Global and regional influences on equatorial shallow-marine carbonates during the Cenozoic

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ABSTRACT

The SE Asian carbonate record allows insight into the poorly known response of equatorial marine systems to regional and global change during the Cenozoic. There is a marked change from larger benthic foraminifera to corals as dominant shallow-marine carbonate producers in SE Asia around the Oligo-Miocene boundary. The Early Miocene acme of coral development in SE Asia lags Oligocene coral development in the Caribbean and Mediterranean, despite local tectonics providing apparently suitable habitable areas. Regional and global controls, including changing CO2, oceanography, nutrient input and precipitation patterns are inferred to be the main cause of this lag in equatorial reefs. It is inferred that moderate, although falling level of CO2, Ca2+ and Ca/Mg when combined with the reduced salinities in humid equatorial waters all contributed to reduced aragonite saturation hindering reefal development compared with warm more arid regions during the Oligocene. By the Early Miocene, atmospheric CO2 levels had fallen to pre-industrial levels. Although this was a relative arid phase globally, in SE Asia palynological evidence indicates that the Early Miocene experienced everwet, but more stable and less seasonal conditions than periods before or after. Tectonic convergence truncated deep throughflow of cool nutrient-rich currents from the Pacific to Indian Ocean around the beginning of the Miocene, thereby directly, and perhaps indirectly (though less seasonal conditions) reducing nutrients. It is inferred that aragonitic reefs were promoted where previously the waters had been more acidic, more mesotrophic, more turbid, and less aragonite saturated. Extensive reefal development resulted in an order of magnitude expansion of shallow-carbonate areas through buildup and pinnacle reef formation in the Early Miocene. Tectonics via increased habitat partitioning and reducing distances to other coral-rich regions may also have contributed to enhanced reefal development. Declining reefal importance at the end of the Early Miocene resulted from uplift of land areas, enhanced oceanic ventilation, through thermohaline circulation and narrowing of oceanic gateways as well as increased seasonal runoff, at least in SE Asia through initiation/intensification of the monsoons. Implications of this study are that with current anthropogenically-induced environmental changes it will be the diverse reefs of SE Asia that are likely to be amongst the first and hardest hit as oceanic aragonite saturation decreases and terrestrial nutrient runoff increases.

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1. Introduction

The response of equatorial marine systems remains poorly known to long-term global change spanning the Cenozoic. This is despite recent realisation that equatorial regions have not remained static during global climatic shifts (Pearson et al., 2001), and that as well as being participants tropical oceans may be dominant drivers of climate change (Kerr, 2001). Shallow-marine carbonates are known to be highly responsive to changing environmental conditions. The hypothesis is that by evaluating spatiotemporal changes in equatorial carbonates it should be possible to infer main controls on shallow-marine systems, and whether any trends are consistent with theories of how the tropics respond to global change. Major global trends in the Cenozoic include the transition from greenhouse to icehouse conditions (Zachos et al., 2001), radical variations in atmospheric CO2 levels (Pearson and Palmer, 2000; Pagani et al., 2005), the development of the monsoons (Jia et al., 2003), and the evolution of modern reefs (Perrin, 2002). Additionally plate tectonic reorganization, eustasy, oceanography and trophic resources are all involved in environmental feedback loops, strongly influencing marine systems (Perrin, 2002; Halfar and Mutti, 2005). SE Asia has the most extensive and complete record of equatorial carbonates spanning the last 50 My: the Eocene-Recent (Fulthorpe and Schlanger, 1989; Wilson, 2002). The aims of this work are: 1) to present new data on spatiotemporal changes in Cenozoic SE Asian carbonates, 2) to evaluate factors controlling...
regional carbonate development, and 3) to assess if, and how the equatorial marine systems may be responding to regional and global change.

2. Methodology and data

The location, age, and components of all SE Asian carbonate formations analyzed by Wilson (2002) are plotted onto plate tectonic and palaeogeographic time-slices reconstructions (Fig. 1a–g and Appendix A, Hall, 1996, 2002; Wilson and Rosen, 1998). To determine long-term trends the selected time slices fall within the major subdivisions of the Cenozoic and away from environmental short-term perturbations at epoch boundaries (Zachos et al., 2001). Although the reconstructions of Hall (1996, 2002) were used, plotting the carbonates onto plate tectonic reconstructions by other workers (Rangin et al., 1990, Daly et al., 1991; Lee and Lawver, 1995) would yield a similar picture of spatial and temporal carbonate development.

Warm-water, light-dependent biota predominated in all shallow-water limestones. Using only limestones (250 out of 299 formations) dominated by these components eliminated any variations due to depths below the photic zone, major eutrophication, or temperatures below an annual average of 16 °C. The shallow-water limestones were subdivided into three biofacies (Fig. 1 and Appendix A). These are dominated by: 1) aragonitic corals (and sometimes Halimeda), 2) diverse calcitic larger benthic foraminifera (and sometimes coraline algae, including rhodoliths), and 3) mixed biofacies containing abundant corals and larger benthic foraminifera. Deposits reported as coral-rich in the literature, or reefal with corals (with few larger benthic foraminifera described), were plotted as dominated by corals. Zooxanthellae are not preserved in fossil corals. However, where described the solitary and colonial corals from all ages in SE Asia are almost all z-corals, z-like or z-like? (Adams et al., 1990; Wilson and Rosen, 1998), rather than azooxanthellate. Larger benthic foraminifera are biostratigraphic indicators in SE Asia and their occurrence and abundance are often qualitatively recorded. Appendix A tabulates for the first time the areas and biofacies types for each shallow-carbonate formation from the literature and geological maps. Where possible, entries (15% out of the 250 shallow formations) were validated by the author’s independent field, sample and/or petrographic analysis to quantify biofacies types for each formation (Appendix A). The results of this independent biofacies analysis did not differ significantly from the published literature.

New data collected on temporal changes in the areas of carbonate biofacies, numbers of extensive platforms versus localized shoals or buildups are plotted against regional and global events to evaluate...
possible main factors influencing equatorial carbonate development (Figs. 2 and 3). Shoals/buildups are defined as being less than ∼20 km across. The carbonates of SE Asia, particularly surface outcrops without hydrocarbon potential, remain understudied. The biofacies of only around 10% of the carbonate formations tabulated by Wilson (2002) have been documented in detail. There is little regional systematic data on the evolution and extinction of corals or the diversity of reefal deposits (Wilson and Rosen, 1998). Geochemical data such as O or C isotopes are sparse since Pre-Quaternary aragonitic components have been altered, and the abundant tests of calcitic larger benthic foraminifera may not be in equilibrium with seawater. Future study on these topics would help elucidate short-term changes, but despite limitations long-term trends are apparent (Fig. 2). Most deposits have been dated through their larger benthic foraminifera (using the East India Letter Classification; Adams, 1970), and/or microfossils if present. More workers are beginning to use strontium isotope dating for Oligo-Miocene sections (Lunt and Allan, 2004). Although the detailed dates of individual formations may change with further dating, on the basis of recent redating it is unlikely that the overall general trends will change significantly.

3. Results: patterns and trends

Long-term trends (Figs. 1, 2 and 3) are: 1) Shallow, warm-water carbonates are present in SE Asia throughout the Eocene-Recent and ∼10% are mixed biofacies in most periods. 2) Biofacies dominated by larger benthic foraminifera are present throughout the Cenozoic, and although corals are known from the Eocene, coral-dominated systems are not reported until the Late Oligocene. 3) A change in the dominant biota from larger benthic foraminifera to corals around the Oligo-Miocene boundary. 4) A minor gradual increase in the area of carbonate production from the late Eocene through the Oligocene, a marked increase around the Oligo-Miocene boundary, followed by a decline to the present. 5) A minor gradual increase then decrease in the number of large-scale platforms through the Cenozoic, whereas there is over an order of magnitude increase in the number of buildups and shoals around the Oligo-Miocene boundary followed by a decline to the present.

SE Asia has a complex tectonic evolution during the Cenozoic, being the site of convergence of the Indo-Australian and Philippine-Pacific Plates with the stable Sundaland (Asian) mainland, all interacting with many smaller microcontinental and oceanic fragments (Hall, 1996, 2002). The tectonostratigraphic context was studied to help evaluate possible regional or global influences on carbonate trends.

Paleocene and Early Eocene carbonates are rare in SE Asia. By the Late Eocene extensive carbonate platforms were common on microcontinental blocks in eastern SE Asia or along the margins of newly formed marine extensional basins bordering eastern Sundaland (van de Weerd and Armin, 1992; Wilson et al., 2000; Wilson, 2002). During the Late Eocene and Early Oligocene extensive platforms formed in New Guinea (Leamon and Parsons, 1986; Brash et al., 1991), as the Australian craton and associated microcontinental blocks drifted northwards, and also along the margins of the developing extensional S China Sea Basin (Adams, 1965; Holloway, 1982; Hinz and Schlüter, 1985). These Paleogene carbonates are dominated by diverse larger
benthic foraminifera and less commonly coralline algae (Adams, 1965; Brash et al., 1991; Wilson et al., 2000; Wilson, 2002). The larger benthic foraminifera are mostly perforate forms, and were variously adapted to occupy the full range of habitats within the photic zone. Carbonates were not extensive in western SE Asia as a consequence of a major land area extending from mainland Asia, through Sumatra and Borneo during the Paleogene (Wilson, 2002). Localized, and often transient, carbonates only accumulated on the narrow shelves when clastic input was insufficient to hinder production resulting mainly in mixed biofacies (Wilson, 2002). During the Eocene and most of the Oligocene corals are rare, with solitary or isolated colonial forms present in shallow and sometimes muddy coastal deposits, such as those documented in the Tonasa and Tampur Limestones (de Smet, 1992; Wilson and Rosen, 1998; Wilson, 1999). Patch reefs, reefal buildups or reef rimmed margins only start to be reported from in the later part of the Oligocene (Fulthorpe and Schlanger, 1989; Wilson and Rosen, 1998). These develop in the marine backarc basins of Java and Sumatra (Sharaf et al., 2005), along the subsiding margins of the Sundaland craton, close to emerging islands in the Philippines (Porth et al. 1989), and possibly in New Guinea (Brash et al., 1991).

There was a marked increase in the extent of carbonates, and a change from larger foraminifera to coral dominance around the Oligo-Miocene boundary (Fig. 2). Corals were widespread, abundant and diverse throughout the region during the Neogene. Many modern genera or species and all the growth forms typical of the modern Indo-West Pacific are present in these Miocene reefs (Wilson and Rosen, 1998). The accompanying biota is also closely comparable with modern reefs, with diverse benthic foraminifera, echinoderms, molluscs, coralline algae and *Halimeda*. During the Early Miocene reefal carbonates, with buildups and pinnacle reefs, were common in all the marine basins bordering mainland SE Asia (Fulthorpe and Schlanger, 1989; Grötsch and Mercadier, 1999; Wicaksono et al., 1995; White et al., 2007). To the east, reefal production occurred on microcontinental blocks, despite some collision-related uplift (Hall, 2002). The Early Miocene was a major phase of carbonate deposition both in SE Asia and throughout much of the tropics and sub tropics, with reef corals occurring in higher latitudes than today (Fulthorpe and Schlanger, 1989). During the mid-Miocene, the area of carbonate deposition, though still extensive and diverse, had been reduced, due to the emergence of land areas, resulting in part from microcontinental collisions (Hall, 1996) and the associated shedding of clastics. This trend of reduced areal extent of high diversity carbonates continues to the present day. Neogene foraminifera-dominated and mixed biofacies are generally in coastal areas receiving terrestrial runoff, in areas of upwelling associated with oceanic currents, or perforate foraminifera dominate over corals in deeper photic areas (Wilson and Vecsei, 2005).

4. Discussion: controls on equatorial carbonates

Possible controlling influences must be consistent with the main trends in equatorial carbonates and their exceptions as outlined above. The paucity of corals in most Paleogene deposits also needs explanation,
particularly during the Oligocene when corals and reefs are common in other tropical areas such as the Caribbean and Mediterranean (Wilson and Rosen, 1998; Edinger and Risk, 1994; Budd, 2000; Perrin, 2002).

4.1. Tectonics and biogeography

Regional tectonics via plate tectonic movement, extensional basin formation and uplift was the dominant control on the location of carbonates during the Cenozoic in SE Asia (Wilson and Hall, submitted for publication). These processes controlled movement into the tropics, emergence and disappearance of shallow-marine areas. Locally, the creation of faulted highs, volcanic edifices, microcontinental blocks, and basins trapping siliciclastics influenced the location of carbonate initiation. The extent of large-scale platforms, increasing slightly into the Miocene then decreasing (Fig. 2), is related to the tectonic formation, drift, and subsequent subaerial exposure through tectonic uplift of large-scale, shallow-water areas. Although there was widespread subsidence of basins around the Oligo-Miocene boundary, local tectonics cannot be the cause of the major change in biota around this time. A biogeographic cause may help explain the paucity of corals during the Paleogene in SE Asia, since the tectonic context resulted in geographical isolation from other coral-rich areas (Wilson and Rosen, 1998). However, additional environmental factors are inferred since corals were present in the Paleogene, but other than locally did not become dominant contributors until around the Oligo-Miocene boundary.

4.2. Eustasy

There is no positive correlation between the area of SE Asian carbonates and periods of global highstands or late transgressive phases on the scale of the Cenozoic, as might be predicted from sequence stratigraphic principles. Eustasy was therefore not the dominant control on the regional extent of carbonates. As an exception, a period of eustatic high, together with subsidence of many basins during the Early Miocene may have partially influenced the areal extent of carbonates (Greenlee and Lehmann, 1993), but does not explain the change in biota. Glacio-eustatic fluctuations of sea level are a major feature of the Neogene. Corals may have been promoted at this time because they are able to ‘keep-up’ with the rapid rises, and because suitable lithified substrates for colonization were provided via meteoric cementation from repeated subaerial exposure. However, corals are also capable of colonizing shells or pebbles in soft substrates. Also this ‘fluctuations’ hypothesis cannot explain why corals are common in other tropical regions outside SE Asia during much of the Oligocene. Smaller-scale buildups or shoals are mainly of Neogene age in SE Asia, and the increase in areal extent of carbonates in the Early Miocene was only possible through their development (Figs. 2 and 3). Whatever the cause, the change to coral dominance would have enhanced the potential for buildup formation through framework development and faster accumulation rates than the larger benthic foraminifera (Fig. 3; Wilson, 2002).
4.3. Temperatures

The high temperatures of the early Paleogene (Pearson et al., 2001) may have inhibited corals in the equatorial tropics, through processes such as coral bleaching (Sheppard, 2003; Scheibner et al., 2005). Larger benthic foraminifera are much less susceptible to symbiont expulsion due to increased temperature (Hallock, 2000). However, coral communities can become acclimatized to higher temperatures (Hallock, 2005). The SE Asian data does not support temperature being the prime limiting factor since corals are often present in very shallow, near coastal deposits during the Paleogene where seawater temperatures would have been at a maximum. Rises of ~4–6 °C (Zachos et al., 2001) in deep-sea and low latitude surface temperatures around the Paleocene Eocene Thermal Maximum are inferred to have hindered coral growth (Scheibner et al., 2005). However, by the late Eocene (when the main Cenozoic SE Asian carbonates record begins) sea surface temperatures (SST) in low latitudes were ~2–4 °C higher than today. SE Asia has probably always been a region of depressed SST due to oceanic throughflow (Kuhnt et al., 2004) and past temperatures of up to 34 °C (today 26–30 °C; Gordon et al., 2003) are unlikely to have hindered corals. A warm phase may have allowed the expansion of reefal corals during the Early Miocene into much higher latitudes than today (Fulthorpe and Schlanger, 1989). This was followed by global cooling in the Middle Miocene perhaps related to organic-carbon-rich deposition, resulting in drawdown of atmospheric CO₂ and East Antarctic ice-sheet growth (the ‘Monterey Hypothesis’; Vincent and Berger, 1985; Flower and Kennett, 1993; 1994). Pomar and Hallock (2007) speculated that during the Early Miocene high summer temperatures and exposure to full sunlight via clear skies in the Mediterranean may have caused loss of symbionts in shallow-water corals, resulting in few reefs building to sea level. Available data from SE Asia suggests that reefs built to sea level throughout the Neogene. If elevated temperatures were an issue in other regions, the presence of an active oceanic gateway and the commonly cloudy skies in SE Asia may have maintained temperatures below the threshold for symbiont expulsion.

4.4. Ocean/atmosphere interactions

High CO₂ levels and/or low Mg/Ca ratios in the early Paleogene may have both hindered the recovery of aragonitic corals following the end Cretaceous extinction event. Aragonite saturation in surface waters decreases as both pCO₂ and Ca/Mg increase, and under these conditions calcitic organisms are promoted (Stanley and Hardie, 1998; Kleypas et al., 1999; Hallock, 2005). Fine and Tchernov (2007) have shown that aragonitic corals decalcify when seawater pH is reduced where increased oceanic acidification is related to elevated CO₂. Total decalcification occurred when pH values were reduced from 8.3 (today’s value) to 7.4 (postulated to occur within the next 300 years). During the Eocene, pCO₂ values varied around 1000–2000 ppm (Pagani et al., 2005; Fig. 2) with a likely associated reduction of 0.3 to 0.5 of a pH value (Caldeira and Wickett, 2003). The global predominance of calcitic larger
benthic foraminifera and coralline algae over aragonitic corals and calcareous green algae in shallow waters during the Eocene has been related to these elevated CO$_2$ and/or Ca/Mg values (Stanley and Hardie, 1998; Hallock, 2005).

Although fluctuating, values of atmospheric CO$_2$, together with oceanic Ca$_2^+$ and Ca/Mg ratios were all falling through the Oligocene (Stanley and Hardie, 1998; Pagani et al., 2005). Aragonite hypercalcification needed for reef framework formation, is promoted by low atmospheric CO$_2$ levels, Mg/Ca ratios >3, increased temperatures and additionally normal to elevated salinities (Stanley and Hardie, 1998; Kleypas et al., 1999). Due to high equatorial runoff the surface waters of SE Asia have significantly reduced salinities (30–34‰) compared with global averages (36‰). This is true around coasts of everwet islands (such as Borneo), or those with a seasonal monsoonal climate (such as Sulawesi or Java; Gordon et al., 2003; Wilson and Vecsei, 2005). Moderate CO$_2$ levels during the Oligocene combined with reduced salinities in SE Asia may have hindered aragonitic reef formation and promoted calcitic larger foraminifera. Although the diversity of corals may have recovered, their ability to hypercalcify was hindered by low aragonite saturations, meaning that although corals were present reef development was patchy, indicating a geochemical control (anonymous referee, pers. comm., 2008). In comparison with SE Asia, more arid areas outside the equatorial region, such as the Caribbean and Mediterranean, are likely to have had higher aragonite saturations, promoting earlier extensive reef growth (Kleypas et al., 1999, 2001).

Simulations of ocean chemistry related to postulated rising CO$_2$ levels over the next century show that the aragonite saturation in equatorial regions (and SE Asia in particular) will drop below those suitable for reef development (Ω-arag >4) significantly earlier than for the Caribbean (Kleypas et al., 1999). Due to reduced salinities, SE Asian waters typically show aragonite saturations of ~0.5–1 less than those for the Caribbean or Red Sea, translating to ~10% reduction in calcification rates.

The Indo-West Pacific is the largest coral-reef province and may partially ‘swamp’ the perceived trend of Cenozoic coral reefs with a global acme in the late Oligocene to Early Miocene (Perrin, 2002; Hallock, 2005). Although difficult to make direct comparison due to the lack of diversity data on corals from SE Asia, reefs are abundant and diverse in the Caribbean and Mediterranean during the late Oligocene and decline in importance in the Early Miocene (Perrin, 2002; Edinger and Risk, 1994; Budd, 2000; Pomar and Hallock, 2007). Reasons for this Early Miocene decline in the Caribbean and Mediterranean include closure of the Tethys seaway resulting in a reduced dispersal pool and increased upwelling, together with increased turbidity and cooling in the Caribbean (Edinger and Risk, 1994, Budd, 2000; Perrin, 2002). High temperatures and exposure to full sunlight may have also limited shallow reef growth in the Mediterranean (Pomar and Hallock, 2007).

4.5. Nutrification

Factors influencing the distribution of Neogene foraminifera-dominated carbonates are indicative that periods of siliciclastic runoff and/or elevated nutrients causing reduced water clarity associated with plankton blooms may also have strongly influenced Cenozoic
carbonate producers (Pomar et al., 2004; Wilson and Vecsei, 2005). SE Asian modern and Miocene perforate foraminifera biofacies are promoted in areas of terrestrial runoff or upwelling, with an indication that nutrients (high oligotrophy to mesotrophy rather than eutrophy) may be influencing Cenozoic development of this biofacies (Renema and Troelstra, 2001; Wilson and Vecsei, 2005). Corals, when associated with terrestrial runoff, may occur as mixed deposits, but are restricted to the shallower parts of the photic zone (Titlyanov and Latypov, 1991; Wilson and Lokier, 2002; Sanders and Baron-Szabo, 2005; Hallock, 2005; Wilson, 2005). Although larger benthic foraminifera and corals are associated with oligotrophic conditions, both can switch from dominantly photoautotrophy to increasing mixotrophic under increasing mesotrophy (Anthony and Fabricus, 2000; Mutti and Hallock, 2003). Among larger benthic foraminifera, nummulitids and alveolinids are increasing mixotrophic r-strategists (Scheibner et al., 2005), and both are common in SE Asia. Although excessive nutrients may hinder both corals and larger benthic foraminifera (Hallock, 2001), it is the reduced water clarity associated with plankton blooms during nutrient increases that may be influential in SE Asia (Wilson and Vecsei, 2005, cf. Mutti and Hallock, 2003, Hallock, 2005). Many hermatypic corals contain different photosynthetic symbionts from perforate larger benthic foraminifera that restrict them to shallower levels in the photic zone (Falkowski et al., 1990; Lee and Anderson, 1991). Larger benthic foraminifera may also have an advantage over corals under mesotrophy because they are shorter lived and can perhaps cope better with a seasonal lack of light than corals (anonymous reviewer, pers. comm., 2008). There is a strong global correlation between increased depth of abundant coral development with reduced nutrients and increased water clarity (Fig. 4). Coral growth in SE Asia is abundant to depths of 20 m, where nutrient levels are elevated due to high terrestrial runoff and oceanic upwelling. This compares with abundant coral growth to depths of 100 m in clearer, lower nutrient regions.

It is inferred that nutrient influx to the seas of SE Asia decreased in the early Miocene related to changes in terrestrial runoff and upwelling, and that this may have promoted reef development. Globally, the Early Miocene is thought to have been a relatively dry period with restricted polar glaciation related to reduced precipitation, perhaps linked to low greenhouse gas levels (Zachos et al., 2001) and oceanographic change (Dumai et al., 2005). Although early work suggested that many areas including SE Asia (Morley, 2000) and the Mediterranean (Alvarez Sierra et al., 1990; Cabrera et al., 2002) were drier during the Early Miocene, recent studies reveal a more complex picture (Morley et al., 2003; Hamer et al., 2007). Palynological data indicates that areas on the equator including Borneo remained everwet during the Cenozoic (Morley, 2000). However, adjacent regions such as Malaysia and Java had everwet climates in the Early Miocene, but seasonal climates prior to, and following this interval (Morley, 2000; Morley et al., 2003). In the warm tropics, although organic productivity is high under everwet conditions, runoff is more stable and cumulatively there is less siliciclastic and nutrient runoff than under seasonal conditions (Cecil and Dulong, 2003; Cecil et al., 2004).
Fig. 2. Carbonate biofacies, numbers of platforms/buildups in SE Asia plotted against regional and global events during the Cenozoic.
Paradoxically, a humid but stable climate during the Early Miocene compared with strongly seasonal ones may have resulted in less nutrient input, clearer waters and therefore promoted reef growth.

Today, SE Asia remains as the only equatorial gateway for major oceanic throughflow (from the Pacific to the Indian Ocean), with Quaternary changes in the Indonesian Throughflow shown to influence global climate (Gordon et al., 2003; Visser et al., 2003). The formation of bathymetric barriers in the Philippines around the Oligo-Miocene boundary due to the Australian Plate impacting on the Philippine Sea Plate restricted the deep to intermediate, nutrient-rich part of this major oceanic throughflow (Kuhnt et al., 2004). It is inferred that this change in trophic resources of decreased nutrients promoted increased coral development in the Early Miocene in SE Asia through expansion of the photic zone. A positive feedback mechanism linking changes to the regional oceanic currents and precipitation (both reducing nutrient influx) has been suggested (Morley et al., 2003; Morley, 2006). Restricting the deep throughflow reduced the input of cool deep waters (Kuhnt et al., 2004). The resultant increase in sea surface temperatures would promote evaporation and the development of humid, but stable conditions (Morley et al., 2003). Independent evidence for changes in nutrient partitioning in the oceans around the Oligo-Miocene boundary come from a positive δ13C excursion in the deep oceans (Fig. 2; Zachos et al., 2001), variations in the δ13C signature from the deep to intermediate waters of the Indian compared with the Pacific Oceans (Kuhnt et al., 2004), but a paucity of organic rich rocks of Early Miocene age in SE Asia (Howes, 1997). Corals continue to be important framework producers during the later Neogene in SE Asia with diversity perhaps influenced by increased habitat partitioning due to continued tectonic convergence. Overall however the areal importance of corals diminishes post Early Miocene likely due to increased uplift of land areas and increased

Fig. 3. Changes in morphology and accumulation rates of SE Asian carbonates during the Cenozoic. On the upper diagram Neogene buildups plot in the field shown, but to aid clarity not all are shown. Maximum values for carbonate accumulation rates for formations shown in the lower diagrams are from Wilson et al. (2000), Adams (1965), Cucci and Clark (1993), Saller et al. (1993), Dunn et al. (1996), Park et al. (1992) and Jones and Desrochers (1992).
These changes relate to low atmospheric CO2 levels, greater water clarity acidic, more mesotrophic, more turbid, and less aragonite saturated. Early Miocene in SE Asia where previously the waters had been more Oligocene. It is inferred that aragonitic reefs were promoted by the development compared with warm, more arid regions during the contribution to reduced aragonite saturation hindering reefal development. Multiple factors, including reduced salinities in equatorial waters, probably all considered major factors.

Regional oceanographic change, nutrient input due to development or intensification of the East Asian Monsoon (Jia et al., 2003). Nutrient upwelling due to global intensification of oceanic ventilation (Halfar and Mutti, 2005) combined with constriction of ocean currents due to continued closure of the Indo-Pacific ‘ocean gateway’ may have also contributed to post Early Miocene reduced extent of corals in SE Asia (Fulthorpe and Schlanger, 1989).

5. Summary

This study highlights that there are strong spatiotemporal differences in the development of shallow-water reefs and carbonates during the Cenozoic influenced by both global and regional factors. Although corals and larger benthic foraminifera are present in SE Asian carbonates throughout the Cenozoic coral-dominated facies are only apparent from the Late Oligocene, and their importance together with the areal extent of carbonates increases markedly around the Oligo-Miocene boundary. Corals would have enhanced the potential for buildup development through framework development and faster accumulation rates than larger benthic foraminifera. The Early Miocene acme of reefal carbonates in SE Asia lags a Late Oligocene peak in other regions such as the Caribbean and the Mediterranean. Although the areal extent of carbonates declines after the Early Miocene in SE Asia, coral-dominated facies continue to be important to the present day.

Major factors most likely to be linked to these changes are: 1) global CO2 levels, together with 2) regional oceanographic change, 3) nutrient influx and 4) precipitation. In SE Asia, as in many other regions, local tectonics provided the template allowing carbonate development. The inundation of a number of basins by marine waters around the Oligo-Miocene boundary likely contributed to Early Miocene expansion of carbonates. However, a marked increase in small-scale buildups and associated increase in areal extent of carbonates in the Early Miocene in SE Asia was only possible through promoted coral development. Tectonic, eustatic or temperature changes are not dominant controls influencing this biota change, instead global CO2 levels, together with regional oceanographic change, nutrient influx and precipitation are considered major factors.

Moderate, although falling levels of CO2, Ca2+ and Ca/Mg when combined with the reduced salinities in equatorial waters probably all contributed to reduced aragonite saturation hindering reefal development compared with warm, more arid regions during the Oligocene. It is inferred that aragonitic reefs were promoted by the Early Miocene in SE Asia where previously the waters had been more acidic, more mesotrophic, more turbid, and less aragonite saturated. These changes relate to low atmospheric CO2 levels, greater water clarity through reduced nutrient runoff (year-round everwet precipitation compared with more seasonal conditions) and reduced nutrient-rich upwelling (through tectonic truncation of deep oceanic currents).

With predicted anthropogenically-induced rising CO2 levels and continued high, deforestation-linked runoff in equatorial regions, what does the future hold for SE Asia’s reefs? If the Cenozoic record is a good analogue for the future, then this century’s postulated decimation of reefs due to reduced aragonite saturation (Kleypas et al., 1999) together with changes towards mesotrophication will likely hit the most globally diverse reefs of SE Asia earliest and hardest.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.palaeo.2008.05.012.

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