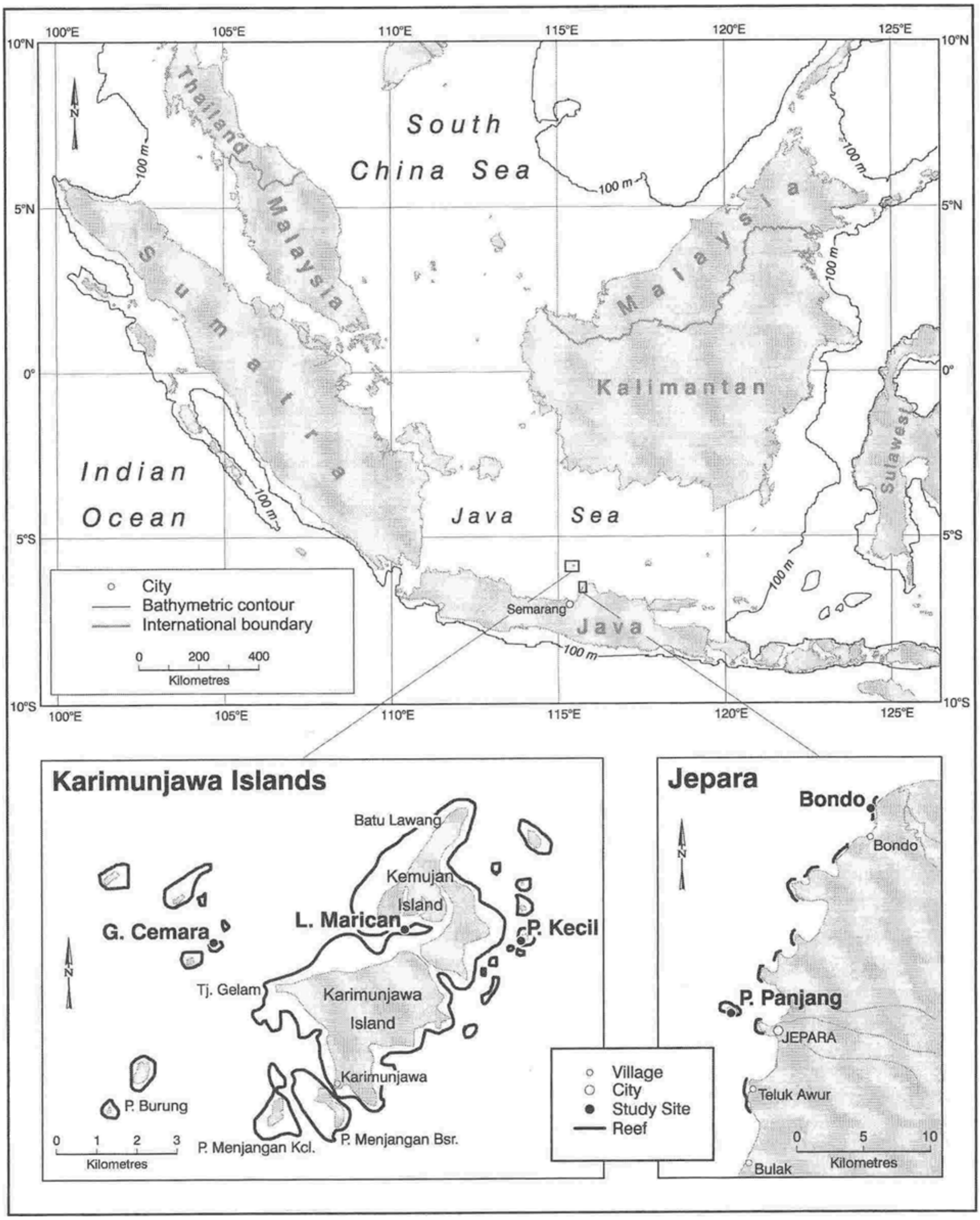

Fig. 2. Map of Indonesia, showing Java Sea and Sunda Shelf regions. Reefs sampled in the Karimunjawa Islands and Jepara areas are shown in insets.

from framestones and skeletal grainstones under oligotrophic conditions, to bafflestones and floatstones under more eutrophic conditions (Wood, 1993). Under eutrophic conditions exposed to high wave energy or sediment starvation, hardgrounds are sometimes developed, often with significant bioerosion of the hardground (Palmer, 1982; Hallock, 1988; Edinger, 2001). Extremely high nutrient levels may lead to organic-rich facies when high sedimentation rates trap organic matter, or to phosphorites in condensed horizons (Riggs, 1984). The faunal shift accompanying eutrophication leads to carbonate facies poor in corals and, in modern oceans, numerically dominated by bryozoans, crinoids, molluscs and brachiopods, and red algae (Littler and Littler, 1985; Birkeland, 1987; Hallock, 1988; Wood, 1993). These latter faunal groups may resemble the typical components of cool water carbonate benthic communities (James, 1997).

2 MODERN: THE JAVA SEA

2.1 Java Sea Geography and Sediments

The Java Sea, as one of the few existing modern epicontinental seas in the tropics, hosts coral reefs in a dominantly siliciclastic environment, has a well-understood monsoonal circulation system, and lies outside the tropical cyclone belt (Fig. 2). As part of the Sunda Shelf, the Java Sea is less than 100m deep, and was entirely drained and exposed during the Pleistocene glaciations (Tjia, 1980). The Sunda Shelf has an area of approximately 1.85 million km^2, of which approximately 500,000 km^2 are covered by the Java Sea. The Java Sea is bordered by land on three sides: Borneo (Kalimantan) to the north, Java to the south, and southern Sumatra to the west. It has marine connections and significant monsoonal flowthrough; the primary marine border is with the Flores Sea and Makassar Strait on the east; smaller connections link the Java Sea to the Indian Ocean through the Sunda Strait, and to the South China Sea through the Karimata Strait. The southern portion of the South China Sea is also part of the Sunda Shelf, and like the Java Sea, was drained and exposed during the Pleistocene glaciations. Drowned Pleistocene river channels on the Sunda Shelf are evident in side-scan sonar (Wyrtki, 1961; Tjia, 1980).

Surface currents in the Java Sea are monsoonal, and reverse between the east and west monsoons (Fig. 3). During the east monsoon (May-October), winds blow north and west from Australia toward mainland southeast Asia, driving surface currents westward and northward. During the west monsoon (December - March), winds blow east and south from mainland southeast Asia toward Australia, reversing the surface currents. Open ocean water enters the Sunda Shelf from Makassar Strait and Flores Sea during the east monsoon, and from the deep basin of the South China Sea during the west monsoon. Water exits the Sunda Shelf through Malacca Strait and Sunda Strait during both the east and west monsoons (Wyrtki, 1961). Sea surface temperatures range between 25 and 28°C, and average surface salinity is 32 in the wet season, and 33 ‰ in the dry season (Wyrtki, 1961), 2-3 ‰ below ocean averages.

At the eastern edge of the Sunda Shelf (at the margin of Makassar Strait and Flores Sea), deep water upwells onto the shelf during the east monsoon. This seasonal upwelling brings an additional source of nutrients favouring algal growth over coral growth, and extensive *Halimeda* bioherms have grown at the eastern edge of the Java Sea (Roberts and Phipps, 1988). Elsewhere in the Java Sea, however, fleshy algae such as *Sargassum* are common on shallow reef fronts and may dominate in nearshore eutrophic settings (Edinger, 1998; cf. Schafelke and Klumpp, 1998). The Java Sea has the highest primary productivity of the Indonesian seas (Polunin, 1983). The euphotic layer is <50m deep, and waters are generally mesotrophic, with locally eutrophic environments nearshore, and hypertrophic conditions in areas subject to organic pollution. Coastal phytoplankton biomass concentrations in the wet season are typically double those of the dry season (Edinger, 1998).

Modern Java Sea sediments are dominated by siliciclastic mud, except around coral reefs (Tjia, 1980). These sediments are not generally anoxic, but typically contain 2-10% organic matter (Dewi, 1997). Miocene deposits in the Java Sea host extensive oil and gas reserves, formed when global sea levels were higher (Tomascik et al., 1997). Water from the oxygen minimum zone of the Flores Sea and the South China Sea, at about 500m depth, may have extended into parts of the Sunda Shelf during the Miocene, when sea levels were higher, contributing to the extensive oil and gas deposits of Sumatra, Java, Kalimantan, and the Java Sea. (Fig. 1C). The combined oceanographic, sedimentologic, and stratigraphic evidence suggests possible quasi-estuarine type conditions in the Java Sea.

2.2 Java Sea Circulation

Quasi-estuarine circulation in the Java Sea was interpreted using current, depth, precipitation, evaporation and river discharge data. Depth and current data were taken from the Indonesia Marine Atlas (Bakosurtanal, 1998). Average annual river discharge data for all major rivers emptying into the Java Sea and southern South China Sea were compiled by Dr. Imam Soeseno, Bogor Agricultural Institute (Edinger and Browne, 2000). Average monthly and annual rainfall data for all the major coastal cities on the Java Sea and southern South China Sea were gathered from the Indonesian Centre for Meteorology and Geophysics (BMG), using 30-year averages of 1960-1990 (Table 1a). Evaporation data were available for Jakarta only, and only for the years 1969-1979, plus the 30 year average of 1930-1960 (Table 1b). The average of precipitation data for all cities, and evaporation data for Jakarta, were applied to the surface area of the Java Sea and the southern portion of the South China Sea, an area of approximately one million km^2. 63.4% of precipitation fell during the wet season (November - April), and 36.6% fell in the dry season (May - October). Accordingly, 63.4% of fluvial discharge was assigned to the west monsoon (the wet season in Java, southern Sumatra, and southern Kalimantan), and the remainder was assigned to the east monsoon (the wet season in northern Sumatra, Singapore, Malaysia, and northern Kalimantan).

Estuarine circulation driven by salt balance was calculated based upon river discharge, precipitation less evaporation, and differences in surface salinity. Estuarine inflow was estimated as:

$$Q_i = (Q_r + Q_p - Q_e) \times S_o/(S_i - S_o)$$

where Q_i= estuarine inflow, Q_r = river discharge, Q_p = precipitation, Q_e = evaporation, S_o = Java Sea surface salinity, and S_i = salinity of open ocean water entering the Java Sea (35 ‰).

Estuarine outflow was estimated as:

$$Q_o = (Q_r + Q_p - Q_e) \times S_i/(S_i - S_o)$$

Where Q_o = estuarine outflow, Q_r = river discharge, Q_p = precipitation, Q_e = evaporation, S_o = Java Sea surface salinity, and S_i = salinity of open ocean water entering the Java Sea (35 ‰).

A. Average monthly precipitation for major cities on the Java Sea and southern South China Sea, 1960-1990. Dry season: April - October. Wet season: November - March.				
Region	City	Elev. (m)	dry season sum (mm)	wet season sum (mm)
Sumatra	Ranai	2	1102	1239
Sumatra	Tj. Pinang	2	1489	1572
Sumatra	Tarempa	4	1217	1238
Sumatra	Palembang	11	823	1687
Sumatra	Jambi	26	826	1312
Sumatra	Pangkal Pining	33	924	1642
Sumatra	Tj. Pandau	44	1114	1804
Java	Bawean	2	512	1817
Java	Tj. Priok	2	326	1332
Java	Tegal	3	366	1253
Java	Semarang	3	563	1469
Java	Tj. Perak	3	233	1299
Kalimantan	Ketapang	10	1202	1898
Kalimantan	Pangkalanbun	10	1084	1653
Kalimantan	Ketabaru	10	1117	1397
Kalimantan	Banjarmasin	20	740	1812
Kalimantan	Pontianak	30	1474	1723
average			889	1538

B. Average monthly evaporation, Jakarta, 1969-1979, and 30-year average 1930-1960. Dry season: April - October. Wet season: November - March		
year range	dry season sum (mm)	wet season sum (mm)
1930-1960 avg	546	438
1969-1979 avg	546	439

Table 1. Precipitation and evaporation data, Java Sea.

The flushing time of the Java Sea was calculated as

$$T_f = V_{total}/Q_r + Q_p - Q_e$$

where V_{total} = the volume of the Java Sea, estimated as the area (approximately 5 x 10^5 km^2) multiplied by the average depth of 60 m.

Estimated estuarine inflow and outflow fluxes were compared with estimated fluxes from wind-driven circulation. Current speed (m/sec) was converted to flux (m^3/sec) by integrating the current speeds over the depth of the given strait, multiplied by the width of the given strait. Because currents in the Java Sea are driven primarily by monsoonal winds, surface current speeds were assumed to attenuate exponentially with depth, such that current speed at 10m depth was 10% of surface current speed. Average current speeds and fluxes during the east monsoon (August) and west monsoon (February) were reported separately. All fluxes are reported in Sverdrups, i.e. units of 10^6 m^3/sec.

Total river discharge onto the Indonesian portions of the Sunda Shelf excluding the Strait of Malacca is approximately 9.09 x 10^{11} m^3/year, of which roughly 28% drains from Sumatra, 61% from Kalimantan (Indonesian Borneo), and 11% from Java. Excluding the rivers of East Kalimantan that drain into Makassar Strait, the west monsoon component of this runoff is estimated as 16.4 x 10^3 m^3/sec, and the east monsoon component as 9.5 x 10^3 m^3/sec (table 2). Total inflows and total outflows balance to within 2% in August, and 8% in February (equivalent to the error range of the input data). Estuarine driven outflows are Q_o=0.261 Sv (August) and Q_o=0.395 Sv (February), while estuarine driven inflows are Q_i= 0.246 Sv (August), and Q_i=0.361 Sv (February). Estuarine driven outflows equal 46% of total surface outflow in August, and 57% of total surface outflow in February. Flushing time based on fluvial input only is approximately 37 years. True flushing time, incorporating fluxes derived from wind-driven surface currents, is probably between 15 and 20 years.

2.3 Modern Reef Environmental Variables

Chlorophyll A concentration, suspended particulate matter concentration (SPM), and sediment resuspension were measured on the Java Sea reefs using standard methodology (Parsons et al., 1984). Water samples for chlorophyll and SPM analysis were collected from each reef twice monthly for the nearshore reefs and monthly for the offshore reefs. Chlorophyll A sampling and analysis followed Parsons et al. (1984) and Burnison (1980). SPM was measured by filtering 11 of seawater onto a pre-weighed glass-fibre filter. Sediment resuspension (total downward sediment flux) was measured in sediment traps deployed at 1m, 3m, and the base of the reef on the nearshore reefs, and at 3m, 10m, and the base of the reef on the offshore reefs. Some depths were not adequately sampled due to theft of the sediment traps. Sediment traps were collected twice monthly on nearshore reefs and monthly on offshore reefs, during the seasons in which reefs were safely accessible due to the constraints of weather. Water quality and sedimentation rate data were published previously (Edinger et al., 2000); sediment composition data and correlation coefficients among environmental factors and cover types are presented here.

2.4 Java Sea Reef Composition

The modern Java reefs sampled include two offshore coral cays in a national park, an unpolluted fringing reef in

Parameter	rate (Aug)	Rate (Feb)	flux (Aug)	flux (Feb)
surface salinity	33 ‰	32 ‰		
rainfall	889 mm	1538 mm	14.1 x 10^3 m^3/sec	24.3 x 10^3 m^3/sec
evaporation	546 mm	439 mm	8.6 x 10^3 m^3/sec	7.0 x 10^3 m^3/sec
river runoff			9.5 x 10^3 m^3/sec	16.4 x 10^3 m^3/sec
Estuarine outflow			0.261 Sv	0.395 Sv
Estuarine inflow			0.246 Sv	0.361 Sv
Anambas Strait	24-50 cm/s	18-38 cm/s	0.376 Sv	0.277 Sv
Natuna Strait		12-25 cm/s	0.119 Sv	0.366 Sv
Malacca Strait	12-25 cm/s	18-38 cm/s	0.036 Sv	0.054 Sv
Sunda Strait	18-38 cm/s	12-25 cm/s	0.036 Sv	0.022 Sv
E. Sunda/Bali Sea	12-25 cm/s	18-38 cm/s	0.536 Sv	0.605 Sv

Table 2. Oceanographic characteristics of the Java Sea used in constructing circulation model.
Rates: rainfall, evaporation: mm/yr. Currents: cm/sec. Fluxes: rivers, rainfall, evaporation: m^3/sec. as written. Currents: Sv (10^6 m^3/sec).

Setting	Reef name	Lat/long	Description
offshore	Gosong Cemara	5°49.5'S/ 110°23'E	Unvegetated submerged coral cay with *Halimeda* and seagrass bed on reef flat
offshore	Pulau Kecil	5°49'S/ 110°30.5'E	Vegetated emergent coral cay
mangrove fringe	Lagun Marican	5°49'S/ 110°28'E	Fringing reef adjacent to mangroves, in carbonate-siliciclastic sediment lagoon.
nearshore	Pulau Panjang	6°34.7'S/ 110°37.5'E	Vegetated emergent coral cay subject to sewage and siliciclastic sedimentation
nearshore	Bondo	6°29'S/ 110°42'E	Fringing reef, subject to siliciclastic sedimentation

Table 3. Locations of modern reefs studied. Full site descriptions of each reef are published in Edinger, (1998), Edinger et al., (1998), and Edinger et al., (2000).

mangroves in a national park, a polluted nearshore coral cay, and a polluted nearshore fringing reef (fig 2, table 3). The mangrove fringing reef and the two polluted reefs are all subject to high levels of siliciclastic sedimentation derived from Pleistocene andesite volcanoes (on the Java highland) or weathering of Pliocene basalt flows and pre-Tertiary arkosic sandstones (mangrove fringing reef). The polluted reefs are also subject to anthropogenic eutrophication from sewage, agricultural runoff, and aquacultural effluent (Edinger et al., 1998).

The growth form and species composition of modern reefs was measured using line-intercept transects (Loya, 1978), following the standard methodology used by the Indonesian Institute of Science (English et al., 1994). On coral cays, twelve replicate non-adjacent, non-overlapping transects, each 20m long, were measured on each reef, with three transects at each depth (3m, 10m) and exposure (windward, leeward). The deep transects at the nearshore coral cay were measured at 6m depth, because the maximum depth of coral growth was 8m. Fringing reefs (mangrove site, high sediment site) were measured using three replicate transects at 3m depth; no transects were measured at 6m depth because the maximum depth of coral growth was 4m and 5m at mangrove site and high sedimentation site, respectively. Corals were divided into growth form categories according to English et al. (1994), and were also identified to species using Veron (1986). *Acropora* corals were identified to species groups (Veron and Wallace, 1984). Growth form

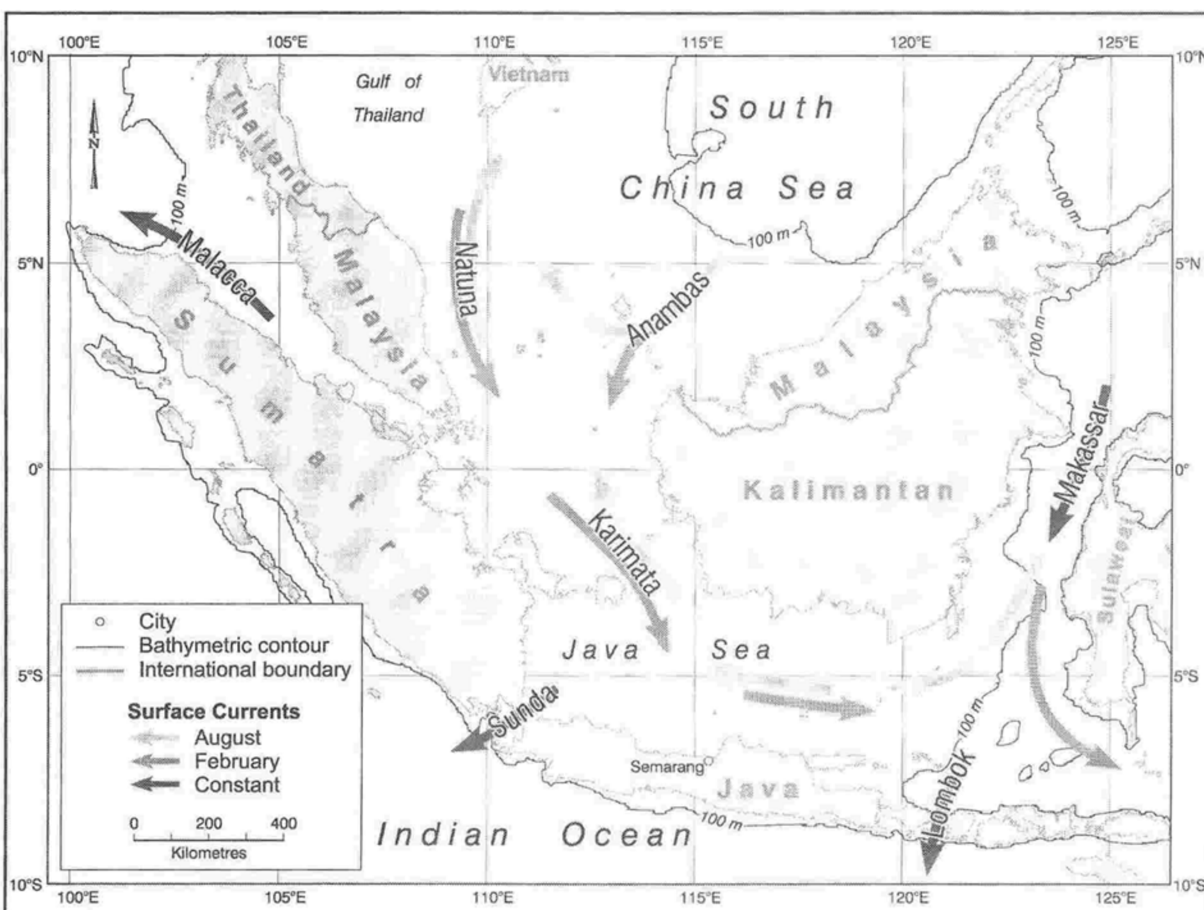

Fig. 3. Java Sea surface currents. Wind directions and current directions shift seasonally. Shown here are major current directions for and August (East Monsoon) and February (West monsoon). Surface currents flow into the Java Sea through the Natuna and Anambas Straits during the West monsoon, and into the Java Sea from the Makassar Strait and Flores Sea during the East monsoon. Surface currents always flow out of the Java Sea through the Strait of Malacca , Sunda Strait, and Lombok Strait.

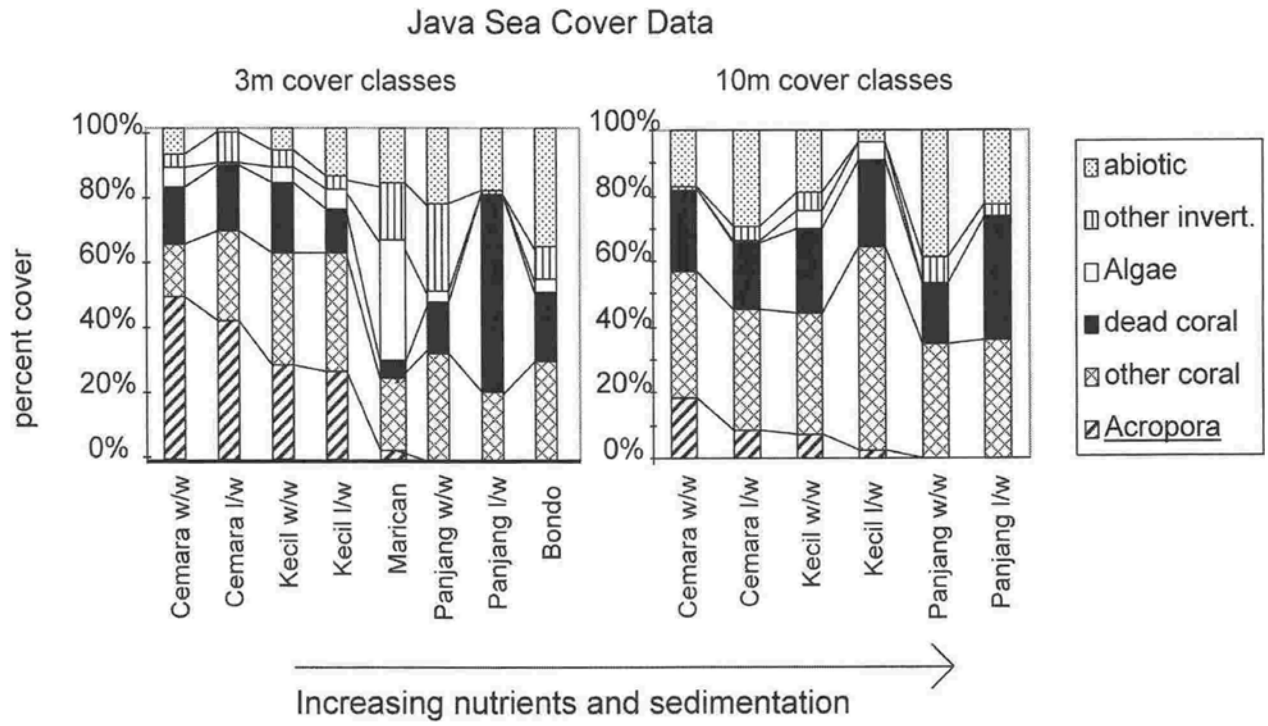

Fig. 4. Cover classes on Java Sea coral reefs. Average cover values for three or more 20 m transects per site and depth.

composition of nearshore and offshore reefs were averaged separately, and separated by depth and exposure. Reef sites (separate depth and exposures) were then classified using ternary diagrams based on coral morphologies (Edinger and Risk, 1999).

Nearshore reefs are dominated by massive and submassive corals, and by non-calcified invertebrates, primarily sponges and alcyonarian soft corals (Fig. 4). Algae are abundant only at the mangrove fringing reef (Lagun Marican), where they are composed primarily of turf algae, rather than calcareous green algae such as *Halimeda* or calcareous red algae such as *Lithothamnion*. The dominant coral growth forms on the nearshore reefs are massive and submassive corals. Branching corals, foliose corals, and *Acropora* each contribute less than 5% of the total coral cover (Fig. 5A). *Acropora* are particularly sensitive to high sedimentation (Rogers, 1990). The growth form composition of the nearshore and offshore reefs is significantly different (two-way ANOVA, interactions F=4.97, p<0.0001).

Offshore reefs are dominated by branching and tabular *Acropora* corals on windward sites, and on all sites at 3m depth (Fig. 5 B,C). Most sites at 10m depth are dominated by branching *Acropora*, branching non-*Acropora* corals (principally *Porites cylindrica)*, foliose corals (principally *Montipora foliosa, Mycedium elephantotus, Pavona cactus*, and *Echinopora lamellosa* and *E. gemmacea)*, and by a mixed assortment of massive corals (Fig. 5D). Algae and non-calcified invertebrates are relatively scarce on all the offshore reefs, at either 3m or 10m depth, but *Halimeda* are common on some of the reef flats at <1m depth. Growth form composition is significantly different between 3m and 10m depth zones (two-way ANOVA, interactions F=3.61, p<0.0001), but not between windward and leeward reefs (two-way ANOVA, interactions F=0.91, p>0.5).

Nearshore and offshore reefs were readily distinguished using ternary diagrams based on coral growth forms (Fig. 6). All of the nearshore reefs were dominated by stress-tolerators, and grouped together. The stresses that these coral morphologies tolerate are related to turbitidy, sedimentation, and nutrient concentrations, rather than temperature or salinity variations (Table 4; see environmental data, Edinger et al., 2000). The offshore reefs at 3m were generally dominated by fast-growing ruderals (r-selected species; *Acropora* corals), while the offshore reefs at 10m were dominated by competitors (branching non-*Acropora* and foliose corals), or had an even distribution of coral growth forms.

2.5 Java Sea Reef Sediments

Modern Java Sea reef sediments were sampled by taking replicate surface grab samples from each reef using a hand-held 7.5 cm diameter PVC pipe with caps at each end. Each reef was sampled at both 1m depth and at the base of the reef; coral cays were sampled on both the windward and leeward sides. Sediment samples were split for analysis in Indonesia and in Canada, and were again split for grain size and constituent analysis, acid-insoluble content, and organic content. Grain size distribution was determined by wet-sieving sediments into a basin, and drying each fraction. The mud (<63 μm) fraction was estimated as the remainder accumulated in the basin. Separate 2 g subsamples were analyzed for acid-insoluble content and organic content. Acid-insoluble content was determined by dissolving the sample in 10% HCl, neutralizing with distilled water, decanting off ca. 75% of the supernatant, drying and weighing the remainder. Acid-isoluble residues were examined visu-

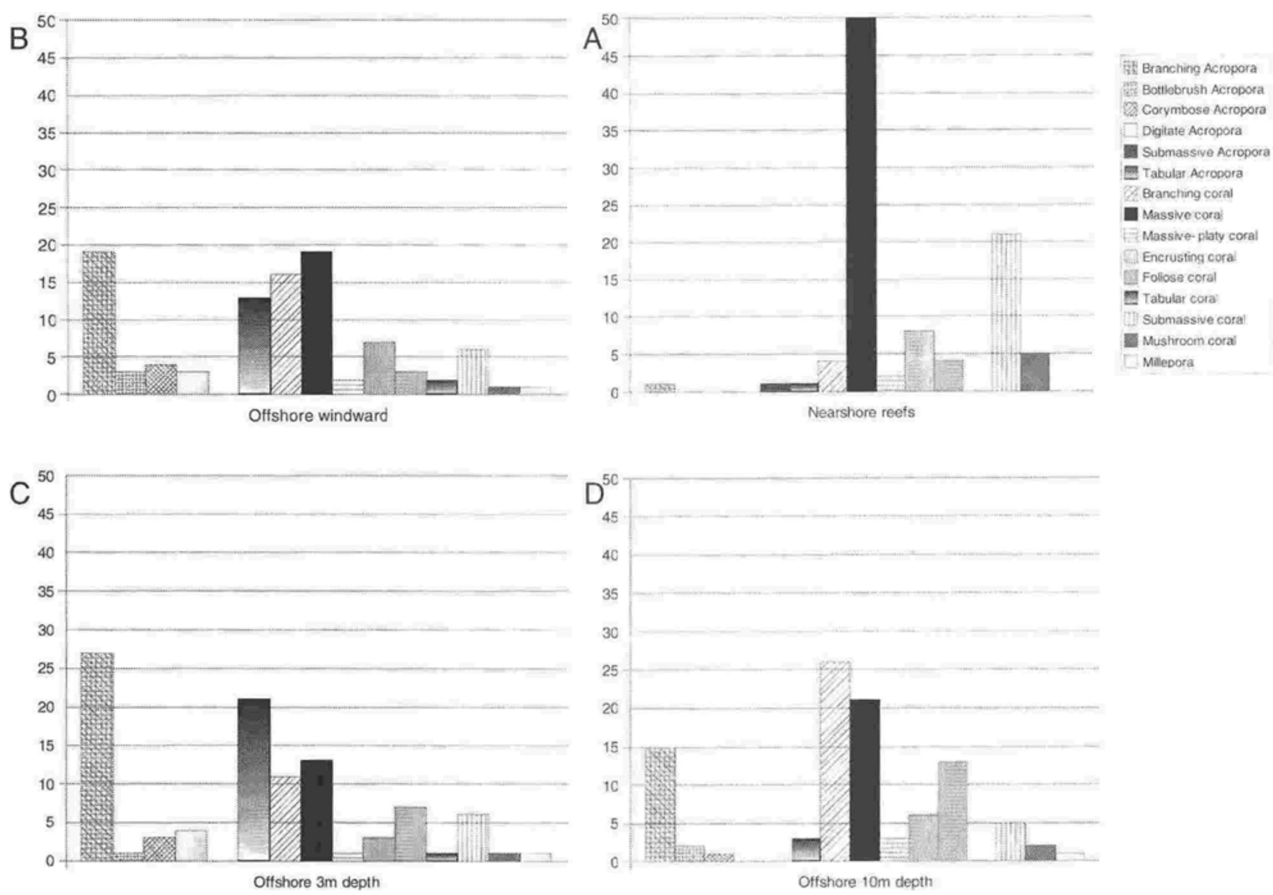

Fig. 5. Growth form composition of Java Sea reef corals. A: Nearshore reefs subject to high sedimentation and eutrophication. B: Offshore reefs, windward, all depths. C: Offshore reefs, 3m, windward and leeward. D: Offshore reefs, 10m, windward and leeward. Average values for three 20m transects per reef. Massive-platy corals are mainly *Euphyllia and Lobophyllia*. Submassive corals are mainly *Galaxea*, *Goniopora*, and *Porites*.

ally to check for calcium chloride crystals and to determine mineralogy of visible non-carbonate grains. Organic matter content was measured by adding 30% H_2O_2 to dried reef sediment, decanting off the supernatant, and drying and weighing the remainder.

Both nearshore and offshore Java Sea reef sediments are dominated by carbonate sand and rubble, represented as the gravel size fraction (Fig. 7). Only the mangrove fringing reef has more than 20% mud. Lithified, most of the Java Sea reef sediments would be considered grainstones or rudstones. Not surprisingly, shallow reef sediments have a higher representation of the gravel size fraction, and deeper reef sediments had a higher representation of sand and mud sized fractions. The rubble size fraction is primarily composed of coral fragments. The sand size fraction on the offshore reefs is primarily composed of the large benthic foraminiferan *Marginopora* and up to 10% *Halimeda* flakes on the unvegetated coral cay (Gosong Cemara) and the large benthic foraminifera *Baculogypsina* and *Marginopora* on the vegetated coral cay (Pulau Kecil); (fig 8). The sand size fraction on the nearshore reefs contains abundant molluscan and coral fragments and alcyonarian spicules, but relatively little *Halimeda* or large benthic foraminifera (Sherwood et al., 1999).

Average acid-insoluble content of offshore reef sediments is 1.25% (range 0.3% - 3.7% acid-insoluble). Average acid-insoluble content of nearshore reef sediments is 17.75% (range 9% - 32% acid-insoluble). Acid-insoluble materials at the nearshore reefs in Jepara (P. Panjang, Bondo) are exclusively siliciclastic mud. The mangrove fringing reef (L. Marican) contains abundant detrital quartz and feldspar grains from the adjacent arkosic sandstone to the south, as

	% carbonate	% organic	% mud	Chlorophyll A	SPM	sed. traps
% carbonate	—					
% organic	-0.67*	—				
% mud	-0.56*	0.51	—			
Chlorophyll-A	-0.88**	0.86***	0.51	—		
SPM	-0.33	0.46	0.33	0.51	—	
sed. traps	-0.80**	0.80***	0.38	0.98***	0.56	—

Table 4. Correlation coefficients between Java Sea reef sediment composition and environmental variables. *** = $p<0.001$. ** = $p<0.01$. * = $p<0.05$. N = 13 for all variables except sediment traps, where n=12.

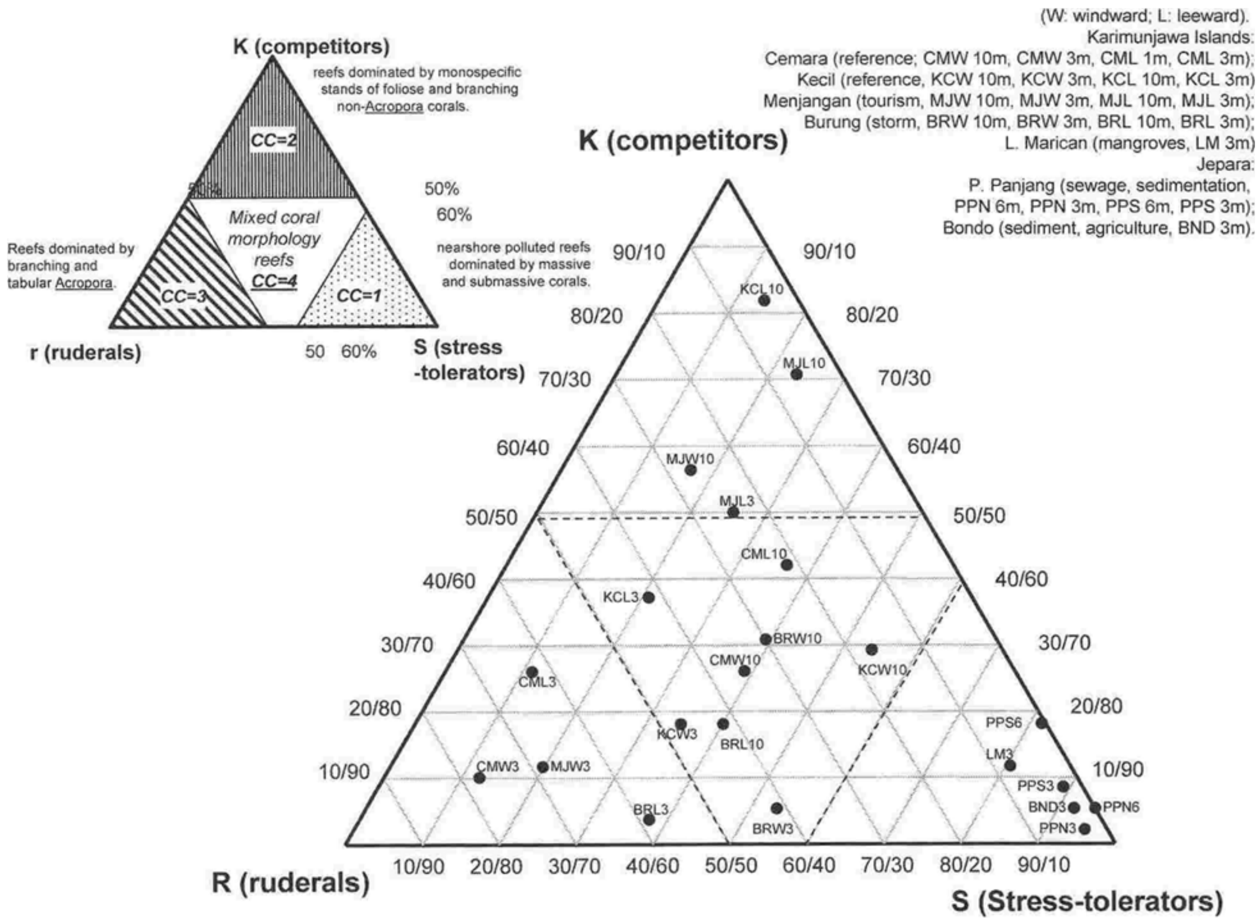

Fig. 6. Ternary diagram showing growth form composition of Java Sea reef corals. Data are averages of all transects in each site. Ruderals ("r-selected", short-lived rapidly growing corals, disturbance-adapted) include the *Acropora* corals. Competitors ("K-selected", long-lived rapidly growing competitive dominant corals, forming large monospecific stands) include foliose, branching non-*Acropora*, and platy corals. Stress-tolerators (S, long-lived, resistant to wave impact and water quality deterioration) include massive and submassive corals.

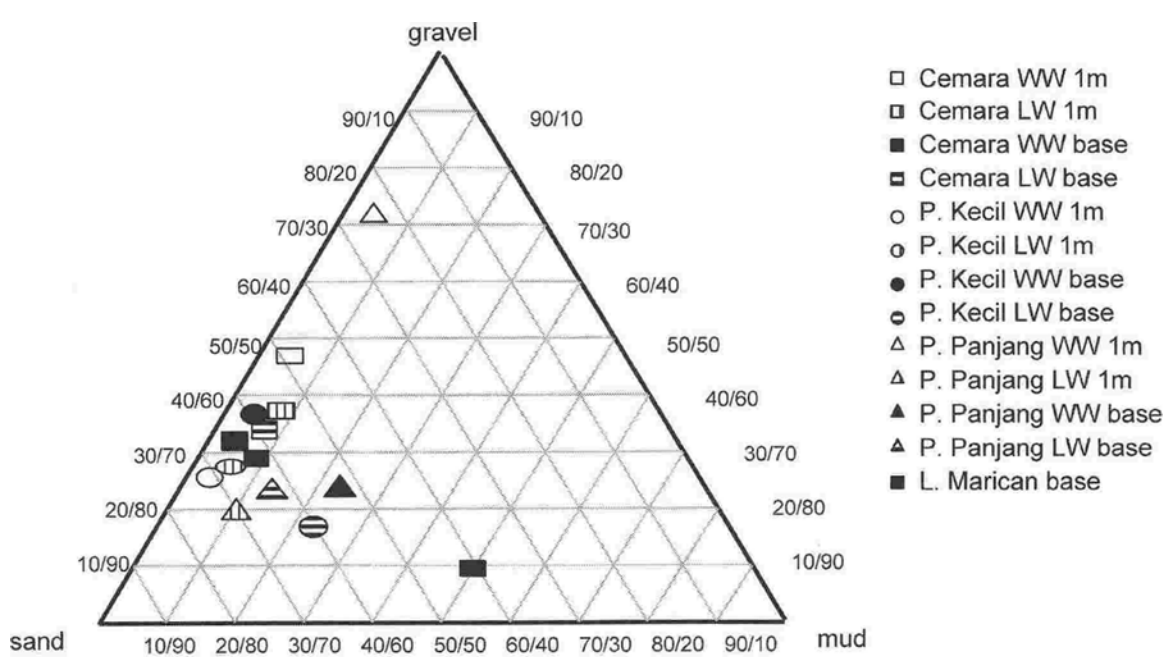

Fig. 7. Grain size composition of Java Sea reef surface sediments. Each point represents the average composition of three sediment samples from each site and depth.

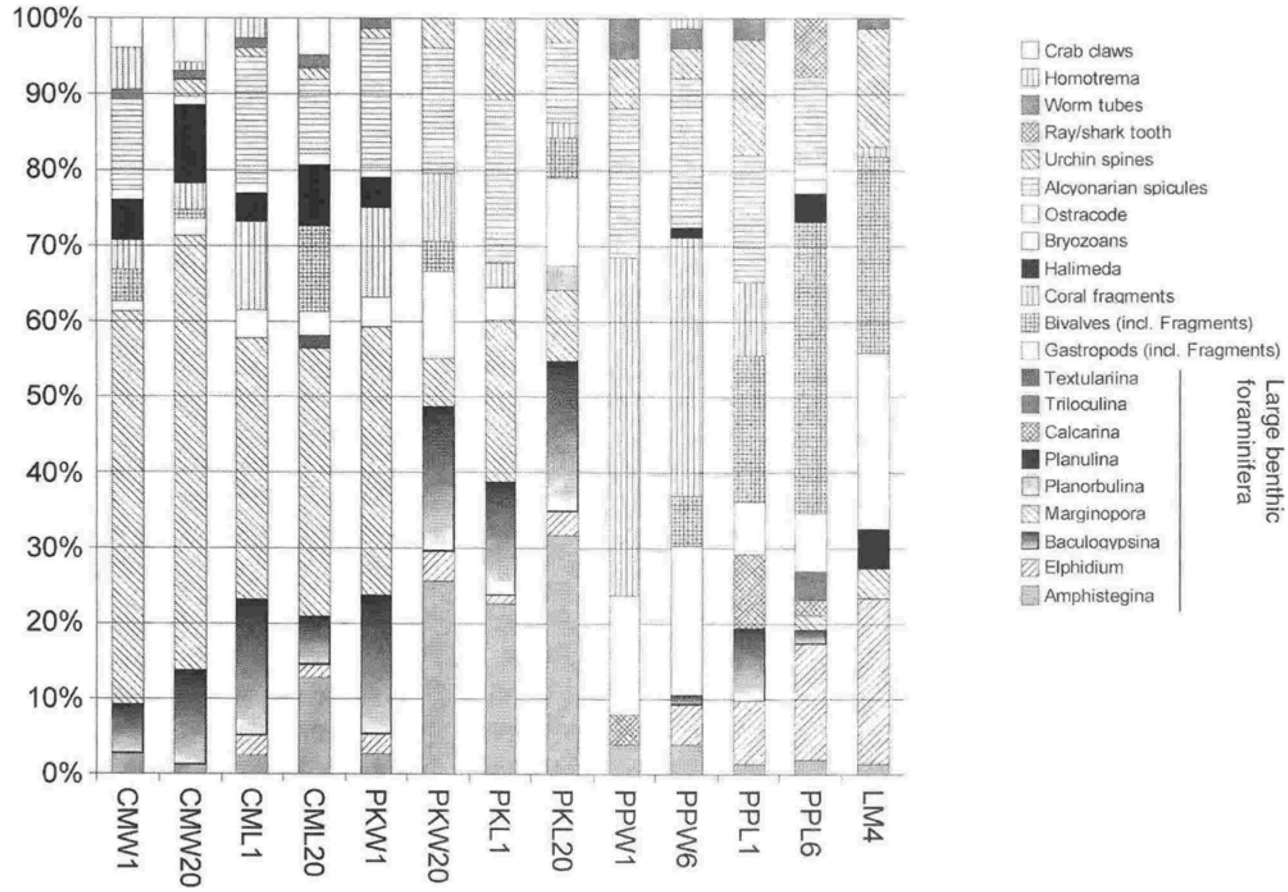

Fig. 8. Grain constituent composition of Java Sea reef sediments. Averages of point-count data from 3 samples from each reef, exposure, and depth. CMW: G. Cemara windward; CML: G. Cemara leeward; PKW: P. Kecil windward; PKL: P. Kecil leeward; PPW: P. Panjang windward; PPL: P. Panjang leeward; LM: Lagun Marican. Numbers at ends of sample codes indicate water depth (m) at which samples were collected.

well as siliciclastic mud derived from weathering of the Pliocene basalts to the north. Average organic matter content of offshore reef sediments is 3.6% (range 2.3 - 6.6%). Average organic matter content of nearshore reef sediments is 9.7% (range 7.1% - 11.2%). Acid-insoluble content and organic content are significantly positively correlated, indicating that most organic matter is either terrigenous in origin or fed by terrigenous nutrients. Organic matter concentration in sediments is significantly positively correlated with chlorophyll A concentration and with sediment resuspension (table 4).

3 DEVONIAN: APPALACHIAN AND MICHIGAN BASINS

3.1 Paleogeographic Context

On a global basis, Early Devonian metazoan reefs increased in size (thickness and diameter), abundance, and geographic distribution from the Lochkovian through Eifelian, (Copper, 1997; Kiessling et al., 1999). Reefs and carbonate platforms reached maximal size and distribution during the Middle Devonian (Eifelian-Givetian), at the end of which they lost about 50% of their coral and stromatoporoid diversity. Middle Devonian coral-stromatoporoid reefs occurred possibly as far north as 60°N, and as far south as 45-50°S, i.e. in Morocco and Algeria on the northeastern margin of Gondwana (see maps in Copper, 2002). During the middle Frasnian there was a final spurt of reef expansion, though reefs did not reach the latitudinal highs of the Mid-Devonian, and many former carbonate platforms had disappeared, e.g. in northern Laurentia (Kiessling et al., 1999; Copper, 2001). During the 21 myr long Famennian, there were virtually no metazoan reefs anywhere, though calcimicrobial reefs persisted, and a few scattered occurrences of stromatoporoid patch reefs were present, especially in the terminal Famennian (Copper, 2001).

Small coral-stromatoporoid patch reefs exposed in the Emsian age Helderberg sequence of the Appalachian Basin (e.g. Precht, 1989; Mesolella, 1978) grew at 40-45° south latitude on the southern fringes of Laurentia. Emsian Reef mounds in the Saharan region of North Africa also grew at high southern latitudes, up to 50° south. Reefs also developed in Iran and Afghanistan, Sardinia, the Montagne Noire, the Carnic and Dinaric Alps, and in the Czech Republic-Moravia at this time, all probably on isolated plates positioned north of Gondwana in relatively high latitudes south. Reef abundance increased through the Emsian, particularly in southern Europe, with this trend continuing through the Eifelian and Givetian (Copper, 2001). Emsian-Eifelian reefs

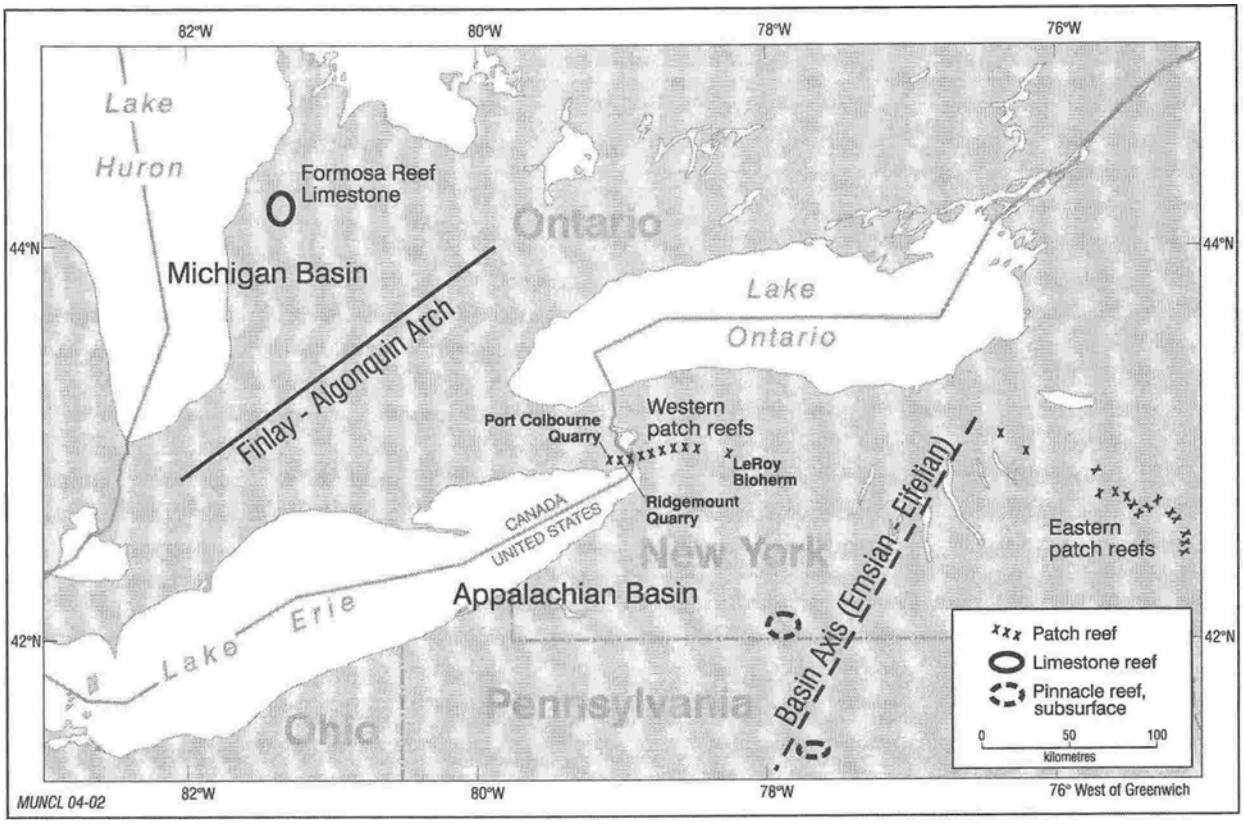

Fig. 9. Map of Middle Devonian Onondaga Formation (Appalachian Basin) and Formosa Reef Limestone (Michigan Basin), showing modern Great Lakes, Canada-USA border, and state borders within the US. Onondaga reefs include the western and eastern patch reefs, and the subsurface pinnacle reefs close to the Appalachian Basin axis. Four Onondaga reefs in the western patch reefs belt were studied: Port Colborne North, Port Colborne South, Ridgemount Quarry, all in Port Colborne, Ontario, and the LeRoy Bioherm, New York State. Outcrop location of Formosa Reef limestone is shown, as well as the position of the Finlay-Algonquin Arch that separates the Appalachian and Michigan basins.

in North America were largest and most abundant in the Canadian Arctic, particularly Ellesmere Island, Cameron Island, Prince of Wales Island, the western shore of Victoria Island, and the Yukon. These reefs grew close to the equator, as did those of Baltica, the Pechora-northern Urals Basin, Novaya Zemlya, the southern Urals, Kazakhstan, Siberia, and south China (see maps in Copper 1994a; Copper, 2002). Middle Devonian (latest Emsian-early Eifelian) reefs of the Onondaga formation and correlative Formosa Reef Limestone occurred in epeiric sea basins (the Appalachian Basin and Michigan Basin, Fig. 9), of approximately the same scale as the Java Sea and Sunda Shelf (Table 5), and both contain well-studied and well-preserved reef faunas (Oliver, 1954, 1956; Fagerstrom, 1961; Wolosz and Paquette, 1989; Wolosz, 1992a,b). The reefs of these formations had relatively low diversity in embayments at low to mid latitudes (Oliver, 1976, 1977). The faunas of these Ontario and New York reefs differ substantially from European counterparts, as well as those from the Western Canada and Arctic faunas of the Old World Realm. This pattern illustrates the relative isolation of the Appohimchi province in semi-enclosed basins within the Eastern Americas Realm (Oliver, 1977).The reefs of the Onondaga and the Formosa Limestone allowed us to examine contemporaneous reefs that shared some coral species, yet may have grown under considerably different oceanographic conditions (Edinger and Risk, 1998).

3.2 Appalachian Basin: Onondaga Formation

The Emsian-Eifelian Onondaga Formation lies at the base of the Middle Devonian sequence in the Appalachian Basin (Fig. 10). The Onondaga outcrop belt runs across New York State, USA, and into southern Ontario, Canada, over a distance of roughly 500 km. Its lateral equivalents in Ohio and Kentucky are the Columbus Limestone, and in the Michigan Basin, the Detroit River Group, including the Amherstberg formation, and its inlier, the Formosa Reef Limestone (Woodrow, et al., 1988). The Onondaga unconformably overlies the Emsian Bois Blanc Formation, and is conformably overlain by the shales and calcareous

Basin	Size	Latitude	Dominant Lithology
Java Sea	500,000 km^2	5-9°S	siliciclastic mud and sand, some reefs
Appalachian Basin	1,500,000 km^2	35-40°S	muddy limestone, black shales, some reefs
Michigan Basin	600,000 km^2	25-30°S	limestone and dolostone, some reefs

Table 5. Geographic characteristics of the modern Java Sea and the Devonian Appalachian and Michigan Basins.

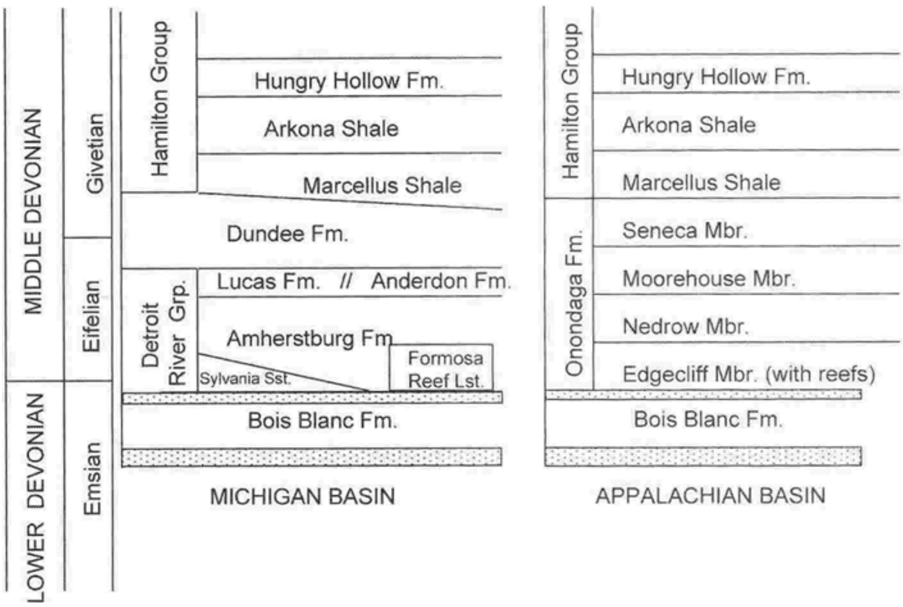

Fig. 10. Middle Devonian Stratigraphy of Great Lakes region, showing formation names and ages in Michigan Basin and Appalachian Basin. Redrafted from data in Woodrow et al., 1989.

mudstones of the Givetian Hamilton Group (Brett and Baird, 1986). The reef-bearing Edgecliff Member of the Onondaga, however, has yielded no diagnostic conodonts and could be of latest Emsian age. The Onondaga - Hamilton group is part of a transgressive cycle, with relative sea level rise driven by both eustasy and downwarping of the Appalachian foreland basin with the onset of the Acadian Orogeny (Woodrow, et al., 1989).

The Appalachian Basin trended ENE-WSW at this time, and was bounded on the north and west by the exposed craton, and on the east by the Adirondack highlands and the North Atlantic Peninsula of the Old Red Sandstone continent. To the southwest, the basin opened onto the Rheic Ocean. Scotese (1997) placed the Appalachian Basin at approximately 35° South, in the southern sub-tropics, and on the southeastern side of Laurentia. Considering that the broad tropical climate zones of the greenhouse Early and Middle Devonian stretched to 50-60° latitudes, climatic conditions would have been within the tropical realm (Copper, 2002).

A series of patch reefs are exposed in the NW and NE portions of the Onondaga outcrop belt (Oliver, 1956; Lindemann, 1989; Wolosz and Paquette, 1989, 1994, 1995; Wolosz, 1992a,b), and pinnacle reefs are found in the subsurface close to the basin axis (Mesolella, 1978; Fig. 9). The Onondaga Limestone is increasingly silty, then shaly and cherty, toward the basin centre, but silicified fossils and chert nodules are common throughout the formation (Oliver, 1954). The Onondaga hosts a diverse fauna of tabulate and rugose corals, brachiopods, and molluscs, but few stromatoporoids and calcareous algae (Wolosz, 1992a). The scarcity of stromatoporoids and calcareous algae, along with other biogeographic factors, have led to several suggestions of cold water conditions in the Appalachian Basin during Onondaga time (Koch and Boucot, 1982; Wolosz and Paquette, 1989; Wolosz, 1991), although the area was not in the path of cool upwelling gyres, nor on the western side of the paleocontinent (Parrish, 1982; Scotese, 1997).

3.3 Michigan Basin: Formosa Reef Limestone

The Amherstberg Formation of the Michigan Basin correlates with the Onondaga Formation in the Appalachian Basin (Fig. 10). The Amherstberg Formation is primarily dolomite and dolomitic limestone, and includes, as an inlier, the Formosa Reef Limestone (Fagerstrom, 1961; Pratt, 1989). The Amherstberg Formation unconformably overlies the Emsian Bois Blanc Formation, and is conformably overlain by dolomites and anhydrites of the Lucas Formation to the west, and by dolomites and limestones of the Anderdon Formation to the east. These sediments were separated from the Appalachian basin by the Finlay - Algonquin Arch. With continued transgression, the late

Formation	*Reef*	*Province/State*	*Lat/Long*	*Site description*
Onondaga	Port Colborne Quarry	Ontario, Canada	42°52'N/ 79°18.5'W	Partially flooded quarry, 1 km W of Port Colborne, N and south ends measured separately.
Onondaga	Ridgemount Quarry	Ontario, Canada	42°55.5'N/ 79°00.5'W	Active quarry, 5 km E of Port Colborne, E wall.
Onondaga	LeRoy Bioherm	New York, USA	43°01.3'N/ 78°01'W	Abandoned quarry 5 km NNW of LeRoy, Genesee County.
Formosa Reef Limestone	Formosa Reef Limestone	Ontario, Canada	44°04.5'N/ 81°13'W	Roadcut 1 km north of Formosa

Table 6. Locations of Paleozoic reefs studied. Descriptions of individual reefs published in Wolosz and Paquette (1989), Wolosz (1992a), Lindemann (1989), Fagerstrom (1961), and Pratt (1989).

Eifelian Dundee Formation spanned the Finlay Arch and included both Appalachian Basin and Michigan Basin portions of the formation. These two regions of the Dundee differed considerably in their degree of dolomitization, clay content, organic content, and porosity and permeability (Birchard, 1990). The Formosa Reef Limestone, with its well-preserved stromatoporoid fauna (Fagerstrom, 1961), represents a series of patch reefs developed in the shallow margins of the Michigan Basin (Pratt, 1989). Eifelian age pinnacle reefs are not known from the Michigan Basin. Eifelian strata in the western Michigan Basin are laminated dolomites containing solution collapse breccias, mud cracks, and evaporite crystal molds (Kluessendorf, et al., 1988).

The Michigan Basin lay due north of the Appalachian Basin during Emsian - Eifelian times, at approximately 30-35° S (Scotese, 1997). The abundant evaporites within the Late Silurian and Early and Middle Devonian sequences of the Michigan Basin indicate high rates of evaporation and low freshwater input within the dry belts of the paleotropics (Witzke and Heckel, 1989).

3.4 Fossil Reef Composition and Sediment Analysis

3.4.1 Onondaga Formation Reef Composition

Four Onondaga reefs were studied: the Port Colborne Quarry North and South reefs in Port Colborne, Ontario, Ridgemount Quarry reef about 5 km east of Port Colborne, Ontario, and the LeRoy Bioherm, about 75 km east of Buffalo, New York (Table 6; Fig. 9). All four reefs have been documented and described qualitatively (Wolosz and Paquette, 1989; Lindemann, 1989; Wolosz, 1992a; Wolosz and Paquette, 1994). Growth form and species composition of fossil reefs were measured using replicate 10m line-intercept transects on the Onondaga Fm. Sites. Three to eight transects were measured at each Onondaga reef. Onondaga transects were generally laid horizontally parallel to the vertical outcrop face, and were measured separately for reef core and reef flank facies. The reef flank facies at the Port Colborne South site is a bedding-plane exposure, and transects were laid horizontally. Reef-building coral taxa were identified to genus and, where possible, to species level, using the *Treatise on Invertebrate Paleontology* and *Index Fossils of North America*. Average growth form composition of each reef was calculated for reef core and reef flank facies. Growth forms were assigned to r-K-S categories, and the reefs were classified using r-K-S ternary diagrams (cf. Edinger and Risk, 1999). The r-K-S classification has been applied successfully to Indo-Pacific Recent and Quaternary reefs (Edinger et al., 2001), and can apparently be applied to modern Caribbean reefs with slight modification (Risk et al., 2001). Fossil coral morpholgies were assigned to r-K-S categories according to their competitive ability or stress-

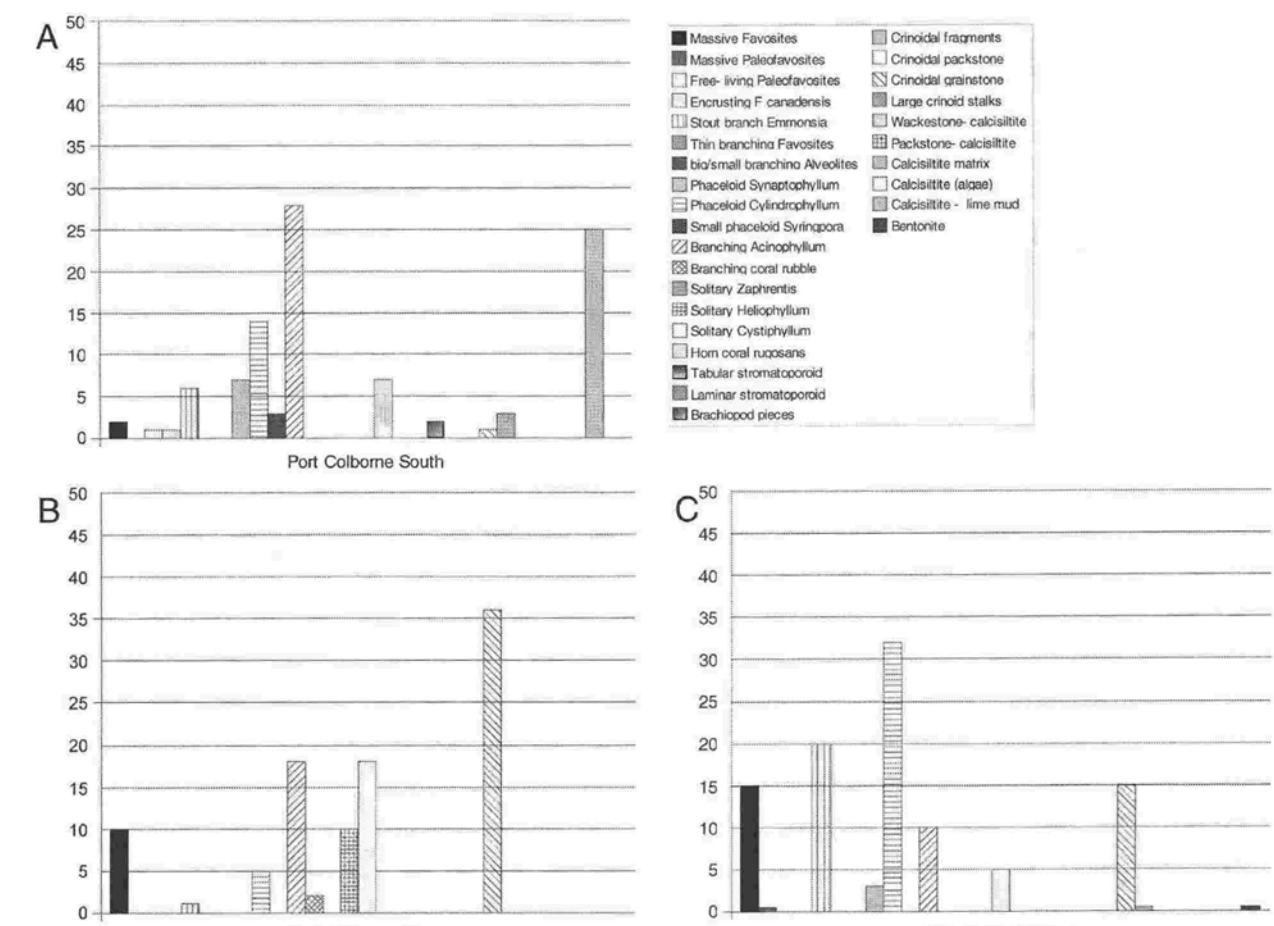

Fig. 11a-c. Taxonomic and growth form composition of Onondaga Formation reef biota. A: Port Colborne South. B: Port Colborne North. C: Ridgemount Quarry.

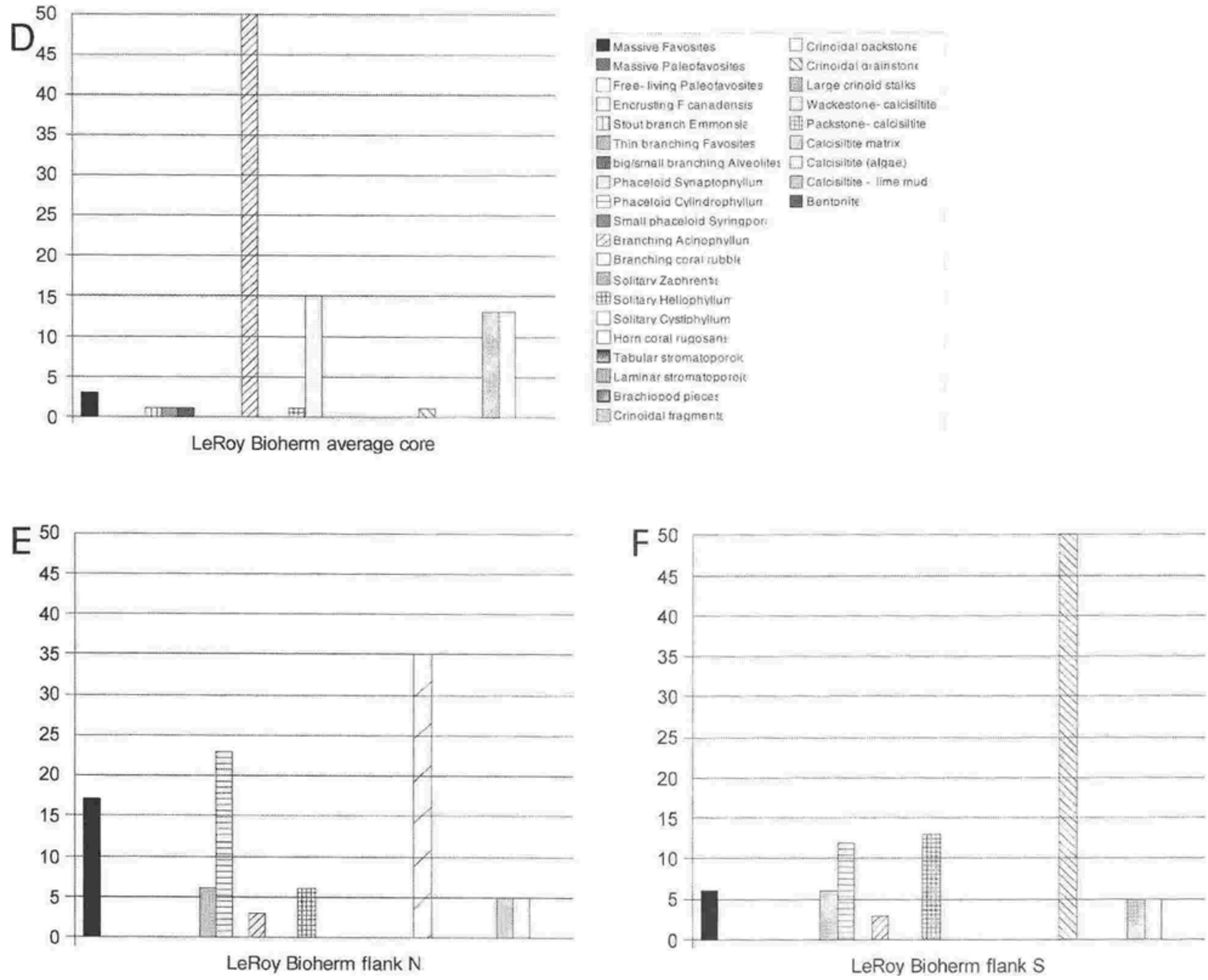

Fig. 11d-f. Taxonomic and growth form composition of Onondaga Formation reef biota. D: LeRoy Bioherm, core. E: LeRoy Bioherm, north flank. F: LeRoy Bioherm, south flank. Averages of 3 to 5 x 10 m transects per facies

tolerance based on patterns of occurrence (Copper 1994b). Tabular stromatoporoids, domal colonial corals, and other rapidly calcifying Paleozoic reef organisms probably harboured photosymbionts (Wood, 1993, 1995), allowing them to attain skeletal growth rates equivalent to those of modern hermatypic corals on reefs (Gao and Copper, 1997; Edinger and Copper, 2000).

Fossil reef sediments were classified according to Embry and Klovan (1971) while measuring transects or quadrats. The relative abundance of rock types was averaged for each site and facies, and the results plotted on a ternary diagram. The diagram presents a qualitative view of sediment composition only.

Reefs of the Onondaga Formation are mostly dominated by the phaceloid branching rugose corals *Synaptophyllum* and *Cylindrophyllum*, by the slender dendroid rugose coral *Acinophyllum*, the columnar to stout branching favositid coral *Emmonsia*, and by massive domal *Favosites* (Fig. 11A-F). The solitary rugose corals *Heliophyllum*, *Cystiphyllum*, and *Siphonophrentis* were common in the reef flank facies and inter-reef sediments, but were rare in reef core facies. The core facies of the LeRoy bioherm differs from the other Onondaga sites in having a much higher proportion of *Acinophyllum*, and lower proportion of massive *Favosites* (fig 11D, Wolosz, 1992a). Tabular stromatoporoids were not recorded in the Onondaga Formation reefs, and laminar stromatoporoids were recorded only in inter-reef sediments, usually atop firmgrounds.

Reef sediments at three of the four Onondaga reefs studied were dominantly crinoidal grainstones in reef core facies, and calcisiltite in the flank facies (Fig. 12). At the LeRoy Bioherm, however, the reef core facies was dominated by calcisiltite, and the reef flank facies was dominated by calcisiltite and crinoidal packstone and grainstone (Fig. 12). Onondaga reef sediments generally had less than 3% acid-insoluble material, excluding large silicified fossils (Johnston, 1990). Clay content within the Onondaga is generally less than 5% in the periphery of the basin, and less than 25% near the basin axis (Oliver, 1976). The pinnacle reefs of the Onondaga are mostly subsurface, and known from core and seismic records (Mesolella, 1978). The Mt. Tom reef in central New York State also appears to be a remnant of an Onondaga pinnacle reef (Wolosz, et al., 1991). These reefs are dominantly composed of large

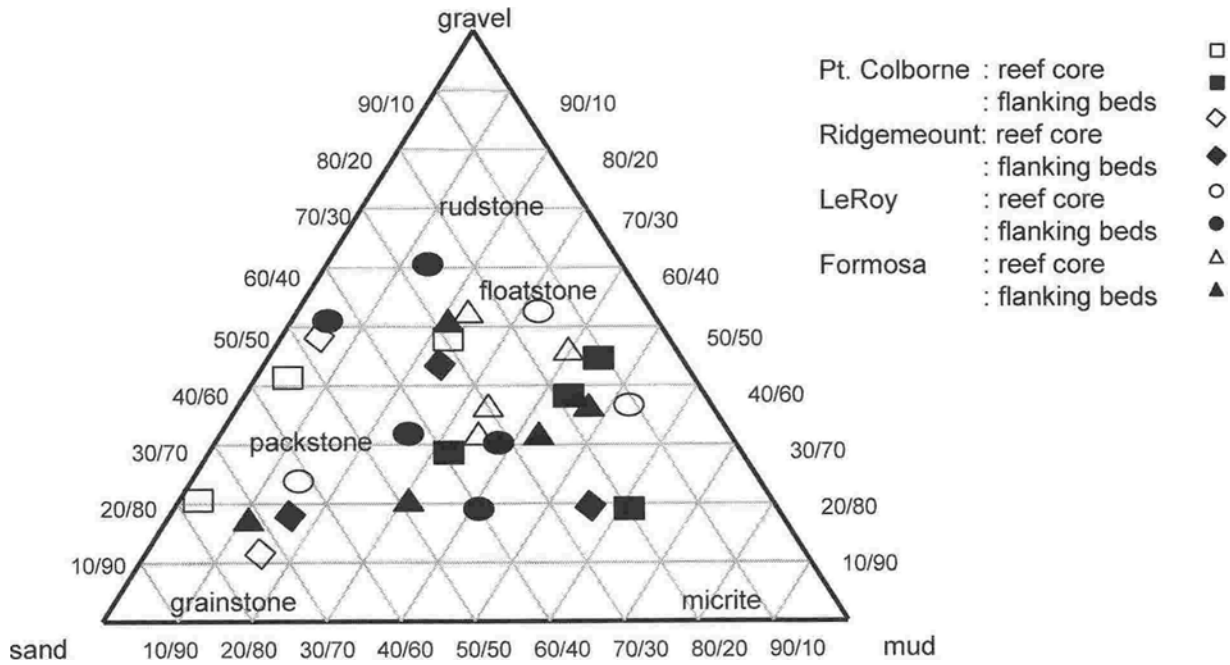

Fig. 12. Grain size composition of Onondaga Formation and Formosa Reef Limestone reef sediments. Semi-quantitative data points derived by estimating abundance of micrite, floatstone, packstone, grainstone, and rudstone on transects or quadrats through reefs. Each point represents average for one transect or quadrat.

phaceloid rugose corals such as *Cylindrophyllum*, with lesser contributions of small dendroid rugose corals such as *Acinophyllum*, and crinoidal grainstone (Wolosz and Paquette, 1989). The Onondaga pinnacle reefs in the subsurface of New York State and Pennsylvania host considerable oil and gas pools (Mesolella and Weaver, 1975). *Cylindrophyllum* may have thrived most in deeper waters around pinnacle reefs, and contributed to branching coral thickets that temporarily dominated individual shallow water bioherms (Wolosz, 1997).

3.4.2 Formosa Reef Limestone Reef Composition

The Formosa Reef limestone was studied at the type locality 1 km north of the village of Formosa, Ontario (Table 6, Fig. 9). Reef composition in the Formosa Reef Limestone was measured using eleven replicate 1 m^2 quadrats, because outcrop distribution was not favourable for line intercept transects. The reef core facies of the Formosa Reef Limestone reef was dominated by tabular and laminar stromatoporoids, crinoidal packstone, and calcisiltite wackestone (Fig. 13A, B). The flank facies were also dominated by laminar (<5 mm thick) stromatoporoids, crinoidal packstone, calcisiltite packstone, massive domal *Favosites*, columnar to stout branching corals, solitary rugose corals including *Heliophyllum* and zaphrentids, and tabular (> 5 mm thick, generally, 1-3 cm thick) stromatoporoids (Fig. 13 C). *Cylindrophyllum* was not recorded in the Formosa Reef limestone, and *Synaptophyllum* and *Acinophyllum* were rare. Formosa reef limestone sediments were dominated by crinoidal packstones and wackestones (Fig. 12).

Ternary diagram classification of Onondaga and Formosa Reef Limestone reefs showed that all but one of the Onondaga reefs were dominated by stress-tolerant coral growth forms (Fig. 14). The exception was the LeRoy bioherm reef core facies, which was dominated by ruderals (fine branching corals, *Acinophyllum*). By contrast, both the reef core and reef flank facies of the Formosa Reef limestone was dominated by competitors, primarily tabular and laminar stromatoporoids.

4 DISCUSSION

4.1 Relative Influences of Paleogeography, Zonal Circulation, and Local Circulation Patterns

The Onondaga Formation, and the Devonian Appalachian Basin, share similarities and differences with the modern Java Sea. Both the post-Onondaga Appalachian Basin and Java Sea are highly productive, siliciclastic dominated shallow tropical seas with locally developed coral reefs. Those reefs are under some stress, but maintain moderate to high species diversity. In both cases, the high marine productivity at sea-level highstands produced black shale facies (Hamilton Group, Appalachian Basin) and extensive hydrocarbon deposits (Miocene, Java Sea, Borneo, Sumatra). In both cases, high mountains with apparently high rainfall and runoff surrounded the basin, on at least one side. The Java Sea receives runoff, freshwater, and nutrients from Borneo, Sumatra, and Java, all with high mountains, and Java with active volcanism. Similarly, the rising mountains of the Acadian Orogeny to the east of the Appalachian Basin would have provided runoff and nutrients, and were the source of the large siliciclastic wedge that filled the Appalachian Basin in post-Onondaga Devonian time.

The geographic positions of the Onondaga and the Java Sea differ. The Java Sea lies within ten degrees of the

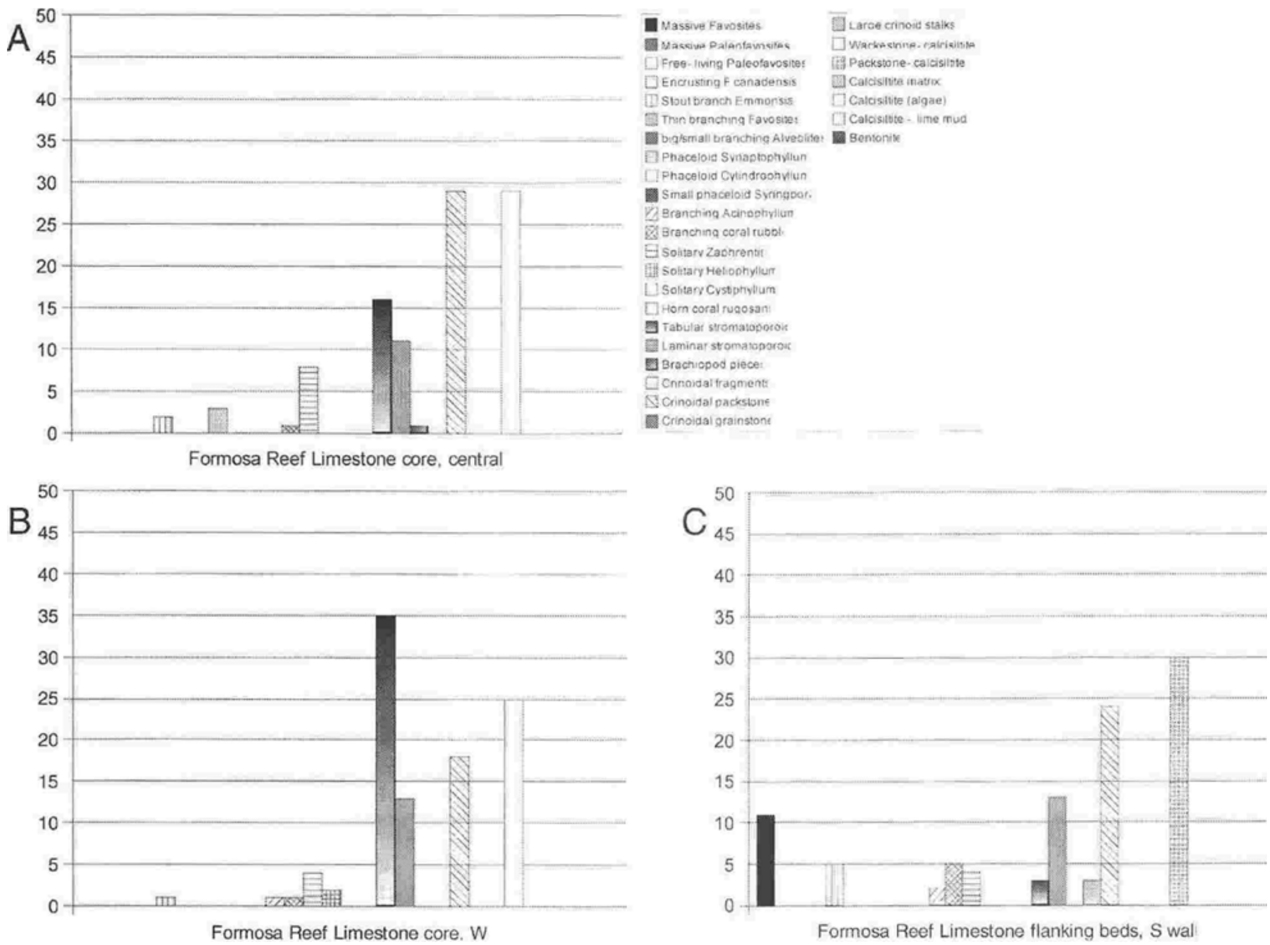

Fig. 13. Taxonomic and growth form composition of Formosa Reef Limestone reef biota. A: Reef core facies, central area. B: reef core facies, W side of road. C: flanking beds, S end of outcrop. Averages of at least three 1m^3 quadrats in each facies.

equator, and outside of the cyclone belt. The Appalachian Basin lay in the Devonian sub-tropics, about 35°S, opened southward into the Rheic Ocean, and was strongly influenced by storms (Brett et al., 1986). The tropical climatic zones were broader in the Devonian than today, and waters at the northern end of the Appalachian Basin remained well within the tropical climatic zones (Copper, 2001). Emsian and Eifelian paleogeographic reconstructions portray the Rheic ocean as a large deep-water ocean between Laurentia and Gondwana, with currents flowing southward along the eastern edge of Laurentia, analogous to the modern Gulf Stream (Scotese, 1997).

The Devonian Appalachian Basin was largely storm dominated (Brett, et al., 1986), although the reefs themselves appear to have grown during relatively quiescent periods (Wolosz, 1997). Middle Devonian seas housed extensive crinoid meadows, which produced vast amounts of carbonate sand in non-reefal facies of the Onondaga Formation and elsewhere. No modern analogue for non-reefal crinoid meadows exists in most of the Java Sea, where most carbonate production is intimately associated with reefs, and *Halimeda* bioherms are very localized at the shelf-edge (Roberts and Phipps, 1988). This difference may partially explain the higher carbonate content in non-reefal facies of the Onondaga than in non-reefal facies of the Java Sea.

The nearshore Java Sea reefs have reef composition and reef sediments similar to archetypal cool-water carbonate buildups and sediments, but also similar to high productivity carbonate buildups and sediments. The relatively small contribution of corals to nearshore reef composition and reef sediments, high cover of fleshy algae, and the high proportion of molluscan fragments in nearshore reef sediments are all considered characteristics of cool-water carbonate buildups, or cool-water carbonate sediments (James, 1997). *Halimeda* bioherms in the Java Sea are limited to upwelling-dominated sites at the eastern margin of the Sunda shelf (Roberts and Phipps, 1988). *Halimeda* flakes were moderately abundant in the sediment of some of the Java Sea reefs sampled in this study, comprising up to 10% of surface sediments at deep sites on one of the two offshore reefs (Fig. 8), but *Halimeda* plants were rare on the reefs, as were other calcareous algae (Fig. 4). Only the low importance of bryozoans and calcareous red algae differentiate the nearshore reef and reef sediment compositions from typical cool-water carbonate sediment composition. The reef composition and sediment characteristics of the nearshore reefs are also typical of reefs in high productivity environments (Wood,

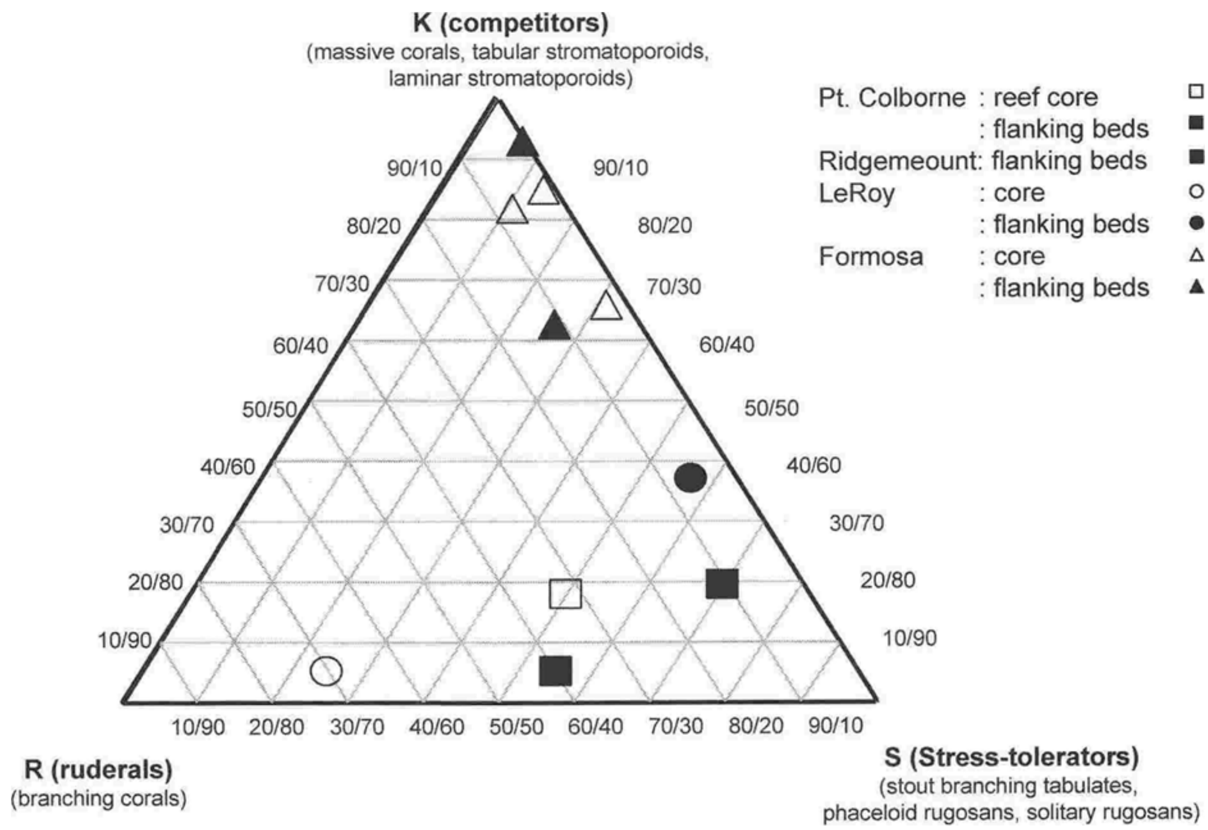

Fig. 14. Ternary diagram showing growth form composition of Onondaga Formation and Formosa Reef Limestone reef biota. Each point represents average composition of all transects/quadrats on each reef and facies.

1993). These features of nearshore Java Sea reefs and reef sediments emphasize the ability of local environmental conditions to produce false cold-water carbonate signals within the core tropics (Wood, 1993).

Contrasting with both the Onondaga Formation and the modern Java Sea, the Formosa Reef limestone was formed in a reefal facies in an almost pure carbonate domain, preserved as dolomite and dolomitic limestone. The dominant organisms on the Formosa Reefs, tabular stromatoporoids and massive corals, were probably spatial competitors, rather than the stress-tolerant dendroid and phaceloid rugose corals that dominated the Onondaga Formation reefs (Copper, 1994b; Wolosz, 1997). In Middle Devonian time, the Michigan Basin lay northward of the Appalachian Basin, and would have been at around 30-35°S latitude. Furthermore, the Michigan Basin was farther removed from high mountains, and received less runoff, nutrient, and terrigenous sediment than the Appalachian Basin (Scotese, 1997). Previous work on the Onondaga reefs had suggested cold-water conditions based on several criteria, including (1) the lack of tabular stromatoporoids and calcareous red algae in Onondaga Reefs (Cassa and Kissling, 1982; Wolosz, 1997), (2) the absence of gypidulinid brachiopods in the Onondaga, and from the cold water Malvinokaffric Realm (Koch and Boucot, 1982), and (3) the small size and low faunal diversity of Onondaga bioherms, compared to Middle Devonian bioherms of western or Arctic Canada (Wolosz and Paquette, 1989). Geochemical, taphonomic, and paleogeographic evidence, however disagree with a cold-water interpretation. $\delta^{13}C$ and $\delta^{18}O$ signatures from Hamilton Group brachiopods indicate warm water conditions (25-35° C) in the Middle Devonian Appalachian Basin (Bates and Brand, 1991). These data also indicate significant facies control over isotope composition, with both carbon and oxygen stable isotopes becoming heavier basinward. This pattern is consistent with a large influx of freshwater into nearshore zones, and with quasi-estuarine circulation (Bates and Brand, 1991). Tempestites and occasional biostromes with corals and algal microborings indicate that the abundant black shales of the Givetian Hamilton Group may have accumulated under hyposaline shallow water conditions, rather than deep, anoxic, fully marine conditions (McCollum, 1989). The geochemistry of these black shales is also consistent with high productivity shallow-water conditions with seasonal stratification (Murphy, et al., 2000a,b). The preponderance and diversity of tropical-type fossils in the Onondaga Formation, particularly corals, suggests that warm conditions were common in the Onondaga, if not pervasive, and that limits to reef growth were dominantly driven by local conditions.

There are striking similarities in faunal morphology and sediment composition between the Onondaga reefs and modern nearshore eutrophic reefs of the Java Sea. We suggest that the apparent "cold-water" characteristics of the Onondaga reef fauna resulted not from cold water, but from moderately high nutrient, turbid conditions generated by local quasi-estuarine circulation. The scarcity of calcareous algae in the Onondaga does not suggest high nutrient conditions, but many of the other aspects of faunal and sediment composition do. Nor were calcareous algae common on the high nutrient nearshore Java Sea reefs; these had high abundances of *fleshy* algae.

Salinity-driven quasi-estuarine circulation, leading to high nutrient conditions and moderate to high siliciclastic sediment input may have all contributed to the false cold-water nature of the Onondaga Formation. High runoff from the rising Acadian mountains to the east supplied both abundant fresh water and siliciclastic sediments to the Appalachian Basin during Hamilton Group time and later, pushing the basin into quasi-estuarine circulation. The beginnings of the Acadian Orogeny during Onondaga time initiated this pulse of runoff and siliciclastic sedimentation, and could account for the high silt and clay concentrations in the non-reefal facies of the Onondaga Formation (Brett and Baird, 1986). As in the Java Sea, quasi-estuarine circulation (QEC) would not have decreased salinity enough to cause major deviations in $\delta^{18}O$ values, because QEC would have drawn large amounts of open ocean water into the basin to maintain salt balance.

The contrasts between the Appalachian Basin, characterized by QEC, and the Michigan Basin, characterized by AEC, are somewhat analogous to the contrasts between Primo (P) and Secundo (S) oceanographic states defined for Silurian Seas (Jeppsson, 1990). Primo and Secundo states, however, are defined as global shifts in climate and oceanography, rather than differences between contemporaneous conditions in separate basins. Contemporaneous rocks in the Appalachian and Michigan Basins reflect markedly different oceanographic conditions that are relatively stable, rather than cyclic changes through time.

4.2 Other Paleozoic Examples of Quasi-Estuarine Circulation in Epicontinental Seas

High nutrient levels and/or quasi-estuarine circulation may also explain the facies patterns observed in several other Paleozoic carbonate embayments of eastern North America. Upper Ordovician (Caradoc: Trenton) strata of the St. Lawrence Lowlands region of Quebec have been interpreted as cold-water carbonates, containing abundant colonial rugose and tabulate corals and calcareous red algae, but locally featuring bryozoans, molluscs, brachiopods, and crinoids, (Lavoie, 1995). These features were interpreted as analogues for modern high-latitude cool-water carbonate ramps, although paleogeographic reconstructions place this region in the core tropics during late Ordovician time. Accordingly, Lavoie (1995) proposed that the tropical regions were considerably reduced to low latitudes in the Late Ordovician, with temperate water conditions reaching as low as 17°S latitude during late Caradoc - early Ashgill times. This model, however, contradicts the higher diversity of the Caradoc - mid Ashgill, and benthic faunal decline thereafter (e.g. Copper, 1999). Abundant reefs and diverse tropical faunas on contemporaneous sequences in Anticosti Island, Quebec do not suggest deposition under cold-water conditions (Long, 1997; Copper, 1998). We suggest that the apparent Ordovician cold-water carbonates of the St. Lawrence lowlands are more likely related to local (i.e. basin-scale) conditions, specifically high nutrient conditions produced by quasi-estuarine circulation.

Strata contemporaneous with the St. Lawrence lowlands exposed in the Lac Saint-Jean region, Quebec, and Ontario contain phosphatic hardgrounds, suggesting high nutrient conditions (Lavoie and Asselin, 1998). These results led to the proposal for upwelling of deep, cold, nutrient-rich waters as the cause of cool-water type carbonate deposition in eastern North America (Lavoie and Asselin, 1998; cf. Patzkowsky and Holland, 1993; Pope and Read, 1997). Similarly, the slightly older mid-Caradoc Black River Group of southern Ontario is suggested to have been deposited under cool-water conditions within the core tropics (Brookfield 1988).

The Rheic ocean margin of eastern North America at this time lay along an approximately NE-SW line, bringing warm tropical surface water from NE to SW along this coastline (Wilde, 1991; Scotese, 1997). Such a circulation regime may have induced local Ekman spiral upwelling. Analogous seasonal upwelling occurs in the modern Gulf of Arabia (latitude 25°N), when monsoonal winds drive surface waters northeastward (Coles, 1997). Early zonal circulation models for Paleozoic oceans did not predict such upwelling along the southeast margin of Laurentia (Parrish, 1982). Indications of high-nutrient or cool-water conditions, however, are patchy in the spatial and temporal distributions within the Upper Ordovician sequence of eastern North America. Regional-scale Ekman spiral upwelling should have produced widespread organic-rich facies driven by high surface primary productivity (Parrish, 1982), but these are not known in North America until the late Caradoc, e.g. the Utica-Collingwood-Blue Mountain black shales, following Trenton deposition. Quasi-estuarine circulation has been proposed to explain the origins of black shale facies within the Late Ordovician Collingwood Formation of southern Ontario, Canada (Rancourt and von Bitter, 1998). We suggest that nutrients and cooler water may have reached coastal embayments in the region as a result of localized upwelling driven by quasi-estuarine circulation, producing the apparent cold-water signals described in the St. Lawrence lowlands, southern Ontario, and New York state.

Holmden et al. (1998) used neodymium model ages and carbon and oxygen stable isotopes to propose a model of "aquafacies" in Late Ordovician (mid-Ashgill) epicontinental seas, in which waters close to the landmass were dominated by terrestrial runoff, while waters near the edge of the continental shelf were dominated by open ocean conditions. Intermediate aquafacies were recorded in mid-shelf regions, showing mixing of watermasses, and intermediate neodymium and oxygen isotopic values. Regions close to the rising Taconic Mountains showed greater influence of terrestrial runoff on their carbon and oxygen stable isotope compositions, but not in their neodymium model age estimates.

Similar to QEC, the Holmden et al. (1998) model suggests that the amount of terrestrial runoff reaching a particular portion of an epicontinental sea was important to the nature of oceanographic conditions there. Regional variation in stable isotope signatures further suggests that quasi-estuarine circulation, rather than Ekman-spiral upwelling, was responsible for localized organic-rich facies in the Ordovician strata.

Silurian sediments in the Baltic region are suggested to have reflected alternating quasi-estuarine and anti-estuarine circulation (Bickert et al., 1997; Samtleben et al., 2000). The Silurian sequence in Gotland, Sweden, contains periods of reef development alternating with periods of marl deposition that are difficult to explain by transgressive-regressive cycles. Cyclic changes in carbon and oxygen isotopes from brachiopod shells of Gotland are interpreted to suggest that seawater in the Baltic region became less or more saline through time, ranging between 32.5 and 38.0 ‰, and corresponding with humid or arid conditions, respectively (Bickert et al., 1997). These cyclic changes in salinity reflect alternating quasi-estuarine or anti-estuarine, conditions, and were referred to as H-episodes (humid, QEC) and A-episodes (arid, AEC). The H-episodes correlate with the Primo states (Jeppsson, 1990) while the arid A-episodes correspond to the Secundo states (Samtleben et al., 2000). Reef development was suggested to be greater during the A-episodes, and was severely restricted by terrigenous sedimentation and more nutrient-rich water during H-episodes (Samtleben et al., 2000). Nevertheless, reefs occurred almost uninterruptedly throughout the Gotland succession from the late Llandovery through the end Ludlow, and the reconstructed paleolatitudes place the section in the tropics. Changes in the composition of reef faunas, however, were not discussed, except for a greater incidence of oncolites during A-episodes (Samtleben, et al., 2000).

It is not clear whether the H-and A- episodes in the Baltic reflect either regional or global shifts in climate and oceanographic conditions (Samtleben et al., 2000). Carbon and oxygen isotope values may vary within a basin, let alone between basins, implying that global isotope curves derived from epicontinental sea sequences must be interpreted with great caution (Holmden et al., 1998). Furthermore, quasi-estuarine and anti-estuarine circulation depend on *differences* in salinity between an epicontinental sea basin and the open ocean, which maintains its salinity more or less constant (Witzke, 1987). The H- and A-episodes described from the Silurian of Gotland may best be regarded as local, i.e. basin-scale, until and unless they are demonstrated to be global in scale. The H- and A-episodes are apparently tied to Jeppsson cycles in global climates and ocean circulation, which could have had broader influence without changing global ocean salinity.

The differences in circulation among contemporaneous Devonian sedimentary basins we describe appear to have been driven by local geography and oceanography rather than global cycles (but see House (1985) for examples of global cycles of ammonoid evolution corresponding to sedimentary cycles). Silurian reefs appear to show global episodes of development that have been interpreted as corresponding to Primo and Secundo (P and S-state, cf. Jeppsson 1990) cycles (Brunton et al., 1998). However, age estimate of some Silurian reefs are inaccurate, and cast doubt on the validity of these apparent reef cycles. At the present time, the only distinctive megacycle for Silurian reefs is from the Telychian through Homerian (Wenlock). In Ludlow time, reefs were more sporadic in abundance, and major regressive sealevel lowstands for the 1-2 myr long Pridoli eliminated most carbonate platforms. (Copper, 2001).

5 CONCLUSIONS

The Java Sea is proposed as a modern analogue for mid-Paleozoic siliciclastic-dominated tropical epeiric seas. The Java Sea can be characterized by Quasi-Estuarine Circulation. Java Sea reefs consist of (1) small patch reefs in siliciclastic muddy environments with limited vertical relief and restricted diversity, and (2) nearly pure carbonate pinnacle reefs rising from >30 m depth, with relatively high diversity and morphological complexity. Study of Java Sea reef carbonates in nutrient-rich nearshore environments only would deceptively suggest a cold-water carbonate aspect.

The Middle Devonian Appalachian and Michigan Basins in North America were in geographic proximity and shared fauna, but had markedly different oceanographic systems. The Appalachian Basin was probably characterized by quasi-estuarine circulation, while the Michigan Basin had anti-estuarine circulation. Both included reefs deposited under tropical climatic conditions, but with considerably different faunas. Appalachian Basin reefs are poor in stromatoporoids and calcareous algae. Apparent indicators of cool-water carbonate deposition in the Appalachian Basin can be explained by quasi-estuarine circulation. QEC may explain other apparent cool-water carbonates deposited in tropical locations, such as the Upper Ordovician carbonates of Ontario and Quebec, Canada, and Silurian marls of Gotland, Sweden.

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