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Palaeoenvironmental analysis of the upper Cenomanian and lower Turonian limestone beds in the Sergipe Basin, northeastern Brazil, based on microfacies analysis, micropalaeontology, and stable isotopes

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Abstract

Palaeoenvironmental and microfacies analyses of the upper Cenomanian–lower Turonian limestone beds (mid-Cretaceous) of the Sergipe Basin, northeastern Brazil, were carried out. Three outcrop areas were sampled from northeast to southwest of the basin: the Japaratuba, Laranjeiras and Itaporanga areas. Eleven sections were investigated where previous biostratigraphical studies have indicated the position of the Cenomanian–Turonian transition, and 230 thin sections analysed. Four lithologic units and four microfacies types (MFTs) were defined, and a facies model was established for the Sergipe Basin. The microfaunal content was analysed for biostratigraphical purpose and palaeoenvironmental interpretation. Stable isotope analyses (^{13}C, ^{18}O) were carried out in order to estimate the completeness of the stratigraphical succession and to correlate the sampled sections.

The depositional environment of the upper Cenomanian–lower Turonian transition was that of a ramp with a gentle dip. The deepening of the basin from northeast to southwest is represented by two environments exposed in the study area: the mid ramp and outer ramp.

The mid ramp area is represented by nodular and bedded limestones, intercalated with coquina banks as the result of currents transporting bioclastic material in the basin. In this area bioclastic mud- to wackestones (MFT 1 and 2) and echinoderm-inoceramid packstones (MFT 3) dominate the succession. These microfacies types mainly occur in the notheastern and central parts of the basin (Japaratuba and Laranjeiras areas). The southwestern part (Itaporanga area) is dominated by MFT 4, a laminated marly mudstone, deposited in the outer ramp area.

The microfauna consists mainly of foraminifers, calcispheres, radiolarians and rare ostracods. Because of poor preservation foraminifers are only of limited use for biostratigraphical purpose, however, they can be used as palaeoenvironmental indicators. In addition, roveacrinids can be used as a biostratigraphical tool. The planktonic foraminiferal assemblages of the northeastern and central parts of the basin (Japaratuba and Laranjeiras areas) suggest shallow to middle neritic environments under well-oxygenated conditions. This is also indicated by the occurrence of bioturbation throughout these sections. The low-diverse, sparse benthic microfaunal assemblages of the southwestern sections (Itaporanga area) in addition to lamination structures, indicate oxygen-depleted conditions in middle to deep neritic environments.

A stratigraphical gap in the southern Japaratuba area was detected by the δ^{13}C curve. The observed fluctuations in the carbon isotopic curve can tentatively be correlated throughout the studied areas and is in agreement with the biostratigraphy.

Key words: Cretaceous, Cenomanian, Turonian; foraminifers, roveacrinids; microfacies, sedimentology, facies, carbonates; palaeoenvironment, startigraphy, oxygen depletion, stable isotopes; Sergipe Basin, Brazil.

Kurzfassung

Die Kalksteinschichten des oberen Cenoman– unteren Turon (mittlere Kreide) des Sergipe Beckens in Nordost-Brasilien, wurden bezüglich des Paläoenvironments und der Mikrofazies untersucht. Dazu wurden drei Aufschlussgebiete vom Nordosten nach Südwesten des Beckens beprobt: das Japaratuba-, Laranjeiras- und Itaporanga-Gebiet. In der Region, in der durch vorherige biostratigraphische Studien die Lage des Cenoman-Turon-Übergangs nachgewiesen werden konnte, wurden elf Profile beprobt und 230 Dünnschliffe angefertigt. Vier lithologische Einheiten und vier Mikrofazies-Typen konnten unterschieden werden. Daraufhin wurde für das untersuchte Gebiet ein Faziesmodel erstellt. Die Mikrofauna wurde auf ihre biostratigraphische Verwendbarkeit analysiert und zur Interpretation des Paläoenvironments. Stabile Isotope (^{13}C, ^{18}O) wurden gemessen, zum einen um die Vollständigkeit der stratigraphischen Abfolge zu überprüfen und zum anderen um die beprobten Profile miteinander zu korrelieren.

Der Ablagerungsraum der oberen Cenoman- und unteren Turon-Schichten war eine leicht geneigte Karbonatrampe. Die Vertiefung des Beckens von Nordosten nach Südwesten ist in zwei Ablagerungsbereichen aufgeschlossen: der mittleren und äusseren Rampe.

Die Mikrofauna der untersuchten Schichten besteht hauptsächlich aus Foraminiferen, Calcisphären, Radiolarien und wenigen Ostrakoden. Der Erhaltungszustand der Foraminiferen ist relativ schlecht. Aus diesem Grund sind sie zur Interpretation des Paläoenvironments geeignet, konnten für biostratigraphische Zwecke aber nur begrenzt benutzt werden. Neben Foraminiferen lassen sich Roveacriniden als Grenzmarker nutzen. Die Vergesellschaftung planktonischen Foraminiferen des nördlichen und zentralen Bereich des Beckens (Japaratuba- und Laranjeiras-Gebiet) weisen auf ein flaches bis mittleres neritisches environment unter gut durchlüfteten Bedingungen. Dafür spricht ausserdem die starke Bioturbation der Schichten. Die niedrig-diversen, wenig verbreiteten benthischen Mikroorganismen des südwestlichen Bereichs des Beckens (Itaporanga-Gebiet) weisen auf ein mittleres bis tief-neritisches environment unter sauerstoff-reduzierten Bedingungen hin. Die Laminationsstrukturen dieser Schichten unterstreichen dies.

Die Schichtlücke im südlichen Japaratuba-Gebiet konnte mit Hilfe der δ^{13}C-Kurve nachgewiesen werden. Die auftretenden Fluktuationen der Kohlenstoff-Kurve lassen eine Korrelation der einzelnen Profile zu, die mit der Biostratigraphie übereinstimmt.

Schlüsselwörter: Kreide, Cenoman, Turon; Foraminiferen, Roveacriniden; Mikrofazies, Sedimentologie, Fazies, Karbonate; Paläoenvironment, Stratigraphie, Sauerstoffarmut, Stabile Isotope; Sergipe Becken, Brasilien.

Resumo

Foram realizadas análises paleoambientais e microfaciológicas de camadas de calcário do Cenomaniano superior-Turoniano inferior (Cretáceo médio) da Bacia de Sergipe, nordeste do Brasil. Três áreas de afloramentos que estendem-se do nordeste ao suduoeste da bacia foram amostradas: área de Japaratuba, Laranjeiras e Itaporanga. Onze seções e 230 seções delgadas foram analizadas, onde estudos bioestratigráficos anteriores tem indicado o posicionamento da transição do Cenomaniano-Turoniano. Quatro unidades litológicas e quatro tipos de microfácies (MFT’s) foram definidas, e um modelo de fácies foi estabelecido para a Bacia de Sergipe. A microfauna encontrada foi analizada tendo como objetivo proposta bioestratigráfica e interpretação paleoambiental. Análises de isótopos foram realizadas a fim de identificar hiatos na seção estratigráfica e correlacionar a seções amostradas.

A transição Cenomaniano superior-Turoniano inferior foi caracterizada por um ambiente deposicional de rampa de mergulho suave. Do nordeste à sudoeste, esse ambiente é subdividido em rampa intermediária e rampa externa identificado em duas áreas expostas que também representa, da área mais rasa à mais profunda da bacia.

A área onde foi indentificada a rampa intermediária, é representada por calcários nodulares e estratificados, intercalados com bancos de coquinas resultantes de correntes que transportavam materiais bioclásticos na bacia. Nesta área, a seção foi dominada por “mud-wackestones” (MFT 1 e 2) e “packstones” originados de equinodermos-inoceramídeos (MFT 3). Essas microfácies ocorrem principalmente na parte nordeste e central da bacia (Japaratuba e Laranjeiras). A parte sudoeste (área de Itaporanga) é dominada por margas laminadas (MFT 4) depositadas em ambiente de rampa externa.

A microfauna consiste principalmente de foraminíferos, calcisferas, radiolários e raros ostracodes. Devido a pobre preservação, o uso dos foraminíferos para propostas bioestratigráficas foi limitado. Contudo, eles podem aparentemente ser utilizados como indicadores paleoambientais. Além dos foraminíferos, os roveacrinídeos podem ser usados como ferramenta bioestratigráfica. As assembléias de foraminíferos planctônicos que ocorrem na parte nordeste e central da bacia (áreas de Japaratuba e Laranjeiras) sugerem um ambiente raso à nerítico médio sob condições de águas bem oxigenadas. Isto também é indicado pela ocorrência de bioturbação por toda a seção. A baixa diversidade, escassez de assembléias de microfauna bentônica nas seções sudoeste (área de Itaporanga), além de estruturas de laminação, indicam condições de depleção de oxigênio em ambientes nerítico médio à profundo.

Um hiato estratigráfico ao sul da área de Japaratuba foi detectado pela curva de ^{13}C. As flutuações observadas no isótopo de carbono podem tentativamente ser correlacionadas por toda área, contudo elas não correspondem a nenhum isótopo estável conhecido da passagem

Palavras-chaves: Cretáceo, Cenomaniano, Turoniano; foraminíferos, roveacrinídeos; microfácies, sedimentologia, fácies, carbonatos; paleoambiente, estratigrafia, oxigênio depleção, isótopos estáveis, Bacia de Sergipe, Brasil.

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Abstract

Chapter 1

INTRODUCTION

1.1 Objectives

The present work is a multidisciplinary study that combines micropalaeontological, sedimentological and stable isotopic data to reconstruct the environmental conditions in the upper Cenomanian–lower Turonian (Cretaceous) limestone beds in the Sergipe Basin, northeastern Brazil. This basin is one of numerous marginal basins of the South Atlantic Ocean and forms the southern part of the Sergipe-Alagoas Basin (Figure 1.1). It is an important hydrocarbon-producing basin and therefore a region where geological investigations have been concentrated. Despite the fact that this economic interest has resulted in a wealth of publications on the palaeontology and stratigraphy of the Cretaceous succession, only a few studies of the Cenomanian–Turonian transitional beds have so far been published.

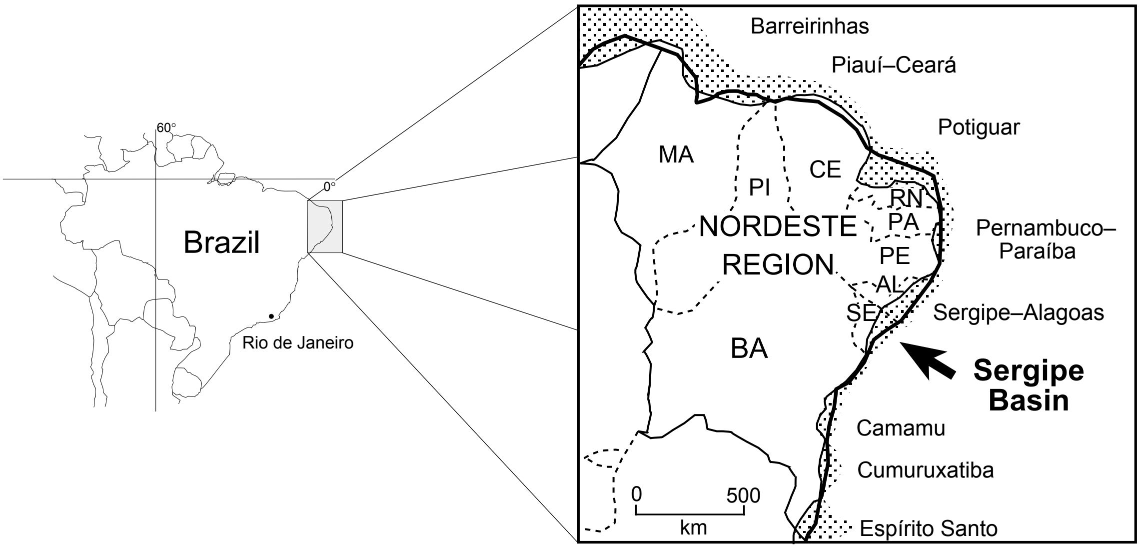


Figure 1.1: Generalised location map of the marginal basins (dotted) of northeastern Brazil (modified after Walter *et al.*, in press). Abbreviations of state names: AL= Alagoas, BA= Bahia, CE= Ceará, MA= Maranhão, PA= Pará, PE= Pernamuco, PI= Piaui, RN= Rio Grande do Norte, SE= Sergipe

The principal objectives were as follows:

(1) to analyse the different lithologies in the studied localities;

(2) to analyse the different microfacies characteristics of the sampled sections;

(3) to analyse the palaeoenvironmental conditions from the fauna, with emphasis on foraminifers and roveacrinids;

(4) to decipher the effect of oxygen-depleted conditions on the shelf sediments and the microfauna of the study area;

(5) to establish a facies model for the Sergipe Basin for the Cenomanian–Turonian;

(6) to analyse the microfossil content concerning its biostratigraphical application;

(7) to establish a δ^{13}C-curve for the boundary succession to estimate the completeness of stratigraphical sections and for local correlation of isolated outcrops and correlation with the biostratigraphical framework and the existing Cenomanian-Turonian carbon stable-isotope data from other areas.

The stratigraphical position of the Cenomanian–Turonian boundary has long been discussed. This is due to many different biostratigraphical horizons having been used as possible boundary markers. The proposal of the Turonian Working Group of the Subcommission on Cretaceous Stratigraphy for a Global Boundary Stratotype section and Point at the base of Bed 86 in the Rock Canyon Anticline Section west of Pueblo, Colorado, USA, is expected to end these arguments. In this section, according to current knowledge, this level coincides with the first occurrence of the ammonite *Watinoceras devonense* Wright & Kennedy, 1981 (Bengtson, 1996).

Based on detailed lithologic and palaeoenvironmental studies a facies model was established for the exposed upper Cenomanian–lower Turonian succession in the Sergipe Basin. Information on the rock texture, the mineral or skeletal nature of the components, the proportion of these components and their distribution within the matrix is preserved in thin sections. Microfacies analysis is an important method for the study of the mode of transport and depositional environment, and provides a tool for obtaining information about the palaeontological and petrological composition of the sedimentary rocks. Besides this it allows differentiation of former biotopes by identification of diagnostic microfossils, sedimentological structures and geochemical composition of a sequence. The study and interpretation of all observable characteristics of a rock in thin section supports the biostratigraphical framework, helps to reconstruct the former depositional environment and the lithogenesis, and provides a tool for local chronostratigraphical correlation as well as data for palaeoenvironmental interpretations.

The material collected comprises 230 lithological samples from three outcrop areas (Figure 1.2):

a) the **Japaratuba area**, in the northern part of the Cenomanian–Turonian outcrop belt,

b) the **Laranjeiras area**, in the central part, and

c) the **Itaporanga area** in the south.

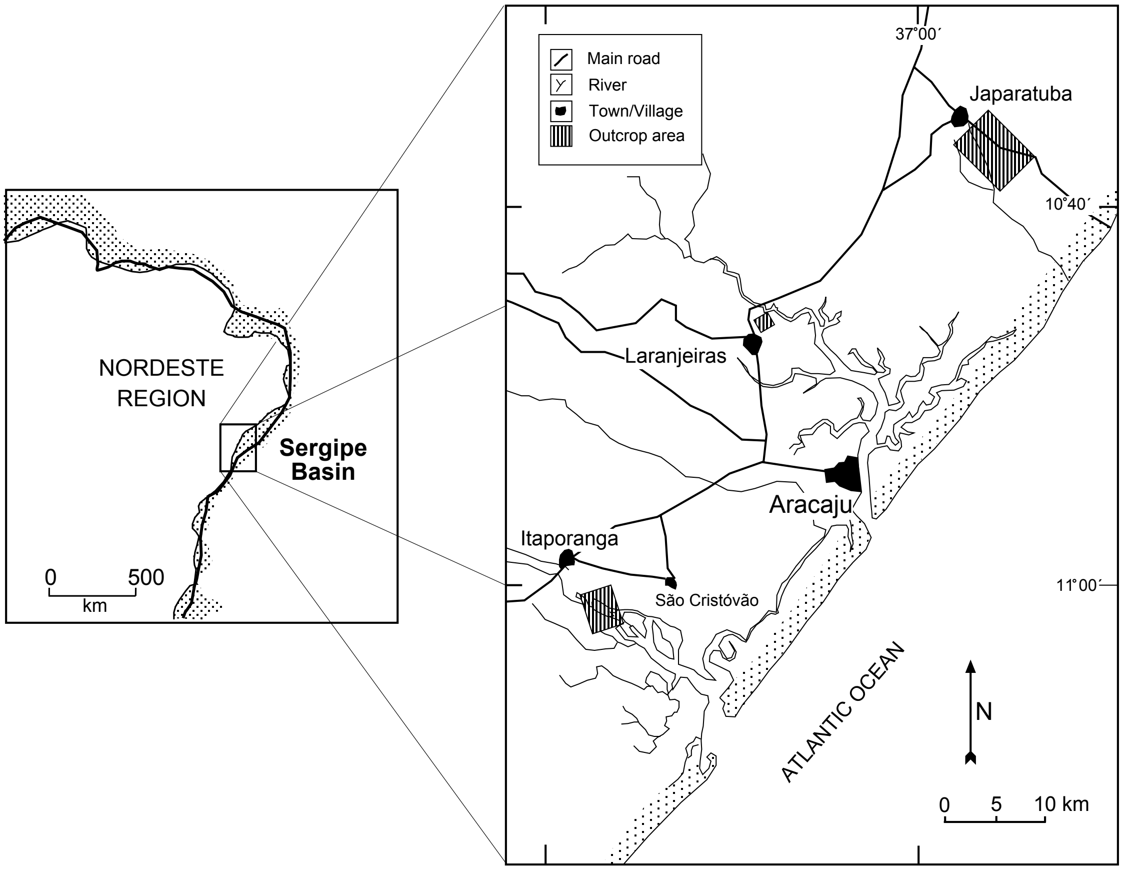


Figure 1.2: Simplified geological map of onshore area of the Sergipe Basin, with location of the principal areas of study: Japaratuba, Laranjeiras and Itaporanga (modified after Bengtson, 1983).

In these areas shallow-water bioclastic carbonates dominate the sequence. The rocks are predominantly light-coloured limestones, which form a rather uniform succession and are macroscopically difficult to distinguish from each other.

The Cenomanian–Turonian succession of the Sergipe Basin in northeastern Brazil is well exposed and contains a diverse macro- and microfauna. This makes the basin an ideal study area to establish a reliable chronostratigraphy for the northwestern South Atlantic, which will provide a basis for comparisons and correlations with surrounding areas.

The present work is based primarily on microfacies analysis and stable isotopic data from the boundary succession. Based on the results of Bengtson (1983) and Berthou & Bengtson (1988) eleven sections were chosen for the study of the upper Cenomanian–lower Turonian limestone beds. The first part was carried out in 1995 and focused on the Japaratuba area; in the second part of the field work, carried out in 1996, sections were chosen from the Laranjeiras and Itaporanga areas. In the sections studied detailed lithologic sampling was carried out and a facies model was established. The model was established for the early Turonian limestone beds, because for this time interval comparable data are available for all three areas studied.

1.2 Scope of research

1.2.1 Oceanic Anoxic Event

Over the last decades the Cenomanian–Turonian boundary has been the subject of international research interest. By the end of the Cenomanian and beginning of the Turonian significant global palaeoceanographic and climatic changes occurred, as shown by the widespread deposition of organic-rich rocks. The deposition of such "black shales" in major oceanic basins was termed the "Oceanic Anoxic Event" (OAE) by Schlanger & Jenkyns (1976). Some authors consider the Cenomanian–Turonian oceanic anoxic event (OAE or *Bonarelli Event* of, e.g. Jenkyns, 1990, 1999) to be a global phenomenon and assume that significant parts of the world ocean were periodically oxygen deficient (e.g. Arthur *et al.*, 1987; Schlanger *et al.*, 1987), whilst others believe that there is no evidence of global anoxia (e.g. Cooper, 1977; Vail *et al.*, 1977; Hancock & Kauffman, 1979; Waples, 1983; Haq *et al.*, 1988).

The causes of such anoxic events are not fully understood because of the difficulty of distinguishing between local geodynamics and global events. Several models have been suggested to explain the factors causing an Oceanic Anoxic Event. Most authors assume a coastal upwelling which lead to increased productivity and an intensified oxygen-minimum-zone (OMZ) (Schlanger & Jenkyns, 1976; Arthur *et al.*, 1987; Schlanger *et al.*, 1987; Jarvis *et al.*, 1988). Some authors postulate that the early Turonian was marked by a peak transgression caused by a wordwide high sea-level stand (e.g. Hancock & Kauffman, 1979; Arthur *et al.*, 1987; Haq *et al.,* 1987; Peryt & Wyrwicka 1991). The association of sea-level peaks with anoxic events has been rejected by Hancock (1993), who explained this hypothesis as a result of misdating the Turonian boundary (e.g. by means of foraminifers or ammonite-inoceramid zonations).

According to Arthur *et al.* (1987) the increase in shelf-sea areas caused by transgressions led to enhanced production of warm saline waters, which sank to bottom-water masses. This process led to an increase in the rates of oceanic turnover because the Cretaceous oceanic circulation was salinity driven. This increased circulation created enhanced upwelling, which triggered the OAE. A different model is favoured by Summerhayes (1987). According to his model, the upwelling was caused by an influx of nutrient-rich oxygen-deficient bottom waters from the northern South Atlantic, triggered by the separation of Africa from South America. However, the dynamics of the Cenomanian–Turonian upwelling event remain poorly understood and few current models adequately explain all the characteristics of the sedimentary deposits of that time (e.g. Jenkyns, 1999). Nevertheless, it is generally accepted that the event did lead to widespread anoxia in the oceans (Jarvis *et al.*, 1988).

Jenkyns (1999) suggested a climate model to explain the causes of an oceanic anoxic event (Figure 1.3).

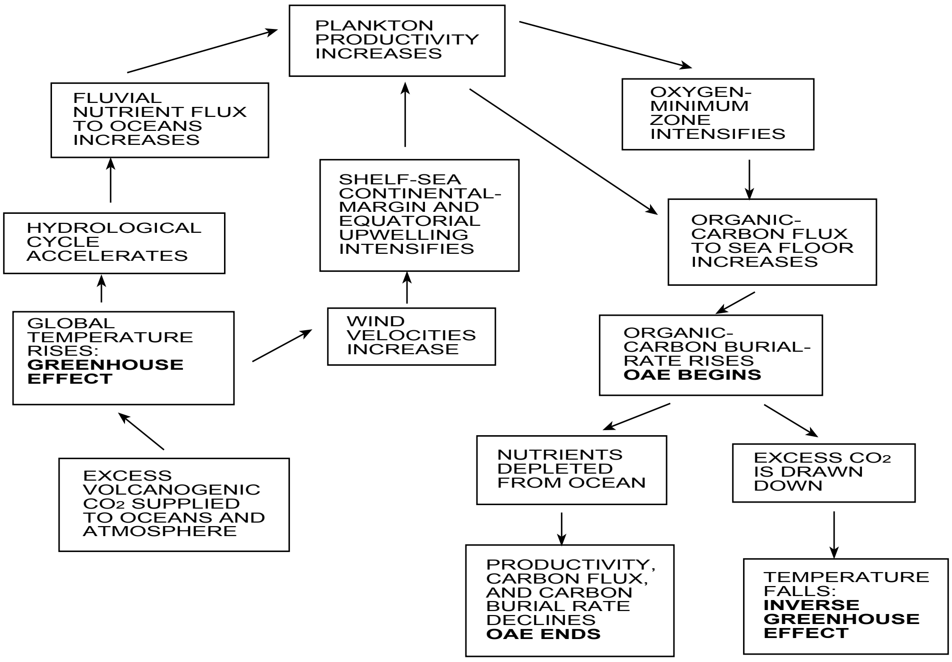


Figure 1.3: Factors causing an Oceanic Anoxic Event (after Jenkyns, 1999)

A triggering factor is the warming-up of the globe due to volcanogenic CO_2 (greenhouse effect), which leads to increased evaporation from the ocean, greater precipitation on land and consequently increased continental weathering and seaward transport of nutrients. The flux of organic matter and biogenic silica to the sea floor would have increased, as would the $\delta^{13}C$ value of sea water and the oceanic anoxic event would have begun (Jenkyns, 1999). The general lack of bioturbation in these beds is taken to indicate an absence of a burrowing fauna due to anoxic conditions (Schlanger & Jenkyns, 1976; Arthur & Schlanger, 1979; Jenkyns, 1980; Schlanger *et al.*, 1987; Arthur *et al.*, 1990; Jenkyns, 1999).

Organisms preferentially extract the lighter ^{12}C isotope during photosynthesis. This leads to a relative enrichment of the heavier ^{13}C isotope in the bicarbonate of the ocean (Scholle & Arthur, 1980; Pratt, 1985; Schlanger *et al.*, 1987; Arthur *et al.*, 1988; Arthur *et al.*, 1990). The ^{12}C-depleted carbon reservoir in the productive water mass is then expressed by the ^{13}C-enriched biogenetic carbonate (Scholle & Arthur, 1980; Pratt, 1985; Schlanger *et al.*, 1987; Arthur *et al.*, 1988; Arthur *et al.*, 1990; Hilbrecht *et al.*, 1992). The $\delta^{13}C$-curves can be used for stratigraphical purposes and may indicate changes in the sediment accumulation/erosion ratio and sea level fluctuations (Voigt & Hilbrecht, 1997).

1.2.2 Mass extinctions

The late Cenomanian–early Turonian eustatic sea-level rise (Haq *et al.*, 1987; Cooper, 1977; Hancock & Kauffman, 1979) has been related to faunal extinctions by many authors (e.g. Elder, 1987, 1991; Fitzpatrick, 1996; Hart, 1996). However, the effect of mass extinctions varies regionally. The anoxic events had a major effect on the planktonic foraminifers and the idea that the movement of the oxygen minimum zone in the water column could affect the evolution of the planktonic foraminiferal population was first suggested by Jarvis *et al.* (1988). Peryt & Lamolda (1996) draw similar conclusions concerning the turnover of the benthic foraminiferal assemblages in northern Spain. Hart (1996) explains a connection between microfossil extinction and a collapse in the food chain, observed in the late Cenomanian Plenus Marls (Europe). According to Elder (1987), the faunal turnover at the Cenomanian–Turonian boundary at Black Mesa, Arizona, probably resulted from changes in the climate or basin/global oceanic circulations. The extinction of approximately 50 percent of molluscan species in the Western Interior Basin was associated with circulation events and a transgressive pulse followed by increasing sedimentation rates (Elder, 1991). In addition, the biotic changes suggested low-oxygen benthic concentrations (Elder, 1989). Extinction steps closely correlate with unusual trace metals (especially Ir), and stable isotope ^{13}C and ^{18}O fluctuations (Orth *et al.*, 1988; Kauffman, 1988, 1996), suggesting cause and effect. This left a worldwide depauperate marine fauna by the end of the Cenomanian (e.g. Jefferies, 1962; Elder, 1987, 1989, 1991).

The characteristic microfossils observed at the Cenomanian–Turonian extinction event, as small planktonic foraminifers (*Heterohelix* sp.), small benthic foraminifers, calcispheres and radiolarians (Hart, 1996; Tur, 1996) all occur in the Cenomanian–Turonian transition deposits studied in Sergipe. Due to the fact that the Cenomanian–Turonian Oceanic Anoxic Event had minor effects on the shallow shelf environment of the area studied, the microfauna was apparently not enough affected for mass extinctions to occur. The only effect observed was the rise of the oxygen-minimum zone, which changed the palaeoenvironment. It may, of course, be that the microfossil content is not representative, due to dissolution, which partly destroyed the original microfaunal assemblage. In the case of the macroinvertebrates a repeated extinction is followed by biotic recoveries and immigration events (Seeling, 1999), but there is no evidence of a catastrophic event. The stepwise pattern of faunal turnover can be interpreted as a response to habitat changes linked to the late Cenomanian sea-level rise (Seeling, 1999).

1.3 Previous works

In his study on the litho- and biostratigraphy of the Cenomanian to Coniacian of the Sergipe Basin, Bengtson (1983) gave a complete annotated listing of the fossils reported in the literature (Bengtson, 1983, Tab. 1–10). Moreover, he added a comprehensive list of the historical development of age assignments and biostratigraphy of the middle Cretaceous sequences of Sergipe. Due to this, only the most important literature mostly about the microfauna and microfacies analysis will be mentioned here.

In the years 1940–1956 prospecting for oil in the Sergipe Basin led to increased investigations shown in a flood of publications and numerous internal reports of the Brazilian national oil company *Petrobras* (Petróleo Brasileiro S.A.), the successor company of the former *Conselho Nacional do Petróleo* (CNP).

From 1961 onwards K. Beurlen published several papers on the geology and palaeontology of the Cretaceous of northeastern Brazil (e.g. Beurlen 1961, 1964, 1970, 1971a, b). He was the first to attempt to establish an ammonite zonation of the Aptian–Albian sequence (Beurlen, 1961). K. Beurlen (1970) added *Paramammites* and *Neoptychites* to the lower Turonian fauna of the Sergipe Basin.

After this variety of publications concerning the macrofauna of the Sergipe Basin, Petri (1962) presented the first foraminiferal zonation for the Turonian. Krömmelbein (1964) did additional work on the microfauna, and described ostracods from the Cotinguiba Formation. Müller (1966) published the first palynological zonation for the Turonian–Coniacian interval. Supplementary works on foraminifers and ostracods were published by Braun (1966), Fernandes (1967), Viana (1969) and Schaller (1970), who contributed a basic geological reference for the basin, resulting from earlier publications.

From the late 1960s onwards, Reyment published several papers on the palaeobiogeography of the South Atlantic (e.g. Reyment 1969, 1972, 1973, 1976, 1977, 1980). Together with several co-authors he studied the Cretaceous geology, palaeontology, biostratigraphy and palaeogeography of western Africa and South America (e.g. Reyment, 1978; Reyment & Tait, 1972; Reyment & Neufville, 1974; Reyment *et al*., 1976).

Simões & Bandeira (1969) and Bandeira (1978) described depositional models, palaeoenvironmental interpretations and identified potential reservoirs for application in petroleum exploration, based on microfacies studies.

Neufville (1973, 1979) described lower Turonian ostracods from Petrobras in the Itaporanga and Japaratuba boreholes. Bengtson (1979) made a comparison of the zonation based on ammonites with that based on foraminifers, nannofossils and palynomorphs. On the basis of ammonites, Bengtson (1983) established a biostratigraphical framework, and subdivided the Cotinguiba Formation (Cenomanian–Coniacian) into eight units. As part of this study on the litho- and biostratigraphy of the Cenomanian–Coniacian sequence, he collected macrofossils from 604 localities, and these are named and described (Bengtson, 1983, appendix 1).

Bengtson & Berthou (1983) and Berthou & Bengtson (1988) attempted a stratigraphical zonation and correlation of the Cenomanian–Coniacian by microfacies analysis. Their study served as an important framework for the upper Cenomanian–lower Turonian boundary bed studied in detail herein.

The stratigraphy, depositional and geological history of the marine Cretaceous carbonate succession of the Sergipe Basin have been discussed by e.g. Ojeda & Fugita (1976) and Feijó (1995), amongst others. In addition a number of studies on the palaeontology and sedimentology of the Cotinguiba Formation were published (e.g. Hessel, 1988; Koutsoukos & Hart, 1990a, 1990b; Koutsoukos *et al.*, 1990, 1991, 1993; Smith & Bengtson, 1991; Koutsoukos 1992; Koutsoukos & Bengtson, 1993; Bengtson *et al.*, 1995; Bengtson & Koutsoukos, 1996; Koutsoukos, 1996; Carmo, 1997).

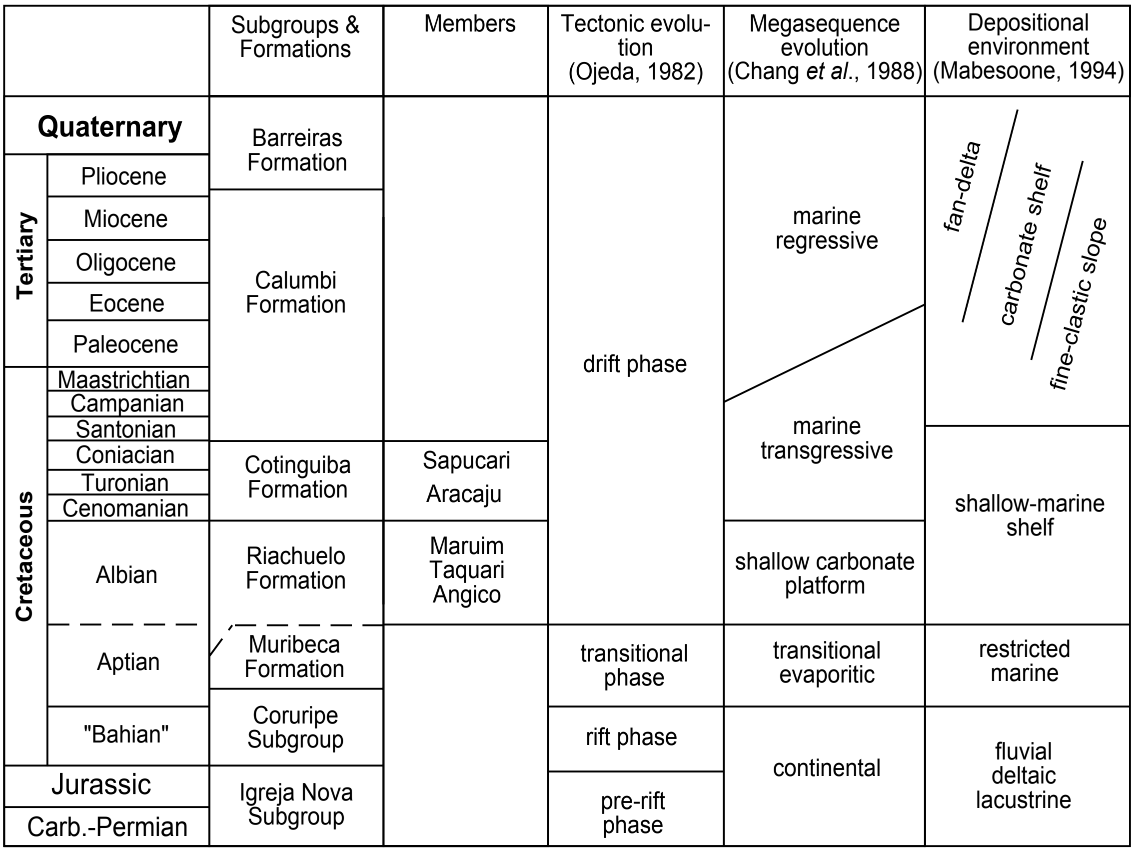
Herrmann (1997) and Schneider (in prep) carried out a geological mapping of the Cenomanian–Turonian boundary beds in the northeastern part of the Basin (Japaratuba area). These results remain unpublished, however, part of the work of Herrmann (1997) contribute to the study of Walter *et al.* (in press).

The most recent work on the palaeontology and biostratigraphy of macroinvertebrates of the Cenomanian–Turonian transitional beds of the Sergipe Basin has been carried out by Seeling (1999) and is partly published (e.g. Seeling & Bengtson, 1999; Seeling, 2000; Andrade & Seeling, 2000; Seeling & Andrade, 2000).

Chapter 2

GEOLOGICAL SETTING

The Sergipe Basin forms the southern part of the Sergipe-Alagoas Basin in northeastern Brazil (Figure 1.2). This Atlantic-type basin was formed as a rift valley by the rupture of the former African-South American continent. The rifting began in the Early Cretaceous and was accompanied by strong tectonic activity, which formed the structural framework of this area. The Sergipe Basin and the contiguous Alagoas Basin, form a half-graben, which is open to the southeast and bounded to the northwest by faults. The counterpart of the basin is presumably the Gabon Basin in West Africa (Wilson & Williams, 1979; Castro, 1987). A permanent deep-water connection between the North and the South Atlantic oceans was established during the Turonian, when sea-floor spreading became dominant in the equatorial region (Castro, 1987). The stratigraphy of the basin was most recently reviewed by Feijó (1995) and its tectonic evolution discussed by Ojeda (1982) among others (Figure 2.1).



		Subgroups & Formations	Members	Tectonic evolution (Ojeda, 1982)	Megasequence evolution (Chang *et al.*, 1988)	Depositional environment (Mabesoone, 1994)
Quaternary		Barreiras Formation		drift phase	marine regressive	fan-delta carbonate shelf fine-clastic slope
Tertiary	Pliocene					
	Miocene	Calumbi Formation				
	Oligocene					
	Eocene					
	Paleocene					
Cretaceous	Maastrichtian				marine transgressive	
	Campanian					
	Santonian					
	Coniacian	Cotinguiba Formation	Sapucari Aracaju			shallow-marine shelf
	Turonian					
	Cenomanian					
	Albian	Riachuelo Formation	Maruim Taquari Angico		shallow carbonate platform	
	Aptian	Muribeca Formation		transitional phase	transitional evaporitic	restricted marine
	"Bahian"	Coruripe Subgroup		rift phase	continental	fluvial deltaic lacustrine
Jurassic		Igreja Nova Subgroup		pre-rift phase		
Carb.-Permian						

Figure 2.1: Stratigraphy and tectonic evolution in the Sergipe Basin after Ojeda (1982) and Chang *et al.* (1988); depositional environments after Mabesoone (1994).

The regional dip averages 10-15° to the southeast, so that progressively younger rocks crop out towards the coast. Depth to basement ranges between 1 and 3 km onshore, whereas offshore depths locally exceed 10 km (Ponte *et al.*, 1980).

2.1 Evolution of the Sergipe Basin

The development of the Brazilian marginal basins has been discussed by several authors (e.g. Ojeda & Fugita, 1976; Ojeda, 1982; Chang *et al.*, 1988). Chang *et al.* (1988) recognised five megasequences (Figure 2.1): (a) continental, (b) transitional evaporitic, (c) shallow carbonate platform, (d) marine transgressive and (e) the marine regressive megasequence. These sequences were defined as ranging from the Jurassic to Cretaceous and related to the breakup of Pangaea and to the evolution of the South Atlantic Ocean.

Mabesoone (1994) subdivided the evolution of the Brazilian Atlantic-type basins according to their palaeoenvironment (Figure 2.1). In Mabesoone´s (1994) publication the tecto-sedimentary evolution proposed by Ojeda (1982) is used. This classification is accepted by most workers and therefore preferred in this paper. The sedimentary fill of the Sergipe Basin consists of four main tecto-sedimentary sequences and can be summarised as follows: (1) the pre-rift phase, (2) the rift phase, (3) the transitional phase and (4) the drift phase.

Pre-rift phase

The basal non-marine pre-rift phase dated as late Jurassic (?) to earliest Createaceous is represented by alluvial fans resting unconformably on the crystalline basement or on Palaeozoic deposits.

Rift phase

The non-marine rift phase ranges from earliest Cretaceous to early Aptian. The tectono-sedimentary part is characterised by deposition of siliclastic and carbonatic material due to the breakup of the continental crust of the Gondwana continent in the early Cretaceous, causing a long central graben and a rift-valley system (Koutsoukos, 1989). The basin opened as a branch of the South Atlantic rift due to differential movement of the NE Brazilian microplate (Mabesoone, 1994). Sedimentary rocks deposited during this phase are represented by the Igreja Nova and the Coruripe Subgroups (Figure 2.1).

Transitional evaporitic phase

The rocks of the overlying transitional phase are of broadly Aptian age. This phase is characterised by progressive spreading allowing the establishment of a narrow epicontinental sea (Koutsoukos *et al.*, 1993). The phase is represented by the Muribeca Formation, which consists of evaporitic and siliclastic deposits formed in hypersaline environments; this unit is subdivided into various members (Mabesoone, 1994).

Drift phase

The following open marine drift phase (Riachuelo, Cotinguiba and Calumbi formations, Figure 2.2) is of Aptian (possibly early Aptian) to Miocene/Pliocene age in the deepest, offshore parts of the basin (Asmus, 1981; Berthou & Bengtson, 1988). The initial stage of the marine drift phase is represented by an extensive carbonate platform extending across 3500 km from the Santos Basin (south of Rio de Janeiro) to the Barreirinhas Basin on the northern equatorial margin.

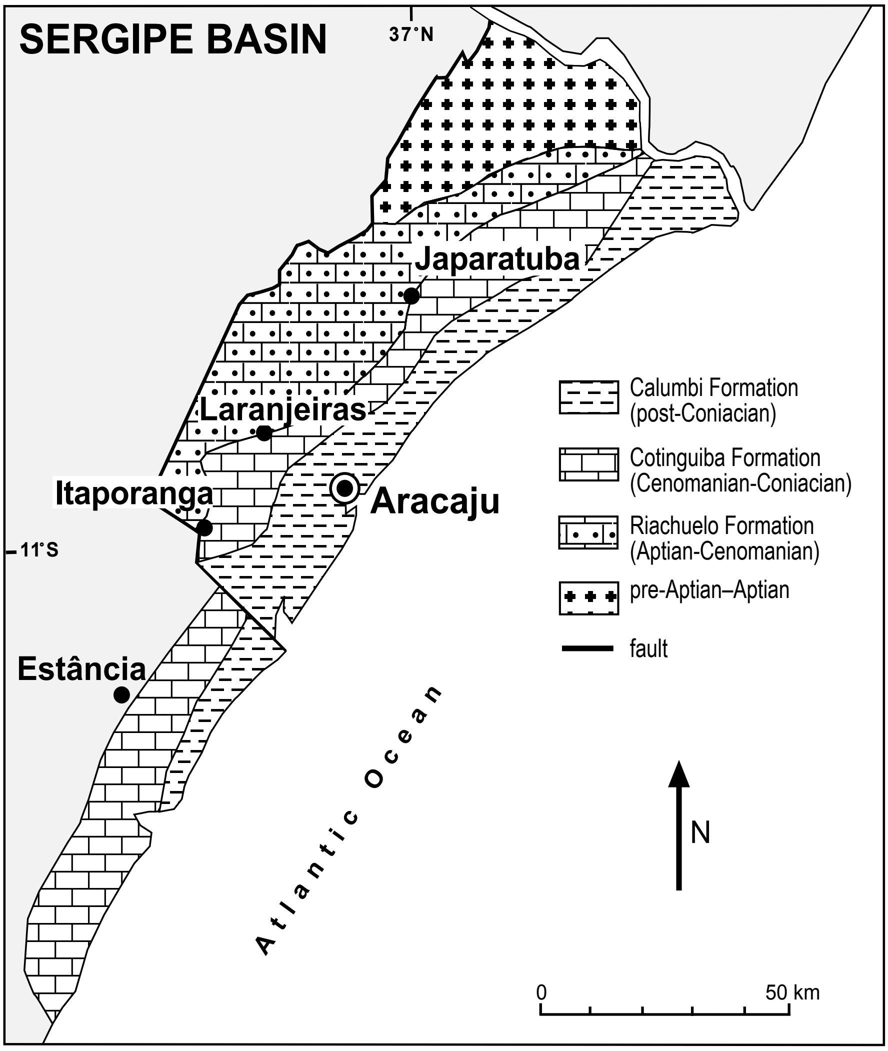


Figure 2.2: Simplified geological map of onshore area of the Sergipe Basin and Estância area (modified after Bengtson, 1983), see Figure 1.2 for position of areas studied.

The Riachuelo Formation (Aptian–Albian) has an average thickness of 500 m and is composed of three members, represented by a mixed carbonate-siliciclastic unit. The Cotinguiba Formation (Cenomanian–Turonian) consists of deep water, fine-grained carbonates, with thickness ranging from 200 m to over 1000 m locally in the onshore part (Koutsoukos *et al.*, 1993). The mostly siliclastic Calumbi Formation represents the depositional cycle of the climatic turnover, which lasted until the Miocene or even Pliocene (Koutsoukos *et al.*, 1993).

The Cenomanian–Turonian sequence studied here is part of the Cotinguiba Formation, which is exposed in a belt running west to north of the state capital Aracaju, and locally in the Estância area south of the Sergipe Basin (Berthou & Bengtson, 1988) (Figure 2.2).

The Cotinguiba Formation consists of two members (Figure 2.3), the Sapucari and the Aracaju Member. The Sapucari Member is represented by grey to blue-grey carbonates with a thickness locally of more than 800 m and with sparse siliciclastic intercalations at the base. The dominantly massive to laminated rock sequence is locally intercalated by chert horizons and nodules, coquinoid limestones and intraformational breccias and conglomerates (Berthou & Bengtson, 1988).

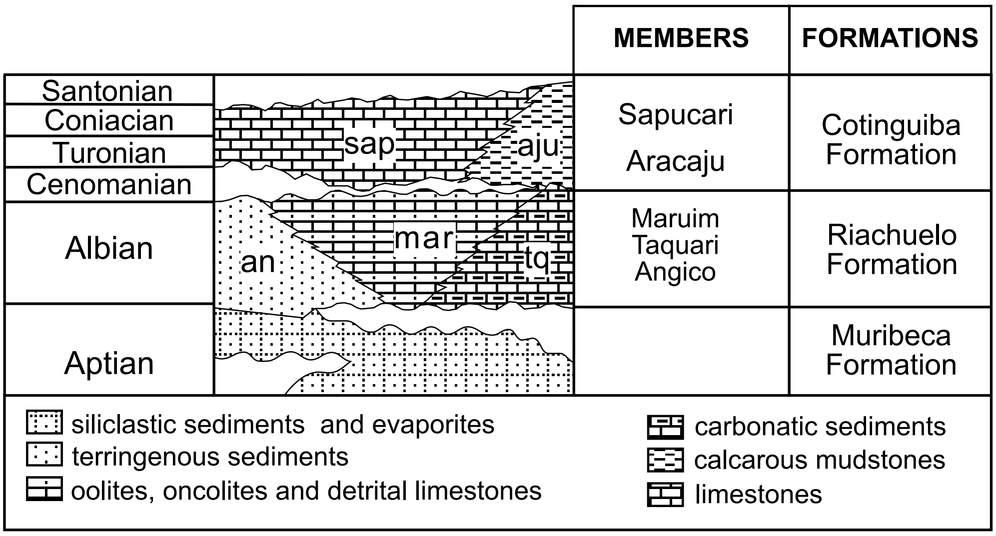


Figure 2.3: Lithostratigraphical units of the marine Cretaceous of the Sergipe Basin (modified after Koutsoukos *et al.*, 1993).

The Aracaju Member (Figure 2.3) represents a distal facies of the Cotinguiba Formation and consists of laminated, organic-rich calcareous shales with intercalations of thin carbonate mudstones and marlstones, reaching a maximum thickness of 300 m (Koutsoukos *et al*., 1993). This member is found in structural lows and the present-day offshore part of the basin.

The overlying Calumbi Formation is dominated by dark shales with intercalations of fine- and coarse-grained sandstones deposited as turbiditic submarine fans. This formation ranges from the middle upper Coniacian/Santonian to the Pliocene (Feijó, 1995; Koutsoukos, 1998).

The Cotinguiba limestones were deposited in the neritic to upper bathyal environment of a carbonate ramp, with moderately dysoxic to truly anoxic bottom conditions and well-oxygenated epipelagic water masses (Koutsoukos *et al*., 1991). The succession was deposited during a relative sea level rise, which caused the drowning of the Riachuelo shallow water carbonate platform (Koutsoukos *et al*., 1993). The occurrence of dysoxic-anoxic episodes during the mid-Cretaceous was due to several factors such as restricted physiography in the deep basin, salinity-stratified water masses, increased epipelagic primary productivity and periodic high sea-level conditions (Koutsoukos *et al*., 1991). Three events of maximum oxygen depletion from middle neritic to upper bathyal environments are recorded in the Cretaceous succession: the first in the late Aptian–earliest Albian, the second in the early Cenomanian and the third around the Cenomanian–Turonian boundary (Koutsoukos *et al*., 1993).

The Sergipe Basin developed under a regime of predominantly extensional stresses (Castro, 1987). During the Cenomanian the depositional rate was low and coupled with tectonic readjustments in the intensely block-faulted floor of the basin (Figure 2.4). As a result there was patchy deposition of calcareous sediments, which in some places contain reworked material and detrital quartz (Berthou & Bengtson, 1988).

The late Cenomanian–early Turonian eustatic rise (e.g. Hancock & Kauffman, 1979; Haq *et al*., 1987) is evidenced by thick carbonate deposits, as a result of subsidence towards the middle of the Turonian (Berthou & Bengtson, 1988). In areas of low terrigenous influx the limestones of the Sapucari Member were deposited, whereas calcareous mudstones of the Aracaju Member were deposited in areas with proportionally lower carbonate production.

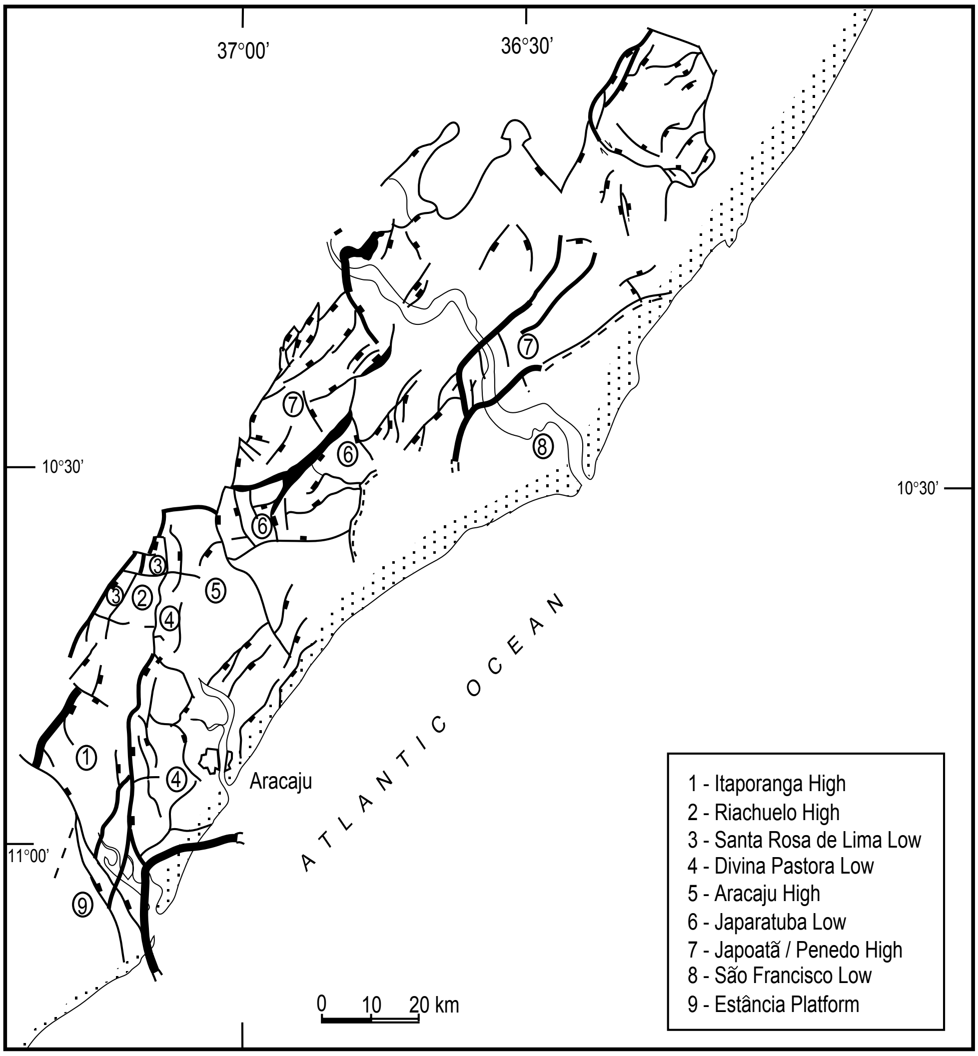


Figure 2.4: Structural framework of the basement in the onshore area of the Sergipe Basin (modified after Koutsoukos *et al.*, 1993)

The middle Cretaceous (upper Aptian–lower Coniacian) carbonate ramp is completely exposed only in the Sergipe Basin (Koutsoukos *et al.*, 1993).

Chapter 3

MATERIAL AND METHODS

3.1 Field work

The field work was carried out over seven months in 1995 and 1996, and concentrated mainly on the upper Cenomanian and lower Turonian deposits aiming at establishing the broad litho- and biostratigraphical relationships in the Sergipe Basin. This project is part of IGCP Project 381 "*South Atlantic Mesozoic Correlations*", under the leadership of Eduardo Koutsoukos (Petrobras, Rio de Janeiro) and Peter Bengtson (University of Heidelberg, Germany). Eleven outcrop sections were selected for facies analyses of the Cenomanian–Turonian boundary strata. This study is based on material collected by the author in co-operation with Jens Seeling (University of Heidelberg, Germany), who concentrated his work on the taxonomy, biostratigraphy and palaeoecology of the macroinvertebrate faunas of the boundary beds.

The material comprises 230 lithologic samples from three major regions, named as follows from northeast to southwest: Japaratuba, Laranjeiras and Itaporanga (Figure 1.2). The initial sampling concentrated on the Japaratuba area, where seven sections were selected and investigated (Localities: Jardim 10, 19, 29, 30, 31, Japaratuba 11, 16, Figure 3.1). The location of these sections is shown in Figures 3.1–3.3 and complete descriptions are given below and in Chapter 5.

In order to reach a more comprehensive view of the facies development of different areas within the basin the sampling was expanded and two supplementary areas were examined. One section was chosen from Laranjeiras (C 652, Figure 3.2) and three from Itaporanga (Rita Cacete 4a, b and 5, Figure 3.3). Localities Rita Cacete 4a, b were taken from one quarry, but show a different lithologic appearance. Two additional sampled sections have not been taken into account in this study: one in the Laranjeiras area (C 673, Figure 3.2) where macro- and microfossils were missing and therefore the stratigraphical position remains unclear; and one in the Aroeirinha area (locality description Bengtson, 1983), which was completely dolomitised, and original sedimentary structures and microfossils were destroyed.

Due to the tropical climate of Sergipe most of the outcrops are deeply weathered. The climate also causes rapid changes in geomorphology and vegetation. Thus, within short periods, small outcrops can disappear. Some of the outcrops described by Bengtson (1983) and Berthou & Bengtson (1988) apparently no longer exist.

In intervals of 20-50 cm approximately 1 kg of sedimentary rock was sampled (Appendix 2). According to Carozzi (1989) this interval is small enough to recognise evolutionary trends and changes in the depositional environment of the limestone succession. In most cases, sampling depended on the outcrop conditions. Unfortunately reliable strike and dip measurements are not always possible, due to the lack of exposed bedding planes. The upper Cenomanian sequence is locally comparatively thin and in many places represented by hiatuses, which complicates correlating the sampled sections.

After analysing the limestone material (e.g. thin sections analysis, fossil extraction, stable isotope analysis) and in addition to microfacies analyses measurements of $\delta^{13}C$ and $\delta^{18}O$ values were carried out, in order to use an additional tool for correlating the outcrop sections with help of stable isotope stratigraphy.

Limited lateral and vertical extent of most exposures hampers biostratigraphic work. Structural highs and lows separate the different outcrop areas, and further complicate local correlation. Another problem is caused by the partial dolomitisation of several sections, which leads to obliteration of the textural characteristics.

3.2 Study area and localities

The Sergipe Basin is located between latitudes 9° and 11° 30´S and longitudes 37° and 35° 33´W. The elongated marginal basin covers an area of approximately 6000 km^2 onshore and more than 5000 km^2 offshore (Koutsoukos, 1998). The narrow coastal belt of the onshore part covers a part of nearly over 16 to 50 km east-west and 170 km north-south direction, and lies entirely within the two small states of Sergipe and Alagoas.

3.2.1 Maps

Topographic and geologic maps on the scale 1:25,000 have been used with permission and support of the Brazilian oil company Petrobras: Mapa topográfico, Serviços Aerofotogramétricos Cruzeiro do Sul S.A.: *Bacia de Sergipe Alagoas* (Petrobras S.A., Rio de Janeiro), sheets 635-3-1 (1967), 635-3-4 (1967), 635-4-3 (1966) and 722-1-2

(1966). Due to the age of the maps they were of limited use and had to be updated during the field work.

Localities mentioned herein are described and plotted on a 1:100,000 map (Bengtson, 1983, p. 30–31, Appendices 1 and 3). Newly introduced sections are described and numbered according to the system introduced by Bengtson (1983).

3.2.2 Japaratuba

From the Japaratuba area seven sections have been described and sampled (Figure 3.1).

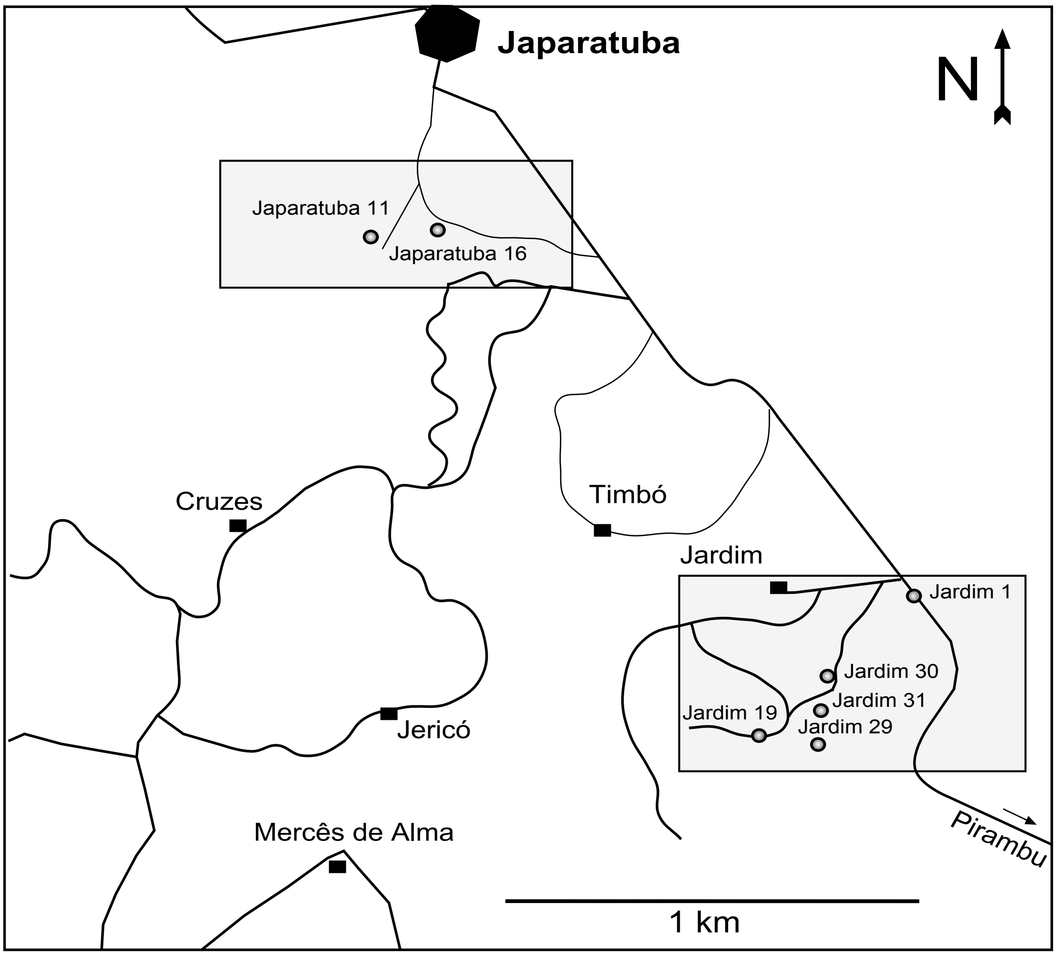


Figure 3.1: Locality map of the sections studied in the Japaratuba area (modified after Herrmann, 1997)

a) Jardim 1

Location: UTM co-ordinates 8 824 100 N/728 400 E. Altitude ca. 25 m, outcrop on both sides of the road from Japaratuba to Pirambu. Height of section 5 m, and lateral extension ca. 30 m.

b) Jardim 19

Location: UTM co-ordinates 8 822 900 N/724 400 E. Altitude ca. 20-45 m. The outcrop section extends over ca. 200 m on the bank on the south side of the road. The height reaches to 3.5 m.

c) Jardim 29

Location: UTM co-ordinates 8 822 800 N/727 800 E. Altitude ca. 25-40 m. Section west of the track up the hillside, facing NW. Height ca. 20 m, length ca. 40 m.

d) Jardim 30

Location: UTM co-ordinates 8 823 130 N/727 550 E). Altitude ca. 25-30 m. Small section in the track up the hill, facing NW. Height ca. 3 m, length ca. 15 m.

e) Jardim 31

Location: UTM co-ordinates 8 823 610 N/727 620 E. Altitude ca. 35 m. The locality is situated on the south side of a hill, at Petrobras well CP-1260.

f) Japaratuba 11

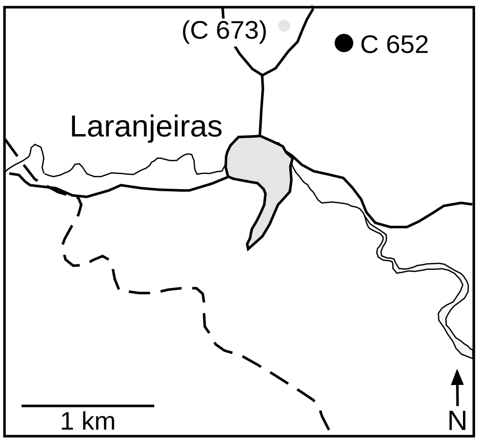
Location: UTM co-ordinates 8 826 600 N/724 350 E. Altitude ca. 30-35 m. Section in track on hill, facing W.

e) Japaratuba 16

Location: UTM co-ordinates 8 826 850 N/724 950 E. Altitude ca. 10 m. The quarry is to the southeast of road, facing NW. Height 5 m, length 60 m.

3.3.3 Laranjeiras

In the Laranjeiras area one section has been chosen (Figure 3.2):



a) C 652

Location: UTM co-ordinates 8 805 800 N/700 600 E. Altitude ca. 25 m. Outcrop on hillside facing SE. Extending over 50 m, height ca. 10 m.

Figure 3.2: Locality map of the section studied in the Laranjeiras area (modified after Seeling, 1999).

3.2.4 Itaporanga

In the Itaporanga area, near the village of Rita Cacete, two sections have been chosen. The quarry at Rita Cacete 4 has been divided in two sections RC 4a and RC 4b (Figure 3.3), RC 4a is located in the northern part of the quarry.

a) Rita Cacete 4a

Location: UTM co-ordinates 8 781 600 N/687 950 E. Altitude 1-6 m. The quarry is active and located 2 km south of the small road from São Cristovão to Itaporanga. The section 4a is being worked and therefore consists of unweathered material. Maximum height ca. 6 m.

b) Rita Cacete 4b

Location: Same quarry as Rita Cacete 4a (see above). This lower part of the section is situated in the western part, which is out of production.

c) Rita Cacete 5

Location: UTM co-ordinates 8 781 950 N/687 850 E. Altitude 5 m. This locality is ca. 400 m northeast of Rita Cacete 4, on a hillside facing S. Height ca. 4 m, extending over 30 m.

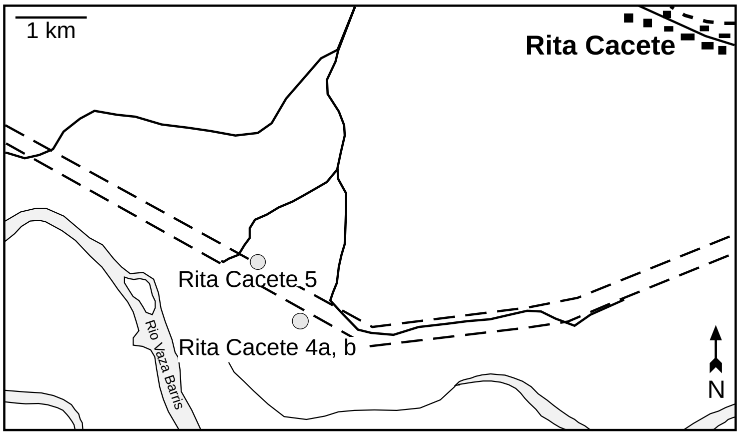


Figure 3.3: Locality map of the sections studied in the Itaporanga area (modified after Seeling, 1999).

3.3 Sample preparation and analysis

3.3.1 Thin sections

A total of 260 thin sections have been prepared. They were investigated under simple polarised and non-polarised light and described using Folk (1959, 1962) and Dunham (1962) nomenclatures. In order to analyse the microfacies of the thin sections, a thickness of 50-60 µm was preferred, because such “thick sections“ often allow us to identify the texture and structure of the limestones. The technique used for the analysis of the thin sections used herein, was that of visual appraisal of the constituents.

Besides lithologic properties, the abundance of macrofossil remains and the microfossil content can classify Cenomanian–Turonian limestones. Biostratigraphically important forms can, in some cases, be identified in thin sections, as for example benthic and planktonic formaminifers, and roveacrinids (see Chapter 4, 6 and 7).

3.3.2 Fossil extraction

The sampled limestones are partly dolomitic. The marly intercalations from the northeastern localities are unsuitable for thin section analysis because they are deeply weathered. Marly material from fresh quarries from the southwestern area has been analysed. Some of the limestone samples did not yield microfossils, because they were either too highly indurated or have been dissolved. In addition to thin section analysis the extraction of microfossils with the petroleum-ether method can lead to a more comprehensive view of the faunal content of the Cenomanian–Turonian limestone succession.

The petroleumether is poured over the dry sample until the entire sample is covered. After 1 hour the samples are allowed to stand, water is heated to 80 °C (not boiling, because this will lead to a rapid reaction, which might destroy fragile specimens). The petroleumether is levigated and hot water is poured over the wet sample. The low boiling point of petroleumether (50–70 °C) means that the hot water causes any of it in the sample to evaporate. This causes the clay lumps and particles to disintegrate. The disaggregated sediment was then washed through a fine-mesh sieve of 0.63–0.063 mm. After drying the samples all size fractions were examined, and the microfossils picked out on a gridded tray and collected into one-hole slides.

3.3.3 Scanning electron microscopy

Specimens were mounted on standard copper stubs with double-sided tape and were shadowcoated with approximately 12–13 A of gold. The scanning electron microscope was a LEO 4-40 of the Institut für Umwelt-Geochemie, Heidelberg (Germany).

3.3.4 Stable isotope analyses

Stable oxygen and carbon isotope analyses were performed on 50 carbonate powder samples taken from bulk rock samples. The samples were first examined under the microscope for signs of secondary alteration of the micritic groundmass or dolomitisation. Only samples that showed no signs of recrystallisation were used for the analysis. The powder was drilled out from the groundmass avoiding shell material.

The stable-isotope compositions of the bulk rock samples were analysed on a Finnigan MAT 252 mass spectrometer with a common bath automated carbonate system at the Pennsylvania State University, USA. Each sample reacted with 100% phosphoric acid at 90 °C. The carbon dioxide gas was measured relative to a laboratory reference gas; NBS-19 was used as a test standard, carbon and oxygen isotopic values are reported in (δ) notation in permil (‰) deviation from the Pee Dee Belemnite standard (PDB).

Chapter 4

BIOSTRATIGRAPHICAL BACKGROUND

Based on published data ammonites, inoceramid bivalves and foraminifers are the main fossil groups utilised in Cretaceous biostratigraphy of the Sergipe Basin. An integrated ammonite and foraminifer zonation was published by Koutsoukos & Bengtson (1993). In the field ammonites and inoceramids are the stratigraphically most useful macrofossils and occur locally in abundance.

Biostratigraphical interpretations of the different faunal elements investigated in this study are discussed in Chapter 9, along with stable isotope stratigraphy and the stratigraphic application of the determined microfacies types. In this section the biostratigraphical background will be outlined briefly.

4.1 Ammonite zonation

Ammonites and inoceramid bivalves provide the best means of correlating the Cenomanian–Turonian boundary (Birkelund *et al.*, 1984). The biostratigraphy of the marine Cretaceous succession of the Sergipe Basin has been studied by several workers, most recently by Bengtson (1983), Kauffman & Bengtson (1985), Hessel (1988), Koutsoukos (1989), and Koutsoukos & Bengtson (1993). However, the limited size of most outcrops and the lack of diagnostic fossils at some localities, do not always allow precise biostratigraphical assignments.

The recently proposed Cenomanian–Turonian Global boundary Stratotype Section and Point (GSSP) at the base of Bed 86 in the Rock Canyon Anticline section west of Pueblo, Colorado, USA, coincides with the first occurrence of the ammonite *Watinoceras devonense* in that section (Bengtson, 1996), which then serves as a marker proxy. However, correlation of the ammonite zonation for the Cenomanian–Turonian of the Sergipe Basin (Koutsoukos & Bengtson, 1993) with the proposed GSSP is difficult, because *Watinoceras devonense* or co-occurring taxa of the Colorado section have not been found in Sergipe yet.

Recent field work by P. Bengtson in the Laranjeiras area has led to a refinement of the boundary zonation of Koutsoukos & Bengtson (1993) through subdivision of the *Vascoceras harttii–Pseudaspidoceras footeanum* Zone into a lower *Vascoceras harttii–Pseudaspidoceras footeanum* Zone and an upper *Pseudotissotia* spp. Zone (Figure 4.1). Based on these new field data, the stage boundary is tentatively correlated with the first occurrence of the ammonite genus *Pseudotissotia* (Walter & Bengtson, 1998). This level is well exposed at locality Japaratuba 11.

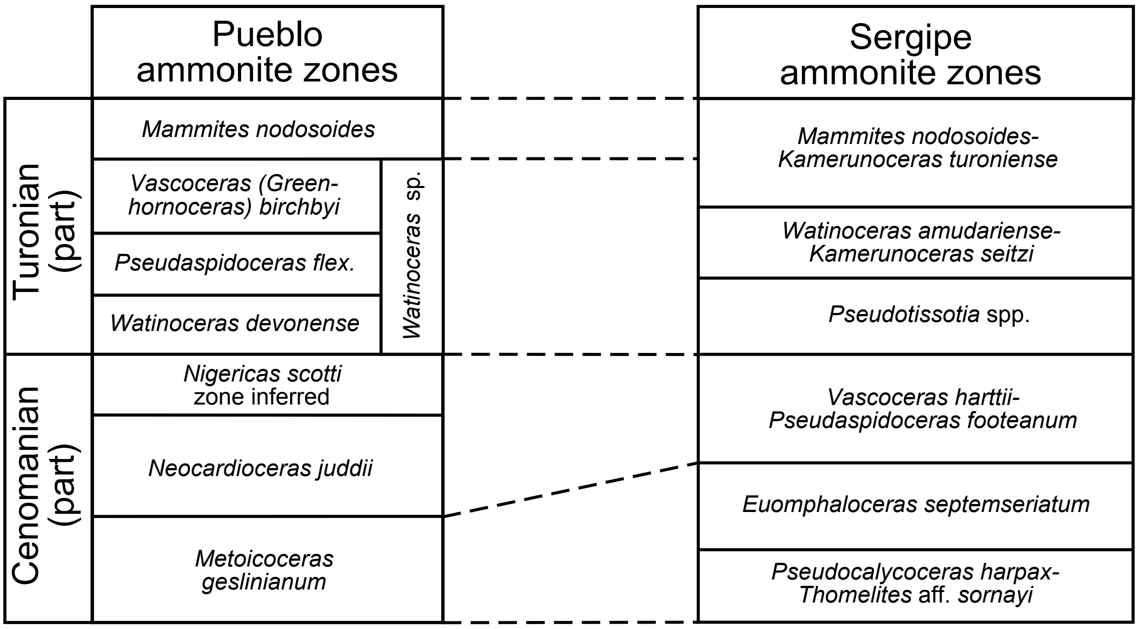


Figure 4.1: Ammonite zonation of the upper Cenomanian–lower Turonian of the Sergipe Basin and tentative correlation with the proposed GSSP at Pueblo, Colorado USA (Walter *et al.*, in press).

Pseudotissotia spp. have been found in the northern Japaratuba area (Japaratuba 11, 16), in Laranjeiras (C 652) and the southern Itaporanga area (Rita Cacete 4); the lowermost Turonian of the southern Japaratuba area is marked by a stratigraphic gap (Chapter 9, Figure 9.4). The occurrence of *Watinoceras amudariense* indicates lower Turonian in this area, although at a higher level than the *Pseudotissotia* spp. Zone. The presence of *Vascoceras* sp. and *Pseudotissotia* sp. in the upper part of Japaratuba 16 is evidence of late Cenomanian–early Turonian age. In addition to ammonites, inoceramid bivalves are used for correlation of the Cenomanian–Turonian boundary beds. A mass occurrence of the genus *Mytiloides* at locality Jardim 29 and the upper part of Rita Cacete 4 is used as an indication of lower Turonian, although here probably representing a lower stratigraphic level than proposed for other regions (see e.g. Hilbrecht, 1986; Hilbrecht & Dahmer, 1994; Seibertz, 1995). This is confirmed by the co-occurrence of these *Mytiloides* with the ammonite *Pseudotissotia* sp. at Japaratuba 11 and lower part of Rita Cacete 4 (Seeling, 1999). No determinable inoceramids were found in the Laranjeiras area, however, in thin sections inoceramid fragments are also observed from here.

A refined biostratigraphical scheme for ammonites and an inoceramid zonation was recently proposed by Seeling (1999). These results are unpublished at the moment. Four intervals were defined to attempt an interregional correlation. For detailed information the reader is referred to Seeling (1999).

Chapter 5

LITHOLOGIC UNITS

5.1 The Cotinguiba Formation

The Cenomanian–Turonian boundary falls within the Cotinguiba Formation (Cenomanian–Coniacian), which is mainly represented by deep-water fine-grained carbonates with an average thickness of around 200 m (Bengtson, 1983), but locally reaching a maximum thickness of about 800 m (Koutsoukos *et al.*, 1993). The formation (Figure 2.3) includes thick successions of carbonate mudstones in the present onshore area (Sapucari Member) and marlstones and shales in the onshore and offshore areas (Aracaju Member) (Koutsoukos *et al.*, 1991).

Numerous variations across small areas and a variety of post-depositional and diagenetic structures like slumps, small-scale faults, nodules and local coquinoidal accumulations (e.g. echinoids at Rita Cacete 4a, Figure 6.5) are characteristic for this formation. The Aracaju Member is characterised by a pelagic facies with an average thickness of 100 m. Shales are interbedded with calcareous mudstones and marlstones (Figure 2.3). The Sapucari Member is composed of a thick succession of calcareous mudstones with occasional thin pelagic layers of shales and marlstones (Figure 2.3). In the study area this member is characterised by cream to yellowish, partly grey limestones, locally clayey and grading into marlstones. Coquina banks are common.

5.2 Lithologic units in the study area

Field work in the three outcrop areas (Figure 1.2) showed that the upper Cenomanian to lowermost Turonian is represented by nodular, bedded, laminated and coquinoid limestones (Figure 5.1). The succession can be broadly subdivided into four lithologic units and is unconformably overlain by Tertiary rocks of the Barreiras Formation. The lithologic units represent different depositional environments.

5.2.1 Lithologic unit 1

Nodular limestones

This unit consists of yellow to cream, nodular limestones, which are partly dolomitised and locally intercalated with small-scale marly limestone layers (Figure 5.1). The nodular limestones mainly occur in the lower part of the southern Japaratuba sections

(Jardim 1, 19, 30, 31) except at locality Jardim 29. The nodular limestones are locally strongly bioturbated (Jardim 1, 19, 31). In the northern Japaratuba area (Japaratuba 11, 16) these limestones are rare, in the Laranjeiras and Itaporanga area these limestones are absent.

5.2.2 Lithologic unit 2

Bedded limestones (partly bioturbated)

Lithologic unit 2 is the most widespread macroscopic feature in the studied area and is represented by partly bioturbated or dolomitised, bedded limestones (Figure 5.1). The light-coloured limestone beds reach a thickness of 10–20 cm. These occur in the southern Japaratuba area (Jardim 29), the northern Japaratuba area (Japaratuba 11), the Laranjeiras area (C 652) and the Itaporanga area (Rita Cacete 4a, 5). The degree of bioturbation varies throughout the sections. Strong bioturbation has mainly been observed at localities Jardim 29, Japaratuba 11, 16 and C 652, and plays a subordinate role in the Itaporanga sections (Rita Cacete 4a, 5).

5.2.3 Lithologic unit 3

Coquinoid limestones

Lithologic unit 3 consists of coquinoid limestones. This unit mainly occurs in the upper part of the northern Japaratuba sections reaching a thickness of 5–10 m. Small-scaled coquina banks with an average thickness of some 10–50 cm are represented as intercalations in the Laranjeiras section (Figure 5.1) and the southern Japaratuba area (Jardim sections).

5.2.4 Lithologic unit 4

Thin-bedded limestones (laminated)

Lithologic unit 4 is represented by grey to yellow coloured, fine-grained, laminated limestones (Figure 5.1). This unit solely occurs in the Itaporanga area. The thin-bedded limestone (average thickness 5 cm) in the fresh quarry of Rita Cacete 4 (a, b) is clearly bedded, whereas in Rita Cacete 5, weathering led to a nodular appearance of the layers. Moreover weathering turns the colour of the limestones from grey to yellow. Macroscopically there is a difference between these two sections (Rita Cacete 4 and 5), due to higher quantities of macrofossil components as represented in the Rita Cacete 5 exposure. Consequently the former lamination structure is partly destroyed.

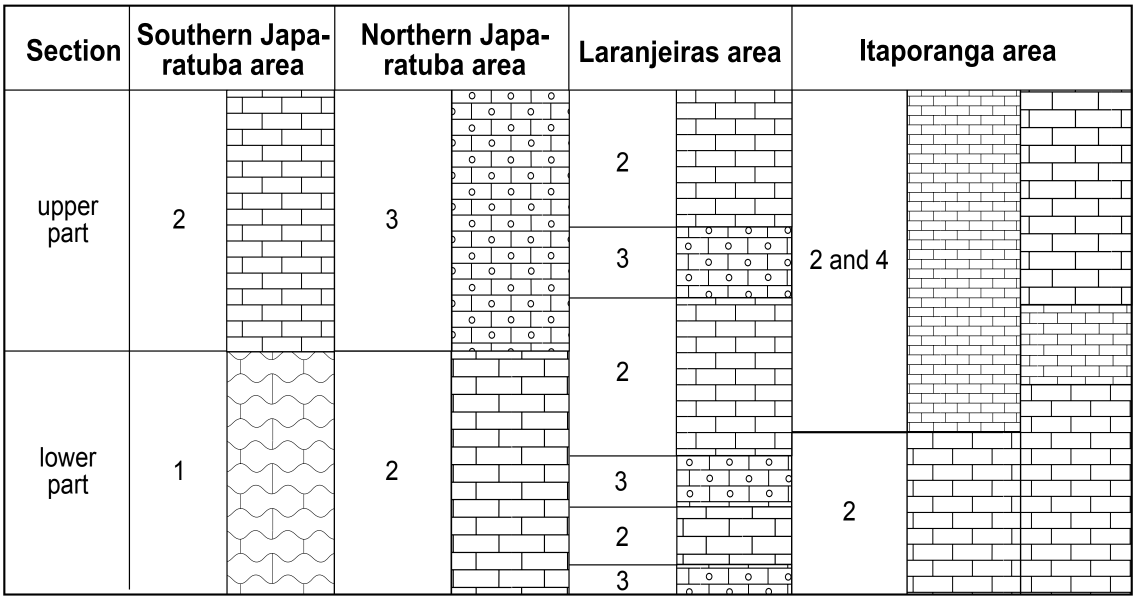


Figure 5.1: Generalised distribution of lithologic units in the study area

5.3 Distribution of the lithologic units in the outcrop sections

5.3.1 Japaratuba area

Jardim 1

Lithologic unit 1: Cream, weathered, nodular limestones interbedded with grey, marly limestones, both strongly bioturbated. The limestone beds reach a thickness of 2–4 dm. One layer with crustacean burrows (*Thalassinoides*) is present, ca. 50 cm thick (Photo 1a, b).

Jardim 19

Lithologic units 1 and 3: Mixed layers of cream, compact limestones and marlstones. The lower part is represented by grey compact limestones. In the upper part less compact marlstones predominate, intercalated by hard limestone layers, which are partly coquinoid. Measurements indicate a local dip of 12° to SE (Photo 2).

Jardim 29

Lithologic units 2 and 3: Fine-grained light-coloured strongly bioturbated, thick-bedded limestones. The lower part of the section consists of fine-grained, light-coloured limestones which in the upper part turn into more compact, hard, partly coquinoid limestones. In the lower part the limestones are characterised by small-scale cavities (Photo 3a, b).

Jardim 30

Lithologic units 1 and 3: Light cream nodular limestone. The lower part of the outcrop consists of loose material only and could therefore not be sampled. The upper part consists partly of coquinoid limestones (Photo 4).

Jardim 31

Lithologic unit 1: Cream to yellow nodular limestones with thin marly intercalations. It resembles those exposed in the upper part of Jardim 1 and 19 (Photo 5a, b).

Japaratuba 11

Lithologic units 2 and 3: Fine-grained, yellow to cream limestone, interbedded with coquinoid limestone; partly bioturbated and dolomitised (Photo 6).

Japaratuba 16

Lithologic unit 3: The lower part is represented by massive saccharoidal limestones, which are strongly dolomitised. The upper part consists of light-coloured coquinoid and bioturbated limestones (Photo 7).

5.3.2 Laranjeiras

C 652

Lithologic units 2 and 3: Greyish-yellowish bedded limestone (Laranjeiras limestone *sensu* Bengtson, 1983) with intercalations of coquinoid limestones. Bioturbation occurs throughout the section (Photo 8a, b).

5.3.3 Itaporanga

Rita Cacete 4a

Lithologic units 2 and 4: Yellow-cream coloured fine-grained, marly limestones. The section consists of alternating thick-bedded and thin-bedded beds (5–20 cm) and is clearly weathered (Photo 9).

Rita Cacete 4b

Lithologic unit 4: Grey, fine-grained, thin-bedded, laminated and marly limestones, the thickness of every layer reaches 5–10 cm (Photo 10).

Rita Cacete 5

Lithologic units 2 and 4: Yellow, bedded partly dolomitised limestones, secondary structure due to weathering nodular. The lower part of the limestone succession is less weathered than the upper part. The layers show a dip to SE (Photo 11).

Photo1a: Jardim 1

Photo1b: Jardim 1

Photo 2: Jardim 19

Photo 3a: Jardim 29

Photo 3b: Jardim 29

Photo 4: Jardim 30

Photo 5a: Jardim 31

Photo 5b: Jardim 31

Photo 6: Japaratuba 11

Photo 7: Japaratuba 16

Photo 8a: Laranjeiras C 652

Photo 8b: Laranjeiras C 652


Photo 9: Rita Cacete 4a


Photo 10: Rita Cacete 4b


Photo 11: Rita Cacete 5

Chapter 6

MICROFACIES ANALYSIS

A variety of properties are available for classifying limestones such as grain or crystal size, colour, composition and texture. The two most important features of a limestone seen in thin sections are the grain properties (including composition) and the rock fabric, that is the relationship of the grains to one another and to any groundmass (Tucker & Wright, 1990). The most widely used classification are those given by Folk (1959) and Dunham (1962).

A total of 250 thin sections throughout the whole succession and outcrop areas were described focusing on petrographical components, such as:

(1) the type of matrix and/ or cement
(2) the relative abundance of principle constituents
(3) the component association

6.1 Microfacies types

As an essential part of facies analysis differentiation of microfacies types (MFTs) for genetic interpretations, which have been carried out. Analysis of thin section characteristics led to four microfacies types (Figure 6.1), which were assigned to various depositional environments within the areas studied.

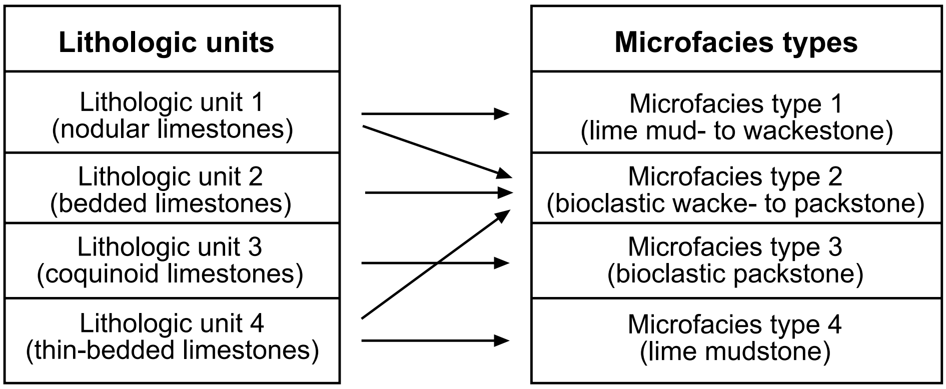


Figure 6.1: Generalised overview of the lithologic units and their corresponding microfacies types in the study area.

The defined lithologic units and microfacies types of the sampled sections are shown in Figures 6.2, 6.3, 6.4 and 6.5. The southern Japaratuba (Jardim) succession shown in Figure 6.2 is composed of five sections. Herrmann (1997) positioned the single sections one on top of the other therefore his composite sections do not correspond to that of the present work. The results drawn from field work show that the outcrop sections of southern Japaratuba (Jardim 1, 19, 29, 30, 31) are more or less overlapping. They have been arranged according to their stratigraphical level based on macrofossils and their geographic position. This composite section has been used as working hypothesis for further investigations. In addition the two overlapping sections of the Itaporanga succession (Rita Cacete 4a, b) have been represented as one in Figure 6.5, as both sections are located in the same quarry.

6.1.1 Microfacies types 1 and 2

In the field chalky nodular limestones (lithologic unit 1) that pass upwards into bedded limestones (lithologic unit 2, Figure 6.2) represent MFT 1 and 2. Microfacies type 1 is represented by a foraminiferal mudstone and MFT 2 by a foraminiferal wackestone.

The groundmass of both microfacies types is a peloidal biomicrite and/or biomicrosparite, with sparite occurring as cement in dissolved shell fragments and pseudosparite as neomorphs.

In the thin sections studied skeletal grains were identified as bioclasts, as well as peloids, cortoids and quartz grains. Cortoids, characterised by coating of relatively thin micritic envelopes are present.

Syntaxial growth of calcite on single crystals of echinoderm fragments and foraminiferal tests have been observed. All trace of original wall structures usually of 2–3 layers has been obliterated during inversion from aragonite to calcite.

Differentiation of both types is based on their bioclastic content. MFT 2 is characterised by the moderately abundance of macrofossil fragments, whereas bioclastic material in MFT 1 is scarce.

The macrofossil material of MFT 2 consists mainly of fragments of gastropods, echinoderms and bivalves (mainly inoceramids and oysters). Echinoid spines, other echinoid fragments, roveacrinids and sponge spicules are common in certain layers (Appendix 1).

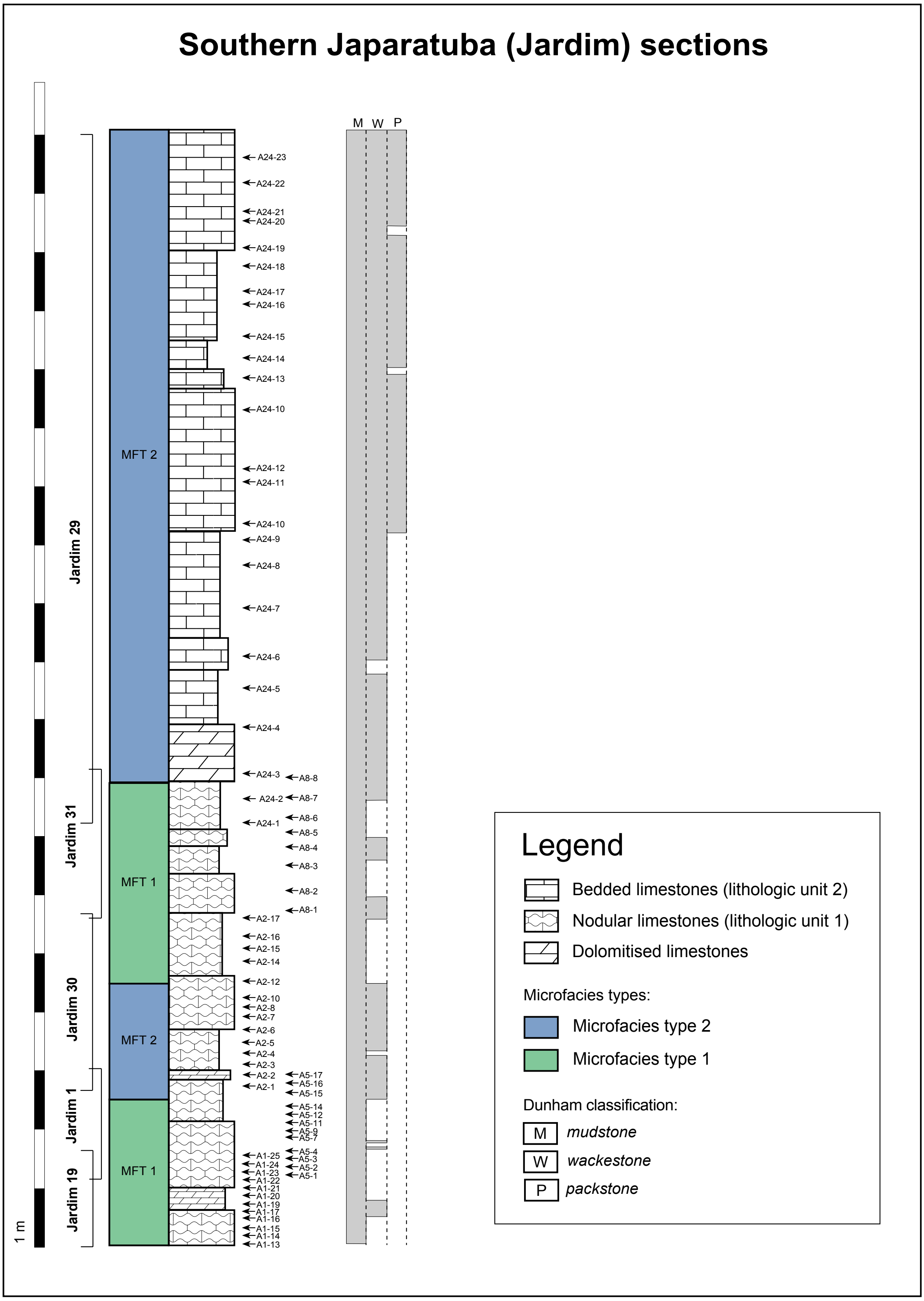


Figure 6.2: Distribution of lithologic units and microfacies types in the southern Jparatuba sections (Jardim)

Echinoid spines are identifiable through their characteristic lacy pattern. Roveacrinids are difficult to classify in thin section, as the cross section does not always show the determinable part of the species, occasionally only brachial parts can be observed (Plate 4; roveacrinids are described in detail in Chapter 7). This macrofossil group is moderately abundant in both microfacies types, whereas micromorph gastropods are more abundant in MFT 2. A variety of shapes were produced by different angles of section through these gastropods. The volume of macrofossil fragments exceeds 25% in some thin sections of MFT 2. These fragments show no signs of orientation and are not rounded. In sections, which are strongly bioturbated, macrofossil remains are generally broken. However, compaction structures are rare. In some sections elongated fragments of inoceramid bivalves are unbroken and some thin sections contain complete outlines of macrofossils (e.g. gastropods, echinoids).

The microfossil remains of both microfacies types consist essentially of benthic and plankontic foraminifers (Plate 2 & 3), i.e. *Heterohelix* sp., *Heterohelix moremani*, *Hedbergella* cf. *aprica*, *Hemicyclammina* sp., *Haplophragmium* sp. or *Thomasinella* sp., *Gabonita levis*, *Ammobaculites* cf. *reophacoides* and fragments of textulariid foraminifers (E.A.M. Koutsoukos, 1997, Rio de Janeiro, personal communication).

Some samples also contain numerous specifically indeterminable hedbergellids. Besides foraminifers some thin sections contain ostracods showing coarse sparry calcite cavity fillings. Radiolarians, carrying a micritic envelope, occur sparsely.

The original bedding or lamination has been locally homogenised by bioturbation. Microfacies type 1 and 2 are shown in Plate 1: a, b, c, d.

6.1.2 Microfacies type 3

In the field bedded limestones (lithologic unit 2) and coquinoid limestones (lithologic unit 3) represent MFT 3 (Figure 6.3 & 6.4). In thin section microfacies type 3 is represented by an echinoderm-inoceramid packstone.

The groundmass consists essentially of a peloidal biomicrite and/or biomicrosparite, with peloids being more abundant than in MFT 1 and 2. Calcitic shell fragments of macrofossils occur in abundance as bivalves (chiefly inoceramids and oysters), ammonites, gastropods, as well as echinoderm fragments (e.g. echinoid spines and roveacrinids). These individual allochems average approximately 1–2 mm in length and are mainly broken, unsorted and angular. Aragonitic shells are replaced by sparite and filled with blocky cements with isometric crystals, which increase in size towards the centre of the shell chamber. Geopetal sediment filling of shell cavity or gastropod chambers is present. Fragments of inoceramid bivalves are recognisable by their distinctive prismatic structures and their characteristic single-crystal extinction behaviour. Oyster shells show alternating constructional layers of lamellar and vesicular calcite. Other shell fragments are present but could not be associated to particular groups, due to replacement of sparite.

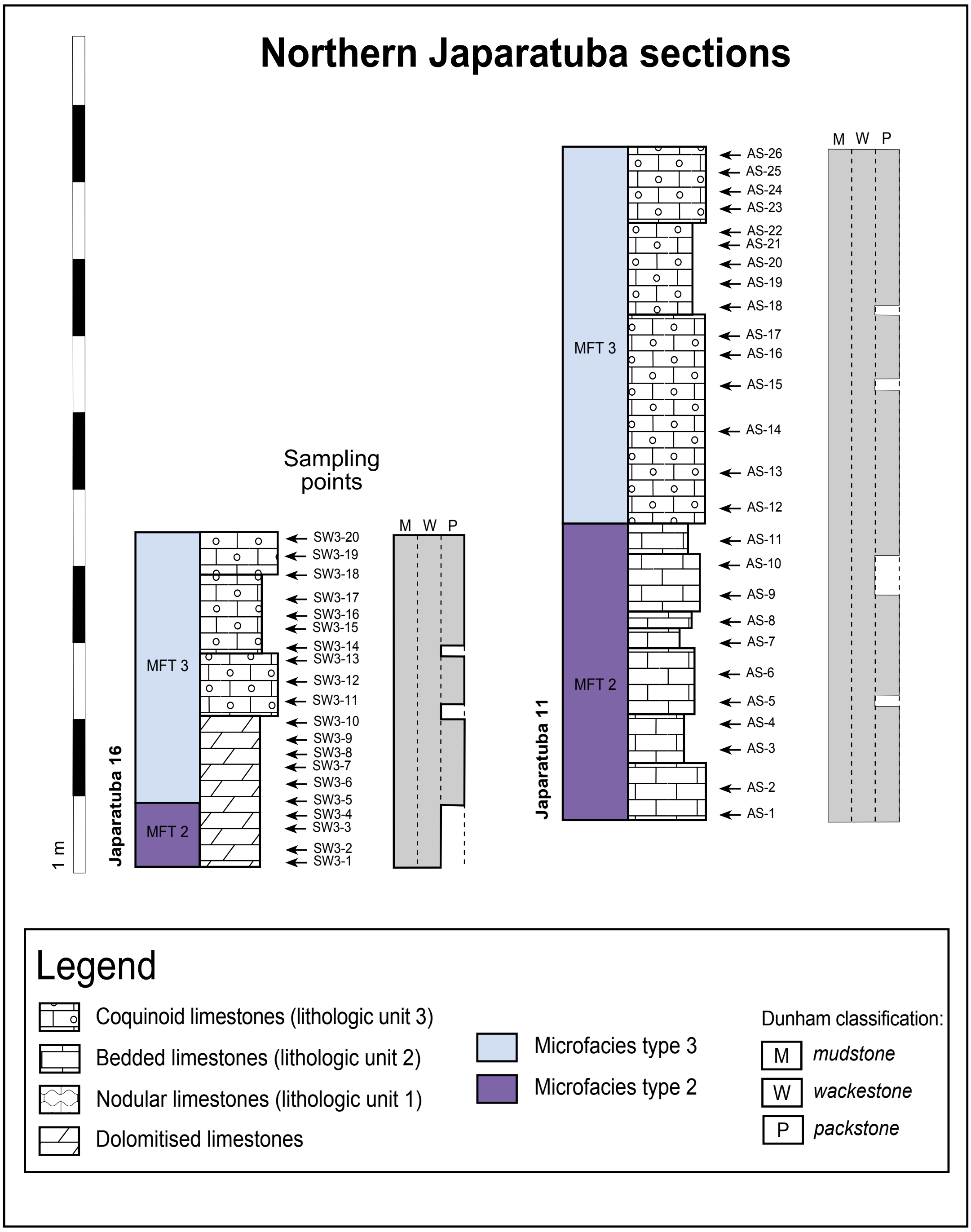


Figure 6.3: Distribution of lithologic units and microfacies types in the Japaratuba sections (northern Japaratuba).

Microfossils such as calcispheres and radiolarians are rare but occur throughout the sections. Ostracods are sparse in the studied area, only two determinable complete specimens were found and in thin sections few specimens occur. Determination of extracted forms show that they belong to the species *Brachycythere sapucariensis* and the genus *Paracypris* (G. Fauth, 1998, Heidelberg, personal communication).

Foraminifers are rare in the northern Japaratuba area, but occur in moderate abundance in the southern part of this area (Jardim sections). They are mainly represented by indeterminable hedbergellids and heterohelicids.

Micritic envelopes are restricted to aragonitic shell fragments. In addition to peloids coated grains are abundant and sparse quartz grains occur. The particle size ranges from fine sand-size of 0.25 mm to silt- and clay-size of < 0.06 mm.

The thin sections representing microfacies type 3 are partially dolomitised. The crystals observed in the thin sections show typical rhombohedral shapes and isolated dolomitic crystals are common and obliterate the textural characteristics. Dolomitisation is in most sections restricted to the micritic groundmass, whereas echinoderm fragments and other macrofossil remains are not affected. Some sections show finely crystalline dolomite replacement of the micritic matrix of a former biomicrite. This type can be classified as planar-e euhedral (Sibley & Gregg, 1987).

As in microfacies type 1 and 2, the original bedding has been locally homogenised by bioturbation. Microfacies type 3 is shown in Plate 1: e, f.

6.3.3 Microfacies type 4

In the field the thin-bedded, fine-grained marly limestones of the Itaporanga areas represent MFT 4 (Figure 6.5). This type is represented by a foraminiferal mudstone.

The groundmass consists of a laminated micrite with sparse quartzose silt. This microfacies type is characterised by the scarcity of macrofossil fragments, which are only present in particular layers. Macrofossil remains are generally scarce, however, two layers contain more than 25% of macrofossil bioclasts, e.g. echinoids and inoceramid bivalves (Appendix 1). The echinoids are neither broken nor rounded, whereas the inoceramid bivalves are only preserved as single valves. Roveacrinids are represented throughout the sections (Plate 4).

Foraminifers, calcispheres and radiolarians are moderately abundant to scarce. The foraminiferal content is represented by *Hedbergella (Whiteinella) aprica*, *Heterohelix reussi* and *Gavelinella reussi*, amongst others (Plate 2 & 3). The foraminiferal assemblage mainly consists of planktonic forms, whereas benthic taxa are rare or absent.

Scattered quartz grains occur, peloids or cortoids are absent.

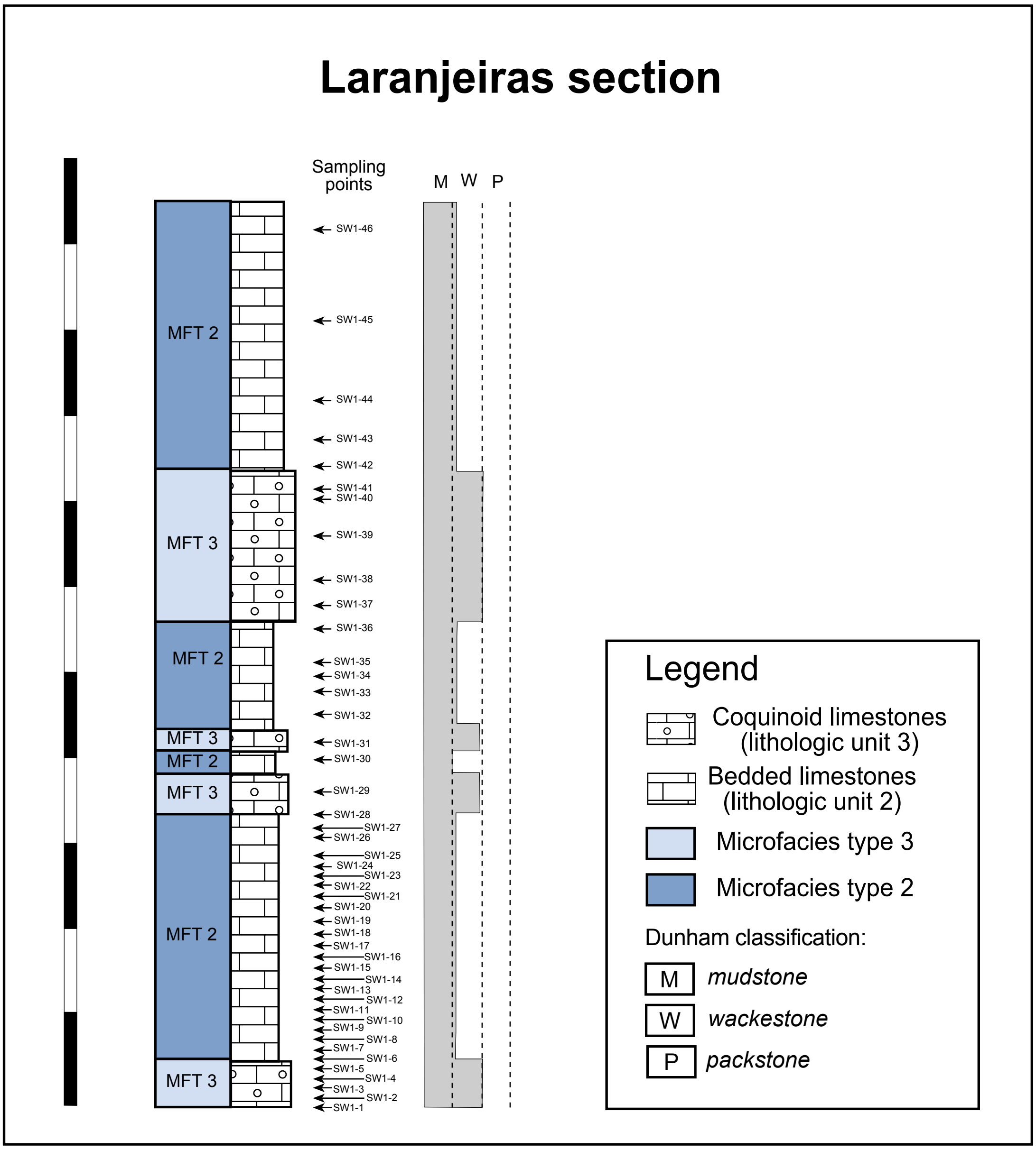


Figure 6.4: Distribution of lithologic units and microfacies types in the Laranjeiras section.

This MF type shows a variation in composition in the Rita Cacete 5 outcrop section, where bioclastic remains are more abundant, compared to Rita Cacete 4. Microfacies type 4 is shown in Plate 1: g, h.

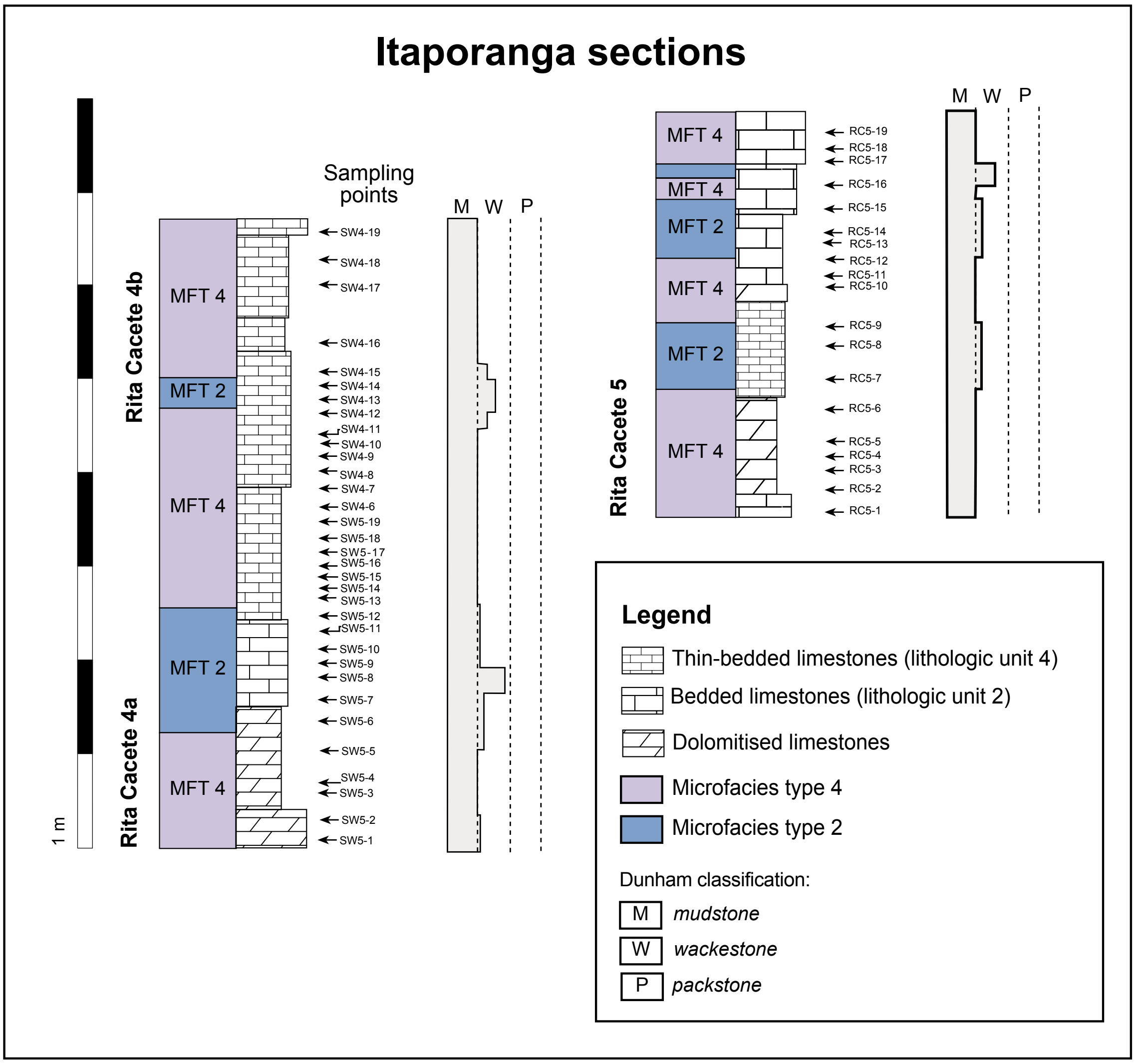


Figure 6.5: Distribution of lithologic units and microfacies types in the Itaporanga sections.

Analysis of the limestones studied led to differentiation of four microfacies types. In the lower part of the southern Japaratuba succession (Jardim area) microfacies type 1 predominates (Figure 6.2), whereas in the upper part microfacies type 2 and 3 dominate the section (Figure 6.3). These two microfacies types are also present in the Laranjeiras area (Figure 6.4). The Itaporanga sections are mainly represented by microfacies type 4 (Figure 6.5). The composition of the limestone beds in this area and hence the microfacies type changes laterally, by showing more bioclastic components in the Rita Cacete 5 outcrop. Lamination structures, the scarcity of benthic micro- and macrofossil remains and the composition of this type is similar in both Itaporanga outcrop sections.

Throughout the sections pressure solution, extensional and compressed fractures as stylolites, dissolution seams and fitted fabrics could not be observed in the sections studied. The absence of compaction structures could indicate early lithification of the sedimantary rocks. Microspar and neomorphic spar indicates that recrystallisation and cementation affected the original textures.

Discussion

Berthou & Bengtson (1988) attempted a stratigraphic correlation scheme for the Cenomanian–Coniacian of the Sergipe Basin with help of microfacies analysis. They subdivided the Cenomanian rocks in seven microfacies types and the Turonian rocks in five microfacies types, with several variation types (Figure 6.6). The possible stratigraphic application of the microfacies types in this study will be discussed in Chapter 9. At this stage the comparison of the MFTs of this study with those of Berthou & Bengtson (1988) will be worked out:

In this study the upper Cenomanian and lower Turonian limestones have been analysed. Owing to the fact that the work has concentrated on the transitional beds, analysis covers a more diminished stratigraphic part. The comparison between the microfacies types of this study with those of Berthou & Bengtson (1988) only consider the types comparable to this study and occurring in the outcrop areas of Japaratuba, Laranjeiras and Itaporanga.

Microfacies type 1 of this study resembles the type Cen E of Berthou & Bengtson (1988), a bioclastic lime mud- to wackestone with locally abundant microfossils (Figure 6.6). This type has been found in the northwestern region of the basin. Microfacies type 2 is comparable to Cen B, but contains small-sized, thin-shelled gastropods or other macrofossil remains (e.g. bivalve shells, echinoderm fragments). The micromorph gastropods are restricted to the southwestern area (Jardim outcrops). The echinoderm-inoceramid packstones classified as microfacies type 3 apparently corresponds to L Tur A (1) of their study (Figure 6.6). This type mainly occurs in the Japaratuba area (Japaratuba 11, 16) and as intercalated beds of various thickness in the Laranjeiras section. According to Berthou & Bengtson (1988) this type is represented in the northeastern (Japaratuba area) and central part (Laranjeiras area) of the basin, which is confirmed in this study, however the occurrence of this type in the Itaporanga area does not agree with the results drawn from this study.

Microfacies types and description in this study	**Microfacies types and description according to Berthou & Bengtson (1988)**
Microfacies type 1 lime mudstone, subordinately lime wackestone, macrofossil remains scarce, calcispheres and planktonic and benthic foraminifers abundant (e.g. *Haplophragmoides*)	Cen E Bioclastic mud- to wackestone, with abundant calcispheres, planktonic foraminifers and roveacrinids
Microfacies type 2 bioclastic lime wackestone, abundant echinoderm fragments, locally small-sized and thin-shelled gastropods abundant, planktonic, benthic foraminifers and calcispheres occur	Cen B bioclastic lime mudstone to wackestone, with abundant fragments of gastropods, bivalves and echinoderms; foraminifers occur
Micofacies type 3 bioclastic lime packstone, abundance of fragments of echinoderms and inoceramid bivalves, peloids and cortoids occur, microfossil remains abundant	L Tur A (1) bioclastic lime wackestone, large sparry sections of gastropods, inoceramids and echinoderms
Micofacies type 4 laminated lime mudstone or subordinately lime wackestone, scarcity or absence of macrofaunal debris and benthic microfossils	L Tur B (1) lime mud- to wackestone poor in macrofaunal debris and rare sponge spicules L Tur B (2) lime mud- to wackestone, finely lamination and more abundant calcispheres

Fig. 6.6: Microfacies types and descriptions according to Berthou & Bengtson (1988) in comparison with the microfacies types recognised in this study.

The laminated lime mudstone rare in macrofossil debris (microfacies type 4 of this study) seems to correspond to the descriptions of L Tur B (1) and L Tur B (2) (Figure 6.6) given by Berthou & Bengtson (1988) represented in the southwestern part of the study area (Itaporanga area). L Tur B (1) is characterised by poor macrofaunal debris and rare sponge spicules, whereas L Tur B (2) is finely laminated and contains abundant calcispheres. The microfacies type 4 of this study comprises both of these characteristics. Berthou & Bengtson (1988) found peloids and echinoderm wackestones only in the Cenomanian, while in this study these components also have been found in the lower Turonian of the Japaratuba and Laranjeiras localities.

The typical Cenomanian packstone microfacies with echinoderm accumulations are missing according to Berthou & Bengtson (1988) which agrees with observations made by the author. Lamination structures, which these authors found in the upper Cenomanian and lower Turonian, are according to this study only represented in the lower Turonian of the southwestern area. Different results cannot only be explained by considering that Berthou & Bengtson (1988) placed the Cenomanian–Turonian boundary at the base of the former *Vascoceras harttii–Pseudaspidoceras footeanum* zone. The current local Cenomanian–Turonian boundary is positioned in the upper part of this zone at the first occurrence of *Pseudotissotia* spp., as explained in Chapter 4.

Different results could also be due to their sampling loose material of more localities of upper Cenomanian rocks, while the author analysed material from quarries and outcrop sections, where bed-by-bed sampling on contiguous sections was possible. The disadvantage of sampling loose material is, that the limestone samples are difficult to classify regarding to their stratigraphic position. Bed-by-bed sampling in small intervals allows to record changes on a smaller scale.

In addition variations in depositional conditions, which fluctuated locally within the study area, led to deviating conclusions between both studies.

Chapter 7

PALAEOENVIRONMENTAL ANALYSIS

Palaeoenvironmental interpretation has been carried out based on facies and microfacies characteristics. The most important faunal indicators in the study area are foraminifers and roveacrinids, due to their widespread abundance. For evaluating the distribution patterns it has to be considered, that the number of samples containing microfossils varies throughout the basin. One hundred and thirty samples (seven sections) were analysed from the Japaratuba area, 46 (one section) from the Laranjeiras area and 62 (three sections) from the Itaporanga area.

7.1 Oxygen deficiency in the Sergipe Basin

The macrofossils of the Sergipe Basin have been studied recently by Seeling (1999). According to his work, the macrofaunal composition in the Itaporanga area strongly differs from that of coeval shallow-water deposits in the northern part of the basin. These differences cannot be explained only by deeper water conditions (Walter *et al.*, in press). In the Japaratuba area an abundant and diverse benthic macrofauna is present, whereas in the southern localities the benthic macroinvertebrate assemblage is only moderately abundant to scarce and almost exclusively represented by the inoceramid bivalve *Mytiloides mytiloides* and irregular echinoids (Seeling, 1999). The inoceramid *Mytiloides* is known to be low-oxygen tolerant (J. Seeling, 1999, Heidelberg, personal communication). In addition ammonites are scarce compared with localities representing shallower environments. The macrofossil assemblages of the Itaporanga sections were interpreted by Seeling (1999) as representing an exaerobic biofacies. In the following this macrofaunal evidence should be controlled by interpretation of the microfossil content and their response to different levels of oxygenation.

7.1.1 Terminology of oxygen deficiency

In many parts of the world the Cenomanian–Turonian boundary is characterised, by the presence of organic-rich rocks deposited under dysoxic-anoxic conditions.

Terminology: The phenomenon of severe oxygen depletion in continental shelf waters is of great geological significance because most of the worlds petroleum has been generated in organic-rich rocks, deposited in oxygen-depleted or oxygen-free environments (Tyson & Pearson, 1991).

Before discussing macro- and microfaunal indications for oxygen-depleted conditions around the Cenomanian–Turonian transition in the Sergipe Basin, some essential terms describing oxygen-related biofacies should be explained. An overview is given in Figure 7.1.

The most commonly used classification scheme for oxygen-deficient environments was originally proposed by Rhoads & Morse (1971). They classified environments of oxygen depletion as anaerobic, dysaerobic and aerobic with 0–0.1, 0.1–1.0 and >1.0 ml/l O_2, respectively. As pointed out by Byers (1977) this classification, in association with sediment fabrics, can be used to determine former shelf environments. Tyson & Pearson (1991) proposed the adoption of a dual terminology:

(a) terms describing oxygenation and related to facies have the ending "-oxic",

(b) terms describing the associated biofacies have the ending "-aerobic".

Roads & Morse (1971)	**Koutsoukos *et al.* (1990)**	**Tyson & Pearson (1991)**	**Savrda & Bottjer (1991)**
aerobic (> 1.0 ml/l)	aerobic (> 1.0 ml/l)	aerobic (8.0-2.0 ml/l)	aerobic (> 1.0 ml/l)
dysaerobic (0.1-1.0 ml/l)	dysaerobic (< 2.0 ml/l)	dysaerobic (2.0-0.2 ml/l)	dysaerobic (< 2.0 ml/l)
	quasi-anaerobic (> 0.1 ml/l)	quasi-anaerobic (0.2-0.0 ml/l)	exaerobic (> 0.1 ml/l)
anaerobic (< 0.1 ml/l)	anaerobic (< 0.1 ml/l)	anaerobic (0.0 ml/l)	anaerobic (< 0.1 ml/l)

Figure 7.1 Terminology for low-oxygen biofacies in marine environments

For a more detailed discussion concerning the terminology of modern and ancient anoxia the reader is referred to Tyson & Pearson (1991). The term "quasi-anaerobic" introduced by Koutsoukos *et al.* (1990) for environments with more than 0.1 ml/l O_2 (Figure 7.1) better conveys the character of the corresponding strata. Anoxic conditions are apparent on the basis of present lamination and absence of *in situ* macrobenthic body fossils. However the microfauna and/or microbioturbations demonstrate that conditions were not absolutely anoxic in the sense of complete absence of oxygen (Savrda & Bottjer, 1991). Discrimination between anaerobic and quasi-anaerobic biofacies is not always possible because the absence or presence of diagnostic macrofossils may be influenced not only by oxygen concentration. According to Savrda & Bottjer (1991) subsequent studies of both modern environments and the stratigraphical record provide a basis for a more detailed assessment of palaeo-oxygenation. They introduced the term exaerobic for environments containing more than 0.1 ml/l oxygen and for strata that lack the recognisable bioturbation of the dysaerobic and aerobic zone (Figure 7.2). According to Koutsoukos *et al.* (1991) this term is synonymous with the quasi-anaerobic biofacies; however, exaerobic biofacies contain *in situ* macrobenthic body fossils.

7.1.2 Oxygen deficiency in the outcrop areas

Indicators for oxygen-deficiency in the area studied are, amongst others: (1) the scarcity or absence of benthic foraminifers, and (2) the lamination structures, indicating the absence of bioturbation.

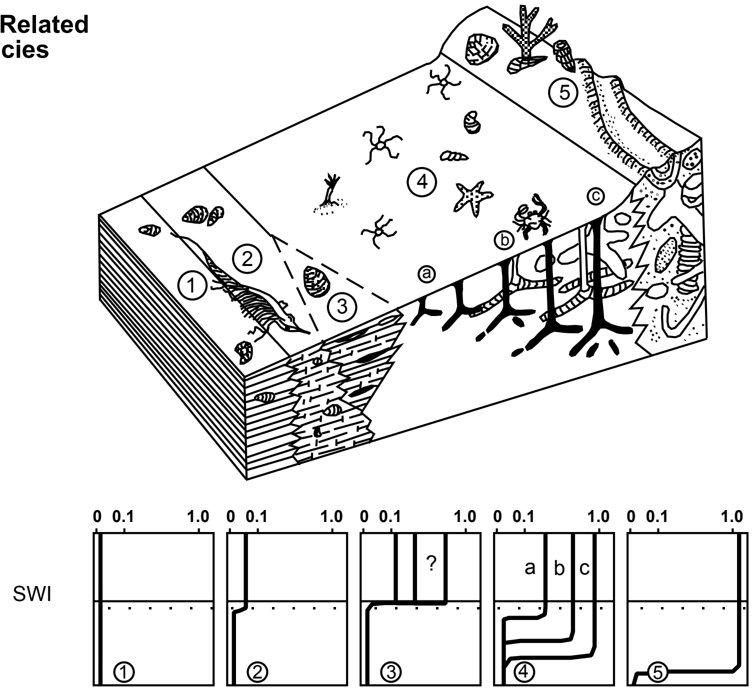
Japaratuba and Laranjeiras areas

Bioturbation throughout the Japaratuba and Laranjeiras limestones demonstrates that in this shallow-water environment bottom waters retrained enough dissolved oxygen for benthic organisms to exist. The microfaunal assemblages in this area are represented by abundant and low-diverse planktonic and benthic foraminifers, calcispheres and radiolarians. The abundance of the benthic fauna and the absence of lamination structures in the Japaratuba and Laranjeiras limestones, indicate aerobic conditions in this shallow-water environment.

Itaporanga area

The benthic microfaunal composition of Itaporanga differs strongly from that represented in Japaratuba and Laranjeiras. Whereas in Rita Cacete 5 a moderately abundant benthic microfauna is present, in Rita Cacete 4a, 4b the benthic assemblages are scarce or absent. Planktonic foraminifers are abundant in this area, whereas the benthic foraminifers are almost exclusively represented by the species *Gavelinella* *reussi*. The distribution pattern of a rich planktonic assemblage and the scarcity or absence of benthic forms in the Itaporanga area was recognised throughout the sections of Rita Cacete 4.

Oxygen-Related Biofacies



①	**Anearobic**	Well-laminated strata lacking *in situ* macro- and microbenthic body fossils and microbioturbation; may contain well-preserved remains of nektonic vertebrates, planktonic, epiplanktonic, or otherwise transported invertebrates, and faecal material of planktonic and/or nektonic origin.
②	**Quasi-Anaerobic**	Laminated strata containing microbenthic body fossils (e.g. foraminifers), but lacking *in situ* macrobenthic body fossils; transported vertebrates and invertebrates and faecal material may be common; laminae disrupted slightly by microbioturbation.
③	**Exaerobic**	Laminated strata similar to that of the anaerobic or quasi-anaerobic biofacies but containing *in situ* epibenthic macroinvertebrate body fossils (e.g. bivalve molluscs and brachiopods).
④	**Dysaerobic**	Bioturbated strata characterized by a low diversity assemblage of relatively small, poorly calcified macrobenthic body fossils or absence of body fossils altogether; diversity size, and depth of penetration of burrows decrease systematically with declining oxygenation within this realm.
⑤	**Aerobic**	Bioturbated strata (where physical processes do not dominate) containing diverse assemblage of relatively large, heavily calcified macrobenthic body fossils; trace fossils and ichnofabric are variable as a function of environmental energy, substrate consistencey, salinity, etc.

Figure 7.2: Oxygen-related biofacies after Savrda & Bottjer (1991)

7.2 Palaeoenvironment-indicating fauna

The described microfacies types are among other features characterised by their faunal associations thus indicating different depositional environments. Besides macrofossil fragments, the microfauna are used as facies indicators and therefore provide comprehensive information about the depositional evolution of the area studied (Figure 7.3, 7.4). The macrofossils have been studied in detail by Seeling (1999). In this work they are only described as part of the thin-section analyses. In addition to foraminifers, which provide the most useful information concerning the palaeoenvironments, roveacrinids are a useful group to reconstruct the depositional setting. Both groups are described in detail in the following section and Chapter 9.

In the Sergipe Basin the microfacies at the Cenomanian–Turonian boundary are comparatively poor in determinable roveacrinidal fragments (5% roveacrinids). The current state of knowledge suggests they have a planktonic larval stage, but if their adult stage is planktonic too this is still questionable. The Sergipe assemblages are relatively well diversified. A total of seven species were determined in the Cotinguiba Formation of the Sergipe Basin (Ferré *et al.*, in press), which can be used as biostratigraphical tool (see Chapter 9). Roveacrinids mostly lived in outer shelf and upper slope environments and therefore can be used as facies indicators for these palaeoenvironments. In addition to roveacrinids, calcispheres, radiolarians and scarce ostracods are present in the upper Cenomanian–lower Turonian limestone beds of the study area.

7.2.1 Foraminifers

The most widespread facies diagnostic microfossils in the study area are represented by foraminifers. These are like many marine microfossils affected by changes in the palaeoenvironment and can therefore be used as facies indicators. The composition and distribution patterns of benthic foraminiferal assemblages indicate a close interaction of palaeobathymetry and the substrate type and its stability (Koutsoukos & Hart, 1990b). As already pointed out, further information is given by distribution characteristics of the foraminiferal assemblages, as the evaluation of the degree of oxygen depletion in the water column and the extent of the oxygen-minimum zone in the depositional environment.

In this study foraminifers are small-sized, moderately abundant, but poorly preserved. The quantity of specimens depends on the depositional environment and the degree of dissolution due to weathering or dolomitisation of the samples. Foraminifers are not recovered throughout the succession but are common in various layers. For statistical evaluation the number of recovered specimens is not sufficient. However, these foraminifers indicate environmental changes.

Determination of foraminifers in thin sections can be difficult due to randomly orientated sections and destruction of original wall-structure by micritisation and recrystallisation. In addition, triserial tests may appear as uniserial or biserial. Determination of the foraminiferal assemblage was done by E.A.M. Koutsoukos (1998, Rio de Janeiro, personal communication) by working with thin sections and extracted forms.

The low-diverse planktonic foraminiferal assemblages of the Japaratuba area are characterised by species of *Heterohelix, Guembelitria, Hedbergella,* and *Globigerinelloides*. Benthic forms are represented by bolivinids (e.g. *Gabonita levis*) and lituolids (e.g. *Ammobaculites, Haplophragmium*) (Figure 7.3, 7.4). In the Laranjeiras sections *Hedbergella, Guembelitria* and *Marssonella* are abundant, with hedbergellids dominating the assemblage.

Foraminifers		**Japaratuba**	**Laranjeiras**	**Itaporanga**
planktonic	*Guembelitria cenomana*	○		○
	Guembelitria cretacea		○	
	Heterohelix reussi			○
	Heterohelix moremani	○		○
	Heterohelix globulosa	○		
	Hedbergella (W.) aprica			○
	Hedbergella (W.) cf. *aprica*	○		
	Hedbergella (W.) cf. *baltica*			○
	Hedbergella (W.) brittonensis		○	
	Globigerinelloides benthonensis	○		○
	Haplophragmium sp.	○		
	Conorboides sp.			○
	Huglobulosa sp.			○
benthic	*Gavelinella reussi*			○
	Thomasinella sp.	○		
	Gabonita levis	○		
	Ammobaculites sp.	○		
	Ammobaculites cf. *reophacoides*	○		
	Marsonella sp.		○	
	Hemicyclammina sp.	○		
	Praebulimina sp.	○		
	Textulariidae	○		

Figure 7.3: Distribution of planktonic and benthic foraminifers in the studied localities

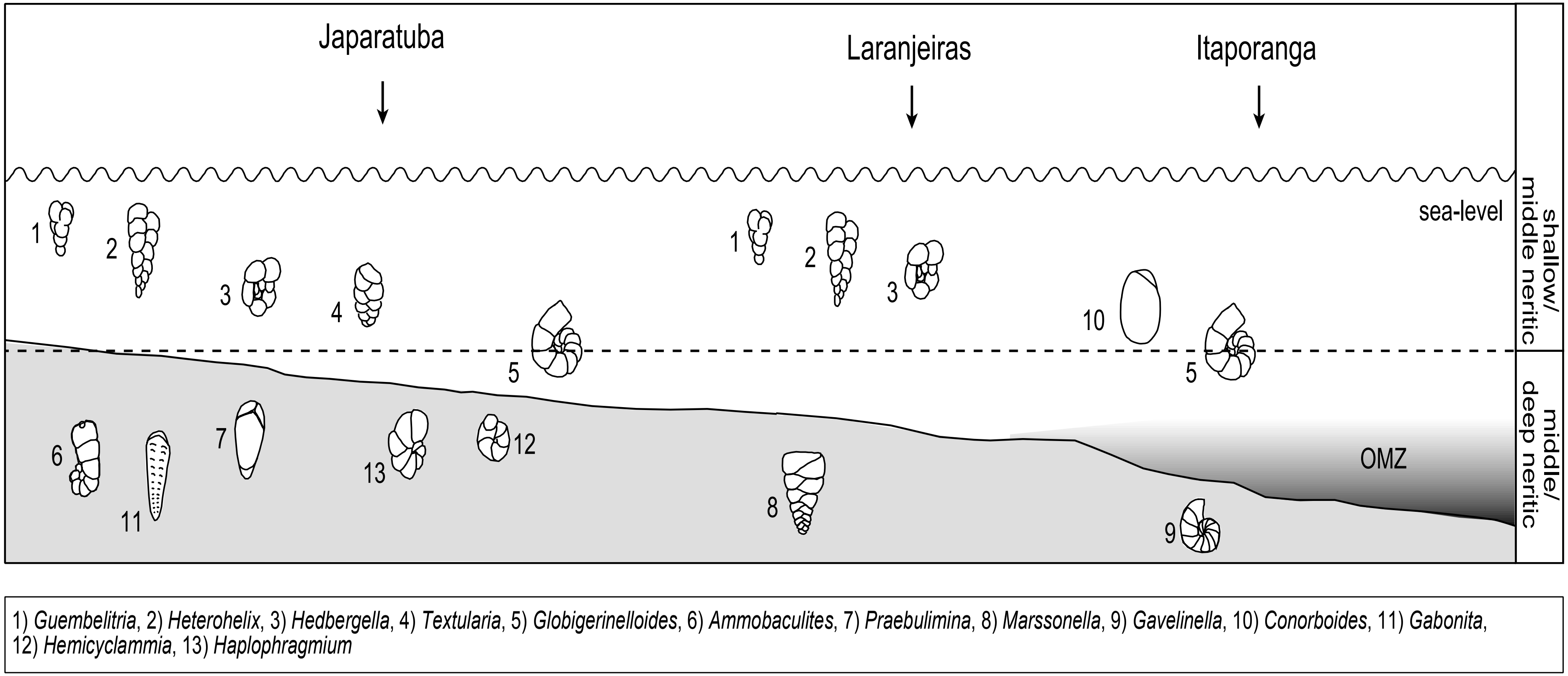
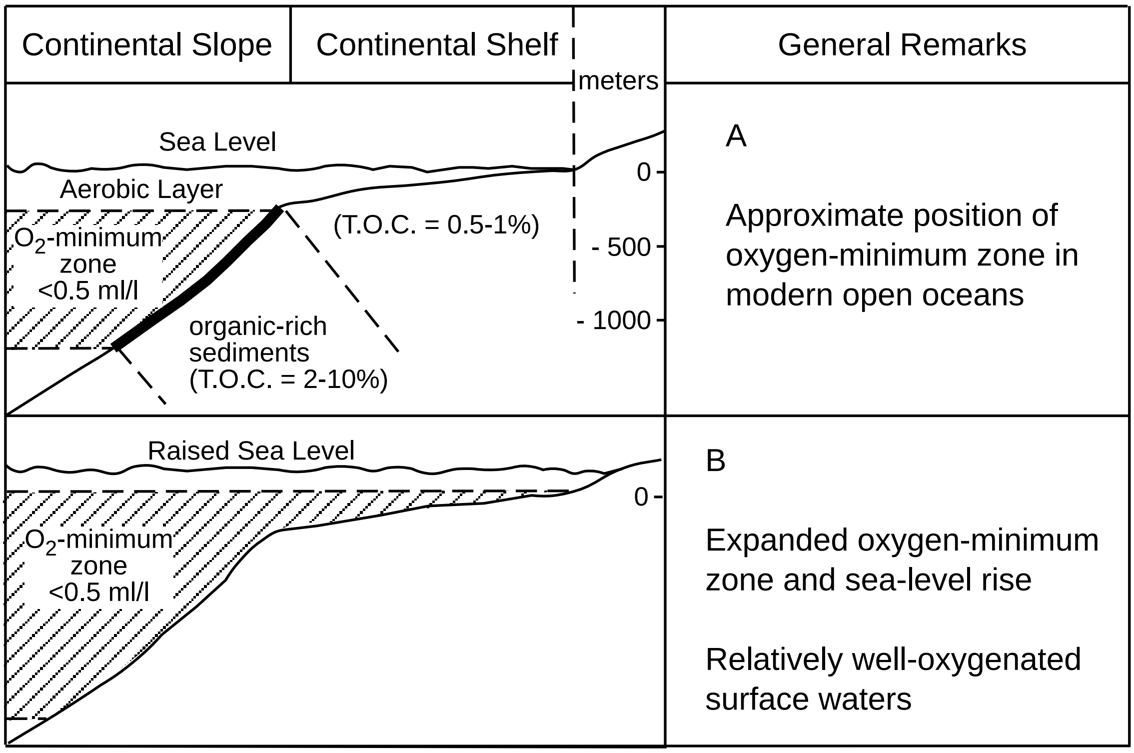


Figure 7.4: Distrubution of benthic and planktonic foraminifers in the studied areas and rising oxygen-minimum zone in the lower Turonian in the Itaporanga area (modified after Koutsoukos, 1989)

Hedbergellids (e.g. *Hedbergella (Whiteinella) baltica*) and heterohelicids (e.g. *Heterohelix moremani*) dominate the planktonic assemblages of the Itaporanga limestones. However, the main characteristic for the Itaporanga succession is the scarcity of benthic foraminifers, which are rare or totally absent here (Figure 7.3, 7.4). The foraminiferal species found in the study area are listed in the following Figure 7.3.

Discussion

In this study the low-diverse planktonic foraminifers consists almost exclusively of *Hedbergella* spp. and *Heterohelix* spp. This phenomenon has been explained as the effect of a possible ecologic barrier formed as the result of heavy influx of fresh waters from tropical rains and rivers. However, according to Bengtson & Berthou (1988), palaeoclimatologic data does not provide unambiguous support for this conclusion. In this study the periodically expansion of the oxygen-minimum-zone was suggested to cause this phenomenon (Figure 7.5). This conclusion largely confirms the results drawn from Noguti & Santos (1973) concerning the foraminiferal assemblages from the Albian and Cenomanian and the interpretation given from Berthou & Bengtson (1988).



Approximate position of oxygen-minimum zone in modern open oceans

Expanded oxygen-minimum zone and sea-level rise

Relatively well-oxygenated surface waters

Figure 7.5: Rising oxygen-minimum zone (after Mello *et al*., 1989)

The influence of oxygen deficiency in the Sergipe Basin on the microfauna has been discussed by Mello *et al.* (1989) and Koutsoukos *et al.* (1990, 1991). Their faunas have been analysed from outcrop and well sections, including one of the sections studied herein (Itaporanga area). In the present study additional sections from shallower environments throughout the shelf area have been analysed in order to recognise the influence and effect of oxygen-depletion on the shelf environment and its faunal association.

According to Gale *et al.* (2000) a decline in benthic diversity is not only related to decreasing oxygenation levels. The key factor controlling benthic diversity must be the palaeoproductivity in the overlying water column, related to palaeooceanographic events (e.g. sea-level rise/fall) (Gale *et al.*, 2000). A rising sea-level cause a switch from mesotrophic to oligotrophic oceanographic conditions and a breakdown of shelf-edge fronts (according to Summerhayes *et al.* (1995) the boundary between shelf seas and open oceans marked by zones of mixing are called shelf-break fronts (Gale *et al.*, 2000)). The decline in benthic diversity has been explained by changes in surface water productivity generated through normal oceanographic processes according to Gale *et al.* (2000). In their study of the mid-shelf environments of SE-England, a constant oxygenation level is evidenced by their macrofauna, their trace fossils and their sedimentary geochemistry. In addition, their limestone beds show bioturbation throughout the succession.

In the sections studied small-sized specimens of benthic foraminifers, low in diversity are suggested to indicate dysoxic conditions. The foraminiferal assemblages in addition to abundant calcispheres and radiolarians are indications of open water conditions at the outer shelf, suggesting high epipelagic primary productivity, with seawater apparently containing high levels of dissolved silica (Mello *et al.*, 1989; Koutsoukos *et al.*, 1990, 1991). On the other hand, the benthic assemblage indicates bottom waters depleted in oxygen, with low pH and enriched in carbon dioxide (Mello *et al.*, 1989). The abundance of radiolarians, calcispheres and planktonic foraminifers in the Itaporanga limestones provides strong evidence that anoxia was locally related to the development of an intense oxygen-minimum zone caused by enhanced ocean-surface productivity. In particular, the microfaunal association is interpreted as representing an exaerobic facies *sensu* Savrda & Bottjer (1991). According to Sagemann *et al.* (1991) this zone represents a small-sized region, in which shelly epifauna colonised substrate surfaces during transitions between anoxic and dysoxic event layers. The exaerobic biofacies is characterised by laminated strata containing epibenthic macroinvertebrates and the lack of bioturbation of the dysaerobic and aerobic facies but contain *in situ* macrobenthic body fossils in contrast to the anaerobic and quasi-anaerobic biofacies. This biofacies apparently has been deposited under anoxic conditions with periodically experienced episodes of re-oxygenation. Savrda & Bottjer (1991) suggested that it is currently impossible to accurately determine absolute oxygen concentrations during development of other biofacies, although it seems reasonable to assume bottom-water oxygen levels at or below 0.1 ml/l for quasi-anaerobic and anaerobic biofacies.

Neither the presence of bioturbation nor the absence of organic-rich deposits prove that an oxygen-minimum zone has not developed in the water column (Jarvis *et al*., 1988). On the other hand the decline of microfossil abundance and diversities in the Sergipe limestone succession strongly suggests that bottom waters became significantly depleted in oxygen, but does not indicate truly anoxic bottom conditions.

Well-oxygenated conditions are suggested for the Japaratuba area (Figure 7.4). This conclusion coincides with the observed macrofaunal content described by Bengtson (1983), who concentrated his work on ammonites, and the results drawn by Seeling (1999) concerning bivalves, gastropods and echinoids. The benthic foraminiferal assemblage in the Laranjeiras area is relatively poor compared to that of the Japaratuba area. It has to be considered that only one section has been sampled in this area compared to seven sections studied in the Japaratuba area. However, the depositional environment was similar to that of the Japaratuba area, due to resembling sedimentary structures (e.g. bioturbation), macro- and microfossil content and microfacies types (Figure 7.4). Along with low diversity and scarcity of the benthic fauna, the presence of laminated mudstones of the Itaporanga area indicates low-oxygen conditions (Figure 7.4).

Dysoxic to anoxic waters are frequently observed to expand upwards and outwards during warmer episodes and after upwelling events, when the water column is temporarily stratified by a strong thermohaline (Tyson & Pearson, 1991). These localised and temporally variations in oxygen content could explain the increasing presence of benthic organisms and bioturbation structures observed in Rita Cacete 5. With rising sea level, the oxygen minimum zone expanded upwards and affected also the outer ramp area, as indicated by the microfaunal assemblage of the Itaporanga limestones (Rita Cacete 4 a, b). The oxygen minimum zone generally creates stratification in degree of oxygen depletion, which increases with depth (Mello *et al.*, 1989). For the area studied, two layers can be broadly distinguished: an upper aerobic layer (> 1.0 ml/l O2) and a lower thicker exaerobic layer (> 0.1 ml/l O2). The estimated water-depth in which the exaerobic layer arises is the middle- to deep neritic environment. Both layers are represented in the Itaporanga area, with an aerobic surface layer, where a diverse planktonic fauna developed and an exaerobic bottom layer, which hampered the fully development of benthic assemblages.

7.3 Conclusions

The Japaratura benthic assemblages (e.g. *Hemicyclammina* sp., *Haplophragmium* sp. and *Ammobaculites* sp.) indicate shallow neritic to paralic conditions, which may be hyposaline, but not necessarily. These forms developed locally in very shallow landlocked environments within the tropical belt (Koutsoukos, 2000, Rio de Janeiro, personal communication). The benthic forms of the Laranjeiras section indicate a shallow to middle neritic environment and are represented by eggerellids (*Marssonella*). The benthic assemblages in the Itaporanga area (*Gavelinella reussi*) indicate among other rare diagnostic microfossils, middle to deep neritic conditions.

Roveacrinids occur in association with calcispheres in middle to deep neritic environments in the Japaratuba area as well as in the Laranjeiras, but are more abundant in the Itaporanga area.

Shallow conditions (paralic to shallow neritic) are recognised towards the northeastern region (Japaratuba area). The deepest environments in the Sergipe Basin seem to have been restricted to the southwest area (Itaporanga area) through a long narrow seaway.

The Japaratuba and Laranjeiras areas show more or less similar depositional and palaeoenvironmental conditions indicated by resembling microfacies types and microfaunal content. The assemblages of the Itaporanga area indicate oxygen depleted biotopes, characterised by the nearly absence of benthic microfossils and lamination structures. The hypoxic/anoxic conditions are a probable consequence of the periodic expansion of the oxygen-minimum zone. The oxygen-minimum zone affected the shelf and slope regions and created stratification in degree of oxygen depletion.

The planktonic foraminiferal assemblages are characterised by specimens indicating widespread oxygenated epipelagic layers of variable thickness in space and time throughout the basin in all three areas studied.

Together with sedimentological and micropalaeontological data, the Japaratuba and Laranjeiras sections indicate oxygenated conditions, representing an aerobic biofacies; the Itaporanga limestones (Rita Cacete 4 and 5) indicate low-oxygen conditions, representing an exaerobic biofacies (*sensu* Savrda & Bottjer, 1991).

The hypoxic conditions (*sensu* Koutsoukos *et al.*, 1990, 1991) of the mid-Cretaceous deposits seemed to coincide with abundance peaks of roveacrinids. They seem to have thrived in such environments where they developed abundant opportunistic populations probably feeding on calcisphere blooms (Ferré *et al.*, in press).

Chapter 8

FACIES MODEL

A “short-hand” method of studying limestones is the comparison with standard microfacies types (SMF). This system devised by Flügel (1982) from a concept from Wilson (1975) describes 24 standard microfacies assignable to nine standard facies belts. For each outcrop area, several microfacies have been described and selected to illustrate the main depositional types. Four microfacies types were identified (Figure 8.1), of which three can be referred to a facies association that apparently corresponds to Facies Zone 2 proposed by Wilson (1975). This association can be subdivided into microfacies types 1, 2 and 3 (MFT 1, 2, 3). They are represented by a foraminiferal mud- to wackestone (MFT 1 and 2) and echinoderm-inoceramid packstone (MFT 3) characterised by abundant bioclasts. The fourth microfacies type (MTF 4) is represented by a foraminiferal mudstone and apparently corresponds to Facies Zone 3 of Wilson (1975). According to Carozzi (1989) this concept to build a generalised depositional concept appears as an oversimplification. Because there are many exceptions, this model can only give a broad overview, which has to be refined in every single case. Wilson´s (1975) universal model is basically that of carbonate shelf sedimentation, and in the author´s opinion not applicable for the carbonate sections studied of the Sergipe Basin. In recent times the concept of the ramp model has become an alternative to the shelf model and will be preferred herein.

Based on lithological and microfacial analysis studies a depositional model was established for the studied area. Information on the rock texture, the mineral or skeletal nature of the components, the proportion of these components and their distribution within the matrix is preserved in thin section, therefore microfacies is an essential tool for the analysis of the mode of transport and depositional environment of the sediments.

The model presented herein shows depositional conditions during lower Turonian times, due to the fact, that for this time interval the most complete and comparable data was available in the study area.

Terminology: According to Simo (1993) a carbonate ramp is characterised as follows: shallow wave-agitated facies of the nearshore zone which pass downslope without a marked break in slope, into deeper water low energy deposits. Ramps can be subdivided on the basis of profile into homoclinal ramps and distally steepend ramps. The term "platform" characterises in general a break in slope that mark the shelf margin and steeper slope. Three types of platform margins were described by Wilson (1975), but none of them include platforms that lacked a slope break. Several ramp classifications have been offered. Read (1982, 1985) refined the concepts of ramps and recognised six types based on the character of the highest energy facies and the distribution of shallow-water facies. Burchette & Wright (1992) proposed a classification based on the degree of wave, tide and storm activity. They distinguished two main areas:

(a) the mid-ramp area, as the zone between the fair weather wave base and the storm wave base, so that storm processes dominate;

(b) the outer-ramp area, as the zone which extends from below normal storm wave base to the basin floor.

Ramps can develop in a variety of tectonic settings and can be recognised as sedimentary surfaces that represent different tectono-sedimantary settings (Ahr, 1998).

The facies model established herein bases on the classification given by Burchette & Wright (1992) of ramp environments.

8.1 Facies model for the Sergipe Basin

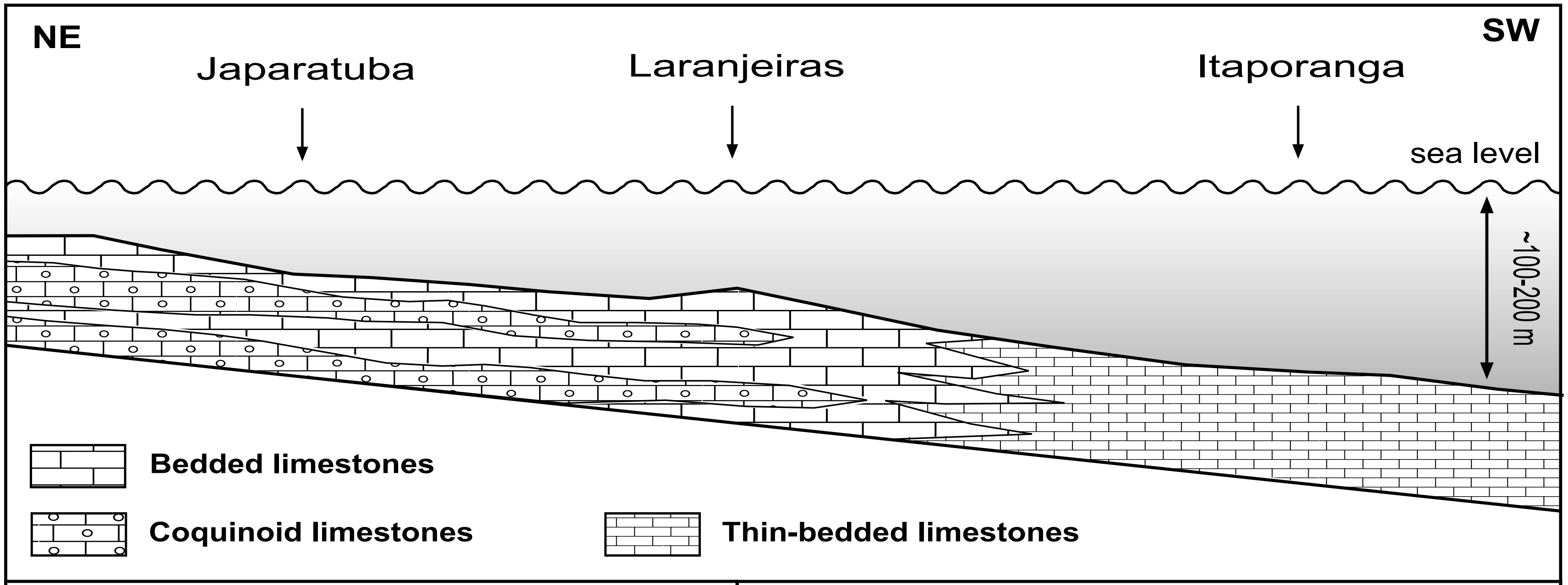
In the presented facies model, the different microfacies types are characteristic for both depositional areas, the mid-ramp and the outer ramp area (Figure 8.1).

8.1.1 The mid-ramp area

The mid-ramp area situated in the northeastern and central part of the Sergipe Basin, is represented by bedded limestones, intercalated with coquinoid limestones (lithologic unit 2 and 3). These beds mainly consist of microfacies type 2 and 3 (Figure 8.2).

Microfacies type 2 is characterised by an abundance of thin-shelled macrofossil remains. In the southern Japaratuba area. Micromorph gastropods are concentrated in certain sections.

The foraminifers and calcispheres indicate deposition in a neritic environment at water depths of 40 to 80 m (D. Dias-Brito, 1997, Rio Claro, personal communication). Roveacrinids are present. Both microfacies types occur in the upper Cenomanian succession, predominantly in the lower parts of the Japaratuba sections (Jardim area). In the lower Turonian of the Laranjeiras section, microfacies type 2 predominates.



mid-ramp	outer-ramp
Microfacies type 2 & 3	**Microfacies type 4**
Packstone/Wackestone Increasing bioclasts of echinoderms and inoceramids, roveacrinids moderately abundant high content of planktonic and benthic foraminifers, rare calcispheres, quartz grains, peloids, cortoids and micritic envelopes common, strong bioturbation	Mudstone Macrofossil debris nearly absent, roveacrinids common, planktonic foraminifers and calcispheres occur, benthic microfauna rare, quartz grains, peloids, cortoids and micritic envelopes absent, lamination structure

Figure 8.1: Facies model for the studied area in the lower Turonian (modified after Walter *et al.*, in press)

The mid-ramp area is characterised by abundant bioclasts predominantly echinoderm and inoceramid remains, and a high content of shallow-water organisms (e.g. foraminifers). The level of water-energy is shown by the abundance of peloids and cortoids and the degree of roundness of the bioclastic material. Strong bioturbation throughout this region is indicative of the content of dissolved oxygen in the water column (Figure 8.1 & 8.2).

Microfacies type	**Characteristics**	**Fossil content**	**Depositional environment** (Burchette & Wright, 1992)
1	lime mudstone or lime wackestone, bioturbated, peloids scarce, syntaxial rim cement, quartz grains	Gastropods, bivalves, echinoderms (echinoids, roveacrinids) occur, benthic and planktonic foraminifers abundant, radiolarians scarce, calcispheres scarce	mid-ramp area
2	bioclastic lime wacke- to packstone, bioturbated, peloids scarce, syntaxial rim cement, quartz grains occur	Gastropods abundant, bivalves occur, echinoderms (echinoids, roveacrinids) abundant, benthic and planktonic foraminifers abundant, radiolarians and calcispheres occur	mid-ramp area
3	bioclastic lime pack-stone, bioturbated, peloids occur, peloids, cortoids and quartz grains occur	Gastropods occur, bivalves and echinoderms (echinoids, roveacrinids) abundant, benthic and planktonic foraminifers occur, radiolariens scarce, calcispheres rare	mid-ramp area
4	lime mudstone subordinately lime wackestone, laminated, absence of quartz, grains and peloids	Gastropods absent, bivalves (inoceramids) rare, echinoderms (echinoids, roveacrinids) rare, planktonic foraminifers occur, benthic formaminifers rare, radiolarians occur, calcispheres abundant	outer-ramp area

Figure 8.2: Overview of the different microfacies types and their depositional environment

8.1.2 The outer-ramp area

The outer-ramp environment is characterised by thin-bedded lime to marlstones (lithologic unit 4), represented by microfacies type 4 (Figure 8.1). Macrofossil debris is rare, and locally represented by echinoid or inoceramid fragments. Roveacrinids are common in these facies. Peloids and cortoids are rare (Figure 8.2).

The microfossil content is characterised by moderately abundant planktonic foraminifers and calcispheres, with a few radiolarians present. The benthic microfossil assemblage is scarce or missing. Bioturbation is absence laminated strata is the predominant feature throughout this outer-ramp region.

Discussion

The most important framework builders of the Cretaceous were rudists, corals, sponges and encrusting algae, which are typically absent in the Sergipe Basin (Walter *et al.*, in press). According to Tucker & Wright (1990), slope sediments consist of components brought in by currents from shallower parts of the carbonate platform and sediments deposited from suspension. The reason for the absence of these framework builders could be the lack of suitable shoals on ramps for reefs to develop. This phenomenon has been described from the Niger ramp (Pascal *et al.*, 1993; Mathey *et al.*, 1995). According to Burchette & Wright (1992) shallow-water reef builders are scarce on ramps, however, small isolated build-ups are common. Bengtson (1983) described slumping, intraformational breccias and other coarse-grained sediments from the lower Turonian of other parts of the Sergipe Basin. However, in the areas studied these are missing.

Analysis of foraminifers shows that there is no evidence of wide ranging transport of the specimens. Juvenile forms are as abundant as adult forms. However, the distribution of micromorph gastropods is probably size-dependent due to transport-variations. According to Mancini (1978) the origin of micromorph faunas are multiple. The gastropod tests could have been winnowed out and concentrated separately. There is no evidence for fluctuating environmental parameters leading to paedomorphosis or low oxygen content leading to stunting in this environment. This coincides with the conclusions drawn by Seeling & Bengtson (1999) concerning the accumulation of small-sized oysters in the southern Japaratuba area, which have been explained by size-sorting due to transport. The shell fragments of the coquinoid limestones of the Japaratuba and Laranjeiras area observed in thin sections, are evidence of contact of shells with other bioclasts during transport by currents. The soft mud only partly preserved the elongated shell fragments from breakage in the fossil-poor mudstones.

The origin of micrite remains a major problem in carbonate sediments, it can be of matrix or cement in origin (Flügel, 1982; Tucker & Wright, 1990).

Lithologic unit 1, (nodular limestone) representing the outer-ramp area (Walter *et al.*, in press), is exposed in the southern Japaratuba area (Jardim sections), and corresponds to microfacies type 1 and 2. Cortoids and peloids dominate the lower part of the southern Japaratuba area (Jardim area), where they coincide with shallow-water foraminifers (e.g. *Ammobaculites*), which are characteristic of a neritic to paralic environment. These sediments deposited above and below the storm wave base are of late Cenomanian age and are therefore excluded from Figure 8.2. The most comparable data is of early Turonian age and has therefore been illustrated herein.

Previous models

Berthou & Bengtson (1988) and Herrmann (1997) established different facies models for the Sergipe Basin. The model of Wilson (1975) was preferred by Berthou & Bengtson (1988). The depositional environment according to their microfacies study was that of a carbonate shelf to open sea shelf and slope environment, representing facies belts FZ 2 to FZ 7 of Wilson (1975). To the current state of knowledge the model of a carbonate ramp is supposed to be more practic-related and more precise to represent the depositional environment of margin platform type (e.g. Tucker & Wright, 1990). In his diploma theses Herrmann (1997) proposed the facies model of a carbonate ramp for upper Cenomanian–lower Turonian deposits of the Japaratuba area, however also using the facies zones of Wilson (1975) for describing the depositional environment of the limestones. Two additional sections of this area have been analysed and integrated in this model by the author; the results will be published in Walter *et al.* (in press). The conclusions drawn by Herrmann (1997) and Walter *et al.* (in press) have been supplemented by evaluating the Laranjeiras and Itaporanga sections. Due to the comparison of results of three study areas along the axis of the Cenomanian–Turonian outcrop belt from northeast to southwest in this work the palaeoenvironmental conditions from shallower to deeper parts of the basin have been worked out and the facies model has been completed.

8.2 Conclusions

The depositional environment of the lower Turonian limestone succession in the Sergipe basin was that of a ramp, with a gentle dip (Figure 8.1). The microfacies types represented in the localities studied occur in two regions of the carbonate ramp, the mid-ramp and the outer-ramp area. Sediments from the inner ramp and the basin have not been sampled, or are not present in the study area. Transitional sediments between the lithologic units are not exposed.

The mid-ramp area: The bioturbated bedded limestones (lithologic unit 2), with intercalations of coquinoid limestones (lithologic unit 3), deposited in the mid-ramp area, are exposed predominantly in the northeastern and central part of the Sergipe Basin (northern Japaratuba and Laranjeiras area), and correspond to microfacies type 2 and 3. These sediments were deposited below the fair-weather wave base, probably influenced by storm-wave action. Peloids and cortoids were found in abundance in the upper part of the Japaratuba area, where in addition micritic envelopes and blocky cements are present. The environment of origin of these coated particles and the quartz grains could be the intertidal zone situated in the north of this locality. The southern Japaratuba limestones were strongly influenced by bioclastic material brought in by currents from the littoral zone. These currents also reached the Laranjeiras area, reduced in thickness, where they are responsible for intercalated coquinoid layers.

Sedimentation took place in water depths of 50–100 m, well-oxygenated and of normal salinity with good current circulation, where shallow-water organisms are abundant. Because fair-weather wave action is missing rather uniform composed limestone beds occur as widespread neritic shelf deposits. These are very fossiliferous limestones, bioclastic wackestones with coquina banks, there is much pelleting of the micritic matrix. The sediment is homogenised through burrowing.

The outer-ramp area: The outer ramp area, situated in the southwestern part of the Sergipe Basin (Itaporanga area), is characterised by laminated and bedded lime- to marlstones (lithologic unit 4), and represents the deeper part of the determined facies zone. Here, microfacies type 4 predominates in the sections (Figure 8.1).

Bioturbation is absent and the scarcity of a benthic fauna is evident for oxygen depleted bottom conditions. The calcispheres are in addition to the lithologic features as the fine laminations of these limestones show, that deposition took place in deeper water environments (between 100–200 m water depth) compared with the microfacies types of the Laranjeiras and Japaratuba areas. Peloids and micritic envelopes are absent due to low water-energy.

The absence of bioclastic material in the southwestern area is probably caused by a decrease of current strength from the northeast to southwest, from the Japaratuba to the Itaporanga area respectively (Walter & Bengtson, 1998).

The high degree of sorting and rounding of quartz grains represented in the mid-ramp area suggests that this material was either derived from a high-energy environment, such as the intertidal zone, or reworked from older deposits.

Sedimentation took place below the oxygenation level in dysaerobic water conditions, with restricted current circulation (Chapter 7). Thin-bedded, marly limestones and lime mudstones occur with very small peloids and bioclasts, because wave action is missing. Crinoid accumulations may be present.

Chapter 9

STRATIGRAPHY

Biostratigraphy and correlation by microfacies in combination with stable isotope stratigraphy were the principal methods for establishing the chronostratigraphical position of the sections studied here. The key macrofossil groups for biostratigraphy of the Sergipe Basin are ammonites and inoceramid bivalves. These have been studied, for example, by Bengtson (1983) and Hessel (1988) and, most recently, by Seeling (1999). Microfacies analysis can be of considerable value as a complementary chronostratigraphical tool in areas where diagnostic macro- and microfossils are scarce or lacking. A regional atlas of microfacies types was established by Berthou & Bengtson (1988) for the Cenomanian–Coniacian of the basin. Their microfacies types are compared with those established here, as described in Chaper 6. In the present study roveacrinids and foraminifers were specifically analysed in thin section for biostratigraphical purposes.

In this study a first attempt was made to use stable isotope stratigraphy for correlating the Cenomanian–Turonian outcrop sections of the Sergipe Basin.

9.1 Biostratigraphy in the study area

Macrofossils are represented in the Cenomanian–Turonian boundary beds of Sergipe by ammonites, inoceramid bivalves, other bivalves, gastropods, and echinoderms. Their remains found in thin section play a subordinate role for biostratigraphical purposes but may be indicative in regard to palaeoenvironmental changes. These were discussed in Chapter 7.

Microfossils are represented by foraminifers, calcispheres, ostracods and radiolarians. Calcispheres are abundant in the boundary beds but of limited use for stratigraphical purposes, because of long-ranging taxa. Radiolarians and ostracods - primarily belonging to the genera *Brachycythere* and *Paracypris* (G. Fauth, University of Heidelberg, personal communication 1999) - are rare and therefore also unsuitable for stratigraphical applications.

Palynomorphs are mainly preserved in marlstones (K. Prössl, 1998, Giessen, personal communication). Where these rocks occur, mainly as thin intercalations, they are generally deeply weathered and the palynomorphs are oxidised.

The microfacies study of Berthou & Bengtson (1988) in the Sergipe Basin revealed the existence of echinoderm remains, among which the most prominent were “saccocomid-like” cross-sections. These are also known from coeval beds of the Anglo-Paris Basin (Ferré, 1995; Ferré *et al.*, in press). Ferré & Berthou (1994) referred these echinoderm remains to roveacrinids and discussed their potential as a biostratigraphical tool.

9.1.1 Roveacrinidal zonation

The Cenomanian–Turonian roveacrinids of the Sergipe Basin were studied by B. Ferré (Saint Étienne du Rouvray, France) in collaboration with the author and P. Bengtson (Heidelberg) (Ferré *et al.*, in press). Taxonomic descriptions and interpretations are given in a separate publication (Ferré *et al.*, in press).

Roveacrinids are small pelagic crinoids. Their skeleton consists of low-magnesium calcite, which withstands dolomitisation and weathering better than other biogenic components. Thus, roveacrinid remains are generally well preserved in thin sections and offer possibilities for chronostratigraphical correlation in areas of discontinuous outcrops and patchy occurrences or where other diagnostic fossils are scarce or missing (Ferré *et al.*, in press). Despite the scarcity of stratigraphical studies of roveacrinids a biostratigraphical range chart for the taxa found in Sergipe has been compiled (Figure 9.1) with the aim of eventually extending it to regional or even global applications (Ferré *et al.*, in press).

Roveacrinid remains are widespread in the upper Cenomanian–lower Turonian of Sergipe. They occur in association with calcispheres in middle to deep-neritic environments in the Japaratuba, Laranjeiras and Itaporanga areas. In the southern Japaratuba (Jardim) sections the presence of, e.g., *Roveacrinus geinitzi* indicates upper Cenomanian, whereas in the Itaporanga sections, e.g., *Roveacrinus* cf. *communis* is characteristic of the lower Turonian. The assemblage is relatively well diversified.

Roveacrinidal microfacies can be used to for local chronostratigraphical purposes. Jefferies (1962) reported several abundance horizons within the Plenus Marls of the Anglo-Paris Basin. Moreover, Ferré (1995) demonstrated the coincidence of abundance peaks between assemblages of roveacrinids, ostracods and foraminifers.

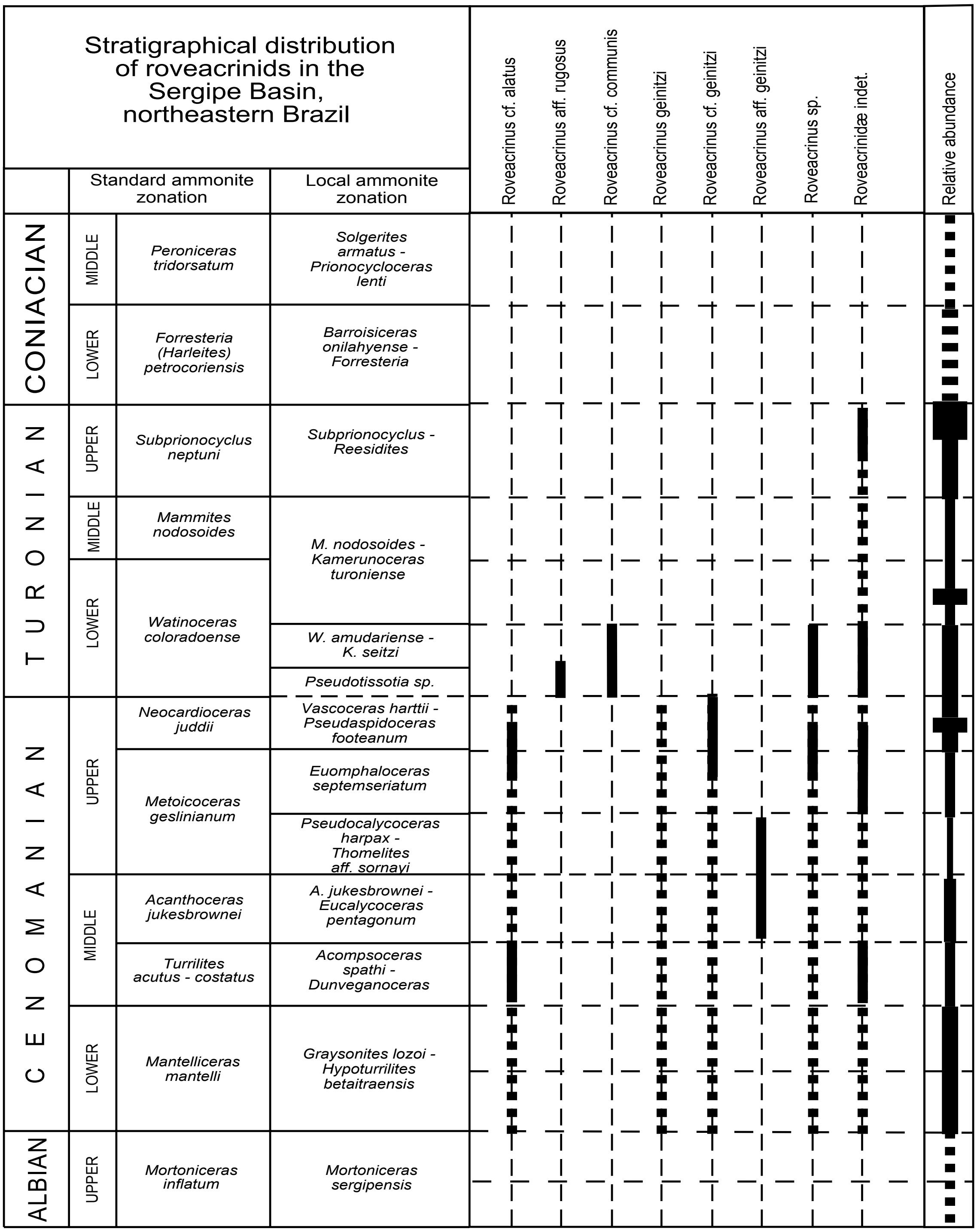
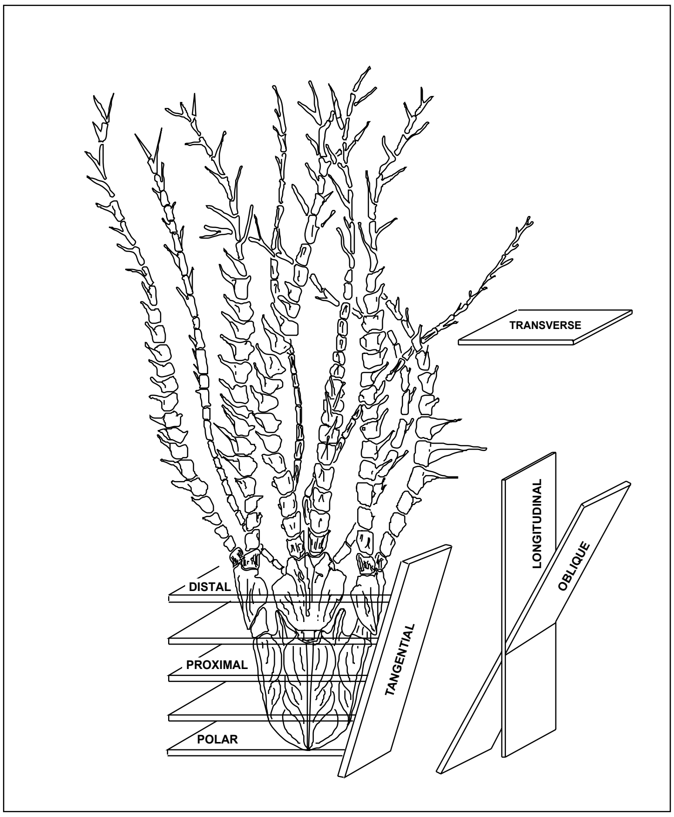


Figure 9.1: Roveacrinidal zonation of the upper Albian to middle Coniacian of the Sergipe Basin and tentative correlation with the proposed standard and local ammonite zonation (Ferré *et al.*, in press).

According to Ferré (1995) roveacrinids can be compared to modern comatulids, without a stem or an anchoring system. The most well-known relative is the saccocomid *Saccocoma tenella* (Goldfuss) from the Tithonian Solnhofen limestones in southern Germany.



A tentative reconstruction of a roveacrinid and its various possible cross-sections has been presented by Ferré & Berthou (1994) (Figure 9.2). The individual consists of a calyx, composed of five basal plates and a set of brachial plates, which compose the arms.

Figure 9.2: Tentative reconstruction of a roveacrinid and its possible cross sections from (Ferré & Berthou, 1994)

The complete specimen is estimated to have reached a size of up to 5 cm. Cross-sections do not always show determinable parts of a specimen and commonly only brachial parts are observed. At the present stage of knowledge brachial parts can only be used for determination down to family level. In addition, sections of isolated plates are very similar to those of saccocomids or ophiurids (Ferré *et al.*, in press). Further details of the reconstruction of roveacrinids are given by Ferré & Berthou (1994) and Ferré *et al.* (in press).

9.1.2 Foraminiferal zonation

Planktonic and benthic foraminifers are relatively abundant, although in most samples they are poorly preserved as a result of dissolution and recrystallisation of the calcareous tests (Plate 2 & 3). The small number of determinable specimens does not permit efficient biostratigraphical work by using statistical analyses but may provide a means of correlating parts of the succession.

The planktonic foraminifers *Hedbergella (W.) aprica* and *Hedbergella (W.) brittonensis* (Plate 2 & 3) are recorded from the lowest parts of the succession exposed in the southern Japaratuba (Jardim) area, indicating upper Cenomanian (see Figure 7.3). *Hedbergella (W.) baltica* from the Itaporanga area is characteristic of the lower

Turonian. A Cenomanian–Turonian boundary marker based on the first or last occurrence of a specific planktonic foraminifer species could not yet be defined.

Benthic foraminifers are depth-related and therefore less useful for biostratigraphy (Koutsoukos, 1989). The *H. (W.) archaeocretacea–H. reussi* Zone (Figures 9.3 and 9.4) is interpreted as straddling the boundary (Koutsoukos & Bengtson, 1993). Unfortunately *H. (W.) archaeocretacea* has not been found in the sampled areas.

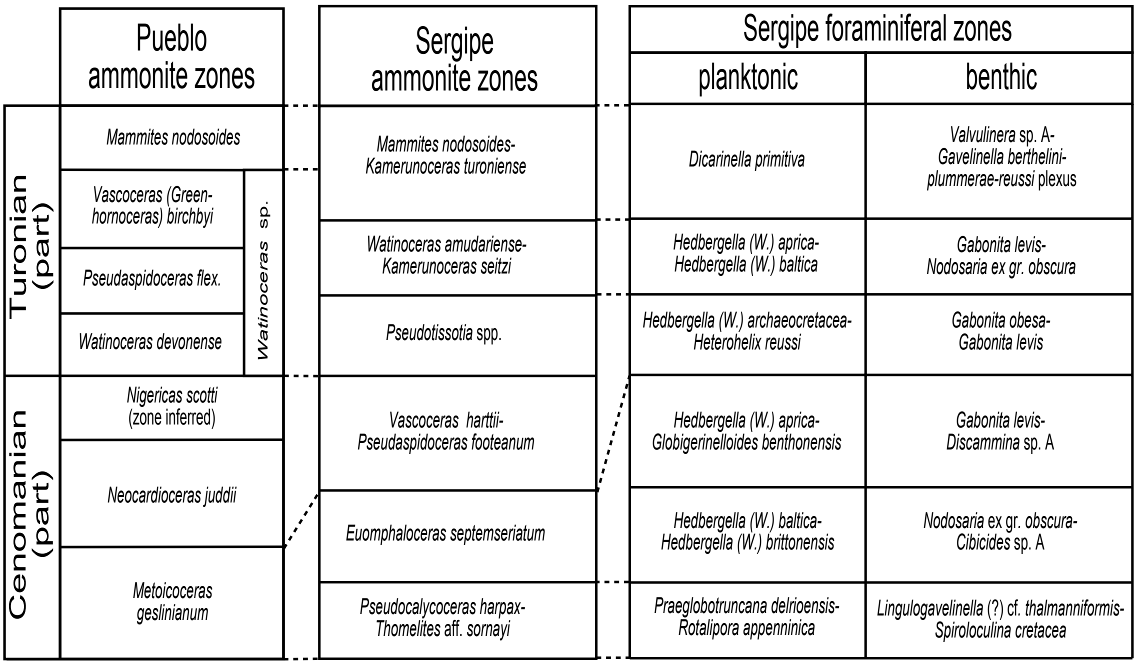


Figure 9.3: Foraminiferal zonation of the upper Cenomanian–lower Turonian of the Sergipe Basin and tentative correlation with the proposed ammonite zonation of this basin (modified after Koutsoukos & Bengtson, 1993).

9.2 Stratigraphy based on microfacies

Microfacies type 1 (MFT 1) is restricted to the upper Cenomanian nodular limestones of the southern Japaratuba (Jardim) area (Figures 6.2 and 9.4), whereas MFT 2 is represented in the Cenomanian–Turonian boundary beds throughout the basin. MFT 3 characterises the lower Turonian of the northern Japaratuba area and occurs as intercalations in the Laranjeiras section (Figure 9.4). In the Itaporanga area MFT 4 is restricted to the northeastern, lower Turonian part of the area, where it occurs intercalated with MFT 2 (Figure 9.4).

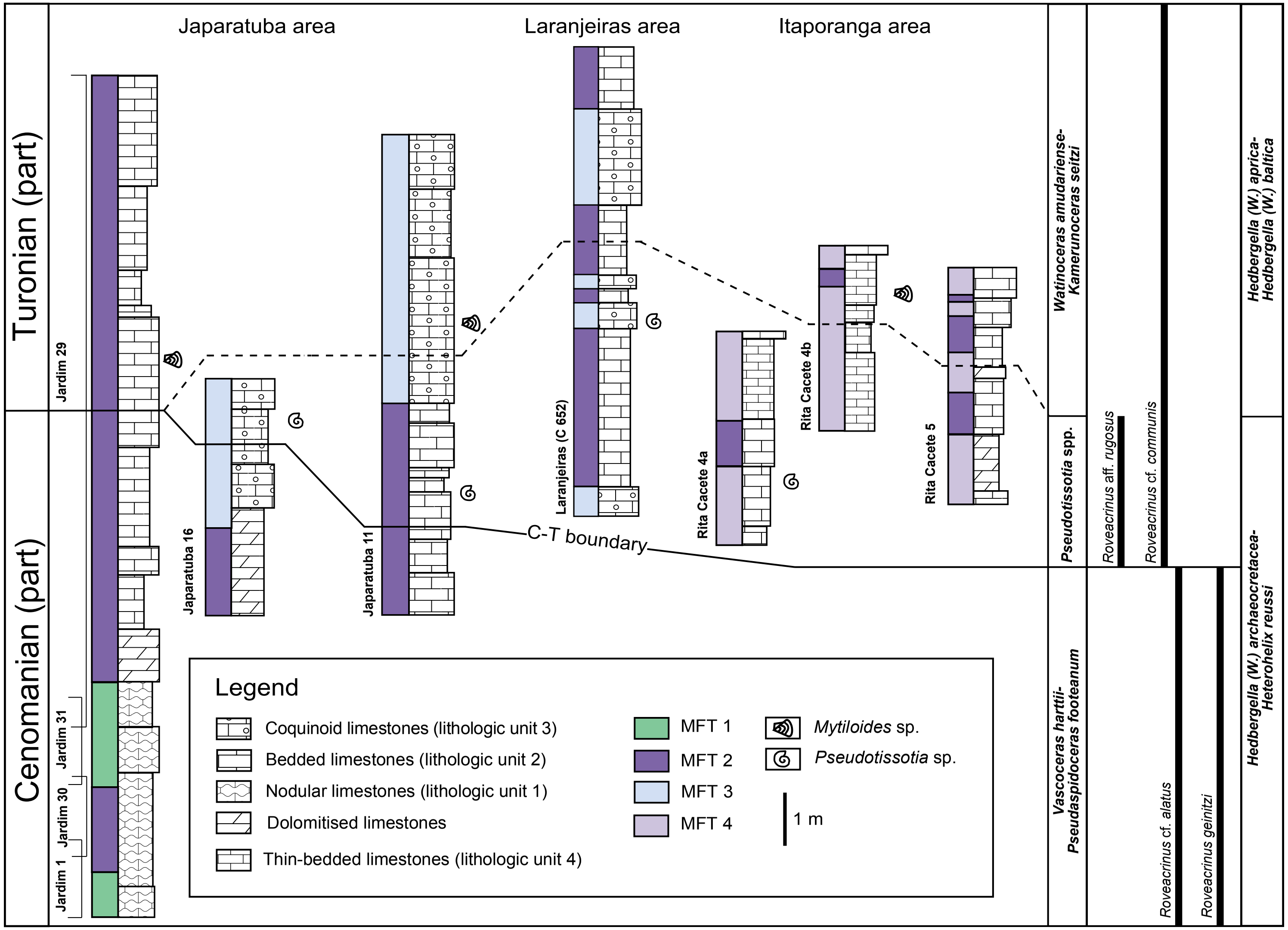


Figure 9.4: Tentative correlation of the studied sections based on biostratigraphic markers and microfacies types. Ammonite zonation after Walter *et al.* (in press), foraminiferal zonation after Koutsoukos & Bengtson (1993), roveacrinidal zonation after Ferré *et al.* (in press).

The combination of conventional biostratigraphy with microfacies analysis as described here led to the positioning of the studied sections as shown in Figure 9.4. In the northern part of the Japaratuba area (localities Japaratuba 11 and 16) the first occurrence of *Pseudotissotia* spp. serves as a Cenomanian–Turonian boundary proxy. In the southern part of the area (Jardim sections) the *Pseudotissotia* spp. Zone is missing (locality Jardim 29). The appearance of *Watinoceras amudariense* and the mass occurrence of representatives of the inoceramid genus *Mytiloides* in the upper part of localities Jardim 29 and Japaratuba 16 indicate the *Watinoceras amudariense–Kamerunoceras seitzi* Zone. In the southern Japaratuba (Jardim) area microfacies type 2 (MFT 2) dominates the succession; the northern area is dominated by coquinoid limestones of microfacies type 3 (MFT 3).

In the Laranjeiras and Itaporanga areas the lower part of the succession is dominated by pseudotissotiid ammonites (localities Laranjeiras C 652 and Rita Cacete 4a). In the upper part of the succession (locality Rita Cacete 4b) a mass occurrence of *Mytiloides mytiloides* indicates the stratigraphical position. The Laranjeiras section is characterised by an alternation of MFT 2 and 3, whereas the Itaporanga sections are represented by MFT 4, with intercalations of MFT 2.

Discussion

The biostratigraphical framework based on ammonites (Koutsoukos & Bengtson, 1993; see Chapter 4) was used as a basis for correlating the studied sections. The biostratigraphical framework can be complemented with microfossils, in particular planktonic foraminifers. Roveacrinid biostratigraphy is still in its early stage but was used as a complementary tool for dating the studied sections.

Stratigraphical correlation based on microfacies analysis as demonstrated by Berthou & Bengtson (1988) is difficult, owing to lateral changes in the composition of the limestone beds (Chapter 6). Three of the four microfacies types established herein represent lower Turonian limestones. Within the microfacies classification, several varieties occur, as a result of changing palaeoenvironmental conditions. Moreover, besides diagnostic microfossils, there is no global standard stratigraphical scale based on unique events that is applicable in microfacies analysis.

In thin sections biostratigraphically important microfossils may permit chronocorrelation of isolated outcrop sections; however, this will require fresh and unaltered material. Dolomitised rocks occur throughout the study area and present correlation problems as the sedimentological and palaeontological characteristics are obliterated. Despite recrystallisation, determination of the microfossil content and microfacies characteristics may be possible.

9.3 Isotope stratigraphy

The use of stable isotopes, particularly carbon isotopes ($\delta^{13}C$), for correlation of Cretaceous sedimentary successions has been demonstrated by several authors (e.g. Scholle & Arthur, 1980; Jenkyns, 1985; Schlanger *et al.*, 1987; Hilbrecht & Hoefs, 1986; Jarvis *et al.*, 1988; Voigt & Hilbrecht, 1997). The most distinctive feature of the Upper Cretaceous carbon-isotope curve is the global positive $\delta^{13}C$ excursion near the Cenomanian–Turonian boundary (Voigt & Hilbrecht, 1997). Increased $\delta^{13}C$ values are thought to result from preferential extraction of ^{12}C from sea water by marine phytoplankton, the organic matter of which was not recycled back to the oceanic reservoir because of widespread burial of organic carbon in marine basins during the OAE (Jarvis *et al.*, 1988). This burial probably lead to a decrease in atmospheric pCO_2 (Arthur *et al.*, 1988; Kump & Arthur, 1999).

For carbonate rocks it is convenient to use the same Pee Dee Belemnite (PDB) standard for both carbon and oxygen isotopes. By definition the PDB standard has the isotopic composition $\delta^{13}C = 0$ and $\delta^{18}O = 0$. These values are close to those of many marine carbonates, in which the δ values are slightly positive or negative relative to PDB. A positive δ value indicates enrichment in the heavy isotope, relative to the standard, and such substances are colloquially called “heavy” in carbon or oxygen (Hudson, 1977). However, hiatuses complicate interpretations of the stable isotope stratigraphy in shallow shelf environments, as demonstrated by Jarvis *et al.* (1988) for limestones displaying anomalous carbon isotope values.

The oxygen isotope composition of a carbonate rock precipitated from water depends primarily on the isotope composition of the water and on temperature. According to Hudson (1977), diagenetically altered limestones are lighter in oxygen than primary carbonate rocks. The isotope composition of limestones changes during diagenesis either by addition of cement generations or by exchange of allochems or earlier cements already present, or both. As a result, neomorphism can lead to heavier or lighter oxygen isotope compositions.

Hilbrecht *et al*. (1992) and Voigt & Hilbrecht (1997) presented evidence for local primary differences in the amplitude and stratigraphical variations of $\delta^{13}C$ values and significant diagenetic effects in permeable rocks.

Sudden shifts in carbon isotope values can be produced by hiatuses. These are confirmed by biostratigraphical evidence, demonstrating that stable isotopes can be used as a means to identify and assess the extent of gaps in the stratigraphical record (Voigt & Hilbrecht, 1997).

9.3.1 Results

A total of 56 samples from the Cenomanian–Turonian boundary beds of Sergipe were analysed. The $\delta^{13}C$ and $\delta^{18}O$ ratios were determined and plotted against lithology.

Japaratuba area:

The coquinoid limestones that dominate the northern Japaratuba area are partly dolomitised and less suitable for analysis of bulk rock samples (see Chapter 3). Therefore, only samples from the southern Japaratuba (Jardim) area were analysed. The carbon isotope values fluctuate but show a clear negative trend throughout the succession (Figure 9.5). The $\delta^{13}C$ values decrease from 2.5 ‰ to 0.5 ‰ in the lower nodular limestones, show a positive peak in the middle part of section Jardim 30 followed by a decrease in the bedded limestones to the base of section Jardim 31 (0.2 ‰). This peak is followed by a short-term positive excursion (1.0 ‰) to a negative value of -1.0 ‰ in the upper part of this section. The section at Jardim 29 starts with a positive $\delta^{13}C$ value of ca. 0.8 ‰ up to 1.0 ‰ and a subsequent decrease towards the top of the section, where the values reach a minimum of -3.5 ‰ in the lower Turonian (Figure 9.5).

The amplitude of fluctuation in $\delta^{18}O$ values is small. In the lower part of the succession the values remain relatively constant (around -3.5 ‰), increase slightly to the top of section Jardim 30 (-2.5 ‰) and then decrease rapidly to values of -4.0 ‰ in the upper part of Jardim 31. A trend with relatively constant values around -3.8 ‰ is interrupted by a positive peak (-2.0 ‰) above the hiatus at the upper Cenomanian–lower Turonian transition (Figure 9.5).

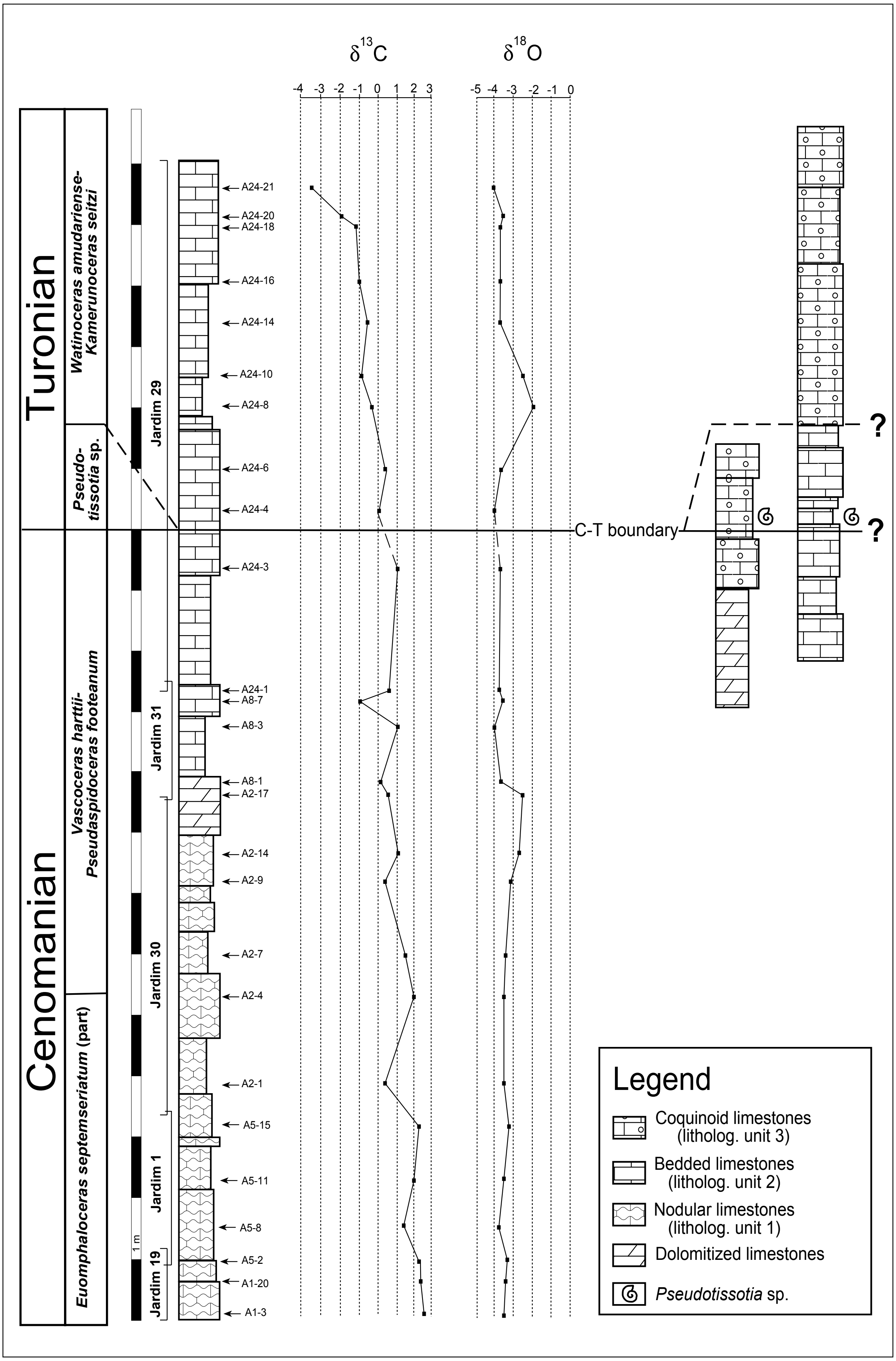


Fig. 9.5: δ13C and δ18O isotopic curves for the Jardim sections in the southern Japaratuba area

Laranjeiras

In the Laranjeiras section (locality C 652) the carbon isotope values fluctuate between a maximum of 2.5 ‰ and a minimum of 0.6 ‰ (Figure 9.6). In the lower part the curve starts at 1.0 ‰, decreases slightly to 0.6 ‰, then increases to 2.4 ‰ and again decreases rapidly to 0.6 ‰. The fluctuations are broader, with a rise to 2.5‰, a decline to 0.9 ‰ and a second rise to 2.5 ‰.

The stratigraphical trend in oxygen isotope values differs slightly from that of the carbon isotope stratigraphy (Figure 9.6). The values fluctuate only from –3.6 ‰ to –4.2 ‰. The most positive $\delta^{18}O$ value nearly coincides with the most negative $\delta^{13}C$ value in the lower part of the succession.

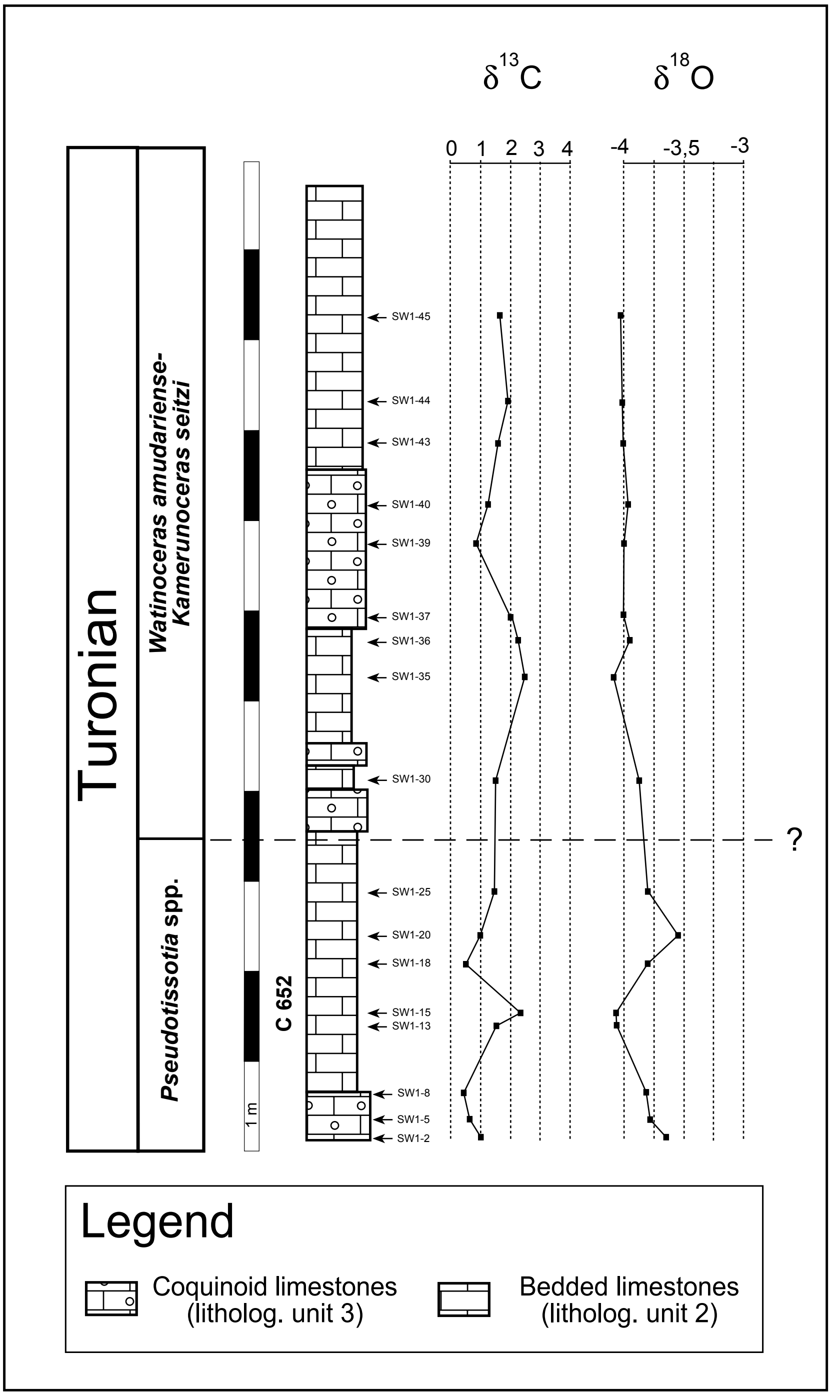


Figure 9.6: $\delta^{13}C$ and $\delta^{18}O$ isotopic curves for the Laranjeiras section

Itaporanga

Samples were collected for analysis only from the upper part of the southern Itaporanga section (locality Rita Cacete 4), as this part contains fresh and undolomitised material (Figure 9.7). The carbon isotope values are nearly constant throughout the section, with a minimum value of 2.4 ‰ and a maximum value of ca. 2.9 ‰.

The oxygen isotope curve starts at a value of -3.4 %, followed by a more positive value of -3.2 ‰, a decrease to -3.3 ‰ and another increase to values of broadly -3.1 ‰. In the upper part of the succession, the values decrease again to -3.4 ‰.

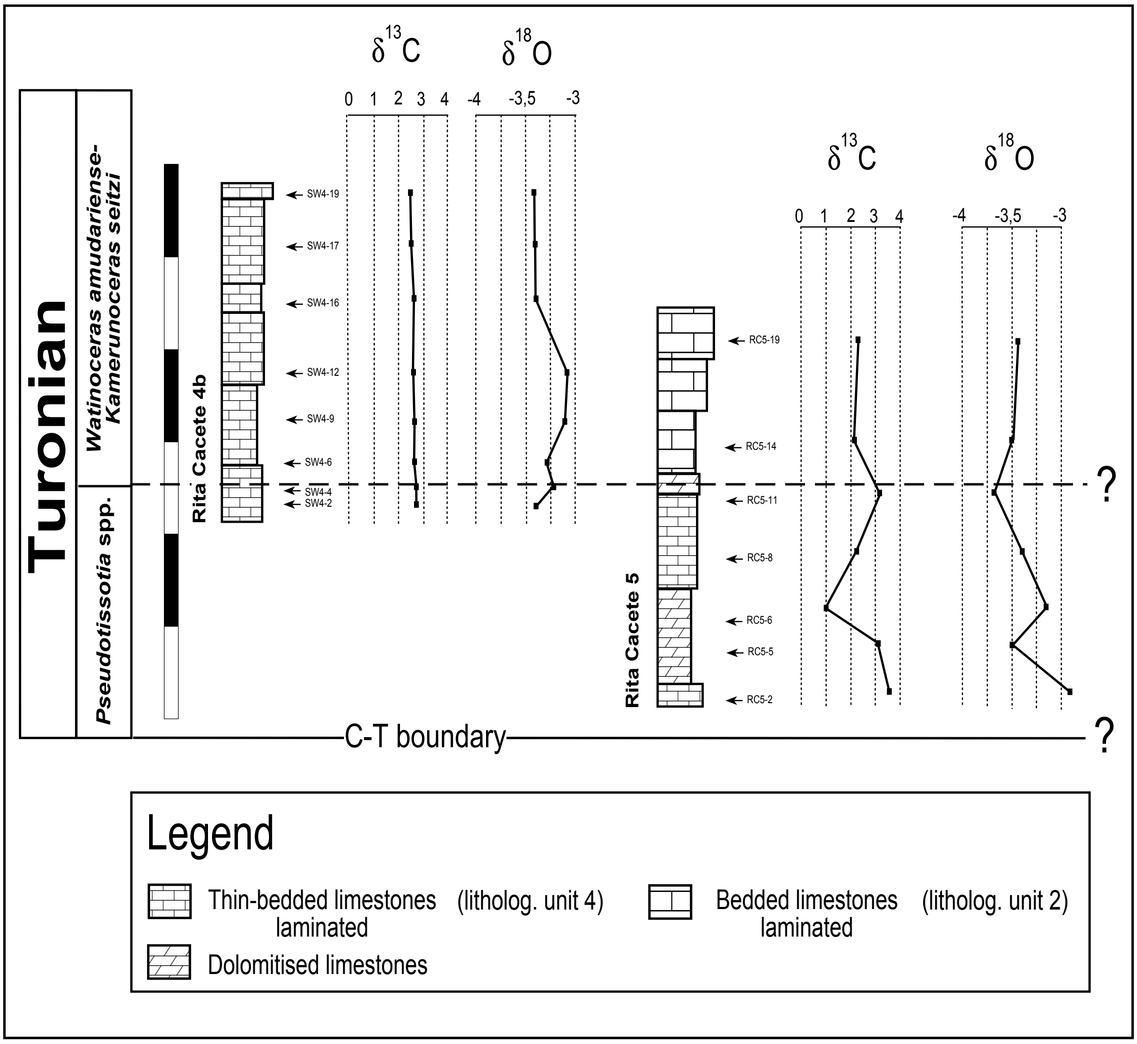


Figure 9.7: δ^{13}C and δ^{18}O isotopic curves for the Itaporanga sections

In the northern Itaporanga section (locality Rita Cacete 5) the carbon isotope values decrease from 3.5 ‰ to 1.0 ‰, followed by an increase to 3.1 ‰ and a decrease to 2.3 ‰ (Figure 9.7).

The oxygen isotope trend is inversely proportional to that of the $\delta^{13}C$ curve. The $\delta^{18}O$ values vary with an amplitude of slightly over 0.5 ‰.

Discussion

The possibility of diagenetic alteration in carbonates is a major problem in the interpretation of stable isotope data. Scholle & Arthur (1980) noted a drop in $\delta^{18}O$ values at or near the Cenomanian–Turonian boundary. Jarvis *et al.* (1988) utilised oxygen isotope data only as a means of isolating diagenetically altered samples and to indicate obvious diagenetic trends. They did not ascribe any primary stratigraphical significance to the $\delta^{18}O$ curve. The positive trend of the $\delta^{13}C$ curve observed is in contrast to the negative trend recorded by Hilbrecht & Hoefs (1986) for sections in Germany. They interpreted their carbon isotope data as indicating falling sea-water temperatures during the latest Cenomanian, an interpretation supported by palaeontological data. Positive $\delta^{13}C$ peak signals are thought to indicate a maximum in productivity (Arthur *et al.*, 1988; Gale *et al.*, 1993).

Alteration of the primary isotope signal shortly after deposition in marine environments depends on the reactivity of the carbonate bioclasts (concentration of metastable aragonite and high-Mg-calcite *versus* concentration of low-Mg-calcite (Patterson & Walter, 1994). According to Jarvis *et al.* (1988) diagenesis will only alter bulk-rock isotope values if there has been cementation or recrystallisation, i.e., an interaction between the sedimentary rock and the surrounding pore-fluid. Such interaction commonly occurs during early diagenesis in sediments composed of metastable minerals.

According to Emrich *et al.* (1970) and Scholle (1974) carbon isotopes are relatively immune to diagenetic modification. This is true for nearly impermeable fine-grained sedimentary rocks. However, in permeable deposits, the primary composition of carbon isotopes changes as a result of migrating pore waters, which transport dissolved $CaCO_3$ through isotopically different areas. Jarvis *et al.* (1988) pointed out that during diagenesis oxygen isotope ratios are far more readily altered than $\delta^{13}C$ values, partly because oxygen isotopes show significant temperature-related fractionation. Primary $\delta^{18}O$ values in carbonates will largely reflect ocean-water temperatures and salinities but will be modified considerably by addition of cements during meteoric diagenesis. Finally, recrystallisation may involve the precipitation of new isotopically light carbonate cements during meteoric diagenesis, leading to lower δ-values of both oxygen and carbon (e.g., Allan & Matthews, 1982; Saller & Moore, 1991). However, meteoric waters in tropical regions are comparably heavy in $\delta^{18}O$. The $\delta^{18}O$ values of -3 ‰ to -4‰ in the limestones studied here suggest diagenetic alteration, possibly caused by meteoric diagenesis.

The $\delta^{13}C$ values were plotted against $\delta^{18}O$ values (Figure 9.8) to reveal correlation patterns between the outcrop areas. The Laranjeiras and Itaporanga samples plot together and have higher $\delta^{13}C$ values than the samples from the southern Japaratuba (Jardim) area. Nevertheless the range of $\delta^{18}O$ values of both data sets is comparable (from –3.1 to –4.1 ‰). It is concluded, that the data reflect approximately the same degree of diagenesis in all regions. Consequently the differences between the $\delta^{13}C$ values must have other causes than purely diagenetic alteration. Therefore, the excursions are interpreted as original trends that may be used for stratigraphical purposes.

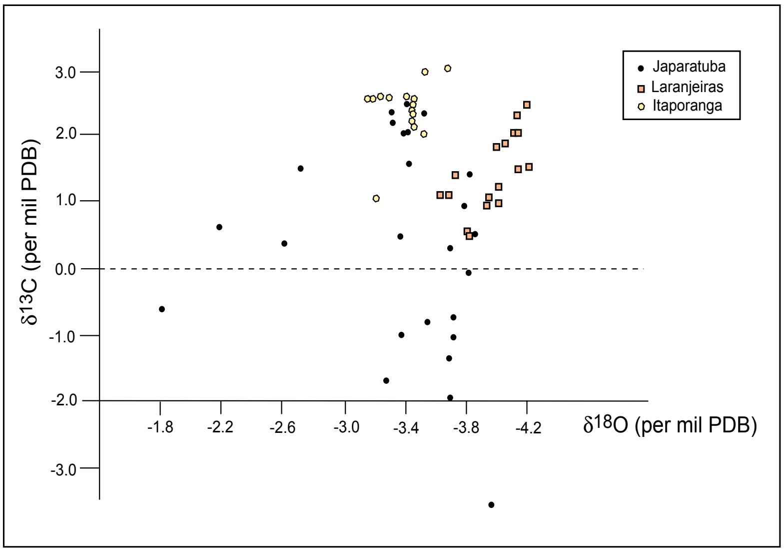


Figure 9.8: Correlation pattern of different outcrop areas, $\delta^{13}C$ plotted against $\delta^{18}O$.

9.4 Biostratigraphy *versus* isotope stratigraphy

The results of the stable isotope analyses have been integrated with macro- and micropalaeontological data. For individual sections or small areas carbon isotope stratigraphy has limited applications when used alone, although it can be successfully used in combination with palaeontological data (Hilbrecht, 1998).

In the southern Japaratuba (Jardim) area, the Cenomanian–Turonian transition does not include the peaks in $\delta^{13}C$ values (Figure 9.9, number 5, 6, 7) recorded in the Laranjeiras and Itaporanga areas. In general, hiatuses are indicated by sudden changes in the isotopic composition. In the southern Japaratuba sections, where the

Pseudotissotia spp. Zone is missing, this gap in the succession is evidenced by a change in $\delta^{13}C$ values of nearly 1 ‰. Thus, it is likely that the $\delta^{13}C$ peaks fall within the hiatus. The long-term trend from heavier to lighter carbon isotope values is known from European and North American sections but includes an overprint by diagenetic alteration. This is evident from the negative values (reaching -3.5 ‰) recorded in the upper part of the section; these are too low to reflect the primary carbon isotopic composition (M. Joachimski, Erlangen, personal communication 2000).

The $\delta^{18}O$ values fluctuate less between the sections than the $\delta^{13}C$ values, but are apparently altered by diagenesis as evidenced by increasingly negative values (cf. Scholle, 1977; Scholle & Arthur, 1980). Nevertheless, the stratigraphical trend for the $\delta^{18}O$ curves resembles that of the $\delta^{13}C$ curves, except for the positive peak in the $\delta^{18}O$ excursion (Figure 9.9, Japaratuba section, between numbers 3 and 2 of the $\delta^{13}C$ curve).

The Laranjeiras $\delta^{13}C$ curve (locality C 652) shows multiple peaks and no long-term trend can be observed. It is possible that the peaks reflect the different lithologies sampled, as the succession consists of an alternation of bedded limestones and coquinoid limestones (lithologic units 2 and 3). The maximum $\delta^{13}C$ value in the upper part of the section (2.5 ‰) coincides with the occurrence of the ammonite *Pseudotissotia* sp. at this locality (Figures 9.6 and 9.9). However, in this section the $\delta^{13}C$ peaks (Figure 9.6, numbers 5, 6, 7) are comparable to those of the Rita Cacete 5 section, where the lithology (lithologic units 2 and 4) is clearly different. The $\delta^{13}C$ peaks (Figure 9.6, numbers 1, 2, 3, 4) in the upper part of the Laranjeiras section can be tentatively correlated with those of the southern Japaratuba (Jardim) sections. The $\delta^{13}C$ and $\delta^{18}O$ curves in the northern Itaporanga area (locality Rita Cacete 5) show opposite trends to those of the Laranjeiras section (C652). The two sections apparently represent the same stratigraphical level, as indicated by the $\delta^{13}C$ curve and the biostratigraphical markers.

It thus appears that the $\delta^{13}C$ values reflect original trends. In addition, the correlation pattern of $\delta^{13}C$ and $\delta^{18}O$ shown in Figure 9.8 suggests that the degree of diagenetic alteration was uniform across the study area.

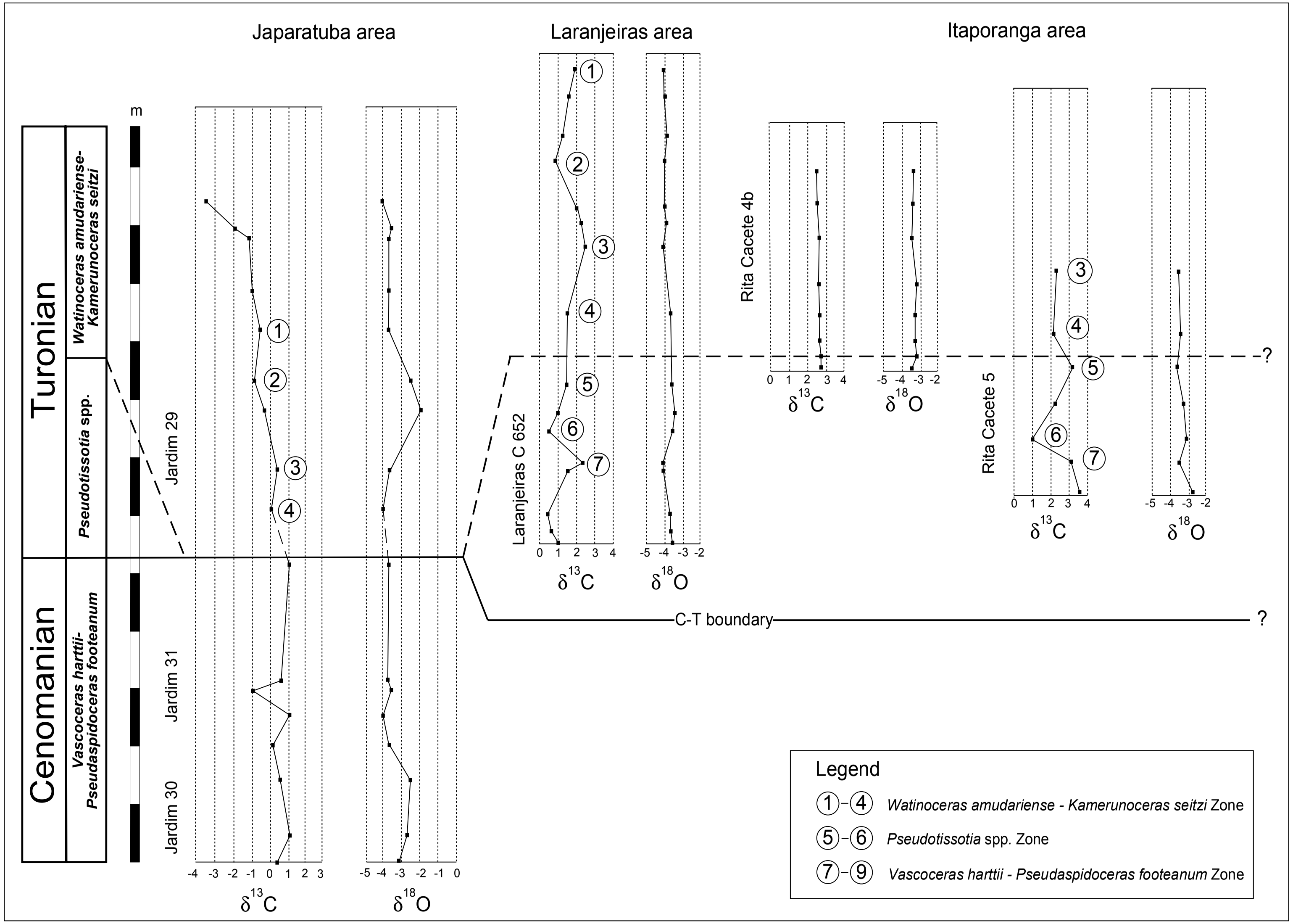


Figure 9.9: Tentative correlation of the $\delta^{13}C$ and $\delta^{18}O$- curves in the studied areas. Circled numbers refer to peaks inferred to be synchronous

The isotope values in the Rita Cacete 4b section in the southern Itaporanga area pose a problem. In this area there is no peak in the carbon isotope curve. The oxygen isotopic composition is also heavier in ^{18}O than in other sections and the $\delta^{18}O$ curve is smooth (Figure 9.9). Fresh material was sampled in order to exclude diagenetic influence, so the reasons for these anomalies are unclear.

9.5 Conclusions

It is concluded that the stable isotope values reflect the long-term trend above the $\delta^{13}C$-event (LOD of *Rotalipora cushmani*), and the short-term fluctuations reveal small-scale lithologic changes in the studied sections or are caused by local gaps in the successions. These fluctuations can tentatively be correlated throughout the study area, as shown in Figure 9.9.

Diagnostic ammonites and inoceramid bivalves were found at all localities sampled and provided reliable biostratigraphical correlation. The chronostratigraphical positioning of outcrop sections with biostratigraphy was confirmed with stable isotope stratigraphy. In the absence of diagnostic macro- and microfossils this method thus provides a tool for the positioning of isolated outcrop sections.

The indication of a hiatus with $\delta^{13}C$ analysis in the southern Japaratuba (Jardim) area (Figure 9.9) provides an example of a successful application of isotope stratigraphy.

Chapter 10

COMPARISONS AND CORRELATIONS

In most regions the LOD of the planktonic foraminifer *Rotalipora cushmani* has been used for correlation of the Cenomanian–Turonian boundary, but this species has not been found in the studied localities. However, comparisons with faunal associations and depositional environments of other regions are possible. In addition to the microfaunal correlation, carbon isotope excursions are generally used for correlating the boundary as they show a significant peak at this level. However, in this study correlation of the boundary using stable isotope data is difficult due to diagenetic alteration, whilst comparisons concerning the microfauna with other regions will be attempted.

10.1 Brazil

The microfaunal assemblages from well-sections in the Sergipe Basin and the Ceará Basin studied by Mello *et al.* (1989) are comparable to those of the studied sections herein. The foraminifers from their sections reflect oxygen-depleted conditions, and this result agrees with the conclusions drawn from this study. Guardado *et al.* (1990) described a scarce benthic fauna and micromolluscs from the Cenomanian–Turonian transition from the Campos Basin, similar to that represented in the Japaratuba and Itaporanga area. A low-diverse benthic microfauna has also been reported by Koutsoukos *et al.* (1990) from this basin, whereas the benthic assemblage is completely lacking in several layers of the Cenomanian–Turonian of the Santos Basin (Viviers, 1986). Offshore drilled sections of early Turonian age were investigated, in the Pará and Maranhão basins, where moderate dysaerobic conditions were characterised by the paucity of benthic microfauna and abundance of planktonic assemblages (Beurlen & Regali, 1987).

10.2 Africa

From Angola to Senegal all coastal basins owe their origin to the break-up of Gondwana and the opening of the South Atlantic Ocean (Kogbe & Me´hes, 1986). They are therefore younger than the Cretaceous and developed similarly to the Brazilian marginal basins. The Cenomanian–Turonian transgression also invaded the intracratonic basins of North and West Africa (Flexer & Reyment, 1989).

Gabon: The Cenomanian of Angola and Gabon is less well delineated. Locally there are benthic as well as planktonic foraminifers occurring like e.g. *Heterohelix, Hedbergella* and *Globutruncana*. The Turonian microfauna of the Gabon is composed of ostracods, *Heterohelix* and other planktonic and benthic forms. However, only where ammonites occur can dating be claimed to be secure (Kogbe & Me´hes, 1986).

Nigeria: Deposits of the mid-Cretaceous of the Benue Trough, Nigeria, generally contain an exclusive planktonic foraminiferal assemblage and sometimes, dwarfed, low-diverse benthic organisms, which suggested deposition in oxygen depleted environments (Petters, 1983a). Oxygen deficient conditions have also been reported from the Cenomanian–Turonian interval of the Calabar Flank, SE Nigeria, evidenced by a flood-abundance of planktonic foraminiferal assemblage and scarcity of calcareous benthic foraminifers, when present (Nyong & Ramanathan, 1985). This resembles the distribution patterns, which have been described in Chapter 7 from the Itaporanga area.

The presence of the arenaceous foraminifers *Ammobaculites* and *Haplophragmoides,* at the time of maximum transgression in the Benue Trough, Nigeria, further supports the indications of very shallow water depths (Petters, 1978; 1983b). Both species occurred in the southern Japaratuba area, in an extremely similar environment.

Niger: The Cenomanian–Turonian rocks deposited on the carbonate ramp of the Iullemmeden and Chad basins (Niger) are characterised by bioclastic wackestones with abundant ammonites, gastropods, bivalves, echinoids and roveacrinids. In this palaeoenvironment salinity-stratified water masses caused oxygen-depletion in the upper part of the bottom sediments (Pascal *et al*., 1993). These observations agree with the conclusions drawn from this study. Mathey *et al.* (1995) described in addition the absence of rudists and corals, and interpreted this fact as the result of an absence of shoals amongst other unfavourable morphological conditions. The absence of brachiopods may have resulted from competition with a pioneer bivalve dominated epifauna and/or excessive turbidity of bottom waters. These interpretations could be transferred to the Sergipe Basin where corals and rudists are missing. Another interpretation has been published by Holmer & Bengtson (1996), who explained the near absence of brachiopods in the Sergipe Basin as resulting from the low oxygen levels at the sediment-water interface, where only few, more tolerant brachiopods were found (e.g. lingulids, discinids). The recorded microfaunal assemblages (*Paracypris* sp., *Haplophragmoides, Heterohelicidae, Textulariidae*) of the study areas also closely resemble those of the Iullemmeden and Chad basins.

Morocco: The rising oxygen-minimum zone related to the Cenomanian–Turonian transgression is also shown in Morocco, where ostracods such as *Brachycythere sapucariensis* and *Paracypris mdaouerensis* probably resisted the dysoxic-anoxic regime (Andreu, 1993), as already described for the study area. The upper Cenomanian foraminiferal assemblages of this platform are composed of a similar association, as observed in the Sergipe Basin indicating well-oxygenated surface waters (e.g. *Hedbergella delrioensis, Globigerinelloides* sp., *Hedbergella (W.)* cf. *brittonensis*).

Tunisia: In the lower Turonian of the homoclinal ramp of west-central Tunisia the benthic fauna becomes sparse and planktonic assemblages occur in abundance (Saïdi *et al*., 1997; Caron *et al.* 1999); this phenomenon resembles that of the outer-ramp area described in this study. In addition, the Sergipe ammonite faunas are most closely related to the central-western and northern African basins of Niger, and Nigeria (Seeling, 1999).

11.3 North America and Europe

From the Greenhorn Formation, Pueblo, Colorado, North America, the Cenomanian–Turonian samples investigated by Leckie (1985) are also characterised by low-diversity of the benthic foraminiferal assemblages already described from other regions (see above).

In SE Devon (UK) the boundary is defined by the appearance of abundant *Mytiloides* spp. bivalves and occasional *Watinoceras* spp. ammonites. Hilbrecht & Hoefs (1986) concluded from their study of the German Cenomanian–Turonian (C–T) boundary succession that the base of the carbon isotope excursion coincided with the extinction of *Rotalipora cushmani* and placed the upper limit of the excursion immediately above the appearance of *Mytiloides* spp. Possible differences between the position of the top of the carbon isotope excursion are more difficult to assess. In both England and Germany the top of the excursion lies immediately above the appearance of *Mytiloides* spp. (Jarvis *et al*., 1988).

The presence of the well-known $\delta^{13}C$ isotopic excursion is confirmed in the data from Lincolnshire and Humberside (Eastern England), and the foraminiferal changes at this level are identical all over the UK, which is also true for the successions described from Spain, France, Poland, Tunisia, Germany and the North Sea Basin (Hart *et al.*, 1993).

In Europe the species *Roveacrinus communis* showed a rapid increase in abundance and dominates the basal Turonian of C–T sections within the Anglo-Paris Basin (Southern England). This species is the sole macroinvertebrate component slightly above the C–T boundary in the Eastbourne section (UK) (Harries, 1993). The occurrence of *Roveacrinus communis* in the Japaratuba and Laranjeiras sections of the study area has also been taken as indicator for the lower Turonian.

Chapter 11

CONCLUSIONS

(1) Four lithologic units have been identified in the study area, which indicate different depositional environments at the Cenomanian–Turonian transition. In the northeastern part of the basin (Japaratuba and Laranjeiras areas) nodular and bedded bioturbated limestones dominate the succession; locally coquina banks are common. In the southwestern part of the basin (Itaporanga area), the limestone succession is represented by thin-bedded and laminated marly limestones.

(2) Microfacies characteristics in thin sections have been described and lead to identification of four microfacies types (MFTs). MFT 1 and 2 consist of a foraminiferal wacke- to packstone, MFT 3 can be designated as an echinoderm-inoceramid packstones and MFT 4 is represented by foraminiferal mudstones. The limestone succession of the Japaratuba and Laranjeiras areas is represented by MFT 1, 2 and 3, whereas in Itaporanga, MFT 4 predominates.

(3) Macrofaunal debris identified in thin sections is represented by fragments of ammonites, inoceramid bivalves, other bivalves, gastropods and echinoderms (echinoids, roveacrinids). Roveacrinids can be used as facies indicators of outer shelf and upper slope environments. These macrofossils are represented throughout the sections studied, in the shallow and deeper parts of the basin.

(4) The microfaunal association consists of foraminifers, calcispheres, radiolarians and rare ostracods. Two foraminiferal assemblages are identified. The Japaratuba and Laranjeiras assemblages indicate shallow neritic to paralic environments, where both planktonic and benthic forms are abundant and along with bioturbation characteristic of well-oxygenated water conditions. The Japaratuba and Laranjeiras area represents an aerobic biofacies. The Itaporanga assemblages suggest oxygen depleted biotopes, characterised by the virtual absence of benthic foraminifers and laminated strata representing an exaerobic biofacies.

(5) The Oceanic Anoxic Event lead to the development of widespread oxygen minimum zone, which has risen during the Cenomanian–Turonian transgression. Oxygen deficiency has been suggested in the outer ramp environment in the southwestern part of the Sergipe Basin (Itaporanga area) by the scarcity of the benthic fauna (e.g. foraminifers) and lamination structures.

(6) The facies model established for the study area is that of a ramp (*sensu* Burchette & Wright, 1992) with a gentle dip. The mid ramp is represented in the northeastern part of the basin (Japaratuba and Laranjeiras areas), indicated by bioturbated bedded limestones intercalated with coquinoid limestones. The southern Japaratuba (Jardim) limestones were strongly influenced by bioclastic material brought in by currents from the littoral zone. The outer ramp deposits consist of laminated thin-bedded marly limestones represented in the southwestern part of the basin (Itaporanga area).

(7) Biostratigraphic zonation with foraminifers is hampered due to poor preservation of specimens, however correlation of parts of the sections is possible. In combination with other diagnostic fossils as ammonites, inoceramid bivalves and roveacrinids, the biostratigraphic framework can be completed.

(8) Stable isotope analyses have been carried out in order to use the $\delta^{13}C$ values for stratigraphic purposes. The positive $\delta^{13}C$ excursion, which has been observed worldwide close to the Cenomanian–Turonian boundary, has not been identified in the sections studied. Careful comparison of stable isotope data within a pre-existent biostratigraphic framework led to reliable local correlation of the limestone succession, which coincides with the positioning based on biostratigraphy. A hiatus in the southern Japaratuba (Jardim) area was detected by a $\delta^{13}C$ peak.

(9) The microfacies characteristics of the Cenomanian–Turonian limestone succession of the Sergipe Basin, such as the low-diverse, sparsely abundant benthic microfaunal assemblages and the abundant planktonic fauna, have been compared to that of other regions. Similar depositional conditions have been recognised within the Brazilian marginal basins, (e.g. Ceará, Campos and Santos basins), the

African marginal basins (Gabon, Nigeria, Niger, amongst others), North America (Colorado) and Europe (Anglo-Paris Basin).

SUMMARY

Palaeoenvironmental and microfacies analyses of the upper Cenomanian–lower Turonian limestone beds (mid-Cretaceous) of the Sergipe Basin, northeastern Brazil, were carried out. Three outcrop areas were sampled bed-by-bed on contiguous sections from northeast to southwest of the basin: i.g. the Japaratuba, Laranjeiras and Itaporanga areas. Eleven sections were investigated and 230 thin sections analysed. Determination of different lithologic units and microfacies types (MFTs) was done and a facies model was established for the Sergipe Basin. The microfaunal content was analysed for biostratigraphical purpose and its use for palaeoenvironmental interpretation. Stable isotope analyses (^{13}C, ^{18}O) were carried out in order to estimate the completeness of the stratigraphical sections and for correlation purposes.

Four lithologic units have been determined indicating different depositional environments in the upper Cenomanian–lower Turonian limestone succession. The sedimentary rocks of the northeastern part of the Sergipe Basin are dominated by nodular and bedded bioturbated limestones with intercalations of coquinoid limestones, whereas the southwestern section is dominated of thin-bedded and laminated marly limestones.

The depositional environment of the lower Turonian limestones of the studied area was that of a ramp with a gentle dip. The microfacies types identified in the sections sampled occur in two regions of the carbonate ramp: the mid ramp and outer ramp environment. Deposits from the inner ramp and the basinal part have not been sampled. Bedded limestones (lithologic unit 2) with intercalations of coquinoid limestones (lithologic unit 3) represent the mid ramp area. Laminated, thin-bedded marly limestones (lithologic unit 4) dominate the outer ramp area.

Thin section analyses lead to determination of four microfacies types of which three (MFT 1, 2 and 3) correspond to a mid ramp environment situated in the northeastern and central part of the basin (Japaratuba and Laranjeiras area). Microfacies type 4 represents the outer ramp environment in the southwestern part of the basin (Itaporanga area).

The macrofauna determined in thin sections consists mainly of ammonites, bivalves, gastropods and echinoderms. The echinodermal group of roveacrinids have been studied and used as facies indicators for outer-shelf and upper slope environments.

Because of their small size they have been locally transported into shallower environments by currents, together with micromorph gastropods.

The microfaunal content of the areas studied is dominated by foraminifers; in addition calcispheres, radiolarians and ostracods occur. The planktonic foraminiferal assemblages of the Japaratuba area indicate shallow neritic to paralic environments and well-oxygenated conditions. In the Laranjeiras area, benthic foraminifers suggest shallow to middle neritic environments.

The low-diverse, sparsely abundant benthic microfaunal assemblages resulting from oxygen-depleted conditions at the lower Turonian in the Itaporanga area are the result of widespread transgressions, as already described from coeval depositional environments of other regions (e.g. Brazilian basins, African basins, North America or Europe). This is also true for the abundant planktonic fauna, which indicates well-oxygenated conditions. Foraminiferal assemblages in the Sergipe Basin, during that time interval, show close affinities to assemblages from other basins, which is evidence for migration pathways and rates in the northern South Atlantic.

Stable isotope analyses have been carried out for stratigraphical purposes. Multiple peaks were observed, but diagenetic alteration hinders interpretation. The $\delta^{13}C$ values increase towards the southwestern sections (Itaporanga). However, the variations do not correspond to any published stable-isotope stratigraphy across the Cenomanian–Turonian transition from other areas. Tentative local correlation of single peaks has been made. The stratigraphical positioning of the sections studied with help of stable isotope stratigraphy is in agreement with the biostratigraphy. This method largely confirmed the dating of most of the limestone sections. In areas with few diagnostic fossils stable isotope stratigraphy can be used for the positioning of isolated outcrop areas. A determination of the completeness of sections is possible. A stratigraphical gap in the southern Japaratuba area detected by the $\delta^{13}C$ excursion is a good example of a successful application of isotope stratigraphy.

Comparison of microfacies characteristics of this study shows similarities with upper Cenomanian–lower Turonian basins of other regions, e.g. Brazilian marginal basins (e.g. Campos and Santos basins), to African marginal basins (e.g. Gabon, Nigeria or Niger basins), to North America (Colorado) and Europe (Anglo-Paris Basin).

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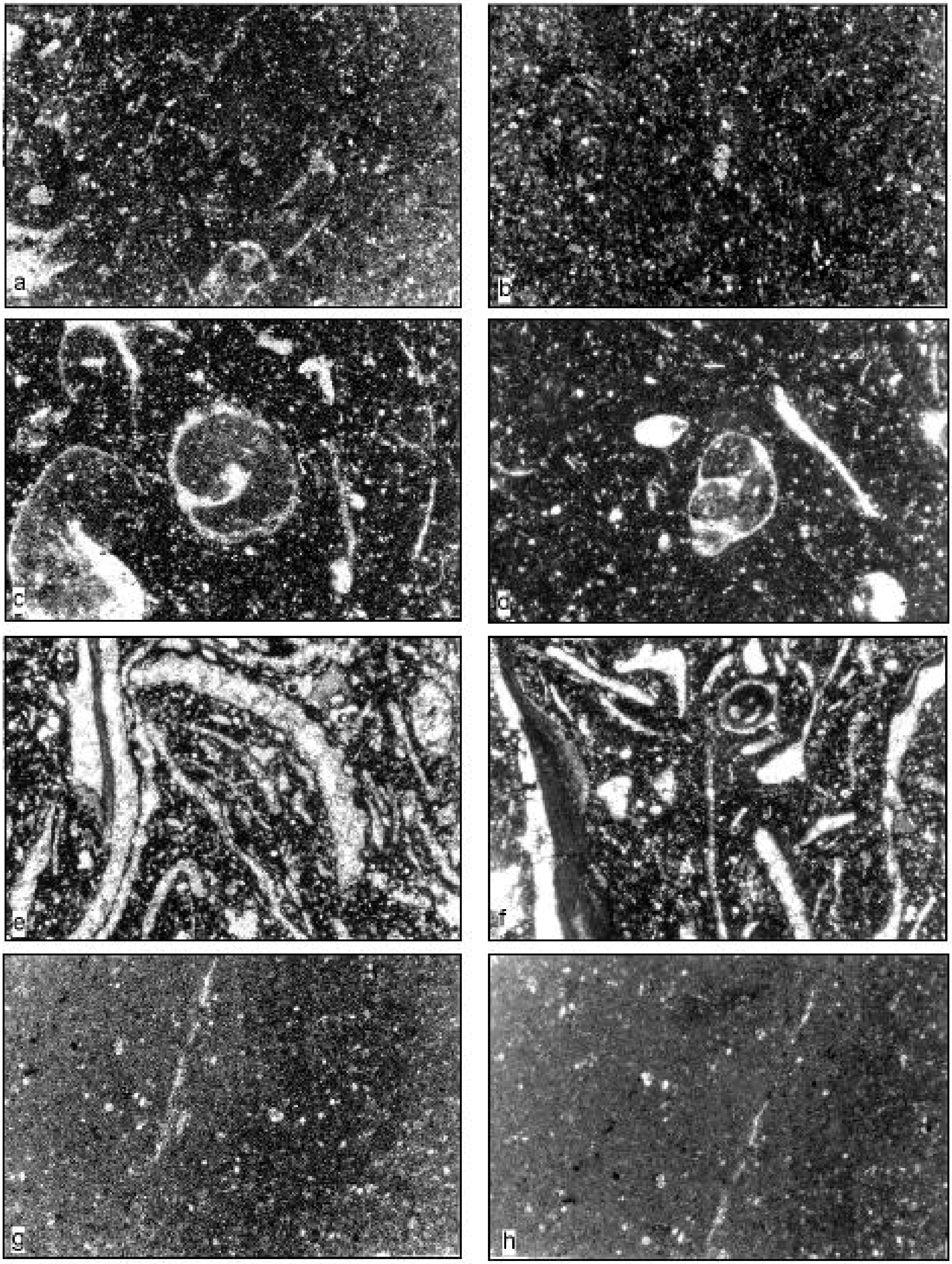
Plates

Plate 1: Microfacies types



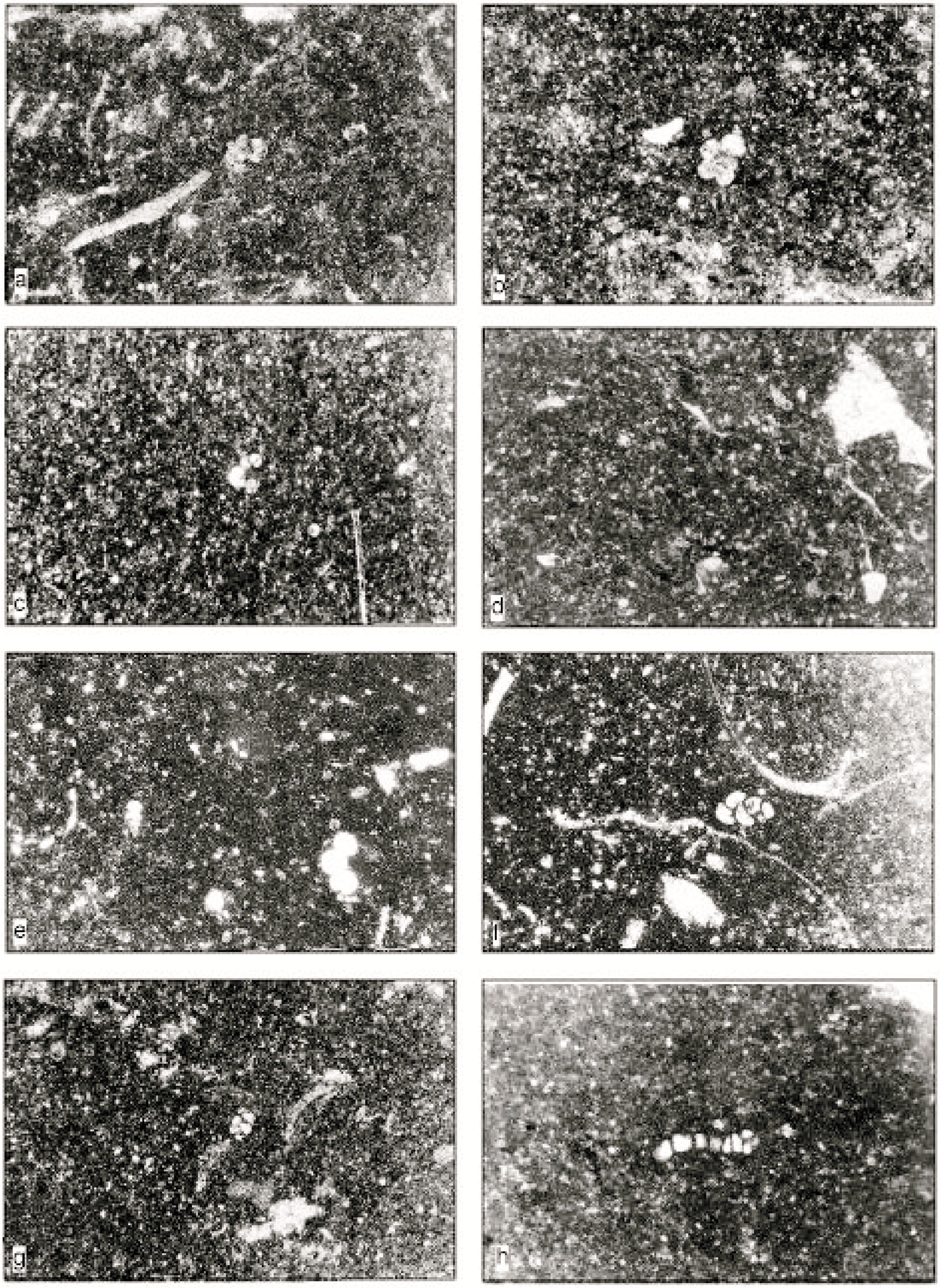
a & b: Microfacies type (MFT) 1

c & d: Microfacies type (MFT) 2

e & f: Microfacies type (MFT) 3

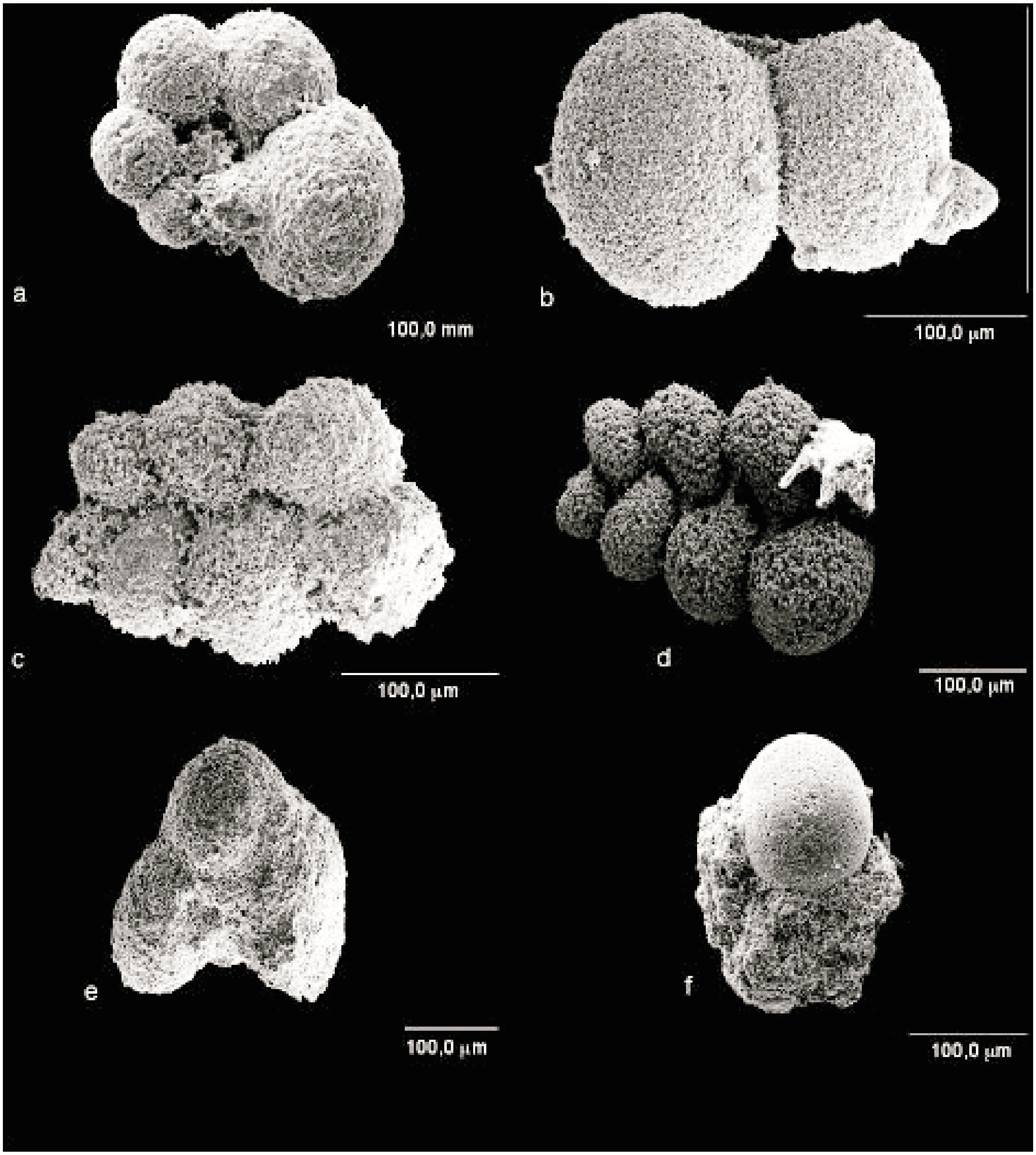
g & h: Microfacies type (MFT) 4

Plate 2: Foraminifers in thin-section



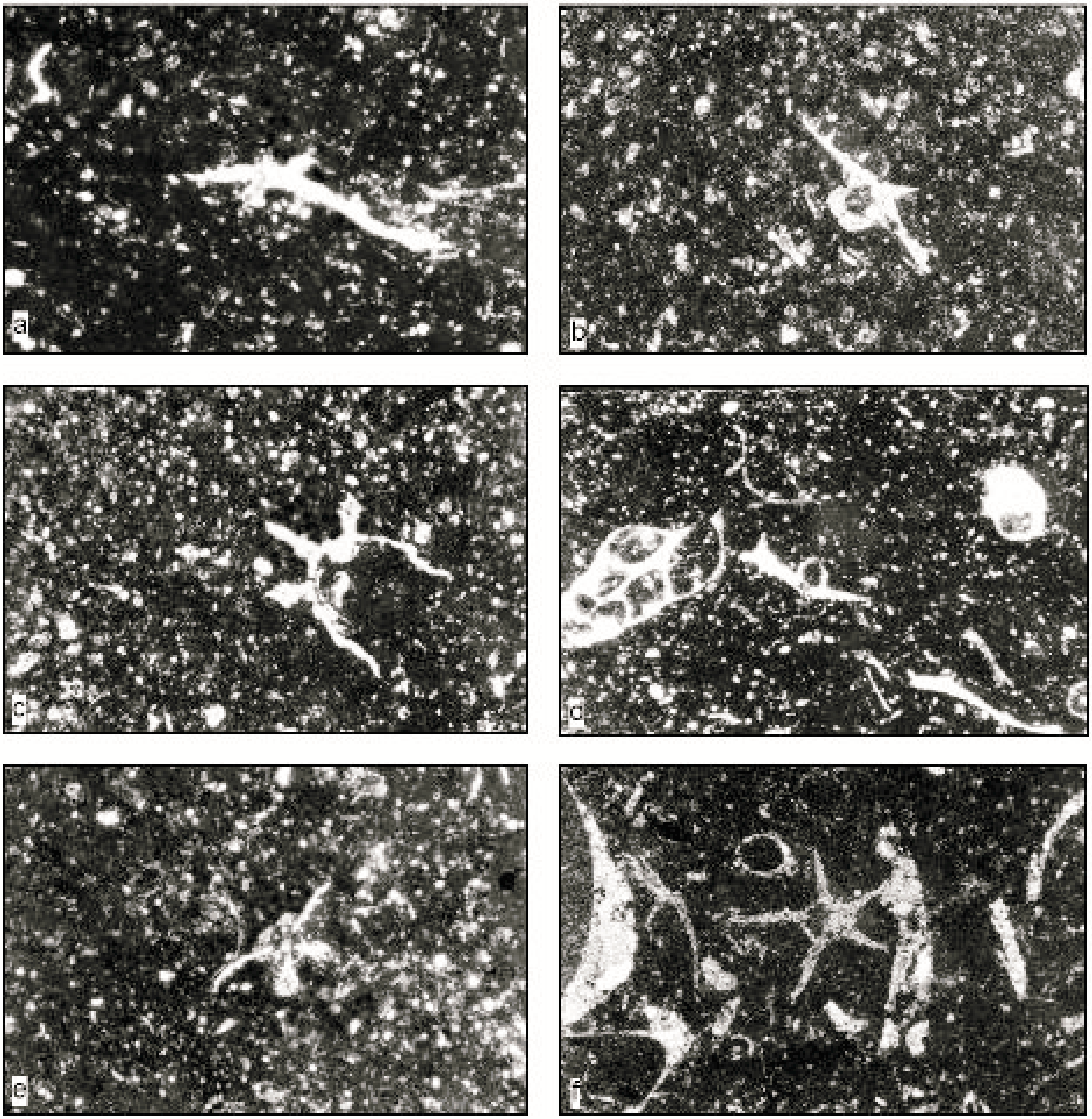
a) *Hedbergella* cf. *brittonensis* (Laranjeiras area, C 652), b) *Hedbergella (W.)* cf. *baltica* (Itaporanga area, RC4), c) *Globigerinelloides benthonensis* (Itaporanga area, RC4), d) *Heterohelix moremani* (Japaratuba area, Jardim 30) e) *Heterohelix* sp.; *Hedbergella (W.)* cf. *aprica* (Japaratuba area, Jardim 19), f) *Textularid* (Japaratuba area, Jardim 19), g) *Marsonella* sp. (Laranjeiras area, C 652), h) *Ammobaculites* cf. *reophacoides* (Japaratuba area, Jardim 19)

Plate 3: Foraminifers and other microfossils



a) *Globigerinelloides benthonensis*, b) fragment of unidentified foraminifer, c) *Heterohelix* (?)
d) *Heterohelix moremani*, e) fragment of unidentified foraminifer, f) calcisphere (?)

Plate 4: Roveacrinids



Roveacrinids:
a) brachial part b) brachial part c) *Roveacrinus* aff. *geinitzi* d) brachial part e) *Roveacrinus* sp.
f) *Roveacrinus communis*

Appendix

Appendix 1: Thin sections

Localitiy Jardim 1

A5-1: Groundmass: micritic (peloidal)
Macrofossils: fragments of gastropods and echinoderms rare, sponge spicules sparse
Microfossils: foraminifers and calcispheres moderately abundant, radiolarians sparse

A5-2: Groundmass: micritic (peloidal)
Macrofossils: fragments of echinodermal modertely abundant (e.g. roveacrinids)
Microfossils: planktonic and benthic foraminifers rare

A5-3: Groundmass: micritic (peloidal)
Macrofossils: fragments of bivalves, echinoderms rare, sponge spicules sparse
Microfossils: planktonic and benthic foraminifers occur

A5-4: Groundmass: micritic (peloidal)
Macrofossils: fragments of bivalves and echinoderms modertely abundant
Microfossils: none

A5-5: Groundmass: micritic (peloidal)
Macrofossils: fragments of bivalves modertely abundant, fragments of gastropods rare, sponge spicules sparse
Microfossils: planktonic and benthic foraminifers and calcispheres rare

A5-6: Groundmass: micritic (peloidal)
Macrofossils: fragments of echinoderms (e.g. roveacrinids) rare
Microfossils: planktonic and benthic foraminifers rare

A5-7: Groundmass: micritic (peloidal)
Macrofossils: fragments of bivalves and echinoderms modertely abundant
Microfossils: planktonic, benthic foraminifers and calcispheres rare

A5-8: Groundmass: micritic (peloidal)
Macrofossils: echinodermal remains occur
Microfossils: planktonic, benthic foraminifers moderately abundant
Remarks: sample strongly bioturbated

A5-9: Groundmass: micritic (peloidal)
Macrofossils: fragments of bivalves rare
Microfossils: calcispheres occur

A5-10: Groundmass: micritic (peloidal)
Macrofossils: echinoids occur, sponge spicules rare
Microfossils: planktonic and benthic foraminifers rare

A5-11: Groundmass: micritic (peloidal)
Macrofossils: echinodermal fragments moderately abundant
Microfossils: planktonic and benthic foraminifers rare

A5-12: Groundmass: micritic (peloidal)
Macrofossils: thin-shelled gastropods occur, sponge spicules sparse
Microfossils: planktonic, benthic foraminifers, calcispheres moderately abundant
Remarks: more bioclasts than A5-11

A5-13: Groundmass: micritic (peloidal)
Macrofossils: fragments of echinoderms moderately abundant, gastropods occur
Microfossils: planktonic, benthic foraminifers and calcispheres moderately abundant

A5-14: Groundmass: micritic (peloidal)
Macrofossils: fragments of gastropods and echinoderms moderately abundant
Microfossils: planktonic, benthic foraminifers and calcispheres occur

A5-15: Groundmass: micritic (peloidal)
Macrofossils: fragments of echinoderms moderately abundant, gastropods occur
Microfossils: planktonic, benthic foraminifers and calcispheres occur

A5-16: Groundmass: micritic (peloidal)
Macrofossils: fragments of echinoderms and thin-shelled gastropods abundant, sponge spicules sparse
Microfossils: planktonic and benthic foraminifers occur
Remarks: sample dolomitized

A5-17: Groundmass: micritic (peloidal)
Macrofossils: fragments of echinoderms and thin-shelled gastropods abundant
Microfossils: planktonic and benthic foraminifers moderately abundant
Remarks: partly dolomitized

Locality Jardim 19

A1-13: Groundmass: micritic (peloidal)
Macrofossils: fragments of roveacrinids rare
Microfossils: planktonic, benthic foraminifers and calcispheres rare

A1-14: Groundmass: micritic (peloidal)
Macrofossils: fragments of roveacrinids rare, sponge spicules sparse
Microfossils: planktonic, benthic foraminifers and calcispheres rare

A1-15: Groundmass: micritic (peloidal)
Macrofossils: fragments of roveacrinids rare
Microfossils: planktonic foraminifers (e.g. *Heterohelix moremani*), calcispheres moderately abundant

A1-16: Groundmass: micritic (peloidal)
Macrofossils: fragments of gastropods rare, fragments of roveacrinids rare
Microfossils: planktonic foraminifers (e.g. *Hedbergella (W.)* cf. *aprica*), calcispheres moderately abundant

A1-17: Groundmass: micritic (peloidal)
Macrofossils:more thin-shelled gastropods than A1-16, echinoid spines and roveacrinids rare
Microfossils: planktonic, benthic foraminifers and calcispheres rare, single ostracods

A1-18: Groundmass: micritic (peloidal)
Macrofossils: fragments of echinoderms and gastropods abundant, fragments of roveacrinids rare
Microfossils: planktonic and benthic foraminifers (e.g. textulariids) rare

A1-19: Groundmass: micritic (peloidal)
Macrofossils: less fragments of gastropods than in A1-18, fragments of echinoderms rare, sponge spicules sparse
Microfossils: planktonic and benthic foraminifers rare, ostracods rare
Remarks: dolomitized

A1-20: Groundmass: micritic (peloidal)
Macrofossils: fragments of gastropods rare
Microfossils: benthic foraminifers (e.g. *Ammobaculites*) moderately abundant
Remarks: dolomitized

A1-21: Groundmass: micritic (peloidal)
Macrofossils: none
Microfossils: planktonic and benthic foraminifers rare
Remarks: dolomitized

A1-22: Groundmass: micritic (peloidal)
Macrofossils: fragments of gastropods moderately abundant
Microfossils: planktonic and benthic foraminifers abundant
Remarks: dolomitized

A1-23: Groundmass: micritic (peloidal)
Macrofossils: fragments of gastropods abundant, sponge spicules moderately abundant

Microfossils: planktonic and benthic foraminifers moderately abundant
Remarks: dolomitized

A1-24: Groundmass: micritic (peloidal)
Macrofossils: thin-shelled gastropods abundant
Microfossils: planktonic and benthic foraminifers (e.g. *Hemicyclammina*, *Ammobaculites, Haplophragmium*) moderately abundant

A1-25: Groundmass: micritic (peloidal)
Macrofossils: fragments of gastropods and roveacrinids abundant
Microfossils: planktonic and benthic foraminifers abundant

Locality Jardim 29

A24-1: Groundmass: micritic
Macrofossils: shell fragments moderately abundant
Microfossils: planktonic and benthic foraminifers moderately abundant
Remarks: dolomitized

A24-2: Groundmass: micritic
Macrofossils: fragments of gastropods, echinoid spines, roveacrinids abundant, sponge spicules sparse
Microfossils: none
Remarks: dolomitizes

A24-3: Groundmass: micritic
Macrofossils: fragments of gastropods, and echinoderms abundant
Microfossils: planktonic, benthic foraminifers and ostracods rare
Remarks: dolomitized

A24-4: Groundmass: micritic
Macrofossils: fragments of echinoids, roveacrinids and gastropods moderately abundant
Microfossils: planktonic and benthic foraminifers moderately abundant
Remarks: bioturbated

A24-5: Groundmass: micritic
Macrofossils: fragments of echinoderms, gastropods and bivalves abundant, sponge spicules sparse
Microfossils: planktonic, benthic foraminifers and ostracods rare

A24-6: Groundmass: micritic
Macrofossils: fragments of gastropods, echinoderms and bivalves moderately abundant
Microfossils: planktonic and benthic foraminifers moderately abundant, ostracods rare

A24-7: Groundmass: micritic
Macrofossils: fragments of echinoderms
Microfossils: planktonic and benthic foraminifers (e.g. hedbergellids) moderately abundant

A24-8: Groundmass: micritic
Macrofossils: fragments of echinoderms (roveacrinids, echinoids) rare
Microfossils: none

A24-9: Groundmass: micritic
Macrofossils: fragments of gastropods and echinoderms rare
Microfossils: planktonic foraminifers rare

A24-10: Groundmass: micritic
Macrofossils: fragments of gastropods, bivalves and echinoderms abundant, sponge spicules sparse
Microfossils: planktonic and benthic foraminifers moderately abundant

A24-11: Groundmass: micritic
Macrofossils: echinoid spines moderately abundant

Microfossils: none
A24-12: Groundmass: micritic
Macrofossils: fragments of echinoderms moderately abundant, fragments of gastropods abundant
Microfossils: none
A24-13: Groundmass: micritic
Macrofossils: fragments of gastropods and echinoderms abundant
Microfossils: planktonic and benthic foraminifers moderately abundant
A24-14: Groundmass: micritic
Macrofossils: fragments of gastropods and echinoderms moderately abundant
Microfossils: benthic foraminifers rare
Remarks: strongly bioturbated
A24-15: Groundmass: micritic
Macrofossils: fragments of bivalves and echinoderms moderately abundant
Microfossils: planktonic and benthic foraminifers moderately abundant
A24-16: Groundmass: micritic
Macrofossils: fragments of gastropods, echinoderms and bivalves abundant
Microfossils: planktonic, benthic foraminifers and calcispheres moderately abundant
A24-17: Groundmass: micritic
Macrofossils: fragments of echinoderms (mainly roveacrinids) moderately abundant
Microfossils: planktonic, benthic foraminifers and calcispheres moderately abundant
A24-18: Groundmass: micritic
Macrofossils: fragments of gastropods and bivalves moderately abundant
Microfossils: planktonic, benthic foraminifers and calcispheres moderately abundant
A24-19: Groundmass: micritic
Macrofossils: fragments of echinoderms abundant
Microfossils: planktonic and benthic foraminifers moderately abundant
A24-20: Groundmass: micritic
Macrofossils: fragments of bivalve moderately abundant
Microfossils: planktonic and benthic foraminifers moderately abundant
A24-21: Groundmass: micritic
Macrofossils: fragments of echinoderms (roveacrinids and echinoid spines) moderately abundant
Microfossils: planktonic and benthic foraminifers rare
A24-22: Groundmass: micritic
Macrofossils: fragments of gastropods and echinoderms rare
Microfossils: planktonic and benthic foraminifers rare
Remarks: sample deeply weathered
A24-23: Groundmass: micritic
Macrofossils: fragments of gastropods and bivalves moderately abundant
Microfossils: planktonic, benthic foraminifers and calcispheres occur

Locality Jardim 30

A2-1: Groundmass: micritic
Macrofossils: fragments of echinoderms (echinoids, roveacrinids) moderately abundant, sponge spicules sparse
Microfossils: planktonic and benthic foraminifers moderately abundant
A2-2: Groundmass: micritic
Macrofossils: fragments of echinoderms moderately abundant
Microfossils: planktonic and benthic foraminifers abundant

A2-3: Groundmass: micritic
Macrofossils: fragments of roveacrinids rare
Microfossils: planktonic and benthic foraminifers abundant, calcispheres moderately abundant

A2-4: Groundmass: micritic
Macrofossils: roveacrinids occur
Microfossils: planktonic and benthic foraminifers abundant

A2-5: Groundmass: micritic
Macrofossils: roveacrinids (e.g. *Roveacrinus* aff. *geinitzi*) moderately abundant
Microfossils: planktonic, benthic foraminifers and calcispheres moderately abundant

A2-6: Groundmass: micritic
Macrofossils: fragments of echinoderms (echinoids and roveacrinids), fragments of bivalves abundant, sponge spicules sparse
Microfossils: planktonic, benthic foraminifers and calcispheres abundant

A2-7: Groundmass: micritic
Macrofossils: fragments of gastropods and bivalves moderately abundant
Microfossils: planktonic, benthic foraminifers and calcispheres moderately abundant

A2-8: Groundmass: micritic
Macrofossils: fragments of gastropods, echinoderms and bivalves rare
Microfossils: planktonic, benthic foraminifers and calcispheres rare

A2-9: Groundmass: micritic (peloidal)
Macrofossils: fragments of gastropods, bivalves and echinoderms abundant
Microfossils: benthic foraminifers (e.g. *Gabonite levis*) and calcispheres moderately abundant

A2-10: Groundmass: micritic (peloidal)
Macrofossils: fragments of gastropods and echinoderms occur, sponge spicules sparse
Microfossils: planktonic and benthic foraminifers moderately abundant
Remarks: sample deeply weathered

A2-11: Groundmass: micritic (peloidal)
Macrofossils: fragments of bivalves and echinoderms moderately abundant
Microfossils: planktonic and benthic foraminifers moderately abundant
Remarks: strongly dolomitized

A2-12: Groundmass: micritic (peloidal)
Macrofossils: fragments of bivalves and echinoderms
Microfossils: planktonic and benthic foraminifers and calcispheres
Remarks: dolomitized sample

A2-13: Groundmass: micritic (peloidal)
Macrofossils: fragments of bivalves rare
Microfossils: none
Remarks: dolomitized sample

A2-14: Groundmass: micritic (peloidal)
Macrofossils: fragments of echinoderms and bivalves rare
Microfossils: planktonic and benthic foraminifers rare
Remarks: strongly dolomitized sample

A2-15: Groundmass: micritic (peloidal)
Macrofossils: fragments of echinoderms rare
Microfossils: planktonic and benthic foraminifers rare
Remarks: strongly dolomitized sample

A2-16: Groundmass: micritic (peloidal)
Macrofossils: fragments of gastropods and echinoderms moderately abundant
Microfossils: planktonic, benthic foraminifers and calcispheres rare
Remarks: strongly dolomitized sample

A2-17: Groundmass: micritic (peloidal)
Macrofossils: fragments of bivalves, gastropods and echinoderms moderately abundant
Microfossils: planktonic, benthic foraminifers and calcispheres rare
Remarks: strongly dolomitized sample

Locality Jardim 31

A8-1: Groundmass: micritic (peloidal)
Macrofossils: fragments of gastropods moderately abundant
Microfossils: planktonic, benthic foraminifers and calcispheres rare
A8-2: Groundmass: micritic (peloidal)
Macrofossils: fragments of echinoderms (echinoids and roveacrinids) moderately abundant, fragments of gastropods rare
Microfossils: planktonic and benthic foraminifers rare
A8-3: Groundmass: micritic (peloidal)
Macrofossils: fragments of echinoderms rare
Microfossils: planktonic and benthic foraminifers, calcispheres and ostracods moderately abundant
A8-4: Groundmass: micritic (peloidal)
Macrofossils: fragments of echinoderms abundant, gastropod fragments moderately abundant, sponge spicules sparse
Microfossils: planktonic and benthic foraminifers and calcispheres abundant
A8-5: Groundmass: micritic (peloidal)
Macrofossils: fragments of gastropods and echinoderms abundant
Microfossils: planktonic, benthic foraminifers and calcispheres moderately abundant
A8-6: Groundmass: micritic (peloidal)
Macrofossils: fragments of gastropods and echinoderms abundant, sponge spicules sparse
Microfossils: planktonic and benthic foraminifers, calcispheres abundant, ostracods rare
A8-7: Groundmass: micritic (peloidal)
Macrofossils: fragments of echinoderms and gastropods abundant
Microfossils: calcispheres moderately abundant, planktonic foraminifers (e.g. heterohelicids) abundant
A8-8: Groundmass: micritic (peloidal)
Macrofossils: echinoderms and gastropods abundant, sparse sponge spicules
Microfossils: calcispheres moderately abundant, planktonic foraminifers (e.g. heterohelicids) abundant

Locality Japaratuba 11

AS-1: Groundmass: micritic
Macrofossils: fragments of gastropods moderately abundant
Microfossils: planktonic and benthic foraminifers rare
AS-2: Groundmass: micritic
Macrofossils: fragments of gastropods and bivalves rare, fragments of echinoderms moderately abundant, sponge spicules sparse
Microfossils: planktonic and benthic foraminifers and calcispheres occur
AS-3: Groundmass: micritic
Macrofossils: none
Microfossils: none
Remarks: sample deeply weathered
AS-4: Groundmass: micritic

Macrofossils: fragments of gastropods and bivalves occur
Microfossils: none

AS-5: Groundmass: micritic
Macrofossils: fragments of echinoderms (echinoid spines, roveacrinids) moderately abundant
Microfossils: planktonic and benthic foraminifers rare

AS-6: Groundmass: micritic
Macrofossils: fragments of gastropods and echinoderms moderately abundant
Microfossils: planktonic and benthic foraminifers rare

AS-7: Groundmass: micritic
Macrofossils: fragments of echinoderms and bivalves abundant
Microfossils: planktonic and benthic foraminifers rare

AS-8: Groundmass: micritic
Macrofossils: fragments of gastropods abundant and echinoderms, sponge spicules sparse
Microfossils: planktonic, benthic foraminifers and calcispheres occur

AS-9: Groundmass: micritic
Macrofossils: fragments of bivalves, gastropods and echinoderms abundant
Microfossils: calcispheres moderately abundant

AS-10: Groundmass: micritic
Macrofossils: fragments of echinoderms (roveacrinids, echinoids) and bivalves (e.g. oysters) moderately abundant
Microfossils: planktonic and benthic foraminifers rare
Remarks: bioclastic material than in AS-9

AS-11: Groundmass: micritic
Macrofossils: fragments of echinoderms abundant
Microfossils: planktonic and benthic foraminifers rare
Remarks: strongly bioturbated

AS-12: Groundmass: micritic
Macrofossils: fragments of echinoderms and gastropods abundant
Microfossils: planktonic and benthic foraminifers moderately abundant, radiolarians rare

AS-13: Groundmass: micritic
Macrofossils: echinoid spines and roveacrinids abundant
Microfossils: planktonic and benthic foraminifers moderately abundant

AS-14: Groundmass: micritic
Macrofossils: fragments echinoderms occur
Microfossils: planktonic and benthic foraminifers moderately abundant

AS-15: Groundmass: micritic
Macrofossils: fragments of echinoderms and gastropods abundant
Microfossils: planktonic, benthic foraminifers, calcispheres and radiolarians moderately abundant

AS-16: Groundmass: micritic
Macrofossils: fragments of gastropods and echinoderms rare
Microfossils: none

AS-17: Groundmass: micritic
Macrofossils: fragments of gastropods and echinoderms rare
Microfossils: planktonic and benthic foraminifers rare

AS-18: Groundmass: micritic
Macrofossils: fragments of gastropods abundant, echinoderms rare, sponge spicules sparse
Microfossils: planktonic and benthic foraminifers rare
Remarks: bioclasts strongly fragmentated

AS-19: Groundmass: micritic

Macrofossils: fragments of gastropods abundant, echinoderms rare, sponge spicules sparse
Microfossils: planktonic and benthic foraminifers rare
Remarks: bioclasts strongly fragmentated
AS-20: Groundmass: micritic
Macrofossils: fragments ofechinoderms (mainly roveacrinids) moderately abundant
Microfossils: planktonic and benthic foraminifers occur
AS-21: Groundmass: micritic
Macrofossils: fragments of echinoderms (e.g. echinoid spines), roveacrinids and gastropods moderately abundant
Microfossils: none
AS-22: Groundmass: micritic
Macrofossils: fragments of gastropods and echinoderms moderately abundant, sponge spicules sparse
Microfossils: planktonic and benthic foraminifers moderately abundant
AS-23: Groundmass: micritic
Macrofossils: fragments of echinoderms sparse
Microfossils: planktonic and benthic foraminifers moderately abundant
AS-24: Groundmass: micritic
Macrofossils: fragments of gastropods and echinoderms occur
Microfossils: planktonic and benthic foraminifers moderately abundant
AS-25: Groundmass: micritic
Macrofossils: fragments of echinoderms moderately abundant
Microfossils: planktonic and benthic foraminifers moderately abundant
AS-26: Groundmass: micritic
Macrofossils: roveacrinids moderately abundant
Microfossils: planktonic and benthic foraminifers moderately abundant

Locality Japaratuba 16

SW3-1: Groundmass: micritic
Macrofossils: fragments of echinoderms, bivalves and gastropods moderately abundant
Microfossils: none
Remarks: dolomitized
SW3-2: Groundmass: micritic
Macrofossils: fragments of echinoderms and fragments of bivalve (oyster shell) moderately abundant
Microfossils: none
Remarks: dolomitized
SW3-3: Groundmass: micritic
Macrofossils: fragments of bivalves (e.g. oysters, inoceramids) moderately abundant
Microfossils: none
Remarks: dolomitized
SW3-4: Groundmass: micritic
Macrofossils: fragments of bivalves (e.g. oysters, inoceramids) moderately abundant
Microfossils: none
Remarks: dolomitized
SW3-5: Groundmass: micritic
Macrofossils: fragments of bivalves abundant
Microfossils: none
Remarks: dolomitized
SW3-6: Groundmass: micritic

Macrofossils: fragments of bivalves and echinoderms moderately abundant
Microfossils: none
Remarks: dolomitized

SW3-7: Groundmass: micritic
Macrofossils: fragments of echinoderms moderately abundant
Microfossils: none
Remarks: dolomitized

SW3-8: Groundmass: micritic
Macrofossils: fragments of gastropods and bivalves moderately abundant
Microfossils: none
Remarks: dolomitized

SW3-9: Groundmass: micritic
Macrofossils: fragments of echinoderms, bivalves and gastropods moderately abundant
Microfossils: planktonic and benthic foraminifers rare
Remarks: dolomitized

SW3-10: Groundmass: micritic
Macrofossils: fragments of echinoderms, bivalves and gastropods abundant
Microfossils: planktonic and benthic foraminifers rare

SW3-11: Groundmass: micritic
Macrofossils: fragments of echinoderms, bivalves and gastropods moderately abundant
Microfossils: none

SW3-12: Groundmass: micritic
Macrofossils: fragments of bivalves and gastropods moderately abundant
Microfossils: none

SW3-13: Groundmass: micritic
Macrofossils: fragments of bivalves (e.g. oysters and inoceramids) moderately abundant, fragments of gastropods rare
Microfossils: planktonic and benthic foraminifers rare

SW3-14: Groundmass: micritic
Macrofossils: fragments of gastropods abundant, fragments of bivalves moderately abundant
Microfossils: planktonic and benthic foraminifers rare

SW3-15: Groundmass: micritic
Macrofossils: fragments of gastropods, echinoderms and bivalves abundant
Microfossils: planktonic and benthic foraminifers rare

SW3-16: Groundmass: micritic
Macrofossils: fragments of echinoderms (echinoid spines, roveacrinids) abundant, fragments of gastropods and bivalves moderately abundant
Microfossils: planktonic and benthic foraminifers rare

SW3-17: Groundmass: micritic
Macrofossils: fragments of echinoderms abundant (echinoid spines, roveacrinids), fragments of gastropods and bivalves moderately abundant
Microfossils: planktonic and benthic foraminifers rare

SW3-18: Groundmass: micritic
Macrofossils: fragments of gastropods and bivalves moderately abundant
Microfossils: planktonic and benthic foraminifers rare

SW3-19: Groundmass: micritic
Macrofossils: fragments of echinoderms abundant (echinoid spines, roveacrinids), fragments of gastropods and bivalves moderately abundant
Microfossils: planktonic and benthic foraminifers rare

SW3-20: Groundmass: micritic
Macrofossils: fragments of echinoderms abundant (echinoid spines, roveacrinids), fragments of gastropods and bivalves moderately abundant

Microfossils: planktonic and benthic foraminifers rare

Locality Laranjeiras C 652

SW1-1: Groundmass: micritic
Macrofossils: fragments of bivalves and gastropods abundant, fragments of echinoderms rare, roveacrinids occur
Microfossils: planktonic and benthic foraminifers moderately abundant
Remarks: veins filled with sparite

SW1-2: Groundmass: micritic
Macrofossils: fragments of bivalves abundant, fragments of echinoderms rare
Microfossils: planktonic and benthic foraminifers moderately abundant
Remarks: fossil remains strongly fragmentated

SW1-3: Groundmass: micritic
Macrofossils: fragments of bivalves moderately abundant
Microfossils: planktonic and benthic foraminifers occur
Remarks: sample strongly weathered

SW1-4: Groundmass: micritic
Macrofossils: fragments of bivalves moderately abundant, fragments of echinoderms rare
Microfossils: none

SW1-5: Groundmass: micritic
Macrofossils: indeterminable bioclasts
Microfossils: planktonic and benthic foraminifers rare

SW1-6: Groundmass: micritic
Macrofossils: fragments of bivalves, echinoid spines and roveacrinids rare
Microfossils: none
Remarks: more sparite than SW1-5

SW1-7: Groundmass: micritic
Macrofossils: fragments of bivalves rare
Microfossils: none
Remarks: groundmass inhomogenous

SW1-8: Groundmass: micritic
Macrofossils: echinoid spines and fragments of bivalves moderately abundant
Microfossils: planktonic and benthic foraminifers moderately abundant

SW1-9: Groundmass: micritic
Macrofossils: fragments of bivalves moderately abundant
Microfossils: planktonic and benthic foraminifers moderately abundant, calcispheres rare
Remarks: sparite veins

SW1-10: Groundmass: micritic
Macrofossils: fragments of bivalves rare, fragments of echinoderms sparse
Microfossils: planktonic and benthic foraminifers rare
Remarks: sparite veins

SW1-11: Groundmass: micritic
Macrofossils: fragments of echinoderms moderately abundant
Microfossils: none

SW1-12: Groundmass: micritic
Macrofossils: fragmenzs of echinoderms moderately abundant
Microfossils: planktonic and benthic foraminifers rare

SW1-13: Groundmass: micritic
Macrofossils: echinodermal fragments rare
Microfossils: planktonic and benthic foraminifers rare

SW1-14: Groundmass: micritic
Macrofossils: fragments of bivalves and echinoids moderately abundant

Microfossils: planktonic foraminifers (e.g. heterohelicids) abundant
SW1-15: Groundmass: micritic
Macrofossils: echinodermal fragments moderately abundant
Microfossils: none
SW1-16: Groundmass: micritic
Macrofossils: echinodermal fragments moderately abundant
Microfossils: planktonic and benthic foraminifers moderately abundant
SW1-17: Groundmass: micritic
Macrofossils: fragments of echinoderms moderately abundant
Microfossils: planktonic and benthic foraminifers moderately abundant
SW1-18: Groundmass: micritic
Macrofossils: fragments of bivalves and echinoderms (roveacrinids) moderately abundant
Microfossils: planktonic and benthic foraminifers rare
SW1-19: Groundmass: micritic
Macrofossils: fragments of echinoderms and bivalves moderately abundant
Microfossils: planktonic and benthic foraminifers abundant
SW1-20: Groundmass: micritic
Macrofossils: fragments of bivalves and echinoderms moderately abundant
Microfossils: planktonic and benthic foraminifers rare
Remarks: sample strongly weathered
SW1-21: Groundmass: micritic
Macrofossils: fragments of bivalves and echinoderms abundant
Microfossils: planktonic and benthic foraminifers rare
Remarks: bioclasts strongly fragmentated
SW1-22: Groundmass: micritic
Macrofossils: gastropods and bivalves moderately abundant
Microfossils: planktonic and benthic foraminifers occur
Remarks: geopetal fillings
SW1-23: Groundmass: micritic
Macrofossils: fragments of echinoderms and bivalves moderately abundant
Microfossils: planktonic and benthic foraminifers occur
SW1-24: Groundmass: micritic
Macrofossils: fragments of gastropods and echinoderms moderately abundant, fragments of bivalves rare
Microfossils: planktonic and benthic foraminifers moderately abundant
Remarks: sparitic fillings
SW1-25: Groundmass: micritic
Macrofossils: fragments of bivalves rare, fragments of echinoderms (roveacrinids, echinoids) rare
Microfossils: planktonic and benthic foraminifers moderately abundant
SW1-26: Groundmass: micritic
Macrofossils: fragments of echinoderms and bivalves rare
Microfossils: planktonic and benthic foraminifers abundant
Remarks: strongly bioturbated
SW1-27: Groundmass: micritic
Macrofossils: fragments of bivalves and echinoderms moderately abundant
Microfossils: planktonic and benthic foraminifers moderately abundant, calcispheres and radiolarians rare
SW1-28: Groundmass: micritic
Macrofossils: fragments of bivalves (oysters) and echinoderms abundant
Microfossils: planktonic, benthic foraminifers and calcispheres occur
SW1-29: Groundmass: micritic
Macrofossils: fragments of bivalves and echinoderms (roveacrinids) moderately abundant

Microfossils: planktonic and benthic foraminifers moderately abundant

SW1-30: Groundmass: micritic
Macrofossils: echinoid spines moderately abundant, fragments of bivalves abundant
Microfossils: planktonic and benthic foraminifers moderately abundant

SW1-31: Groundmass: micritic
Macrofossils: fragments of gastropods and bivalves moderately abundant, fragments of echinoderms rare
Microfossils: planktonic and benthic foraminifers abundant
Remarks: bioclasts strongly fragmentated

SW1-32: Groundmass: micritic
Macrofossils: fragments of bivalves and roveacrinids moderately abundant
Microfossils: planktonic and benthic foraminifers abundant

SW1-33: Groundmass: micritic
Macrofossils: fragments of gastropods rare, fragments of bivalves and echinoderms moderately abundant
Microfossils: planktonic and benthic foraminifers moderately abundant

SW1-34: Groundmass: micritic
Macrofossils: fragments of bivalves and echinoderms abundant
Microfossils: planktonic, benthic foraminifers and calcispheres abundant, radiolarians rare

SW1-35: Groundmass: micritic
Macrofossils: fragments of bivalves and echinoderms moderately abundant
Microfossils: planktonic and benthic foraminifers abundant

SW1-36: Groundmass: micritic
Macrofossils: fragments of bivalves moderately abundant
Microfossils: none
Remarks: sample deeply weathered

SW1-37: Groundmass: micritic
Macrofossils: fragments of bivalves and echinoderms moderately abundant
Microfossils: planktonic and benthic foraminifers rare

SW1-38: Groundmass: micritic
Macrofossils: fragments of echinoderms and bivalves rare
Microfossils: planktonic, benthic foraminifers and calcispheres rare

SW1-39: Groundmass: micritic
Macrofossils: fragments of bivalves and echinoderms moderately abundant
Microfossils: planktonic and benthic foraminifers moderately abundant

SW1-40: Groundmass: micritic
Macrofossils: fragments of echinoderms (roveacrinids) rare
Microfossils: planktonic and benthic foraminifers rare

SW1-41: Groundmass: micritic
Macrofossils: fragments of bivalves moderately abundant
Microfossils: planktonic, benthic foraminifers rare, calcispheres and radiolarians rare

SW1-42: Groundmass: micritic
Macrofossils: fragments of echinoderms moderately abundant (echinoids, roveacrinids)
Microfossils: planktonic and benthic foraminifers moderately abundant, radiolarians rare

SW1-43: Groundmass: micritic
Macrofossils: echinodermal fragments abundant, bivalves occur
Microfossils: planktonic and benthic foraminifers occur

SW1-44: Groundmass: micritic
Macrofossils: fragments of bivalves and echinoderms abundant
Microfossils: planktonic and benthic foraminifers occur

SW1-45: Groundmass: micritic
Macrofossils: fragments of bivalves and echinoderms moderately abundant
Microfossils: planktonic foraminifers and radiolarians occur
SW1-46: Groundmass: micritic
Macrofossils: fragments of bivalves and echinoderms moderately abundant
Microfossils: planktonic, benthic foraminifers and radiolarians moderately abundant

Locality Itaporanga (Rita Cacete) 4a

SW5-1: Groundmass: micritic
Macrofossils: fragments of roveacrinids rare, echinoid spines rare
Microfossils: planktonic foraminifers and calcispheres rare
Remarks: lamination structure
SW5-2: Groundmass: micritic
Macrofossils: fragments of roveacrinids moderately abundant
Microfossils: planktonic foraminifers rare, radiolarians and calcispheres sparse
Remarks: lamination structure
SW5-3: Groundmass: micritic
Macrofossils: fragments of roveacrinids moderately abundant, fragments of gastropods rare
Microfossils: planktonic foraminifers and calcispheres moderately abundant
Remarks: lamination structure
SW5-4: Groundmass: micritic
Macrofossils: fragments of roveacrinids moderately abundant
Microfossils: planktonic foraminifers, radiolarians and calcispheres rare
Remarks: lamination structure
SW5-5: Groundmass: micritic
Macrofossils: fragments of roveacrinids moderately abundant
Microfossils: planktonic foraminifers and calcispheres moderately abundant
Remarks: lamination structure
SW5-6: Groundmass: micritic
Macrofossils: fragments of roveacrinids moderately abundant
Microfossils: planktonic foraminifers and calcispheres rare
Remarks: lamination structure
SW5-7: Groundmass: micritic
Macrofossils: fragments of roveacrinids abundant
Microfossils: planktonic foraminifers and calcispheres rare
Remarks: lamination structure
SW5-8: Groundmass: micritic
Macrofossils: fragments of roveacrinids moderately abundant
Microfossils: planktonic foraminifers and calcispheres rare
Remarks: lamination structure
SW5-9: Groundmass: micritic
Macrofossils: fragments of roveacrinids rare
Microfossils: calcispheres rare
Remarks: lamination structure
SW5-10: Groundmass: micritic
Macrofossils: fragments of roveacrinids rare
Microfossils: planktonic foraminifers rare, calcispheres moderately abundant
Remarks: lamination structure
SW5-11: Groundmass: micritic
Macrofossils: fragments of roveacrinids rare
Microfossils: planktonic foraminifers and radiolarians rare, calcispheres moderately abundant

Remarks: lamination structure

SW5-12: Groundmass: micritic
Macrofossils: fragments of roveacrinids rare
Microfossils: planktonic foraminifers moderately abundant, calcispheres rare
Remarks: lamination structure

SW5-13: Groundmass: micritic
Macrofossils: fragments of gastropods rare, echinoderms (roveacrinids) moderately abundant
Microfossils: planktonic foraminifers and calcispheres rare
Remarks: lamination structure

SW5-14: Groundmass: micritic
Macrofossils: fragments of roveacrinids and echinoid spines rare
Microfossils: planktonic foraminifers and calcispheres rare
Remarks: lamination structure

SW5-15: Groundmass: micritic
Macrofossils: fragments of bivalves, gastropods and echinoderms moderately abundant, roveacrinids abundant
Microfossils: planktonic foraminifers moderately abundant, calcispheres and radiolarians rare
Remarks: lamination structure

SW5-16: Groundmass: micritic
Macrofossils: fragments of echinoderms (mainly roveacrinids) moderately abundant, fragments of inoceramid bivalves rare
Microfossils: planktonic foraminifers, calcispheres and radiolarians rare
Remarks: lamination structure

SW5-17: Groundmass: micritic
Macrofossils: echinoids moderately abundant
Microfossils: none
Remarks: lamination structure

SW5-18: Groundmass: micritic
Macrofossils: fragments of echinoderms (mainly roveacrinids) moderately abundant,
Microfossils: planktonic foraminifers and calcispheres moderately abundant
Remarks: lamination structure

SW5-19: Groundmass: micritic
Macrofossils: fragments of roveacrinids moderately abundant
Microfossils: calcispheres moderately abundant, planktonic foraminifers rare, benthic foraminifers occur
Remarks: lamination structure

SW5-20: Groundmass: micritic
Macrofossils: fragments of roveacrinids moderately abundant
Microfossils: planktonic foraminifers, calcispheres and radiolarians rare
Remarks: lamination structure

SW5-21: Groundmass: micritic
Macrofossils: fragments of roveacrinids rare
Microfossils: planktonic foraminifers, calcispheres and radiolarians moderately abundant
Remarks: lamination structure

SW5-22: Groundmass: micritic
Macrofossils: fragments of roveacrinids occur
Microfossils: radiolarians and calcispheres moderately abundant, planktonic foraminifers rare
Remarks: lamination structure

SW5-20: Groundmass: micritic
Macrofossils: roveacrinids rare

Microfossils: radiolarians and calcispheres moderately abundant, planktonic foraminifers rare
Remarks: lamination structure

Locality Itaporanga (Rita Cacete) 4b

SW4-1: Groundmass: micritic
Macrofossils: fragments of roveacrinids moderately abundant
Microfossils: planktonic foraminifers rare
Remarks: lamination structure
SW4-2: Groundmass: micritic
Macrofossils: fragments of roveacrinids rare
Microfossils: planktonic foraminifers abundant, calcispheres and radiolarians moderately abundant
Remarks: lamination structure
SW4-3: Groundmass: micritic
Macrofossils: fragments of echinoderms (echinoids and roveacrinids, fragments of inoceramid bivalves rare
Microfossils: planktonic foraminifers moderately abundant, calcispheres and radiolarians rare
Remarks: lamination structure
SW4-4: Groundmass: micritic
Macrofossils: fragments of roveacrinids rare
Microfossils: planktonic foraminifers moderately abundant, calcispheres and radiolarians rare
Remarks: lamination structure, sample partly dolomitized
SW4-5: Groundmass: micritic
Macrofossils: fragments of echinoderms rare
Microfossils: planktonic foraminifers moderately abundant, calcispheres and radiolarians rare
Remarks: lamination structure
SW4-6: Groundmass: micritic
Macrofossils: fragments of roveacrinids rare
Microfossils: planktonic foraminifers abundant, calcispheres and radiolarians rare
Remarks: lamination structure
SW4-7: Groundmass: micritic
Macrofossils: fragments of roveacrinids rare
Microfossils: planktonic foraminifers moderately abundant, calcispheres and radiolarians rare
Remarks: lamination structure
SW4-8: Groundmass: micritic
Macrofossils: fragments of roveacrinids rare
Microfossils: planktonic foraminifers rare, calcispheres and radiolarians rare
Remarks: lamination structure
SW4-9: Groundmass: micritic
Macrofossils: fragments of roveacrinids rare
Microfossils: planktonic foraminifers moderately abundant, calcispheres and radiolarians rare
Remarks: lamination structure
SW4-10: Groundmass: micritic
Macrofossils: fragments of roveacrinids rare
Microfossils: planktonic foraminifers, calcispheres and radiolarians rare
Remarks: lamination structure
SW4-11: Groundmass: micritic

Macrofossils: fragments of echinoderms (echinoids and roveacrinids) moderately abundant
Microfossils: planktonic foraminifers moderately abundant, calcispheres rare
Remarks: lamination structure
SW4-12: Groundmass: micritic
Macrofossils: echinodermal remains moderately abundant
Microfossils: calcispheres moderately abundant, planktonic foraminifers and radiolarians rare
Remarks: lamination structure
SW4-13: Groundmass: micritic
Macrofossils: fragments of roveacrinids rare
Microfossils: planktonic foraminifers moderately abundant, benthic foraminifers and calcispheres rare
Remarks: lamination structure
SW4-14: Groundmass: micritic
Macrofossils: fragments of echinoids and roveacrinids moderately abundant
Microfossils: planktonic foraminifers moderately abundant, benthic foraminifers and calcispheres rare
Remarks: lamination structure
SW4-15: Groundmass: micritic
Macrofossils: fragments of roveacrinids rare
Microfossils: planktonic foraminifers moderately abundant, benthic foraminifers and calcispheres rare
Remarks: lamination structure
SW4-16: Groundmass: micritic
Macrofossils: fragments of roveacrinids rare
Microfossils: planktonic foraminifers moderately abundant, benthic foraminifers and calcispheres rare
Remarks: lamination structure
SW4-17: Groundmass: micritic
Macrofossils: fragments of roveacrinids rare
Microfossils: planktonic, benthic foraminifers, calcispheres and radiolarians rare
Remarks: lamination structure
SW4-18: Groundmass: micritic
Macrofossils: fragments of roveacrinids rare
Microfossils: planktonic, benthic foraminifers, calcispheres and radiolarians rare
Remarks: lamination structure
SW4-19: Groundmass: micritic
Macrofossils fragments of roveacrinids rare
Microfossils: planktonic foraminifers, calcispheres and radiolarians rare
Remarks: lamination structure
SW4-20: Groundmass: micritic
Macrofossils: fragments of inoceramid bivalves rare, roveacrinids rare
Microfossils: planktonic foraminifers, calcispheres and radiolarians rare
Remarks: lamination structure
SW4-21: Groundmass: micritic
Macrofossils: none
Microfossils: planktonic foraminifers, calcispheres and radiolarians rare
Remarks: lamination structure
SW4-22: Groundmass: micritic
Macrofossils: fragments of roveacrinids rare
Microfossils: planktonic foraminifers, calcispheres and radiolarians rare
Remarks: lamination structure

Locality Itaporanga (Rita Cacete) 5

RC5-1: Groundmass: micritic
Macrofossils: none
Microfossils: none
Remarks: sample dolomitized
RC5-2: Groundmass: micritic
Macrofossils: fragments of roveacrinids rare
Microfossils: none
Remarks: sample dolomitized
RC5-3: Groundmass: micritic
Macrofossils: rare roveacrinids
Microfossils: none
Remarks: dolomitized
RC5-4: Groundmass: micritic
Macrofossils: rare roveacrinids
Microfossils: none
Remarks: dolomitized
RC5-5: Groundmass: micritic
Macrofossils: fragments of echinoderms
Microfossils: none
Remarks: dolomitized
RC5-6: Groundmass: micritic
Macrofossils: fragments of echinoderms and gastropods rare
Microfossils: planktonic foraminifers and calcispheres rare
RC5-7: Groundmass: micritic
Macrofossils: fragments of echinoderms and gastropods rare
Microfossils: planktonic foraminifers and calcispheres rare
RC5-8: Groundmass: micritic
Macrofossils: fragments of gastropods and roveacrinids rare
Microfossils: planktonic foraminifers and calcispheres rare
RC5-9: Groundmass: micritic
Macrofossils: echinoid spines and roveacrinids rare
Microfossils: planktonic foraminifers and calcispheres moderately abundant
RC5-10: Groundmass: micritic
Macrofossils: fragments of roveacrinids rare
Microfossils: planktonic foraminifers, radiolarians and calcispheres rare
RC5-11: Groundmass: micritic
Macrofossils: small-sized gastropods moderately abundant, fragments of roveacrinids rare
Microfossils: planktonic foraminifers and calcispheres rare
RC5-12: Groundmass: micritic
Macrofossils: small-sized gastropods rare, roveacrinids rare
Microfossils: planktonic foraminifers and calcispheres rare
RC5-13: Groundmass: micritic
Macrofossils: fragments of gastropods and echinoderms moderately abundant
Microfossils: planktonic foraminifers and calcispheres moderately abundant
RC5-14: Groundmass: micritic
Macrofossils: fragments of gastropods and echinoderms moderately abundant
Microfossils: planktonic foraminifers and calcispheres moderately abundant
RC5-15: Groundmass: micritic
Macrofossils: fragments of gastropods and echinoderms moderately abundant
Microfossils: planktonic foraminifers and calcispheres rare
RC5-16: Groundmass: micritic
Macrofossils: fragments of gastropods and echinoderms moderately abundant

Microfossils: planktonic foraminifers and calcispheres rare

RC5-17: Groundmass: micritic
Macrofossils: fragments of gastropods and echinoderms moderately abundant
Microfossils: planktonic foraminifers and calcispheres rare

Appendix 2: Lithology & microfacies type

Locality	**Laranjeiras**	**C 652**	
Sample-ID	m	Lithologic unit	MFT
SW1-1	0.00	3	3
SW1-2	0.50	3	3
SW1-3	0.10	3	3
SW1-4	0.15	3	3
SW1-5	0.20	3	3
SW1-6	0.25	2	2
SW1-7	0.40	2	2
SW1-8	0.50	2	2
SW1-9	0.60	2	2
SW1-10	0.70	2	2
SW1-11	0.85	2	2
SW1-12	0.95	2	2
SW1-13	1.10	2	2
SW1-14	1.25	2	2
SW1-15	1.35	2	2
SW1-16	1.55	2	2
SW1-17	1.75	2	2
SW1-18	1.90	2	2
SW1-19	2.00	2	2
SW1-20	2.10	2	2
SW1-21	2.20	2	2
SW1-22	2.35	2	2
SW1-23	2.65	2	2
SW1-24	2.70	2	2
SW1-25	2.90	2	2
SW1-26	3.10	2	2
SW1-27	3.20	2	2
SW1-28	3.50	2	2
SW1-29	3.80	3	3
SW1-30	4.00	2	2
SW1-31	4.20	3	3
SW1-32	4.50	2	2
SW1-33	4.80	2	2
SW1-34	5.00	2	2
SW1-35	5.20	2	2
SW1-36	5.70	2	2
SW1-37	5.90	3	3
SW1-38	6.40	3	3
SW1-39	6.80	3	3
SW1-40	7.00	3	3
SW1-41	7.10	3	3
SW1-42	7.50	2	2
SW1-43	7.80	2	2
SW1-44	9.20	2	2
SW1-45	10.2	2	2
SW1-46	11.5	2	2

Locality	**Japaratuba 16**		
Sample-ID	m	Lithologic unit	MFT
SW3-1	0.00	2	2
SW3-2	0.35	2	2
SW3-3	0.60	2	2
SW3-4	0.80	2	2
SW3-5	1.05	2	3
SW3-6	1.30	2	3
SW3-7	1.55	2	3
SW3-8	1.75	2	3
SW3-9	2.00	2	3
SW3-10	2.20	2	3
SW3-11	2.45	3	3
SW3-12	2.75	3	3
SW3-13	2.95	3	3
SW3-14	3.05	3	3
SW3-15	3.30	3	3
SW3-16	3.70	3	3
SW3-17	4.00	3	3
SW3-18	4.20	3	3
SW3-19	4.40	3	3
SW3-20	4.60	3	3

Locality	**Japaratuba 11**		
Sample-ID	m	Lithologic unit	MFT
AS-1	0.00	2	2
AS-2	0.50	2	2
AS-3	0.80	2	2
AS-4	1,20	2	2
AS-5	1.70	2	2
AS-6	2.00	2	2
AS-7	2.50	2	2
AS-8	2.80	2	2
AS-9	3.00	2	2
AS-10	3.50	3	3
AS-11	4.00	3	3
AS-12	4.50	3	3
AS-13	4.90	3	3
AS-14	5.40	3	3
AS-15	6.00	3	3
AS-16	7.30	3	3
AS-17	7.90	3	3
AS-18	8.10	3	3
AS-19	8.40	3	3
AS-20	8.60	3	3
AS-21	8.80	3	3
AS-22	9.00	3	3

Locality **Rita Cacete 4b**

Sample-ID	m	Lithologic unit	MFT
SW4-1	0.00	4	4
SW4-2	0.15	4	4
SW4-3	0.35	4	4
SW4-4	0.45	4	4
SW4-5	0.65	4	4
SW4-6	0.80	4	4
SW4-7	0.90	4	4
SW4-8	1.00	4	4
SW4-9	1.20	4	4
SW4-10	1.45	4	4
SW4-11	1.50	4	4
SW4-12	1.70	4	4
SW4-13	1.90	4	2
SW4-14	2.10	4	2
SW4-15	2.30	4	4
SW4-16	2.45	4	4
SW4-17	2.55	4	4
SW4-18	2.65	4	4
SW4-19	2.75	4	4
SW4-20	2.85	4	4
SW4-21	3.15	4	4
SW4-22	3.35	4	4

Locality **Rita Cacete 5**

Sample-ID	m	Lithologic unit	MFT
RC5-1	0.00	2	4
RC5-2	0.20	2	4
RC5-3	0.40	2	4
RC5-4	0.60	2	4
RC5-5	0.80	2	4
RC5-6	1.00	2	4
RC5-7	1.20	2	2
RC5-8	1.40	2	2
RC5-9	1.60	2	4
RC5-10	1.90	2	4
RC5-11	2.00	2	4
RC5-12	2.30	2	4
RC5-13	2.60	2	2
RC5-14	2.80	2	2
RC5-15	3.00	2	4
RC5-16	3.30	2	2
RC5-17	3.50	2	4
RC5-18	3.80	2	4
RC5-19	4.00	2	4

Locality **Jardim 31**

Sample-ID	m	Lithologic unit	MFT
A8-1	0.00	1	1
A8-2	0.30	1	1
A8-3	0.50	1	1
A8-4	0.80	1	1
A8-5	1.00	1	1
A8-6	1.20	1	1

Locality **Rita Cacete 4a**

Sample-ID	m	Lithologic unit	MFT
SW5-1	0.00	2	4
SW5-2	0.10	2	4
SW5-3	0.20	2	4
SW5-4	0.30	2	4
SW5-5	0.50	2	4
SW5-6	0.70	2	2
SW5-7	0.80	2	2
SW5-8	1.10	2	2
SW5-9	1.30	2	2
SW5-10	1.60	2	2
SW5-11	1.90	2	2
SW5-12	2.10	4	4
SW5-13	2.30	4	4
SW5-14	2.50	4	4
SW5-15	2.70	4	4
SW5-16	2.90	4	4
SW5-17	3.00	4	4
SW5-18	3.30	4	4
SW5-19	3.50	4	4

Locality **Jardim 19**

Sample-ID	m	Lithologic unit	MFT
A1-13	0.00	1	1
A1-14	0.20	1	1
A1-15	0.25	1	1
A1-16	0.30	1	1
A1-17	0.50	1	1
A1-18	0.55	1	1
A1-19	0.70	1	1
A1-20	0.85	1	1
A1-21	0.95	1	1
A1-22	1.05	1	1
A1-23	1.15	1	1
A1-24	1.20	1	1
A1-25	1.25	1	1

Locality **Jardim 1**

Sample-ID	m	Lithologic unit	MFT
A5-1	0.00	1	1
A5-2	0.10	1	1
A5-3	0.20	1	1
A5-4	0.25	1	1
A5-5	0.35	1	1
A5-6	0.55	1	1
A5-7	0.70	1	1
A5-8	0.85	1	1
A5-9	1.00	1	1
A5-10	1.15	1	1
A5-11	1.25	1	1
A5-12	1.35	1	1
A5-13	1.45	1	1
A5-14	1.55	1	2
A5-15	1.60	1	2

A8-7	1.40	1	1
A8-8	1.60	1	1

Locality **Jardim 30**

Sample-ID	m	Lithologic unit	MFT
A2-1	0.00	1	2
A2-2	0.10	1	2
A2-3	0.20	1	2
A2-4	0.30	1	2
A2-5	0.50	1	2
A2-6	0.80	1	2
A2-7	1.00	1	2
A2-8	1.20	1	2
A2-9	1.35	1	2
A2-10	1.55	1	2
A2-11	1.70	1	1
A2-12	1.90	1	1
A2-13	2.10	1	1
A2-14	2.40	1	1
A2-15	2.50	1	1
A2-16	2.60	1	1
A2-17	2.80	1	1

A5-16	1.75	1	2
A5-17	1.80	1	2

Locality **Jardim 29**

Sample-ID	m	Lithologic unit	MFT
A24-1	0.00	2	2
A24-2	0.50	2	2
A24-3	1.10	2	2
A24-4	1.50	2	2
A24-5	2.00	2	2
A24-6	2.80	2	2
A24-7	3.20	2	2
A24-8	3.80	2	2
A24-9	4.00	2	2
A24-10	4.50	2	2
A24-11	5.20	2	2
A24-12	6.20	2	2
A24-13	7.10	2	2
A24-14	7.60	2	2
A24-15	8.30	2	2
A24-16	8.90	2	2
A24-17	9.50	2	2
A24-18	9.80	2	2
A24-19	10.30	2	2
A24-20	10.60	2	2
A24-21	10.70	2	2
A24-22	10.80	2	2
A24-23	11.10	2	2

Appendix 3 : Stable isotope values

Sample-ID **Laranjeiras** **C 652**	**m**	**δ carbon**	**δ oxygen**
SW1-2	0.10	1.08	-3.73
SW1-5	0.20	0.91	-3.89
SW1-8	0.70	0.66	-3.80
SW1-13	1.45	1.53	-4.06
SW1-15	1.60	2.35	-4.06
SW1-18	2.20	0.60	-3.80
SW1-20	2.55	1.09	-3.61
SW1-25	3.40	1.48	-3.75
SW1-30	4.30	1.06	-3.91
SW1-35	5.40	2.48	-4.19
SW1-36	5.60	2.19	-3.99
SW1-37	5.90	2.06	-4.19
SW1-39	6.65	0.96	-4.00
SW1-40	6.70	1.24	-4.00
SW1-43	7.45	1.88	-4.15
SW1-44	7.60	1.95	-4.11
SW1-45	7.85	1.63	-4.22
Itaporanga **Rita Cacete 4b**			
SW4-2	0.15	2.77	-3.39
SW4-4	0.45	2.77	-3.20
SW4-6	0.80	2.68	-3.30
SW4-9	1.20	2.68	-3.10
SW4-12	1.70	2.63	-3.11
SW4-16	2.45	2.66	-3.41
SW4-19	2.75	2.50	-3.43
Rita Cacete 5			
SW5-2	0.20	3.27	-3.45
SW5-5	0.60	3.08	-3.50
SW5-6a	1.10	1.12	-3.29
SW5-8	1.50	2.32	-3.43
SW5-11b	1.90	3.11	-3.70
SW5-14	2.55	2.06	-3.49
SW5-19	3.50	2.20	-3.42
Japaratuba **Jardim 29**			
A24-1	0.00	0.57	3.83
A24-3	1.00	0.96	-3.79
A24-4	2.00	-0.08	-3.87
A24-6	2.80	0.33	-3.73
A24-8	3.80	-0.56	-1.89
A24-10	4.40	-0.94	-3.37
A24-14	5.30	-0.67	-3.76
A24-16	5.70	-1.12	-3.75
A24-18	6.80	-1.35	-3.62

Sample-ID	**m**	**δ carbon**	**δ oxygen**
A24-18	6.80	-1.35	-3.62
A24-20	7.80	-2.07	-3.59
A24-21	8.50	-3.51	-3.89
Jardim 30			
A2-1	0.00	2.01	-3.47
A2-4	0.50	1.66	-3.46
A2-8	0.80	-1.75	-3.3
A2-9	2.00	-0.89	-3.53
A2-10	2.20	0.33	-2.66
A2-14	3.00	0.78	-2.19
A2-17	4.20	1.43	-2.76
Jardim 1			
A5-2	0.20	2.33	-3.5
A5-5	0.85	1.34	-3.84
A5-8	1.30	2.07	-3.42
A5-11	1.70	2.35	-3.35
A5-15	2.10	0.55	-3.36
Jardim 19			
A1-3	0.50	2.54	-3.4
A1-20	1.20	2.29	-3.31