Environmental controls of coral growth: Data driven multi-scale analyses of rates and patterns of growth in massive Porites corals around the Thai-Malay Peninsula

Tanzil, J.T.I.

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CHAPTER

FIVE

Luminescent and Density Banding Patterns in Massive *Porites* Corals[4]

This study reports the characteristic annual luminescent and skeletal density banding patterns from massive *Porites* spp. corals from six geograhical locations around the east and west coasts of the Thai-Malay Peninsula in Southeaast Asia. Location-specific annual luminescent banding was found at all six study locations, while annual skeletal density banding was found for only 4 of the 6 study locations. Alizarin staining efforts and subsampling of corals conducted over a period of ~2 years validated that these banding patterns were annual in nature, or not grossly deviant from ~12 months worth of growth. Variations in luminescence intensity were observed to correlate most consistently with salinity and chlorophyll-a concentration, both of which were regarded as proxies of river runoff. Significant links between variations in skeletal density and squall index, used as proxy for sea surface runoff, was noted suggesting that water flow or some closely related parameter are involved. The present study provides some evidence that suggest strong involvement of environmental factors in the formation of luminescent and density banding patterns in massive *Porites* spp.

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5.1 Introduction

The discovery of banding patterns in massive coral skeletons has not only given valuable insight into skeletal growth processes and rates, but also provided a means to date past environmental conditions under which the growth took place (Knutson et al. 1972; Isdale 1984, Lough 2010). Banding is reflected as recurrent variations in density (shown using X-radiographs) and/or luminescence intensity (visible under long-wavelength ultraviolet (UV) light) which appear as alternating bands in slices/slabs of coral skeleton cut parallel to the colony growth axis (Buddemeier et al. 1974; Isdale 1984). In most cases, alternating bands occur in couplets (i.e. a pair of high/low density or bright/dull luminescent bands per year) that are annual in nature, and can therefore be used for sclerochronology and to identify areas from which to measure coral growth parameters (i.e. linear extension rate, skeletal density, calcification rate) (Buddemeier et al. 1974; Lough and Barnes 1990; Scoffin et al. 1992; Lough and Barnes 2000; Tanzil et al. 2009; Cooper et al. 2012).

Though not common, there are, however, less straightforward examples of multiple or indistinct bands that complicate the extraction of such information (e.g. Weber et al. 1975; Scoffin et al. 1989). It is also important to acknowledge that annual growth increments defined in this way rely on an assumption that the timing of band formation (e.g. the onset of deposition of bright/dull luminescent or high/low density bands) occurs around the same time of year for each of the years of interest, and, therefore, that 'years' so defined represent periods that do not deviate grossly from ~12 months of growth. As such, understanding the nature, and ultimately the causes of these banding patterns is crucial in ensuring accurate measurements of growth and sclerochronology.

The causes of both luminescent and density banding patterns in corals have been extensively debated (Highsmith 1979; Scoffin et al. 1989; Barnes and Taylor 2001, 2005; Grove et al. 2010). In the case of luminescent bands, the most robust relationship currently exists where corals are exposed to river runoff, with increased skeletal luminescence corresponding to high riverine discharges (Isdale 1984; Smith et al. 1989; Isdale et al. 1998; Lough et al. 2002; Barnes et al. 2003; Hendy et al. 2003; Lough 2007). The main proposed cause of the luminescence in this case is the incorporation in the coral skeleton of humic/fulvic acids leached from the terrestrial environment which then reaches the corals in river runoff (Boto and Isdale 1985; Susic et al. 1991; Zicheng et al. 2002; Grove et al. 2010; Grove et al. 2012; Llewellyn et al. 2012). However, annually recurring luminescent bands in offshore corals thought to be far removed from terrestrial influences have also been reported (Scoffin et al. 1989; Klein et al. 1990; Susic et al. 1991; Tudhope et al. 1996; Smithers and Woodroffe 2001), as well as anomalous luminescence peaks in the absence of any major river flow event (Jones et al. 2009). Such observations have led to the proposition that luminescent bands are instead related to and caused by variations in skeletal micro-architecture. Barnes and Taylor (2001, 2005) found regions of lower skeletal density in massive *Porites* corals from the Great Barrier Reef (GBR) which were inversely correlated to luminescence intensity, and concluded that most of the luminescence in luminescent bands and lines was associated with changed crystal size and packing. Ramseyer et al. (1997) also found a correlation between luminescence and the skeletal architecture of speleotherms, marine cements, and coral skeletons and subsequently proposed that luminescence was associated with higher porosity and lower calcium carbonate density due to higher amounts of organic fluorophores. However, other studies report a positive relationship between massive *Porites* skeletal density and luminescence (Scoffin et al. 1992; Carricart-Ganivet et al. 2007; Lough 2011). As a result the relationship between luminescent and density banding patterns remains highly tenuous.

Greater uncertainty exists when it comes to the exact cause/s of variations in skeletal density. The appearances of high-density (HD) and low-density (LD) bands visible in X-radiographs/computer tomography are the product of the thickening/thinning of skeletal elements – e.g. thecal walls in *Porites* spp. (Buddemeier and Kinzie 1975) and exothecal dissepiments and costae in *Monstastraea annularis* (Dodge et al. 1992). Factors previously correlated with density band formation include environmental variables such as sea temperature (e.g. Dodge and Thomson 1974; Weber et al. 1975; Buddemeier et al. 1974; Schneider and Smith 1982; Klein et al. 1993; Highsmith 1979; Lough and Barnes 1990, 1992), cloud cover/light level (Highsmith 1979), salinity/freshwater runoff (Scoffin et al. 1989; Barnes and Taylor 2001), rainfall (Buddemeier et al. 1974; Supriharyono 2004) and wave energy (Scoffin et al. 1992), as well as biological parameters/processes such as tissue thickness (Barnes and Lough 1993) and reproduction (Wellington and Glynn 1983; Mendes 2004). Although it is generally believed that LD bands are produced under optimum growth conditions and HD bands accrete during non-optimum conditions (Highsmith 1979; Scoffin et al. 1989), neither proximate nor ultimate causes for density banding patterns have been convincingly demonstrated. Even where a single environmental signal has been found to dominate, relationships can vary from location to location and even within a single location (see Highsmith 1979; Lough and Barnes 1990). For example, while formation of HD bands in massive *Porites* corals was associated with seasonal high sea surface temperatures (SSTs) on the GBR (Weber et al. 1975; Isdale 1983; Lough and Barnes 1990), the converse was observed on western Australian reefs (Schneider and Smith 1982), the Red Sea (Klein and Loya 1991) and even within the GBR (Lough and Barnes 1990), where HD bands formed during the cooler SST months. Perhaps surprisingly, marked density banding has also been found in massive corals from equatorial reefs where seasonal fluctuations in mean monthly SSTs occur within very restricted ranges (e.g. mean monthly SSTs ~27–30ºC) (Scoffin et al. 1989, 1992; Cahyarini 2008; Suharsono and Cahyarini 2012).

Part of the confusion regarding the nature and causes of luminescent and density banding may result from attempts to find a common environmental signal in corals from very different environments (see Weber 1975; Highsmith 1979). It could be that formation of banding patterns at different locations is driven by different factors dependent on the specific set/s of conditions to which the corals are acclimatised. Furthermore, description of banding patterns and association/s with broader spatial-scale environmental parameter/s are sometimes based on single specimens or very small sample sizes (e.g. Klein et al. 1993; Bessat and Buigues 2001; Sazzad et al. 2010). Consequently, this may produce variable interpretations either because of inherent inter-colony differences in banding patterns (e.g. Lough and Barnes 1990), or artefacts in the methods used for visualising the luminescence (Grove et al. 2010) and skeletal density (Le-Tissier et al. 1994).

Massive corals from the genus *Porites* are the most widely used corals for sclerochronological studies in the Indo-Pacific and their skeletons have been used to reconstruct growth parameters as well as to detect local and global marine environmental changes (e.g. Tudhope et al. 1996; Lough 2007; Cooper et al. 2012). The current study aimed to ascertain the nature of recurrent luminescent and density banding patterns in massive *Porites* corals from six geographical locations around the Thai-Malay Peninsula in Southeast Asia. It also tested for any relationship between banding patterns identified with several environmental variables with the aim of identifying potential cues or drivers of band formation in this region. The present study used information from large sample size (n=53), different sites in relatively similar environs (15 reefs, 6 locations), as well as multiple years (5yrs; Dec 2004–Nov 2009) to achieve these aims. By so doing it reduces the effects of individual variations and artefacts in methodology, and increases confidence level when attempting to identify common patterns in luminescence/density variations and their potential cues/drivers.

5.2 Methods

5.2.1 Study site

Fifteen reefs from six locations situated around the coast of the Thai-Malay Peninsula (1–8ºN, 98–105ºE), Southeast Asia (see Fig. 3.1 in Chapter 3, Table 5.1) were sampled. The reefs along the east coast of the Peninsula are based in the South China Sea (western Pacific Ocean), whereas reefs along the west coast are located in the Andaman Sea (northeastern Indian Ocean).

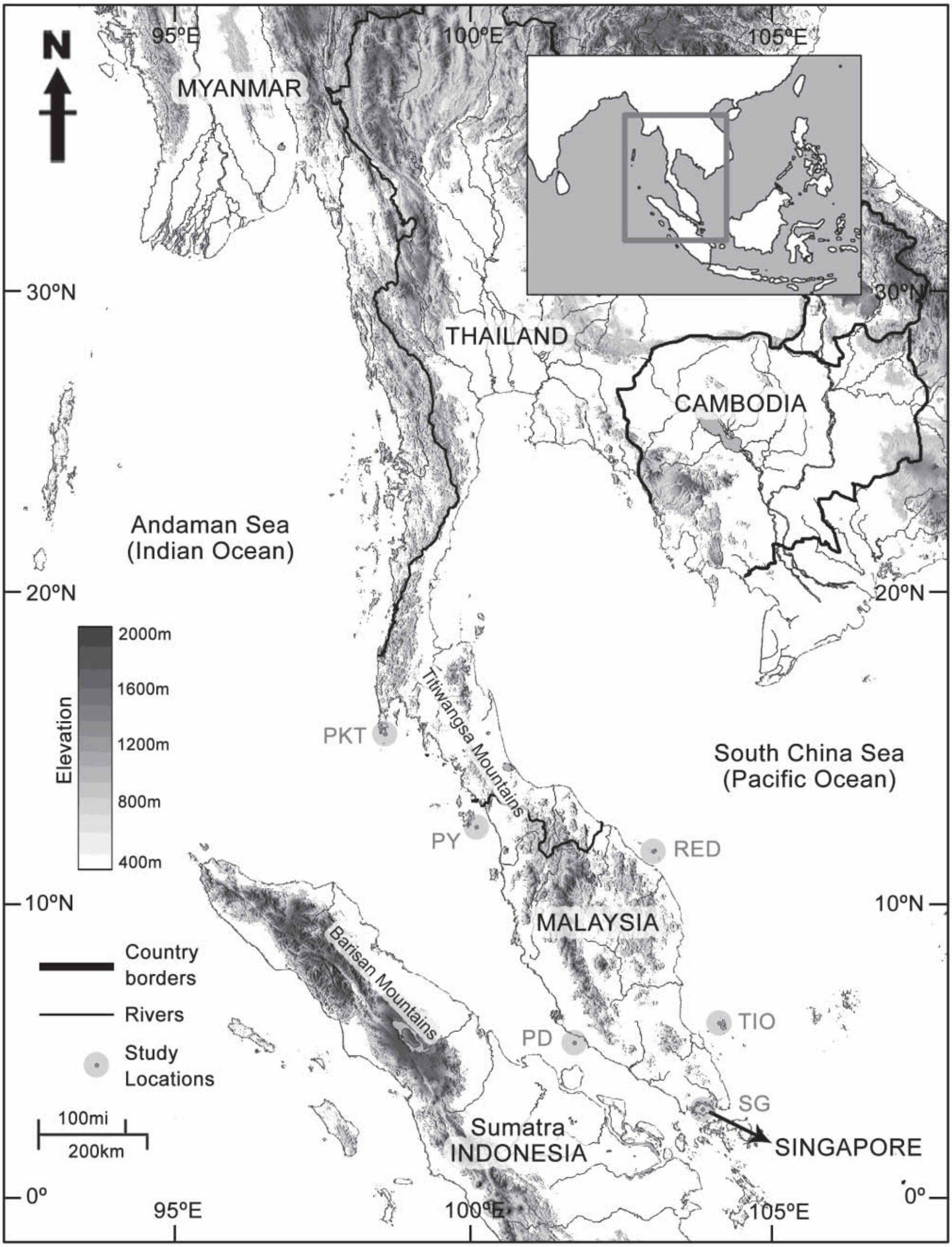

Fig. 5.1. Map showing the mountain ranges, major rivers and the six locations sampled around the Thai-Malay Peninsula, Southeast Asia. *PKT* Phuket; *PY* Pulau Payar; *PD* Port Dickson; *SG* Singapore; *TIO* Pulau Tioman; *RED* Pulau Redang

Table 5.1. Co-ordinates of study sites, and the dates and number of colonies stained with alizarin red-S.

Peninsular coast	Location	Reef	Latitude (°N)	Longitude (°E)	Colonies stained	Staining dates (dd/mm/yyyy)
West	Phuket (PKT)	Yam Yen (YY)	7.808670	98.399842	7	25/01/2010, 06/10/2011
West		Porites Bay (PB)	7.808795	98.410323	–	–
West		Koh Hae (KH)	7.745087	98.383352	–	–
West		Koh Racha Yai (KR)	7.613105	98.372862	10	25/01/2010, 04/10/2011
West	P. Payar (PY)	P. Payar house reef	6.063197	100.042028	8	27/03/2010, 21/06/2011
West	Port Dickson (PD)	Monkey Bay	2.416383	101.852589	–	–
East	Singapore (SG)	P. Hantu (HT)	1.227286	103.746635	10	02/07/2009, 09/11/2009, 15/11/2010, 14/06/2011
East		P. Semakau (SEM)	1.199958	103.756690	–	–
East		P. Jong (JO)	1.214349	103.786874	–	–
East		P. Kusu (KU)	1.225487	103.860138	–	–
East		Raffles Lighthouse (RL)	1.160624	103.740536	10	02/07/2009, 09/11/2009, 15/11/2010
East	P. Tioman (TIO)	Tekek (EDT)	2.817688	104.153781	10	29/10/2009, 25/05/2010, 12/04/2011
East		P. Tulai (PTU)	2.911470	104.097816	10	28/10/2009, 26/05/2010, 14/04/2011
East	P. Redang (RED)	Redangkalong (RDHR)	5.762533	103.028732	10	10/03/2010, 05/07/2011
East		P. Kerengga Besar (RDKR)	5.754261	103.029364	10	10/03/2010, 04/07/2011

Sites around the Thai-Malay Peninsula all experience year-round high mean monthly SSTs of >27–30ºC (Tanzil et al. 2009), which peak during the boreal summer (~June). The region has a monsoonal climate, although the wet season occurs at different times of the year on the east and west coasts. The east coast typically experiences higher rainfall and rougher seas during the northeast (NE) monsoon period whilst similar are found on the west coast during the southwest (SW) monsoon (Lau and Yang 1997; Wong et al. 2009).

The main reason for these effects is the Titiwangsa mountain range which runs through the middle of the Peninsula rising to ~2100m, and effectively shielding the east/west coasts from the brunt of either SW or NE monsoons (Camerlengo and Demmler 1997; Suhaila et al. 2010; Tanggang et al. 2011). Flanking the Thai-Malay Peninsula to the west, the mountain ranges along Sumatra Island, Indonesia also provide additional rain- and wind-sheltering effects for the west coast, in particular for the southwestern coast during the SW monsoon (Fig. 1) (Nieuwolt 1968; Wong et al. 2009). High rainfall on the Peninsula (average ~300mm month^{-1} in the wet season) and numerous short, swift-flowing rivers east and west of the Titiwangsa mountain range result in considerable runoff and substantial loads of river-transported material which are then discharged into coastal waters. The reefs along the west coast of the Peninsula within the Malacca Straits (e.g. P. Payar and Port Dickson) also receive additional input from rivers along the east coast of Sumatra Island, Indonesia (Fig. 3.1). As a result, these reefs are subject to low salinities and high nutrient concentrations as well as high turbidity with sedimentation rates reaching as high as ~50–100mg cm^{-2} day^{-1}, (Chua et al. 1998; BOBLME 2011; Lee and Mohamed 2011). By contrast, offshore island reefs on the eastern and northwestern coasts are significantly less turbid, with sedimentation rates averaging ~0.3 mg cm^{-2} day^{-1} (Lee and Mohamed 2011). The fact that sites along the east and west coasts of the Thai-Malay Peninsula are in a relatively narrow geographical range, and share similarities in certain environmental conditions (e.g. SST) while others are specific to location (e.g. rainfall, wind) presents a unique opportunity for a natural experiment to examine variations in banding patterns and their relationship/s with selected environmental parameters.

5.2.2 Environmental parameters

Several data sets of monthly-averaged environmental variables over the period of Dec 2004–Nov 2009 were examined. Monthly SST (°C) for the 1° area grid encompassing each study location was obtained from the HadISST data set (HadISST, Version 1.1, Hadley Centre for Climate Change, UK Meteorological Office) (Rayner et al. 2003). Estimates of chlorophyll-a (Chl-a) concentration (mg m^{-3}) and surface photosynthetically active radiation (PAR) (µmol m^{-2} day^{-1}) were obtained from Sea-Viewing Wide Field-of-view (SeaWiFs) monthly level 3 Ocean

Color products. Monthly averaged analyses of the aforementioned products for a 0.5º area grid for each study location were produced with the Giovanni online data system, developed and maintained by the NASA GES DISC (Acker and Leptoukh 2007). Monthly salinity (ppt) for 0.5º area grids were obtained from Carton-Giese UMD Simple Ocean Data Assimilation (SODA) v2.1.6 (Carton and Giese 2008). Monthly averaged rainfall (mm month-1) and wind speed (m s^{-1}) were retrieved from the nearest available weather stations to study locations i.e. Phuket – Phuket Airport (8.108ºN, 98.517°E), P. Payar – Langkawi Airport (6.333ºN, 99.733ºE), Port Dickson – Malacca town (2.266ºN, 102.250ºE), Singapore – Changi Airport, P. Tioman – Mersing (2.450ºN, 103.833ºE), and P. Redang – Kuala Trengganu Airport (5.050ºN, 103.100ºE).

These environmental variables were chosen because they represent parameters that might affect coral skeletal luminescence and density banding formation. Salinity was used as proxy for the amount of freshwater/river input reaching the reefs since increased riverine humic/fulvic acids and dissolved organic material from terrestrial sources are strongly correlated to coral luminescence (Isdale 1984; Susic et al. 1991; Isdale et al. 1998). Chl-a is a major pigment involved in phytoplankton photosynthesis and its concentration is widely used as a surrogate of phytoplankton biomass and photosynthetic potential. Blooms of phytoplankton around the coasts of the Thai-Malay Peninsula generally relate to increased nutrients from riverine inputs (Boonyapiwat 1997; BOBLME 2011) and to seasonal monsoon-induced upwelling for certain areas located near deep coastal shelves (e.g. northern Malacca Straits) (Tan et al. 2006). Humic acids created by breakdown of marine phytoplankton are thought to contribute to increased skeletal luminescence (Tudhope et al. 1996; Smithers and Woodroffe 2001). As such, Chl-a was used as proxy of both riverine input and marine sources of humic substances. Rainfall was used as an indicator of the amount of terrestrial/freshwater run-off reaching reefs, which could affect water turbidity (i.e. light availability), salinity, nutrients and concentration of humic/fulvic substances. Wind speed affects generation of surface waves, and was used to estimate sea surface roughness (SSR). SSR was also parameterised by using a simple squall index created from the sum of standardised rainfall and wind scores to account for contribution of both wind-induced surface waves and rain-induced stress on the sea surface. Along with wind speed, precipitating rain (intensity, drop size and duration) is known to be an important parameter modifying SSR (Kumar et al. 2009). Raindrops striking the sea-surface generate ring waves, enhancing SSR and resulting in turbulence in the upper water column (Nystuen 1990; Craeye et al. 1997). Both wind speed and squall index were used as proxies of the amount of hydraulic energy/water movement reefs might receive, which has previously been related to skeletal density variations (Scoffin et al. 1992).

5.2.3 Skeletal luminescence and banding

Cores sampled from 53 individual massive *Porites* colonies from 15 study reefs between Oct 2010 and Jan 2012 were analysed for skeletal luminescence and density banding. All samples were taken from the main growth axis of the coral using a pneumatic drill fitted with a 5cm diameter, 50cm long diamond bit core barrel at depths ~2-3m below mid-tide height from colonies ~1–4m in diameter. Although it was not possible to conclusively identify all samples to species level, the majority (~76%) of colonies were positively identified as *Porites lutea*.

In order to ascertain the nature and timing of luminescent and density banding patterns, repeated alizarin staining of ~85 tagged colonies at 5 of the 6 study locations (with the exception of Port Dickson) was carried out over a ~2-year period (Table 1). This calcium dye is a method to stain the coral skeleton without severely affecting its growth characteristics or mortality rate (Dodge et al. 1994). The coral can then be left to grow and can be stained repeatedly until the point of sampling, with resulting pink lines indicating specific staining periods in the skeleton. At Port Dickson, where alizarin staining was not successfully carried out, previous work and past samples collected by Lee (unpubl.) were used to ascertain the timing of the bands. Sub-sampling of colonies at different times of the year at all study locations was also conducted in order to further validate the timing of luminescent banding patterns.

Slices (~0.7cm thick) were cut from coral cores and examined for annual linear extension (cm year-1) along the main growth axis which was deduced from the annual luminescent banding patterns as visualised from photographs taken under long wavelength (365nm) ultraviolet (UV) light (Fig. 5.2). Skeletal density and luminescence intensity measurements for the period Dec 2004–Nov 2009 were then obtained along overlapping tracks ~0.2cm wide and at a resolution of 72 pixels cm-1 (i.e. at every ~0.014cm). Skeletal densities were analysed using digitised X-ray images (Carricart-Ganivet and Barnes 2007) and verified against gamma densitometry at the Australian Institute of Marine Science (Chalker and Barnes 1990) (Fig. A5.1b and A5.2b in Appendix 5.5). Luminescence intensities were measured from digital images (Canon G10 digital camera) of core slices taken under long-wavelength (365nm) ultraviolet (UV) light source in a customised photography black box. These images were then split into their red, green and blue (RGB) spectral components and the green/blue (G/B) spectral ratio was then used as a measure of luminescence intensity. Luminescence intensity measurements made in this way were validated against luminometry at the Australian Institute of Marines Science (Barnes et al. 2003) (Fig. A5.1a and S5.2a). All image analyses for skeletal density and luminescence intensity extractions were performed using NIH ImageJ (v1.46r) (Schneider et al. 2012).

For every core, luminescence intensity and skeletal bulk density measurements for each of the five annual cycles between Dec 2004 and Nov 2009 were partitioned into 12 categories (i.e. monthly bins; total 60 months for each core) (Fig. A5.3). The monthly-binned luminescence and density data were then converted to monthly anomalies calculated as the difference between the monthly-binned data and the average luminescence/density for the period Dec 2004–Dec 2009 for each core. These were then used to test for any relationship with monthly anomalies in environmental parameters, calculated as the difference between mean monthly values and the average for each of the six study locations. The study period, Dec 2004–Nov 2009, was used as it provided the best growth axes where luminescence and skeletal density were least likely to be misaligned due to skewed growth, or as an artefact of the sampling (i.e. coring or slabbing/slicing) process. No severe anomalous events (e.g. coral bleaching) were recorded during these 5 years, and thus growth and banding patterns were considered representative of 'normal' growth years over this time.

5.2.4 Statistical analyses

Relationships between anomalies in monthly-binned luminescence/skeletal density data and the monthly anomalies in the seven environmental parameters examined (i.e. SST, PAR, rainfall amount, wind speed, squall index, salinity and Chl-a concentration) were performed at both the "region" (i.e. taking data from all 53 cores and all six study locations) and at the individual "location" level (i.e. separate analyses for the each of the six locations sampled) were investigated using Pearson's product-moment correlation tests after checking for normality in the datasets. Any relationships between luminescence and skeletal density anomalies were also tested in the same manner. All analyses were performed using the statistical program R (version 2.15.1) (R Core Team 2012).

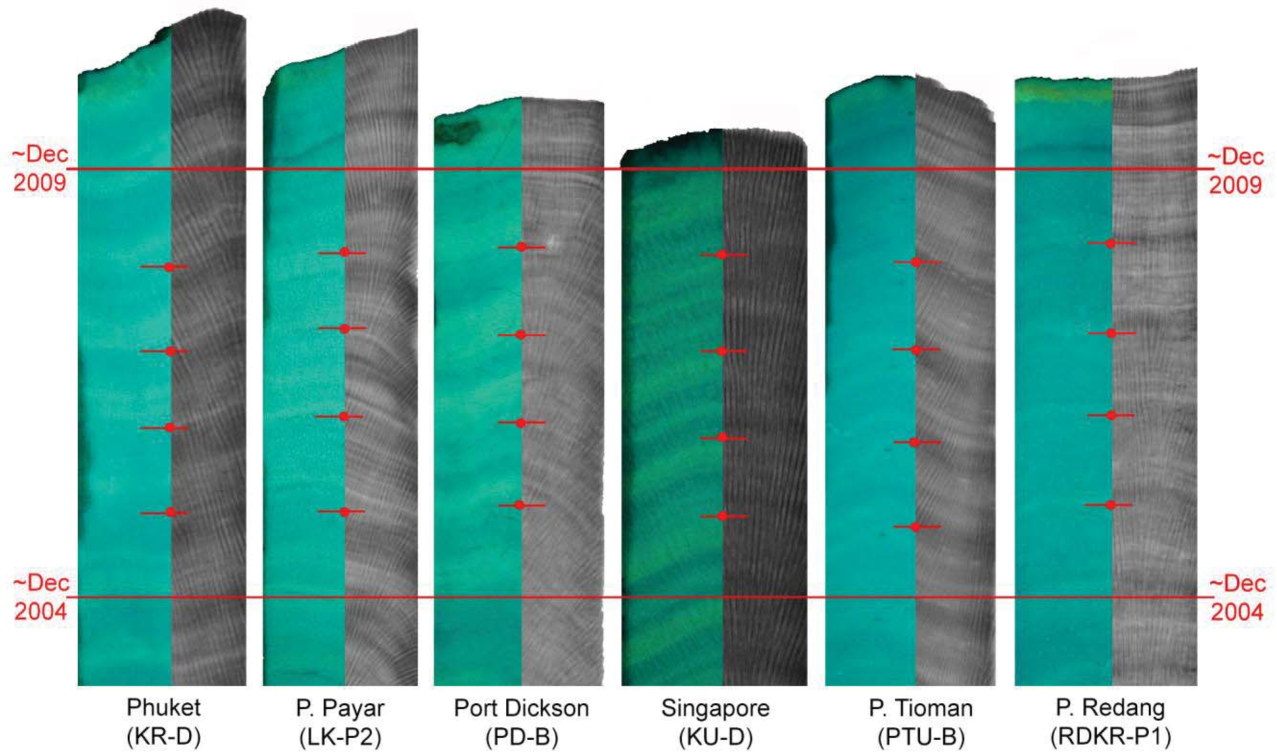

Fig. 5.2. Images of representative coral slices showing annual variation in luminescence intensity (taken under ultraviolet light (365nm) – left side of image) and density (X-ray – right side) for each study location over period ~Dec 2004 to ~Dec 2009.

5.3 Results

5.3.1 Intra-annual variation in environmental parameters

SSTs at all the study locations average ~29ºC (Table 5.2) and are characterised by an annual cycle with a peak in April/May and a minimum in January (Fig. 5.3a), together with a smaller peak in October/November. The annual range of mean monthly SST is, however, relatively small at ~3ºC (i.e. ~27–30ºC) for locations along the eastern coast of the Thai-Malay Peninsula and ~2ºC (i.e. ~28–30ºC) for the western coast. SSTs lag solar radiation patterns (Fig. 5.3b) which exhibit the characteristic bi-modal peaks as the sun passes overhead in its oscillation between the two Tropics (Osborne 2000). The first SST peak (April/May) marks the warmest period for the region with sea temperatures often reaching >30ºC (Lau & Yang 1997; Brown 2007). The second peak is considerably smaller as a result of monsoonal cloud cover reducing the surface solar radiation and hence the resultant sea-warming. At Phuket and P. Payar the cloud cover in the latter half of the year is such that the peak in solar radiation (Fig. 5.3b) and subsequently in SST (Fig. 5.3a) is largely absent.

Average rainfall for study locations varies between ~170 and ~235 mm month-1 (Table 5.2), with maximum rainfall observed ~Jul–Oct for locations along the west coast (i.e. Phuket, P. Payar, Port Dickson) and ~Nov–Jan for locations along the east coast (i.e. P. Redang, P. Tioman, Singapore) (Fig. 5.3c). The split in peak rainfall periods seen at these east/west locations overlap with the NE/SW monsoons respectively and are as described in the study area description earlier. Intra-annual variations in salinity seemed congruent with rainfall patterns only at P. Redang and P. Tioman, where lowest salinities coincided with periods of highest rainfall and vice versa (Fig. 5.3c/d). At Phuket, P. Payar and Port Dickson, salinity minima occurred in ~Nov/Dec, while at Singapore lowest values were observed in ~Aug/Sep (Fig. 5.3d).

Greatest variation and highest estimates of Chl-a concentrations (henceforth [Chl-a]) were observed at Port Dickson, Singapore and P. Payar (locations within and in the vicinity of the Malacca Straits) where [Chl-a] average between ~2 and 3.5 mg m^{-3} (Figs. 5.1 and 5.3e, Table 5.2). At Port Dickson and Singapore (located within/near the southern Malacca Straits), positive anomalies in [Chl-a] mainly overlap ~May/June–October period, while at P. Payar (within northern Malacca Straits) highest concentrations occurred ~Nov–Mar (Fig. 5.3c). At. Phuket, P. Tioman and P. Redang, [Chl-a] were much lower and average <0.5 mg m^{-3} (Table 5.2). Though intra-annual variations remain very modest at these latter locations, positive anomalies in [Chl-a] can be seen to occur mainly towards the end and/or start of the year (Fig. 5.3e).

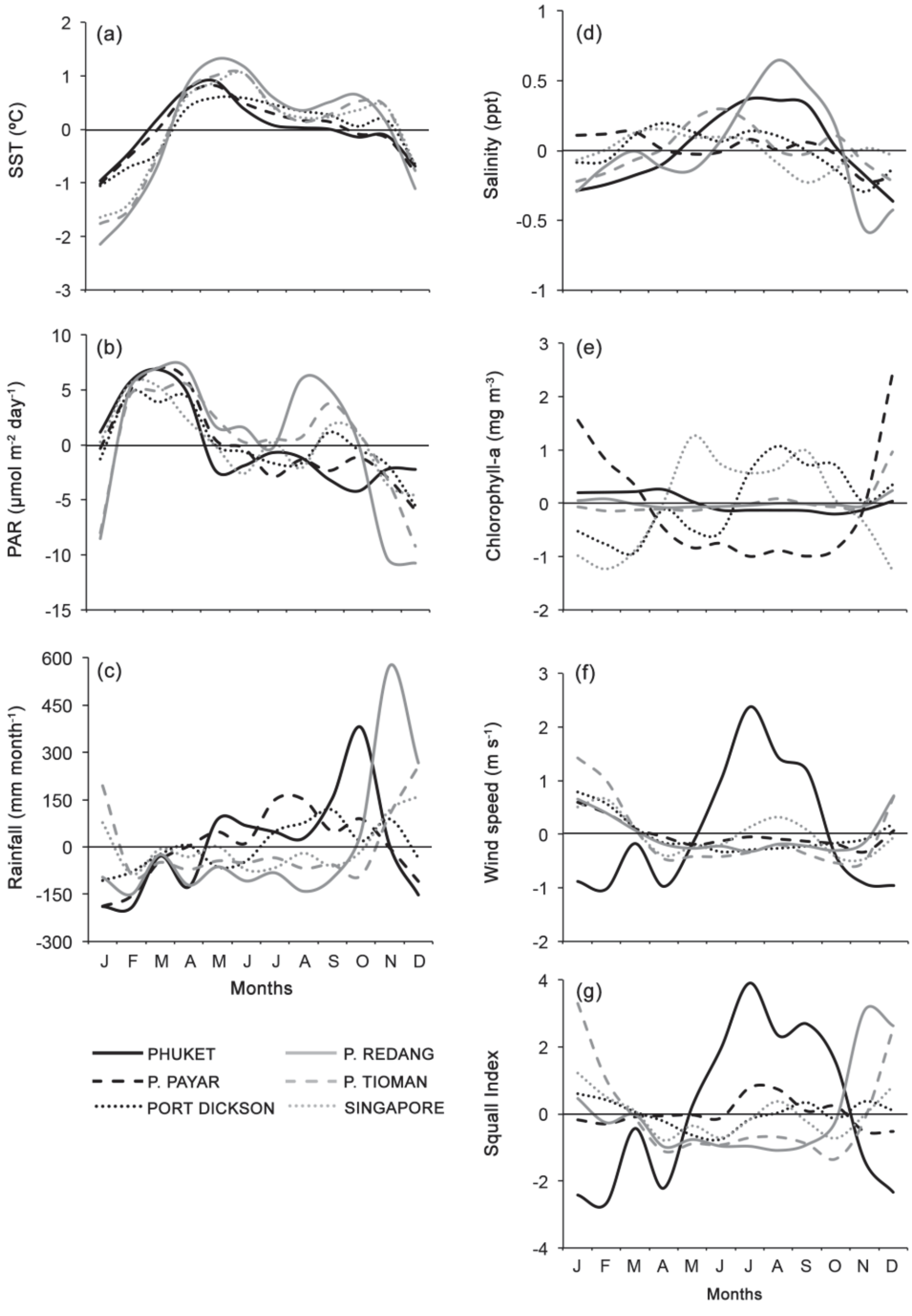

Fig. 5.3. Monthly averaged anomalies for a) SST (ºC), b) photosynthetically active radiation (PAR), c) chlorophyll-a, d) rainfall, e) salinity, f) wind speed and g) standardised rainfall and wind index (proxy for shallow water sea roughness) over the period Dec 2004–Nov 2009 for the six study locations. Confidence intervals omitted for clarity.

Maximum mean monthly wind speeds occurred between Nov–Mar, corresponding with the NE monsoon period, at all study locations except Phuket (Fig. 5.3f). At Phuket, mean wind speeds peak ~July with positive anomalies generally overlapping the SW monsoon period (May–Oct). Taking rain and wind parameters into account, the calculated squall index was highest during the NE monsoon at P. Redang and P. Tioman (east coast locations), and during the SW monsoon at Phuket and P. Payar (west coast locations) (Fig. 5.3g). The annual range for this index was considerably smaller at Singapore and Port Dickson with two maxima and two minima, coinciding with the respective monsoon and inter-monsoon periods (Fig. 5.3g).

5.3.2 Annual banding patterns

From the position of alizarin stain lines (at all locations except Port Dickson), sub-sampling of corals and comparison with material from past sampling efforts (for all locations), the current study found location-specific repeating luminescent banding at all 6 study locations and density banding patterns at 4 locations (Figs. 5.2 and 5.4).

Luminescent bands

For Phuket corals, the annual repeating pattern consisted of one broad bright and one broad dull luminescent band of approximately equal thickness, with bright-band accretion commencing in ~Nov/Dec. A similar pattern and timing of band formation to Phuket was seen for corals sampled at P. Payar (~250km south of Phuket) with the exception of a narrow, fainter secondary luminescent line visible within the broad dull luminescent band (Fig. 5.4b) estimated to form some time in ~Jul/Aug. At Port Dickson, the annual repeating pattern also consisted of a broad bright (with onset also ~Nov/Dec) and dull luminescent band couplet. However, the thicknesses of these bands were less consistent, and more variable from year to year as can be seen from the wide standard error for the first half of the year (Fig 5.4c).

At P. Redang, each year consists of one bright, narrow luminescent band and a much broader duller band (Figs. 5.2 and 5.4d). For Singapore, the annual pattern consisted of a distinct bright band formed in ~Jun–Nov followed by a distinct dull band formed in ~Dec–May (Fig 5.4f). However, a bright luminescent line which varied greatly in relative intensity and thickness between years was also visible within the broad dull band. The annual pattern at P. Tioman was much less distinct, but generally consisted of two bright and two dull luminescent band couplets of similar intensities – the "first" of which is formed ~Nov–Feb and a "second" estimated ~Jul–Sep (Fig 5.4e).

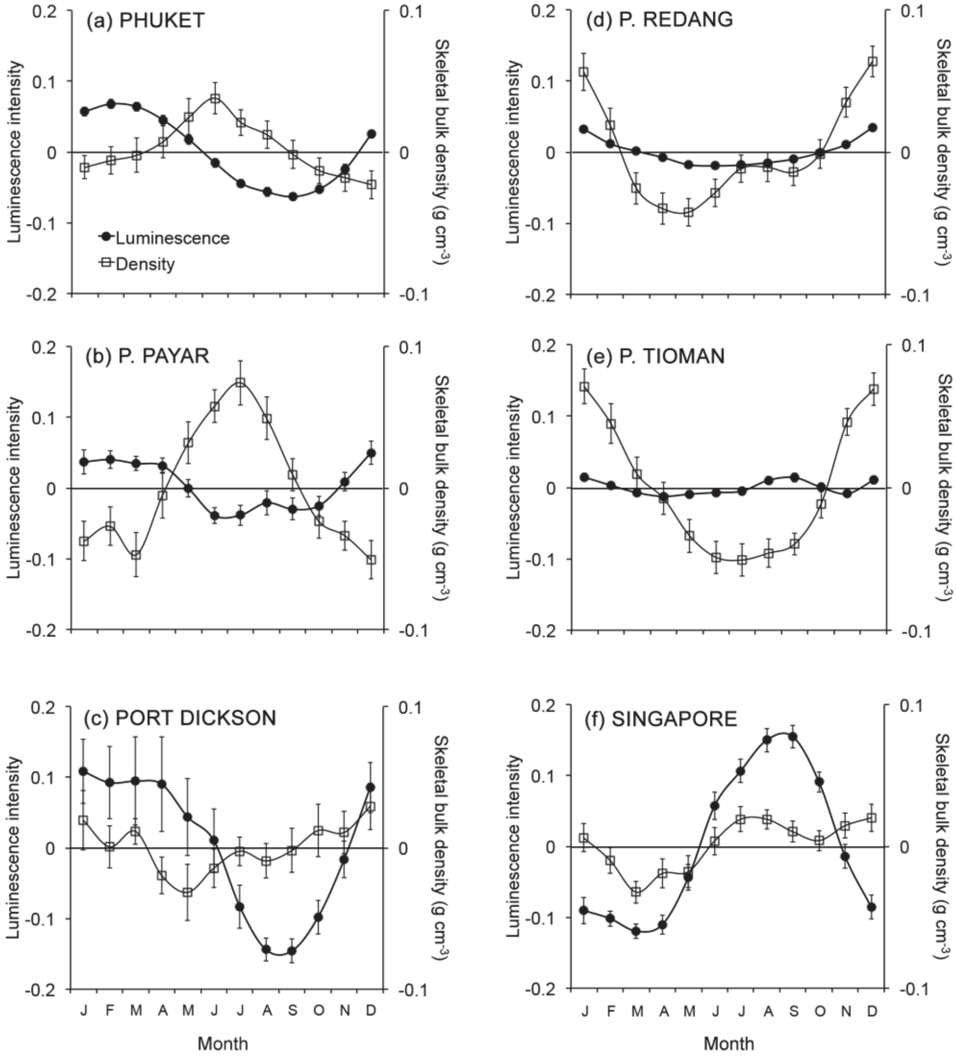

Fig. 5.4 Monthly averaged luminescence intensity and skeletal density anomalies over the period Dec 2004–Nov 2009 for locations along the western (a-c) and eastern (d-f) coasts of the Thai-Malay Peninsula. Error bars are ± SE. See Table 5.2 for absolute values of luminescence and density at each location.

Table 5.2. Average values (± 1 SE) for linear extension rates, skeletal density, luminescence intensity and various environmental parameters for the period Dec 2004–Nov 2009.

Location	Linear extension rates (cm $year^{-1}$)	Skeletal density (g cm^{-3})	Lumin. Intensity	SST (ºC)	PAR (µmol m^{-2} day^{-1})	Rainfall (mm $month^{-1}$)	Wind speed (m s^{-1})	Salinity (ppt)	Chl-a (mg m^{-3})
Phuket	1.998 ± 0.136	1.111 ± 0.021	0.553 ± 0.013	29.121 ± 0.070	45.135 ± 0.595	198.388 ± 36.235	4.224 ± 0.268	31.93 ± 0.057	0.417 ± 0.030
P. Payar	1.939 ± 0.163	1.101 ± 0.012	0.714 ± 0.017	29.241 ± 0.065	45.015 ± 0.599	200.128 ± 17.795	1.658 ± 0.054	31.578 ± 0.048	2.278 ± 0.187
Port Dickson	2.160 ± 0.142	0.923 ± 0.027	0.925 ± 0.048	29.368 ± 0.071	44.954 ± 0.476	169.95 ± 12.996	1.676 ± 0.051	31.871 ± 0.047	3.453 ± 0.211
Singapore	1.855 ± 0.137	0.967 ± 0.017	0.745 ± 0.021	28.010 ± 0.102	38.778 ± 0.580	196.133 ± 16.748	1.758 ± 0.065	31.989 ± 0.045	3.543 ± 0.170
P. Tioman	1.892 ± 0.098	1.227 ± 0.020	0.490 ± 0.007	28.843 ± 0.110	43.540 ± 0.815	209.833 ± 20.250	2.817 ± 0.091	32.210 ± 0.046	0.466 ± 0.044
P. Redang	1.983 ± 0.099	1.146 ± 0.013	0.446 ± 0.006	28.694 ± 0.130	43.835 ± 1.005	235.317 ± 34.791	1.903 ± 0.055	32.408 ± 0.064	0.333 ± 0.023

Skeletal density bands
Annual repeating density banding patterns were observed at Phuket, P. Payar, P. Tioman and P. Redang, and no distinct annual density banding could be discerned from corals sampled at Singapore and Port Dickson (Figs. 5.2 and 5.4). Based on the position of alizarin stain/subsampling and alignment with luminescent bands, high-density (HD) bands in corals sampled from Phuket and P. Payar (west coast locations) were estimated to form between May and Sep with maximum densities ~Jun/Jul (Fig. 5.4a/ b). However, despite this general pattern, complicated narrower multiple dense/less dense lines were also observed within the broad density bands in several specimens sampled from these west coast locations. At P. Redang and P. Tioman (east coast locations), density banding was clear and consistent (Figs. 5.2 and 5.4d/e), and the annual repeating pattern at both locations consisted of a distinct narrower HD band (formed towards the end/start of the year ~Nov–Feb) and a much broader less dense band.

5.3.3 Relationship between skeletal luminescence and density

Taking data from all 53 cores from all six study locations, there was a significant positive relationship between luminescence intensity and density anomalies ($P<0.0001$, $R=0.08$) (Table 3). Separate analyses performed for each of the six locations, however, showed that correlations were variable and there was no significant relationship at Phuket ($P=0.479$) and Port Dickson ($P=0.063$); a significant negative relationship at P. Payar ($P<0.01$, $R=-0.216$); and significant positive relationships at Singapore ($P<0.001$, $R=0.128$), Tioman ($P<0.001$, $R=0.197$) and P. Redang ($P<0.001$, $R=0.303$).

Table 5.3. Result of Pearson's correlation tests between anomalies in skeletal luminescence intensity and density.

	Lumin vs. Density		
Location	P	R	n
REGIONAL	<0.001	0.081	2946
Phuket	0.479	0.028	646
P. Payar	<0.001	-0.216	287
Port Dickson	0.063	0.140	177
Singapore	<0.001	0.128	814
P. Tioman	<0.001	0.197	539
P. Redang	<0.002	0.303	479

5.3.4 Linkages with environmental parameters

Luminescence intensity

Analyses of anomalies in monthly-binned luminescence intensity from all 53 cores and six locations ("region" level analyses) related significantly to monthly anomalies of 4 of the 7 environmental parameters analysed i.e. rainfall (R=-0.119), squall index (R=-0.091), salinity (R=-0.244) and Chl-a concentrations (R=0.287) (Table 5.4).

At the individual "location" level, rainfall was significantly correlated at 4 of the 6 study locations (Table 5.4), with negative correlations at Phuket (R=-0.476), P. Payar (R=-0.330), and Singapore (R=-0.218), but a positive relationship at P. Redang (R=0.188). The results for squall index at the location level were similarly variable, with inverse correlations at three locations (Phuket, R=-0.553; P. Payar, R=-0.197; Singapore, R=-0.194) and positive relationships at the remaining three (Port Dickson, R=0.153; P. Tioman, R=0.086; P. Redang, R=0.342). Salinity at all locations was significantly inversely correlated, with R-values ranging from -0.110 (P. Tioman) to -0.504 (Phuket) (Table 5.4). Chl-a concentrations were significantly correlated at 5 of the 6 study locations (not Port Dickson) with R-values between 0.208 (P. Tioman) and 0.639 (Phuket). Although not significant at the "region" level analyses, significant relationships between SST, PAR and wind speed with luminescence intensity were detected at the individual "location" level (Table 5.4). Luminescence and SST were significantly positively correlated at Singapore (R=0.250), but showed negative relationship at the remaining 5 study locations; Phuket (R=-0.097), P. Payar (R=-0.265), Port Dickson (R=-0.374), P. Tioman (R=-0.156) and P. Redang (R=-0.508). PAR was correlated with luminescence at only two study locations i.e. Phuket (R=0.459) and P. Redang (R=-0.405). Mean wind speeds were correlated at 5 locations (not Singapore) with positive correlations at P. Payar (R=0.156), Port Dickson (R=0.296), P. Tioman (R=0.094) and P. Redang (R=0.462), and inversely related at Phuket (R=-0.479).

Skeletal density

There were significant relationships at the "region" level between anomalies in monthly-binned skeletal density and the monthly anomalies of all seven environmental parameters examined i.e. SST (R=-0.106), PAR (R=-0.170), rainfall (R=0.140), wind speed (R=0.152), squall index (R=0.196), salinity (R=-0.086), and Chl-a (R=-0.071) concentrations (Table 5.4). Density and SST were significantly correlated at all locations except Singapore, with positive relationships at Phuket (R=0.145) and P. Payar (R=0.346), and negative ones at Port Dickson (R=-0.188), P. Tioman (R=-0.355) and P. Redang (R=-0.325). Density and PAR were significantly inversely related at only the three east coast locations (i.e. Singapore, R=-0.120; P. Tioman, R=-0.229; P. Redang, R=-0.336). Rainfall was correlated at 4 of the 6 study locations; P. Payar (R=0.299), Singapore (R=0.071), P. Tioman (R=0.283) and P. Redang (R=0.121). Mean wind

Table 5.4. Results of Pearson's correlation tests between monthly averaged luminescence intensity (LUMIN) and skeletal density (DENSITY) anomalies with various environmental parameters over the period Dec 2004–Nov 2009. * $P<0.05$, ** $P<0.01$, *** $P<0.001$, n.s. = not significant

			Environmental parameter											
			SST			PAR			Rainfall			Wind speed		
Banding	Coast	Location	P	n	R	P	n	R	P	n	R	P	n	R
LUMIN	ALL	ALL	n.s.	3003	–	n.s.	2657	–	***	2617	-0.119	n.s.	2617	–
	West	Phuket	**	707	-0.097	***	623	0.459	***	261	-0.476	***	261	-0.479
	West	P. Payar	***	287	-0.265	n.s.	252	–	***	287	-0.330	**	287	0.156
	West	Port Dickson	***	177	-0.374	n.s.	157	–	n.s.	177	–	***	177	0.296
	East	Singapore	***	814	0.250	n.s.	718	–	***	814	-0.218	n.s.	814	–
	East	P. Tioman	***	539	-0.156	n.s.	476	–	n.s.	539	–	*	539	0.094
	East	P. Redang	***	479	-0.508	***	431	-0.405	***	539	0.188	***	539	0.462
DENSITY	ALL	ALL	***	3003	-0.106	***	2657	-0.170	***	2617	0.140	***	2617	0.152
	West	Phuket	***	707	0.145	n.s.	623	–	n.s.	261	–	*	261	0.154
	West	P. Payar	***	287	0.346	n.s.	252	–	***	287	0.299	*	287	-0.125
	West	Port Dickson	*	177	-0.188	n.s.	157	–	n.s.	177	–	**	177	0.208
	East	Singapore	n.s.	814	–	**	718	-0.120	*	814	0.071	n.s.	814	–
	East	P. Tioman	***	539	-0.355	***	476	-0.229	***	539	0.283	***	539	0.324
	East	P. Redang	***	479	-0.325	***	431	-0.336	**	539	0.121	***	539	0.282

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			Environmental parameter								
			Squall Index			Salinity			Chlorophyll-a		
Banding	Coast	Location	P	n	R	P	n	R	P	n	R
LUMIN	ALL	ALL	***	2617	-0.091	***	2505	-0.244	***	2468	0.287
	West	Phuket	***	261	-0.553	***	575	-0.504	***	611	0.639
	West	P. Payar	***	287	-0.197	***	232	-0.342	***	237	0.331
	West	Port Dickson	*	177	0.153	***	146	-0.351	n.s.	154	–
	East	Singapore	***	814	-0.194	***	672	-0.243	***	559	0.410
	East	P. Tioman	*	539	0.086	*	440	-0.110	***	449	0.208
	East	P. Redang	***	539	0.342	***	440	-0.296	***	458	0.315
DENSITY	ALL	ALL	***	2617	0.196	***	2505	-0.086	***	2468	-0.071
	West	Phuket	*	261	0.141	n.s.	575	–	n.s.	611	–
	West	P. Payar	*	287	0.185	n.s.	232	–	***	237	-0.333
	West	Port Dickson	**	177	0.191	n.s.	146	–	n.s.	154	–
	East	Singapore	*	814	0.083	n.s.	672	–	*	559	-0.083
	East	P. Tioman	***	539	0.366	***	440	-0.256	*	449	0.102
	East	P. Redang	***	539	0.214	***	440	-0.241	**	458	0.153

speeds were correlated at 5 locations (not Singapore) with positive correlations at Phuket (R=0.154), Port Dickson (R=0.208), P. Tioman (R=0.324) and P. Redang (R=0.282) and an inverse relationship at P. Payar (R=-0.125). Squall index was positive correlated at all locations with R-values ranging from 0.141 (P. Payar) to 0.366 (P. Tioman). Salinity was only correlated at two locations (P. Tioman and P. Redang) and Chl-a at four, with positive correlations at P. Tioman and P. Redang and inverse correlations at P. Payar and Singapore.

5.4 Discussion

The current study has demonstrated the occurrence of location-specific recurrent luminescent and/or density banding patterns in skeletons of massive *Porites* corals at all six study locations around the Thai-Malay Peninsula. Although these banding patterns are described as annual in nature in this paper, it is not possible to be certain that they represent exactly one year's growth. However, several lines of evidence suggest that the time frame in which these recurrent bands are formed does not deviate markedly from a 12-month period. Repeated alizarin staining at all study locations with the exception of Port Dickson, and the subsampling of tagged coral colonies at all locations within the period 2009–2011 demonstrated that the timing of bands occurred at the same time of the year, at least within this ~2-year period. For Phuket, results from previous growth studies and alizarin staining efforts also offer confidence in the timing of the luminescent banding chronology (i.e. onset of bright band ~Nov/Dec) (Charuchinda and Chansang 1985; Chansang et al. 1996; Scoffin et al. 1992). Additionally, dating of corals using the ratio of ^{210}Po/^{210}Pb decay series (2-month accuracy) for massive *Porites* specimens collected from P. Tioman, P. Redang and P. Langkawi (in the vicinity of P. Payar) was highly correlated (R=0.976) with growth increments inferred from luminescent bands (Lee 2012). Similar chronological agreement was observed from analysis of Sr/Ca (as proxy for SST) from a Singapore *Porites* core (sampled at every 1mm along the growth axis, equating to approximately monthly resolution) (Suci Nurhati, *pers. comm.*).

Compared to skeletal density, variations in luminescence intensity were studied to provide a more unambiguous signal for demarcation of annual growth increments. Annual luminescent banding was apparent at all 6 study locations, whereas density banding could only be discerned at 4 of the locations (i.e. Phuket, P. Payar, P. Tioman and P. Redang). This finding is consistent with observations from previous growth studies around Southeast Asia, where luminescent banding rather than density banding has been used as the preferred method for extracting sclerochronological information (e.g. Charuchinda and Chansang 1985; Scoffin et al. 1989; Scoffin et al. 1992; Allison et al. 1996; Risk et al. 2003; Tanzil et al. 2009). It should, however, be noted that at P. Redang and P. Tioman, annually recurring density banding was equally, or even more distinct compared to luminescent banding (Figs. 5.2 and 5.3d/e). At Phuket, P. Payar, Port Dickson and Singapore, the average annual luminescence intensity ranges (difference between maximum and minimum values) were ~6–18% higher than ranges for skeletal density. However, at P. Redang, this difference was <0.02%, while at P. Tioman the average density range was higher by ~7% compared to luminescence.

In order to explore possible environmental cues/causes of banding patterns in massive *Porites* coral skeletons, the current study conducted correlation analysis over a 5-year period (Dec 2004-Nov 2009) of anomalies in monthly-binned luminescence intensity and density against monthly anomalies in SST, PAR, rainfall, salinity, wind speed, squall index (sum of standardised rain and wind scores) and Chl-a concentrations, all of which have previously been shown to relate to timing of banding formation in one way or another. These were tested at the "region" (i.e. taking account data all 53 cores from all six study locations) as well as individual "location" levels (i.e. separate analyses for cores sampled from Phuket, P. Payar, Port Dickson, Singapore, P. Tioman and P. Redang). Admittedly, the number of samples and also the strength of the correlations at the individual locations will influence results for "region" level analyses and so any interpretation/s of "region" level results should be made in conjunction with those found at the "location" level. It is reasonable to suppose that any potential environmental cues/causes related to timing of luminescent and density band formation should be significantly and systematically (i.e. only positive or only negative) correlated at both the "region" and "location" levels.

Intra-annual variation in luminescence intensity found in the current study could be broadly categorised into 2 groups – i.e. 1) relatively straightforward repeating pattern of one brighter/duller luminescent couplet per year with onset of the bright luminescent band deposition ~Nov/Dec, and 2) less straightforward pattern with appearance of multiple brighter/duller luminescent band/line couplets per year. Banding patterns discerned at Phuket, Port Dickson and P. Redang would fall under the first category while those seen in cores from P. Payar, Singapore and P. Tioman make up the second category. At P. Tioman, the annual pattern consists of two bright/dull luminescent bands of similar intensities (Figs. 5.2 and 5.4e), the "first" of which starts forming ~Nov/Dec and the "second" ~Jul/Aug. At P. Payar and Singapore, secondary quasi-annual luminescent line is visible within the broad dull luminescent band (Fig. 5.2) that contribute to the appearance of complicated multiple band couplets per year. Nevertheless, annual repeating patterns can be resolved by taking the onset of the broad bright band at P. Payar and the onset of the broad dull band at Singapore, both of which are estimated to start forming ~Nov/Dec (Fig. 5.4b/f).

Significant correlations were found at the "region" level between luminescence intensity anomalies and monthly anomalies for 4 of the 7 environmental parameters examined; rainfall, squall index, salinity and Chl-a concentrations. Of these, only variations in salinity and Chl-a concentration were shown to have consistent relationships with luminescence at the location level. Positive anomalies in luminescence intensity related to negative salinity anomalies at all locations, and with positive anomalies in [Chl-a] at 5 of the 6 study locations (insignificant only at Port Dickson (PD)). The lack of significance at PD could be in part a consequence of the lower sample number at this location (n=3 cores and 154 correlations) (Table 5.4). Tan et al. (2006) also noted a lack of congruency between [Chl-a] estimates from SeaWiFs (also used here) and *in-situ* measurements at this location which could further explain the lack of relationship here. Nevertheless, the significant consistent relationships found at the "region" level and at remaining study locations indicate that, along with salinity, [Chl-a] is a meaningful environmental variable.

Barnes and Taylor (2001, 2005) previously suggested that increased luminescence is likely associated with increased skeletal porosity (crystal size/packing) in response to lowered salinity. However, the current study found no convincing relationship between annual variations in luminescence intensity and density. No systematic relationship was observed at the location level between these two parameters and, although a significant positive relationship was found at the regional level, the variance in luminescence intensity explained by variations in density was only ~0.6% (R=0.081) (Table 5.3). This may reflect the overall stronger influence of inclusions of fluorophores into the coral skeletons occurring at a seasonal scale, as opposed to varying concentrations contributed by skeletal porosity. Therefore, the significant relationships found in the current study between luminescence anomalies with anomalies in salinity and Chl-a concentrations (both used as proxies of freshwater/riverine input) further supports the notion that inclusion of humic/fulvic acids into the skeletons of corals is the major cause of luminescent bands. Nevertheless, the variances (R^2) in luminescence intensity anomalies explained by anomalies in salinity and [Chl-a] occur in wide ranges from ~1.2–25.4% and 4.3–40.8% respectively. Whether this reflects the accuracy of the salinity and [Chl-a] data used (e.g. Tan et al. 2006), suitability of salinity/[Chl-a] as proxies of humic/fulvic acid concentrations, or whether there are other environmental or biological factors unaccounted still requires further investigation.

The lack of clear relationship between luminescence and rainfall patterns noted in the present study is consistent with earlier findings from Phuket (Scoffin et al. 1992) and the Seribu Islands, Indonesia (Scoffin et al. 1989). This, however, may be more an indication of the suitability (or lack thereof) of using localised rainfall as a proxy for freshwater/river input to reefs. Localised rainfall as an estimate of terrestrial/freshwater runoff into reefs is an assumption accommodated only where effects from a single major river and/or landmass is likely to dominate. In such cases, high correlations between rainfall, river discharge and luminescence are observed e.g. at the GBR (Isdale et al. 1998; Lough 2007). However, in more complex hydrological systems, such as those found around the Thai-Malay Peninsula, the interplay of wind-driven circulation, bathymetry, topography and numerous river systems (Wyrtki 1961; Morton and Blackmore 2001; Rixen et al. 2011; Rizal et al. 2012; Jha and Singh 2013) may confound the relationships between rainfall, salinity and terrestrial/freshwater runoff. This is demonstrated by the disjoint in salinity and rainfall patterns found at Phuket, P. Payar, Port Dickson and Singapore (Fig. 5.3c/d). Measurements of $\delta^{18}O$ (as proxy for SST and salinity values) from massive *Porites* skeletons sampled around Phuket and Port Blair (Andaman Islands) also provide further evidence of this disjoint i.e. lowest salinities in ~Nov–Mar occurring during the lowest rainfall period over this area (Allison et al. 1996; Rixen et al. 2011).

Alternating monsoon currents (MC) apparent in the South China Sea and the Andaman Sea (Fig. 5.5) drive the decoupling of the monsoon-related hydrological cycle and salinity observed in this region. For example, wind-driven circulation flushes more saline, clearer waters from the South China Sea during the NE monsoon (Nov–Mar) through the sites around Singapore when rainfall and river discharge (Fig. 5.3c and 5.6) tends to be highest, reducing the effect of seawater dilution. The opposite is seen during the SW monsoon (May–Oct) when a combination of tidal- and wind-driven currents allows more turbid, lower salinity waters from the Java Sea and Malacca Straits to drift/reside longer in Singapore waters thus producing a counterintuitive salinity minimum during the less rainy monsoon period (Fig 5.3c/d) (Robinson et al. 1953; Chen et al. 2005; Rizal et al. 2012). Similarly, seasonal differences in current strength through the Malacca Straits flushes lower salinity, more turbid waters towards the northern mouth of the Straits during the NE monsoon period (Selverajah 1961; Rizal et al. 2012), affecting locations such as P. Payar and Phuket. In the Andaman Sea, reversing MC also carry cold, low salinity water from the northern and western Bay of Bengal towards Phuket during the NE monsoon period (Rixen et al. 2011). Such phenomena could explain the generally higher luminescence intensities observed during the drier, lower rainfall season in *Porites* specimens from Singapore, Port Dickson, Phuket and P. Payar, and also the occurrence of an additional luminescence maximum at P. Tioman (~Jul/Aug) not coinciding with the high rainfall period, or annual river discharge patterns (Fig. 5.4e and 5.6). Only at P. Redang does luminescence show significant relationships with rainfall, salinity and Chl-a concentrations as well as congruence with river discharge patterns, which could suggest a more straightforward hydrological cycle at this location.

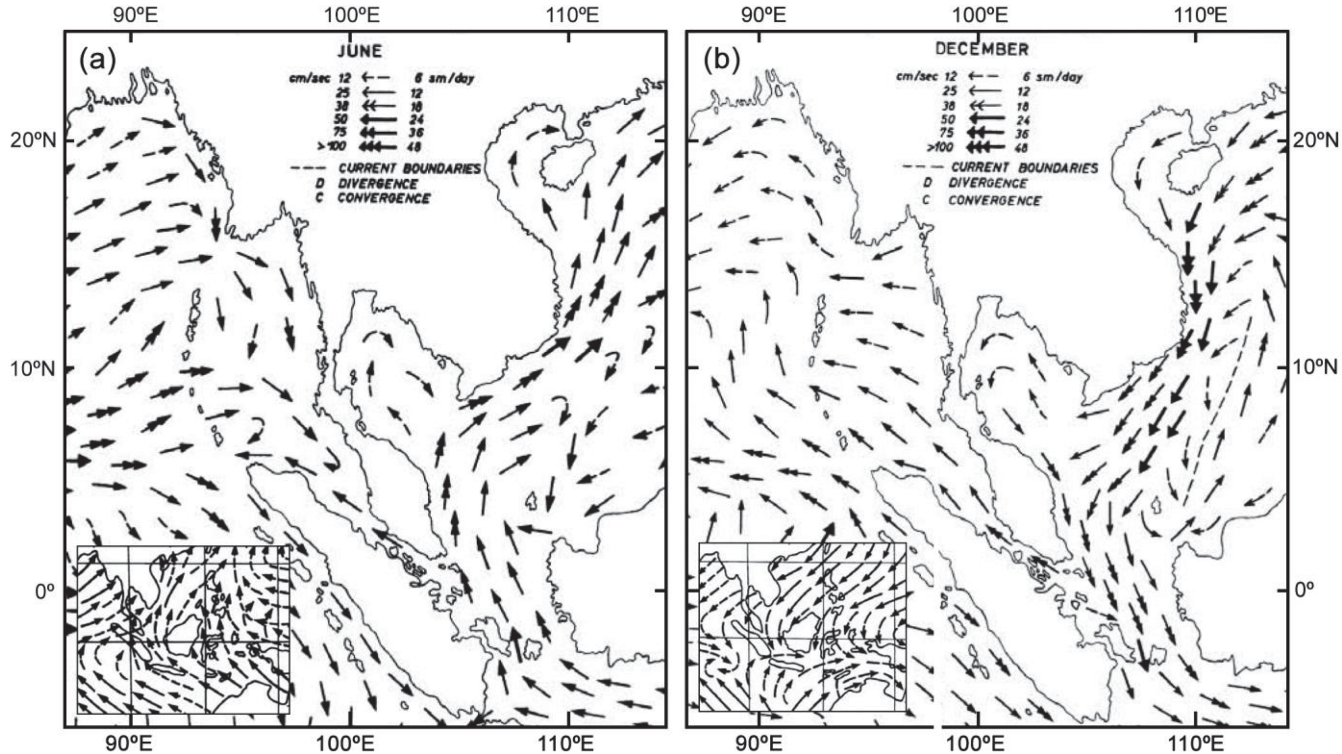

Fig. 5.5. Surface current charts and average wind pattern (inset, lower left corner) for a) June and b) December (modified from Wyrtki 1961).

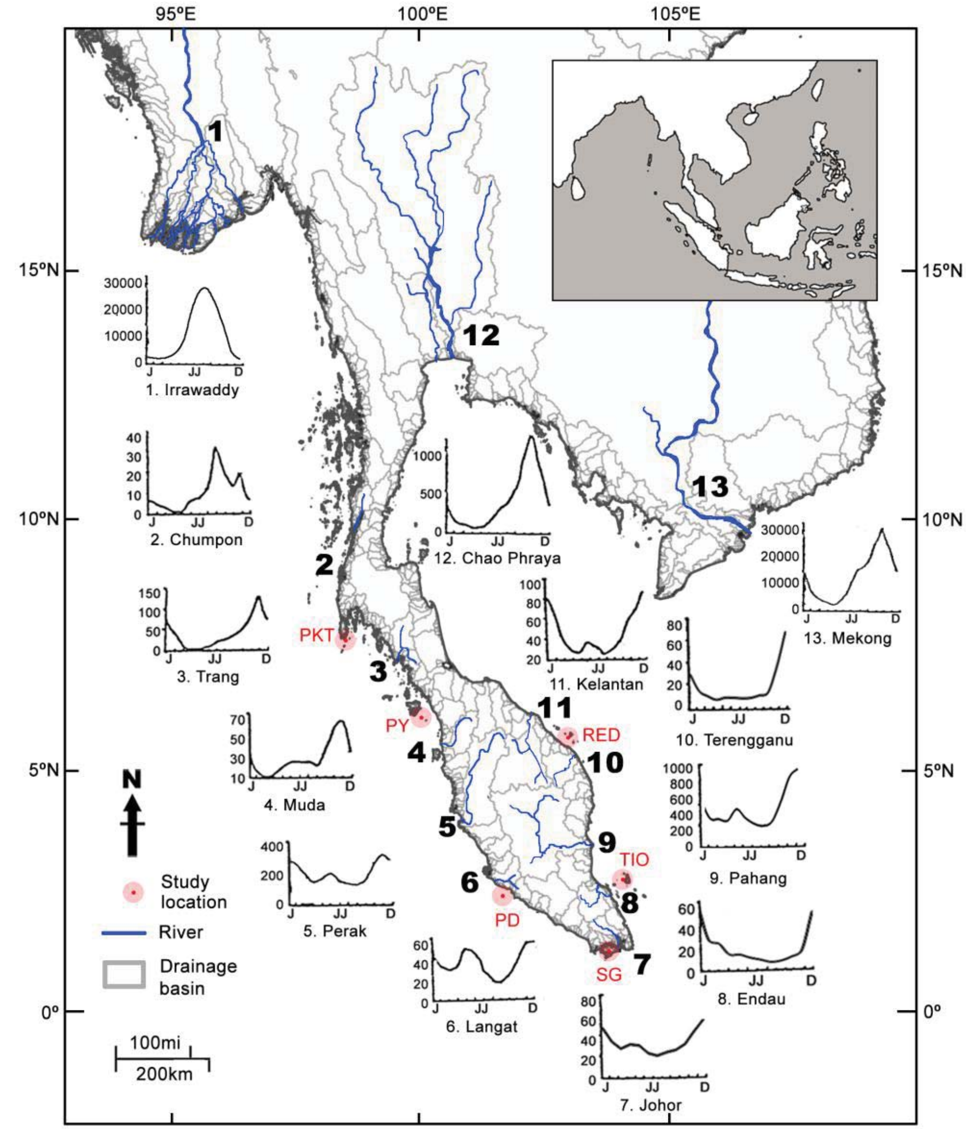

Fig. 5.6. Average monthly discharge ($m^3\ s^{-1}$) of selected major rivers around the Thai-Malay Peninsula (river discharge data from Siripong 1990, the RivDis1.1 (Vörösmarty et al. 1998) and the Department of Irrigation and Drainage Malaysia). PKT – Phuket, PY – P. Payar, PD – Port Dickson, SG – Singapore, TIO – P. Tioman, RED – P. Redang

Intra-annual variation in density at the 6 study locations could be categorized into 3 main groups – i.e. 1) no discernable bands at Singapore and Port Dickson (southernmost locations), 2) dense band deposition commencing ~Nov/Dec at P. Tioman and P. Redang (east coast locations), and 3) dense band formed starting ~May/Jun at Phuket and P. Payar (west coast locations). Although variations in density anomalies correlated significantly with monthly anomalies in all 7 environmental parameters examined at the regional level, only its positive relationship with squall index was systematically significant at all study locations (R=0.08–0.37) (Table 4). Squall index here was used to parameterise sea surface roughness (SSR), and by proxy hydraulic energy received by reefs, as the sum of standardised rainfall amounts and wind speeds. Although wind speed is generally taken as the driver of sea surface roughness, both wind and rain have the ability to affect momentum transfer at the air-sea interface (Kumar et al. 2009) and hence hydraulic energy, especially in shallow water reefs such as those sampled for the current study (average depth ~2–3m at mid-tide). This is most apparent at P. Payar where observed mean wind speed was interestingly highest ~Dec–Feb (~3m s^{-1}) during the NE monsoon period despite being located along the west coast of the Peninsula. While it might be expected that SSR would be highest during this high wind period, rougher seas are reported during the SW monsoon when squall events in the northern Malacca Straits (typically referred to as the "Sumatras") are most prevalent (Kamaruzaman 1998; Yi and Lim 2007). Consequently, accounting for both rain and wind may allow for better estimation of hydraulic energy received by shallow water reefs around the Thai-Malay Peninsula.

There is considerable evidence that hydraulic energy and coral density are related. Brown et al. (1985) found that skeletons of *Acropora aspera* corals in more exposed environments were denser. Scoffin et al. (1992) also identified water movement as the predominant influence on skeletal bulk density increasing along a gradient of increasing hydraulic energy around Phuket reefs. A similar finding was likewise reported by Tanzil et al. (2009). Within limits, increased water movement is believed to be beneficial to corals by flushing waste, removing sediment, reducing salinity and temperature extremes as well as enhancing the diffusion of nutrients, bicarbonate, and gases by reducing the thickness of the diffusion boundary layer around the coral (see Todd 2008). Dennison and Barnes (1988) reported increases in photosynthesis, respiration and calcification rates in *Acropora formosa* subjected to increased water motion over short incubation periods (~2 hours). Conversely, high hydraulic energy also tests the mechanical strength of the coral colony structure, and thus having higher skeletal density would reduce the likelihood of breakage in such environs (Denny et al. 1985). It is, therefore, not improbable that the intra-annual variation seen in the Thai-Malay Peninsula massive *Porites* is a response to changes in hydraulic energy on the reef. It should, however, be noted that the squall index used in the current study only explained a maximum of ~13.4% (at P. Tioman) in the variation found in density (Table 5.4). Again, as in the case of salinity and [Chl-a] discussed above, further investigation is needed in order to ascertain whether this reflects the suitability of the squall index as an estimate of SSR/hydraulic energy or an indication that other equally/more important factors are involved.

To surmise, the current study found location-specific recurrent annual luminescent and density banding patterns in massive *Porites* from around the Thai-Malay Peninsula, and identified some potential environmental cues/drivers of these banding patterns. The systematic significant correlations between luminescence and salinity and Chl-a concentrations as proxies for river runoff, and the lack of convincing relationship between luminescence intensity and intra-annual variations in density, support the notion that the timing for the deposition of bright/dull luminescent bands is caused by inclusions of humic/fulvic acids into the coral skeleton at time or very close to time of growth. Skeletal density variations found in the present study are most likely related to water movement/hydraulic energy, or some other linked environmental parameter/s. It is, however, important to be reminded that correlations do not confer causation, and further validation is undoubtedly required to ascertain cause and effect of the environmental parameters identified in the present study on variations in both density and luminescence intensity. Furthermore, in complex coastal systems, such as those found around the Thai-Malay Peninsula, it may be prudent to be aware of, if not ascertain, the accuracy of environmental proxies in estimating actual reefal conditions.

Additionally, in view of the great variability in luminescence and density banding patterns as well as occurrences of quasi-annual lines/bands demonstrated in the current study, it is important to consider proper validation of band formation timing (e.g. through alizarin stating, repeated subsampling, geochemical dating) as well as verification from multiple cores to increase certainty when identifying commonalities in banding patterns. For example, although the timing of luminescent banding for Phuket *Porites* discerned in the current study is consistent with those observed in earlier studies (Charuchinda and Chansang 1985; Scoffin et al. 1992), the same could not be said for density banding at this location. Based on one specimen at Porites Bay (PB), Phuket, Scoffin et al. (1992) concluded that the timing of dense band formation is during ~Nov–Mar at this site. However, analyses of the 12 cores sampled from around Phuket, including two at the overlapping PB site, showed a different pattern where denser bands were estimated to form between May and Sep in all cores. Inter-colony variation in the timing of density bands has previously been observed at the GBR (Lough and Barnes 1990). It is possible that the disparity in the timing of density band formation at this site is due to such variability, and puts further emphasis on the need to ensure banding patterns are not elucidated from single specimens.

5.5 Appendix

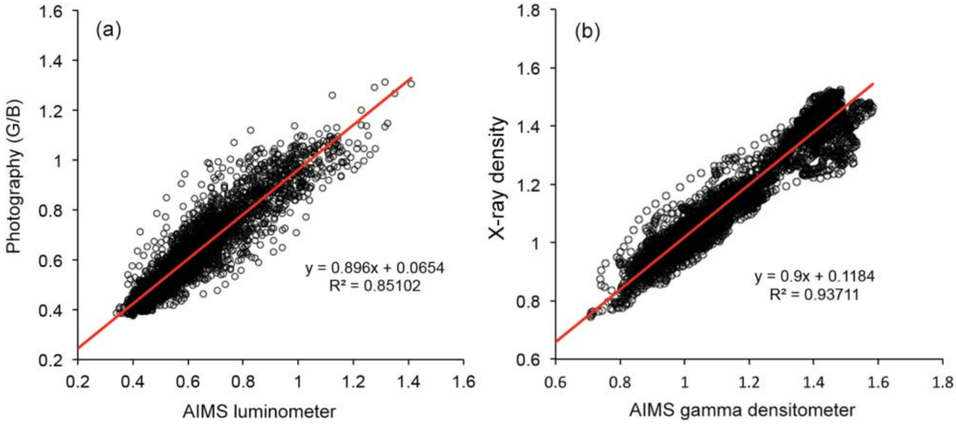

Fig. A5.1. Comparison of measurements of a) luminescence intensity and b) skeletal density obtained respectively from photography (Green/Blue spectral ratio) and digitised X-radiograph methods vs. AIMS luminometer/gamma densitometer.

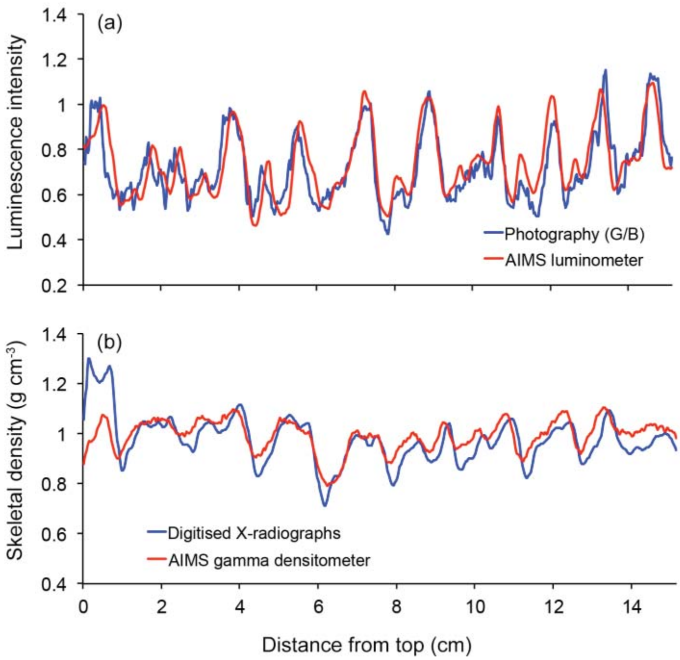

Figure A5.2. Example comparison of a) luminescence intensity and b) skeletal density from a single core (KU-B) obtained over almost overlapping tracks obtained using the different methods.

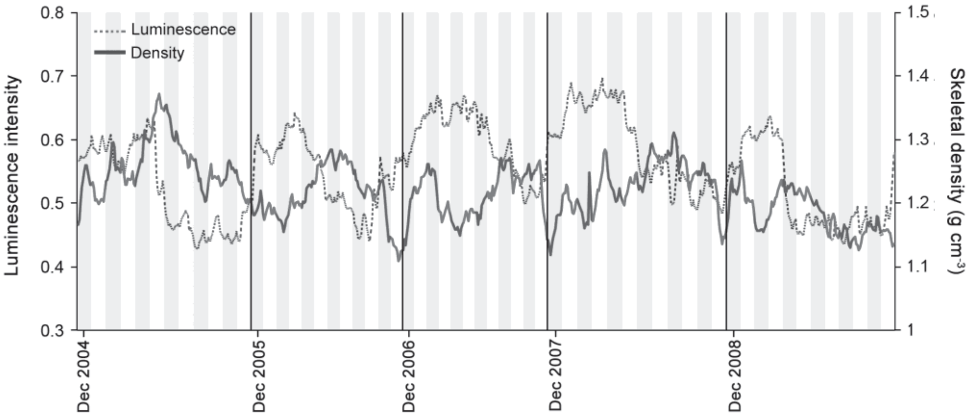

Figure A5.3. Luminescence intensity and skeletal bulk density measurements over the five annual cycles between Dec 2004 and Nov 2009 from a single core (KR-D). Alternating shaded and unshaded areas within each annual cycle represents the partitioning of luminescence and density values into the 12 monthly bins.