Carbonate-siliciclastic facies patterns related to the closure of the Central American Seaway: A comparison between the Pliocene of Costa Rica and the present-day Gulf of Panama and Gulf of Chiriqui

Karbonat-siliziklastische Faziesverteilung in Bezug zur Schliessung des zentralamerikanischen Seeweges: Ein Vergleich zwischen dem Pliozän in Costa Rica und dem heutigen Golf von Panama.

Dissertation

zur Erlangung des Doktorgrades
der Mathematisch-
Naturwissenschaftlichen Fakultät
der Christian-Albrechts-Universität
zu Kiel

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von

Thorsten Bauch

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Cover: Turitella Hill; Lower Gatun Formation, Panama; located at Refinería Panama, S.A., age about 9 Ma; photograph: Thorsten Bauch

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ABSTRACT

After the closure of the Central American Seaway around 3.6 Ma, the benthic carbonate ecosystems developed differently in the Caribbean and on the Pacific side of the Isthmus of Panama. In this thesis, fossil and recent carbonate systems were studied and a comparison was made between fossil and present-day carbonate ecosystems from the same paleolatitude. This opens up the possibility to document the evolution of these sedimentation systems through time.

Pliocene reef systems that represent the carbonate producing benthic ecosystem in the Caribbean shortly before the closure of the Central American Seaway were studied in Limon, Costa Rica. This part of the thesis (Chapter 3) focused on two Lower Late Pliocene reef units, the Las Islas roadcut and the newly discovered Contact Cut outcrop. They are located at the contact between the siliciclastic sediments of the Rio Banano Formation and the mixed reefal and coral bearing deposits and siliciclastic sediments of the Quebrada Chocolate Formation. During a rise in sea level and a slight progradation during the following decrease in sea-level rise, extensive reef growth is shown at the Contact Cut outcrop. In a later phase the reefs become stressed by siliciclastic input. Rapid burial of the corals through siliciclastics were shown at the Las Islas roadcut. A distinct facies diversification during the final stages of the closing of the Central American Seaway was documented by both time-equivalent reefs. The reefs developed in an environment stressed by siliciclastic input, which ultimately caused a decrease in coral diversity and abundance followed by a complete demise of the reefs. The reef systems showed that two reefs developing at the same time, in direct vicinity, which show similar communities, nevertheless can react very differently to siliciclastic input and thus leave a different sedimentary imprint in the geological record.

For the interpretation of fossil facies pattern and their paleontological, mineralogical (e.g. aragonite, high-magnesium calcite, low-magnesium calcite), and sedimentological diversity (e.g. grain size, sorting) it is important to better understand the geological-biological relationships that exist in recent carbonate environments, with respect to the oceanography parameters like water temperature and salinity. These types of modern-day mixed carbonate-siliciclastic environments

were studied in the Gulf of Panama and the Gulf of Chiriquí on the Pacific side of Panama.
The terrigenous sands present in both gulfs, predominantly consists of quartz, feldspar and volcanoclastic grains. Latter result from the weathering of the volcanic islands within the gulfs or are erosional products of the volcanic dominated mainland that are transported into the gulfs by rivers. The distribution of clays to fine sands In the Gulf of Panama is mainly influenced by the counter-clockwise current in the gulf which is induced by the extensions of Humboldt Current. The sedimentation pattern observed in the channels within the Archipelago de Las Perlas (Gulf of Panama), which show terrigenous sediment transport, are comparable with the environment as found in the Limon study area shortly before the final closure of the Central American Seaway, with rivers and channels transporting terrigenous material towards the carbonate producing bays around the islands.

Carbonate production mainly occurs in the shallow-water areas surrounding the small islands present in both gulfs and shows minor sediment transport. The Gulf of Chiriquí (non-upwelling) and the Gulf of Panama (upwelling) show significant differences in their main carbonate producing biota. The Gulf of Panama is influenced by seasonal upwelling and shows mainly heterozoan assemblages around the islands dominated by Balanidae, Echinodermata and/or molluscs. Those heterozoan assemblages in the Gulf of Panama evolved in response to the upwelling conditions that developed in the Gulf of Panama after the closure of the Isthmus. The Gulf of Chiriquí shows photozoan (coralgal) assemblages within the shallow water areas surrounding the islands and mollusc-dominated facies within deeper waters towards the shelf. These assemblages suggest oligotrophic to mesotrophic conditions in the Gulf of Chiriquí, whereas mesotrophic to eutrophic conditions prevail in the Gulf of Panama.

The modern-day reef ecosystem in the Caribbean and on the Pacific side of Panama developed from the population thriving in this region before the closure of the Panamanian Isthmus. The Pliocene reefs that existed shortly before the closure of the Isthmus, the modern-day Caribbean reefs and the recent reefs on the Pacific side of Panama all show differences in their coral families, genera and species. Nevertheless, the Pliocene reefs show some coral families that today still occur in the Caribbean and others that occur on the Pacific side of Panama in present-day reefs. All studied environments show a mixed carbonate-siliciclastic system in which carbonate benthic ecosystems developed in an environment stressed by terrigenous input.

KURZFASSUNG

Nach der Schliessung der Landenge von Panama vor rund 3.6 Mio. Jahren haben sich die Karbonatökosysteme auf der Karibischen und der Pazifischen Seite unterschiedlich entwickelt. In dieser Studie wurden fossile und rezente Karbonatsysteme aus derselben geographischen Breite untersucht. Dies ermöglicht es, die Entwicklung dieser Sedimentationssysteme durch die Zeit zu untersuchen.

In Limon, Costa Rica, wurden pliozäne Riffsysteme untersucht, welche die Situation der benthischen Karbonatökosysteme in der Karibik kurz vor der letzten, kompletten Schliessung des zentralamerikanischen Seeweges zeigen. Diese Studie konzentriert sich auf zwei Riffe im unteren späten Pliozän, den Las Islas Strassenaufschluss und den neu entdeckten Contact Cut Aufschluss. Diese befinden sich zwischen den siliziklastisch geprägten Sedimenten der Rio Banano Formation und den korallenreichen, gemischt siliziklastisch-karbonatreichen Riffsedimenten der Quebrada Chocolate Formation. Das Contact Cut Riff zeigt ausgeprägtes Riffwachstum während eines Anstiegs des Meeresspiegels und eine damit verbundene leichte Progradierung nach einem starken Abschwächen des Meeresspiegelanstieges. Im weiteren Verlauf der Riffentwicklung unterliegt das Riff mehreren Phasen siliziklastischer Schüttungen, die das Wachstum und die Diversität der Riffbiota einschränken. Das Las Islas Riff hingegen zeigt eine schnelle komplette Verschüttung der Korallen durch Siliziklastika. Zeitgleich zeigen beide Riffe eine deutliche Faziesveränderung während der finalen Phasen der Schliessung der Landenge von Panama. Der siliziklastische Eintrag führte bei beiden Riffen zu einer Abnahme der Häufigkeit und der Vielfalt der Korallen, bis hin zu einem kompletten Absterben der Riffe. Die Untersuchungen zeigen, dass zwei Riffsysteme, die, obwohl sie geographisch dicht beieinander liegen und zeitgleich entstanden sind, unterschiedlich auf siliziklastischen Eintrag reagieren können und somit unterschiedliche geologische Aufzeichnungen im Sediment hinterlassen.

Für die Interpretation von fossilen Faziesmustern und dem Verständnis von paläonthologischen, mineralogischen (z.B. Aragonit, Hochmagnesium Calzit, Niedrigmagensium Calzit) und sedimentologischen Unterschieden (z.B. Korngrössenverteilung, Sortierung der Körner) ist es wichtig, die geologisch-

biologischen Verknüpfungen zu verstehen, die in modernen Karbonatsystemen existieren. Solche rezenten, gemischt karbonat-siliziklastischen Systeme wurden im Golf von Panama und im Golf von Chiriquí untersucht. Dies alles unter Berücksichtigung ozeanischer Parameter wie Temperatur und Salzgehalt des Wassers.
Die vorherrschenden terrigenen Sande in beiden Golfen bestehen hauptsächlich aus Quartz, Feldspäten und Körnern vulkanischen Ursprungs. Letztere sind Verwitterungsprodukte der überwiegend vulkanischen Inseln in beiden Golfen und Erosionsprodukte durch Flusseintrag aus dem vulkanischen Hinterland. Die Verteilung der Tone bis zu den feinen Sanden im Golf von Panama ist überwiegend beeinflusst durch gegen den Uhrzeigersinn verlaufende Strömungen, welche durch Ausläufer des Humboldt-Stromes angeregt werden, die in den Golf von Panama fliessen. Das Verteilungsmuster der terrigenen Sedimente innerhalb der Kanäle zwischen den vielen Inseln im Archipel von Las Perlas zeigt eine Umgebung, wie sie im Pliozän in der Gegend um Limon, Coasta Rica zu beobachten war, kurz vor der Schliessung der Landenge: viele Flüsse und Kanäle, die terrigenes Material in die karbonatproduzierenden Gebiete schwämmen und diese beeinflussen.

Die Karbonatproduktion in den beiden rezenten Golfen findet hauptsächlich im flachen Wasser in der Umgebung der vielen Inseln statt, und zeigt nur geringen lateralen Transport. Der Golf von Chiriquí (nicht Auftriebsgebiet) und der Golf von Panama (saisonales Auftriebsgebiet) zeigen ausgeprägte Unterschiede in der Art der karbonatproduzierenden Fauna. Der durch Auftrieb beeinflusste Golf von Panama zeigt vornehmlich heterozoische Vergesellschaftungen im Sediment (Balanidae, Echinodermata und Mollusken). Diese heterozoischen Gesellschaften haben sich auf Grund des Einflusses durch Auftrieb gebildet, der sich im Golf von Panama nach der Schliessung entwickelte. Der Golf von Chiriqui zeigt photozoische Vergesellschaftungen (Coralgal) im Flachwasserbereich in der Umgebung der Inseln, und Mollusken dominierende Fazies in den grösseren Wassertiefen zum Schelf hin. Die Vergesellschaftung von Biotafragmenten im Sediment spiegelt die oligotrophen bis mesotrophen Bedingungen im Golf von Chiriqui und die mesotrophen bis eutrophen Bedingungen im Golf von Panama wieder.

Die modernen Riff-Ökosysteme in der heutigen Karibik und auf der pazifischen Seite von Panama sind aus einer Population entstanden, die sich in dieser Gegend befand, bevor die endgültige Schliessung der Landenge einsetzte. Die pliozänen Riffe in der Region um Limon, Costa Rica, die Riffe in der heutigen Karibik, sowie die Riffe auf der pazifischen Seite von Panama zeigen unterschiedliche Familien, Genera und Spezies von Korallen. Dennoch existieren in den pliozänen Riffen Korallenfamilien, die wir in der heutigen Karibik finden, sowie andere Korallenfamilien, die wir heute auf der pazifischen Seite von Panama finden. Alle untersuchten Umgebungen zeigen gemischt-karbonat-siliziklastische Systeme, in denen die Karbonatproduzenten durch den Einfluss von terrigenem Eintrag geschwächt werden.

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The author is grateful to his parents for their support during the start of my academic career. I dedicate this thesis to my father, unfortunately he missed the finish.

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CHAPTER 4

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CHAPTER 1

INTRODUCTION

1. INTRODUCTION

The research presented in this thesis addresses two case studies. The first case study concentrates on Pliocene reef occurrences in Costa Rica (Chapter 3). The second case study describes the present-day reef distribution on the Pacific Ocean side of the Isthmus of Panama (Chapter 4 and 5).

The general theme of the thesis is to document the impact of the closure of the Central American Seaway in the Miocene/Pliocene on present-day carbonate ecosystems at the Pacific coast of Panama. The outcrop study presented in Chapter 3 describes Pliocene deposits from Costa Rica that represent the carbonate producing benthic ecosystem in the Caribbean before the closure of the Central American Seaway. The final gateway closure around 3.6 Ma led to formation of the West Atlantic warm pool in the Caribbean while upwelling conditions driven by the northeast-bound trade winds regionally developed along the Pacific coast of Panama. In Chapter 4 and 5 of this thesis the present-day carbonate benthic ecosystems occurring in the Gulf of Panama and the Gulf of Chiriquí are discussed. In the Gulf of Panama, the carbonate producing benthic ecosystem has adapted itself to the new situation after the gateway closure governed by increased nutrient supply through upwelling. In contrast, coral reefs in the Gulf of Chiriquí represent a relict reef ecosystem which is presumed to have occurred widespread in the Caribbean before the closure of the isthmus. The west coast of Panama is influenced by the West Atlantic climate system and the West Pacific warm pool and thus holds a key position connecting both systems. The sedimentological comparison between carbonate factories that occur under upwelling and non-upwelling conditions will expand our knowledge on the interaction between the ocean environment, facies patterns and evolution resulting from the Panama closure.

In this chapter a short summary is given of the general setting of the study area.

1.1 Study Areas, Geographical Overview

1.1.1 Costa Rica

Costa Rica lies between Nicaragua to the north and Panama to the south. It borders the Caribbean Sea in the east and the Pacific Ocean to the west, with 212km Caribbean coastline and 1016 km coastline on the Pacific side. Costa Rica comprises about 52000 square kilometres. The capital city of Costa Rica is San José. National parks are common in Costa Rica, 25% of the national territory is protected within national parks. The main mountain ranges are the Guanacaste Mountain Range, Central Mountain Range, and Talamanca Mountain Range and they are extending the entire length of the country. Several active volcanoes (Arenal Volcano, Irazu Volcano, Rincon de la Vieja Volcano and Turrialba Volcano) exist.

1.1.2 Panama

Panama is located in Central America and connects South America with Central America forming a landbridge. Panama borders Costa Rica in the west and Colombia in the southeast. Panama has two coastlines, the Caribbean and the Pacific coastline

Panama comprises about 77100 square kilometres. The capital and largest city is Panama City. The Panama Canal bisects the country and links the North Atlantic Ocean and the East Pacific Ocean.

Panama has a tropical climate with a prolonged rainy season (May to December) and a short dry season (January to April).

1.2 Plate Tectonic History

Two different models are described in the literature for the plate tectonic evolution of the Caribbean plate. Theory A, “The Pacific Model”, proposes a Late Mesozoic origin of the Caribbean ocean crust in the Pacific region and describes its drift into its present position between North- and South-America (e.g. Pindell and Dewey, 1982, Burke et al., 1984, Pindell, 1985; 1994). Theory B, "The inter-American Model", proposes the formation of the Caribbean crust in a position in between the two Americas but west of its present position (e.g. Klitgord and Schouten, 1986; Frisch et al., 1992, Meschede et al., 1997; Meschede and Frisch, 1998). The plate tectonic evolution used in this study follows the widely accepted aforementioned theory B (interamerican-position) as described in detail in Meschede and Frisch (1998).

Meschede and Frisch (1998) used the relative motions of the North American, African, South American, and Farallon plates during the Mesozoic and Cenozoic (e.g. Pindell and Barrett, 1990; Hay et al., 1998) for the reconstruction of the continental drift in the Caribbean region. During the Callovian / Oxfordian (160 Ma) the North America - , South America - and African Plate were still close together **(Fig. 1.1)**. The start of the rifting process is indicated by a spreading axis between

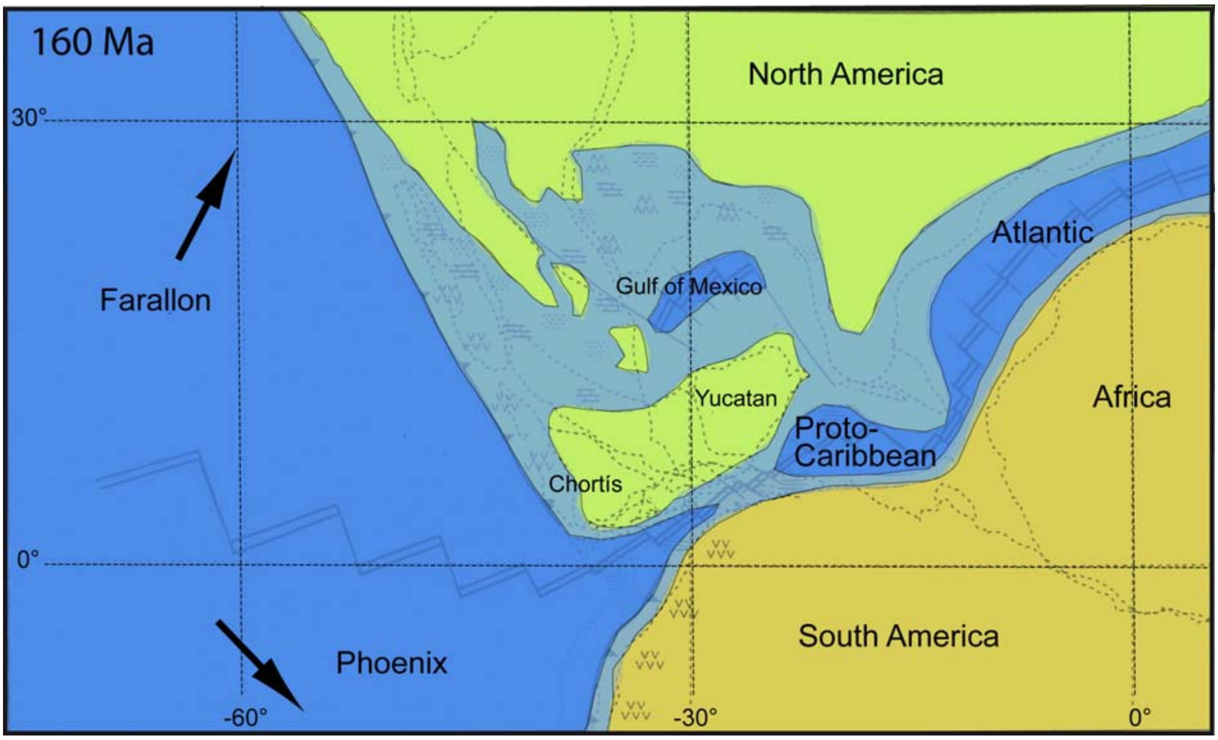

Fig. 1.1 Inter-American plate tectonic model during the Callovian/Oxfordian (modified from Meschede and Frisch, 1998). South America and Africa are still positioned close together. Yucatan and parts of the Chortís Block exist as emerged areas between the North and South American plates. Rifting process and spreading axis between the Farallon and Phoenix plates. Gulf of Mexico opened in the Middle Jurassic.

the Farallon and the Phoenix plates (see Fig. 1.1) that continued into the central Atlantic (Frisch, 1981; Duncan and Hargraves, 1984). The Gulf of Mexico opened in the Middle Jurassic and Yucatan on the North American plate appeared as an island with a pronounced shelf area (Stephan et al., 1990) towards the north.

During the Jurassic and the Early Cretaceous the proto-Caribbean Sea opened between the diverging North and South Americas and volcanic arc activity began in the Antilles region (Meschede and Frisch, 1998). During this time the Central Cordillera formed an island chain off the coast of the emerged part of the South America plate. Yucatan was still emerged and surrounded by shallow water; the Chortís Block was partly submerged. The spreading in the Caribbean ocean terminated at around 100 Ma in the Late Albian and the Costa Rica-Panama Arc arose in the Albian between the Chortís Block and the South America plate (Meschede and Frisch, 1998).

In the Late Albian the Central Cordillera formed **(Fig. 1.2)**, an island off the coast of South America. Parts of the Costa Rica Panama Arc and the Chortís Block were emerged and appeared as islands. In the Santonian (85 Ma) the Chortís Block was still emerged and formed a land tongue connected with the North America plate. Volcanic arcs formed along the western and eastern Caribbean plate boundaries (Meschede and Frisch, 1998). Shallow-water sediments like platform carbonates evolved locally in the area (Sprechmann, 1984). First parts of southern Cuba emerged forming a small island and several small islands existed parallel to the deep-water Costa Rica Panama Arc in deep waters.

During the Campanian the relative movement between North and South America became slightly convergent (Duncan and Hargraves, 1984; Pindell and Barret, 1990), because the Farallon plate changed its movement from a north-eastward to an eastward direction (Engebretson et al., 1985). Because of this process the Cuban Block moved north towards the Bahamian platform.

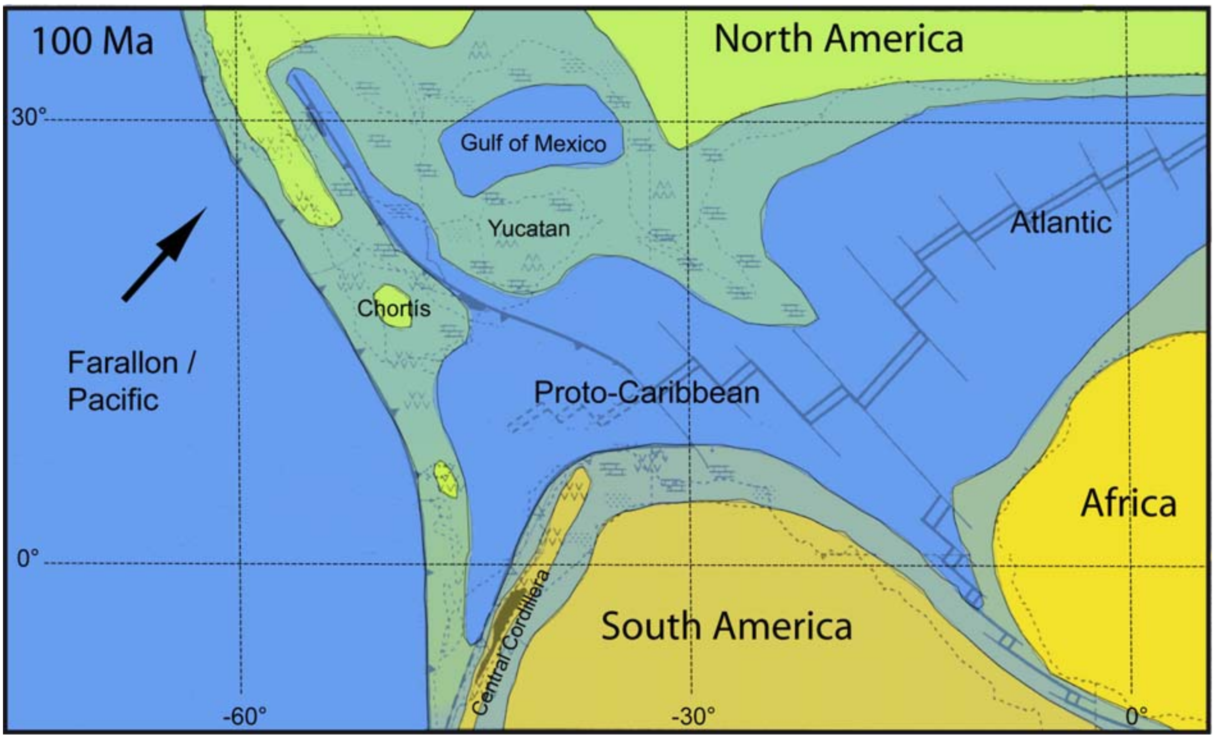

Fig. 1.2 Albian Inter-American plate tectonic model (modified from Meschede and Frisch, 1998). Parts of the Costa Rica Panama Arc and the Chortís Block are emerged and appear as islands. The Central Cordillera forms off the coast of South America.

During the Paleocene (60 Ma) the Cuban Block continued to move towards the Bahamian platform and finally collides with it and became part of the North American plate (Meschede and Frisch, 1998) **(Fig. 1.3)**. The Caribbean plate together with the Chortís Block started to move eastward and because of this process the Cayman trough started to open.

The chain of islands along the Central American Arc within the deep waters became more pronounced and more islands emerged.

During the Eocene (40 Ma) the Farallon plate changed from east- to north-eastward plate motion (Engebretson et al., 1985) and the Pacific plate changed its movement from NNW to WNW (Burke and Wilson, 1976).

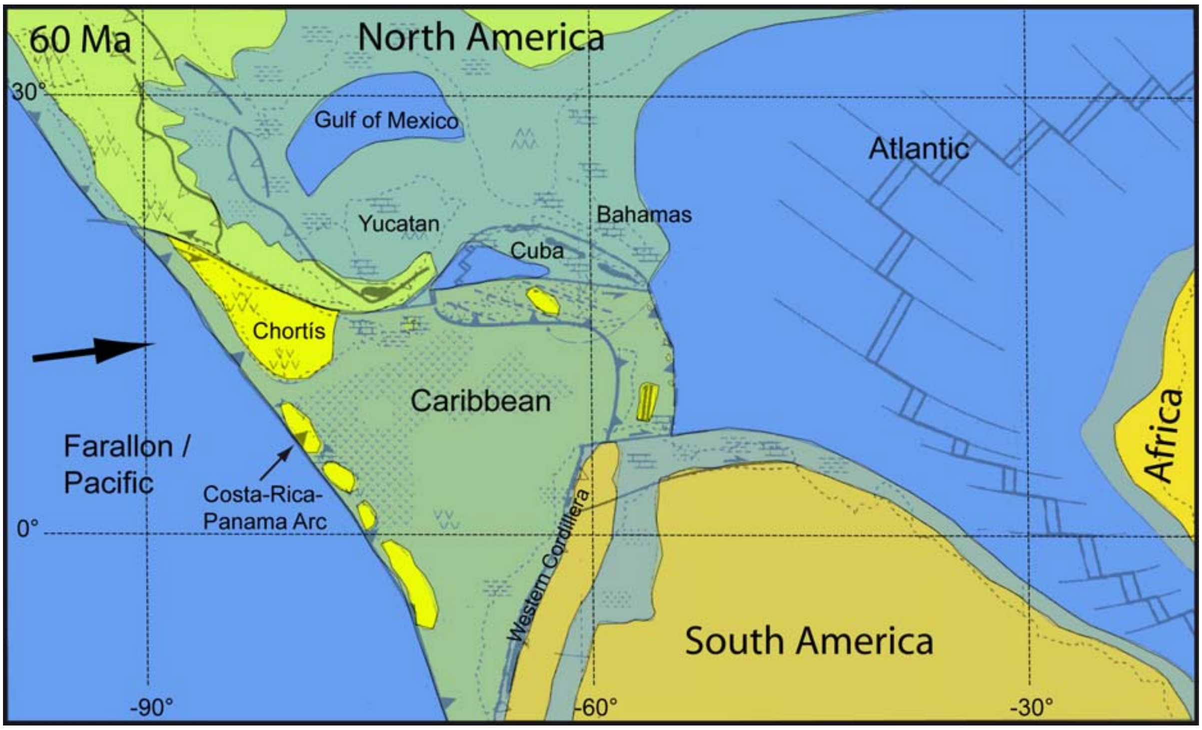

Fig. 1.3 Inter-American plate tectonic model during the Palaeocene (modified from Meschede and Frisch, 1998). The Chortís Block and parts of the Costa-Rica-Panama Arc are emerged. The Cuban Block collides with the Bahamas platform and became part of the North America plate.

During the Late Oligocene to Early Miocene, the Farallon plate split itself **(Fig. 1.4)** into the Cocos plate moving towards the NNE and the Nazca plate moving towards the East (Hey, 1977). The present day northward convexity of the Panama Arc is due to the westward drift of the South America plate and the collision of the Panama arc and the Western Cordillera (Meschede and Frisch, 1998).

Coates et al., (2004) stated that this collision between the eastern part of the Central American Arc and the Western Cordillera took place between 12.8 and 9.5 Ma, and that the Central American arc has appeared to have risen and become more emergent by ~16 Ma before the initial collision. This process is shown by a shallowing from lower - and middle - to upper bathyal, and outer neritic water depth in the southern Limon and Bocas del Toro Basins. The major shallowing began in the Atrato Basin (Fig.1.4) around 12 Ma and at 9.4 Ma the Atrato and Darien Valley showed neritic to upper bathyal depths in inner borderland basins (Duque-Caro, 1990). The first exchange of terrestrial faunas was observed on raccoons and ground sloths between North and South America around 9.3 Ma to 8 Ma (Marshall

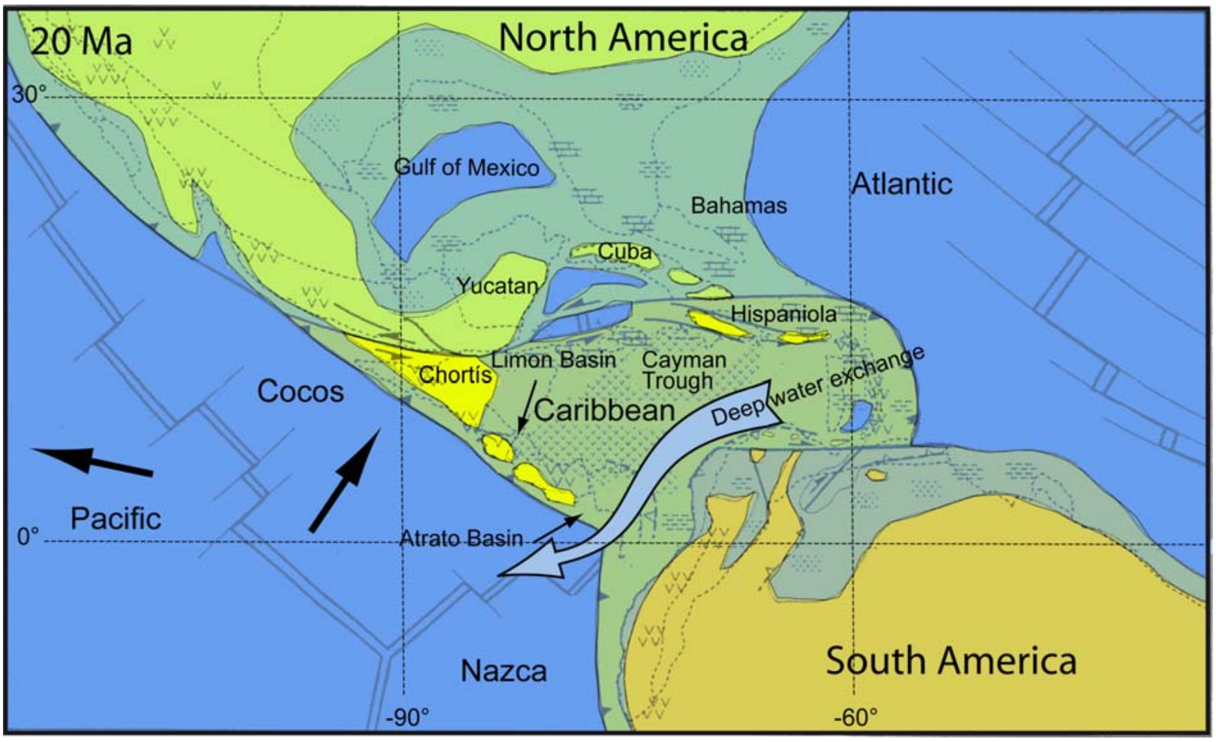

Fig. 1.4 Inter-American plate tectonic model during the Late Palaeocene-Early Miocene (modified from Meschede and, Frisch 1998). The Farallion plate split into the Cocos plate moving NNE and the Nazca plate moving E. The South America Plate drifts westwards; this led to the present day northward convexity of the Panama Arc. At this time deep-water exchange still exists between the

et al., 1979, Marshall, 1985). Coates et al., (2004) stated that the last definitive deep-water connection between the Pacific and Atlantic occurred at 6 Ma. This is shown by the analyses of benthic foraminiferal fauna (Collins et al., 1996b), and through inner neritic sediments overlain by upper bathyal sediments in the Panama Canal Basin. These events correspond with a rise in sea-level (Haq et al., 1987) and therefore show a eustatic rather than a tectonic event that was enough to breach the Isthmus of Panama and locally bring Pacific faunas to the Caribbean (Coates et al., 2004).

The Isthmus of Panama was the last part of the Central American Isthmus that emerged (Coates and Obando, 1996), after the last breach of the Isthmus (6 Ma) the final closure of the Isthmus was around 3.2 to 3.0 Ma (Keigwin, 1978, 1982; Haug and Tiedemann, 1998; Steph, 2005).

1.3 Paleoceanography

Several studies show that the environmental condition in the eastern Pacific and the Caribbean were fairly homogenous (e.g. Kameo and Sato, 2000; Collins et al., 1996a, Terranes et al., 1996; Haug and Tiedemann, 1998; Jackson and Herrera-Cubilla, 2000) before the closure of the American Seaway. The shallowing around the gateway resulted in an intensification of the Gulf Stream (Maier-Reimer et al., 1990) and led to increased North Atlantic Deep Water (NADW) formation around 2.8 Ma in the Labrador Sea and the Greenland-Norwegian Sea.

Coupling of the Northern Hemisphere glaciation (3.2 Ma) with the closure of the Isthmus of Panama led to reoccurring ice ages that interrupted the warm climate of the early to middle Pliocene (e.g. Haug and Tiedemann, 1998; Maier-Reimer et al., 1990).

The closure of the seaway had enormous effects on the hydrography and the carbonate environments in the Pacific and Caribbean region around Panama (Coates and Obando, 1996; Jackson and D`Croz, 1997; Haug and Tiedemann, 1998), but also throughout the entire Caribbean (Budd et al., 1996, 1998; Jackson, 1997; Reijmer et al., 2002). In the Caribbean region tropical carbonate environments in oligotrophic conditions with accelerated reef growth prevail (D`Croz and Robertson, 1997). On the Pacific side studies have shown that warm-temperate carbonate production can prevail, like for example in the Gulf of California (Halfar, 1999, Halfar et al., 2000; 2001; 2005;), as can be found in the Gulf of Chiriquí and the Gulf of Panama (See chapter 4 and 5). However, on the continental shelves of North, Central and South America carbonate environments are rare due to high terrigenous input associated with the tectonically active margins and regional upwelling effects (Halfar et al., 2000). The Gulf of Chiriquí and the Gulf of Panama provide the opportunity to study two different carbonate producing regimes that geographically are located close to each other. The Gulf of Chiriquí shows high productive carbonate environments with coral reefs and rhodoliths facies around the islands in the gulf (Glynn et al., 1972; Glynn and MacIntyre 1977; Linsley et al., 1994). The Gulf of Panama shows different carbonate producing biota due to seasonal upwelling in the dry season, with coral reefs only in protected bays in northern parts of the Archipelago de Las Perlas (Glynn et al., 1972).

1.4 North Atlantic Oscillation (NAO) and El Niño Southern Oscillation (ENSO)

Two phenomena have a major influence on the oceanographic conditions and carbonate environments on the Caribbean side and the Pacific side of Panama: the **N**orth **A**tlantic **O**scillation (NAO) phenomenon (Caribbean / Atlantic) and the **E**l **N**iño **S**outhern **O**scillation (ENSO) (Gulf of Chiriquí and Gulf of Panama / Pacific). The climate in the North Atlantic basin and the adjacent continents is controlled by the NAO (Roth, 2003). Variations in the NAO (positive/negative) (e.g. Hurrel, 1995; George and Saunders, 2001) result in variations in the strength of the trade winds leading to variations of vapour transport across the Panama Isthmus, which affect both salinity concentrations in the Caribbean and strength of upwelling in the eastern Pacific (Hosteler and Mix, 1999).
On the contrary, El Niño events can suppress the yearly cycle of seasonal upwelling at the Pacific coast of Panama and the Panama Bight (http://daac.gsfc.nasa.gov/oceancolor/locus/tutorial_1.shtml), resulting in high inter-annual variability in the Sea Surface Temperatures (SST), as well as the primary productivity regimes and fisheries (Pedraza and Diaz-Ochoa, 2006). The Pacific El Niño events affect the North Atlantic through the Walker and Hadley circulations, favouring warming of the tropical North Atlantic in the subsequent spring of the Pacific El Niño year (Wang, 2002).

1.5 Intertropical Convergence Zone (ITCZ)

The **I**nter**t**ropical **C**onvergence **Z**one (ITCZ) is a global belt of low pressure produced by the convergence of air coming out of the high pressure belt to the north and the high pressure belt to the south. The areas of the tropics dominated by high pressure have very dry weather and many of the world's deserts are located in those regions.

The areas of low pressure are located where the northeast Trade Winds meet the southeast Trade Winds near the earth's equator. The ITCZ shifts position (**Fig. 1.5)** over the course of the year, because ITCZ tends to be located under and near where the sun's rays are most direct. The movements of the ITCZ result in changes in precipitation patterns and cloud cover throughout the tropics. The area around the Isthmus is affected both by changes in the position of the ITCZ and variations in Atlantic trade wind intensities as well as intensity variations of the West Pacific warm pool leading to El Niño oscillations. The eastern

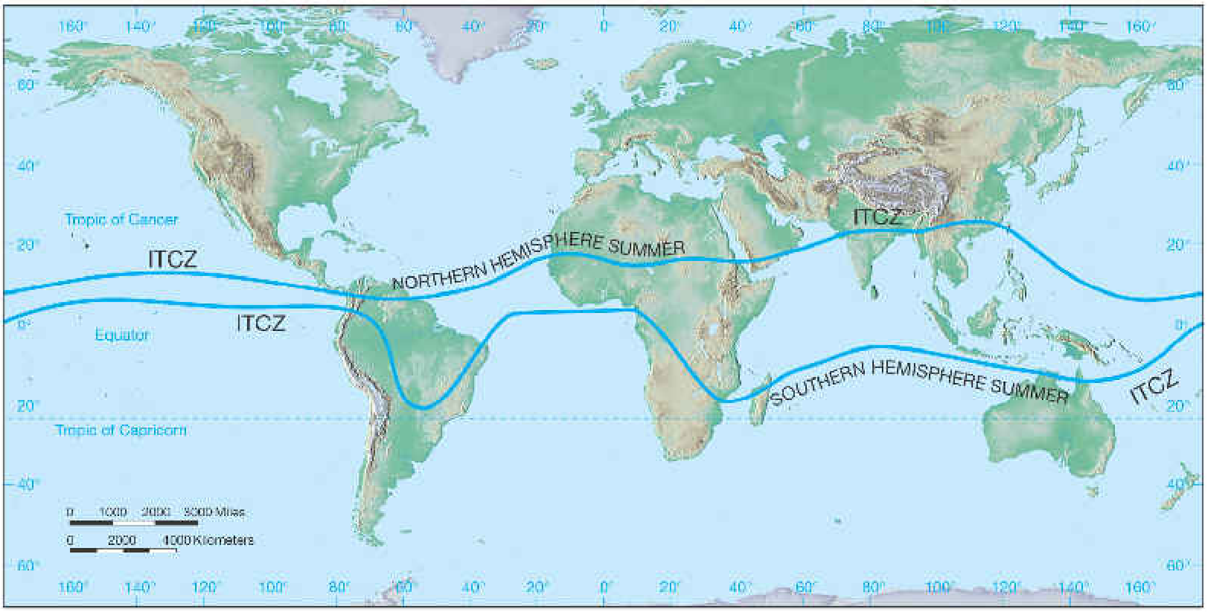

Fig. 1.5 Changes in the position of the ITCZ. The ITCZ moves seasonally, it is drawn towards the area of most intense solar heating, or warmest surface temperatures. It moves towards the Southern Hemisphere from September through February and returns to various positions in the Northern Hemisphere from March to August. The ITCZ is less mobile over the oceanic longitudes, where it holds a stationary position just north of the equator. In these areas, the rain intensifies with increased solar heating and diminishes as the sun moves away. An exception to this rule occurs during an ENSO event when the ITCZ is deflected toward unusually warm sea surface temperatures in the tropical Pacific.

Pacific and Atlantic ITCZ exhibit the largest year-to-year variations in boreal spring. Chiang and Kushnir (2000) showed that the Atlantic ITCZ April-May variability is linked to that for the eastern Pacific through the Walker circulation as it responds to changes in equatorial Pacific convection.

1.6 East Pacific Currents

The ocean current and wind system in the eastern Pacific is coupled to the latitudinal position of the ITCZ (Johnson et al., 2001). The North Equatorial Counter

Current (NECC) transports warm, low saline surface waters eastwards, while the South Equatorial Current (SEC) flows in the other direction transporting surface waters westward (Wyrtki, 1981). The Equatorial Under Current (EUC) is a geostrophic current and flows eastward under the SEC in 30 to 300m water-depth (McPhaden, 1986). The Humboldt Current and the EUC both bring cool and salt-rich

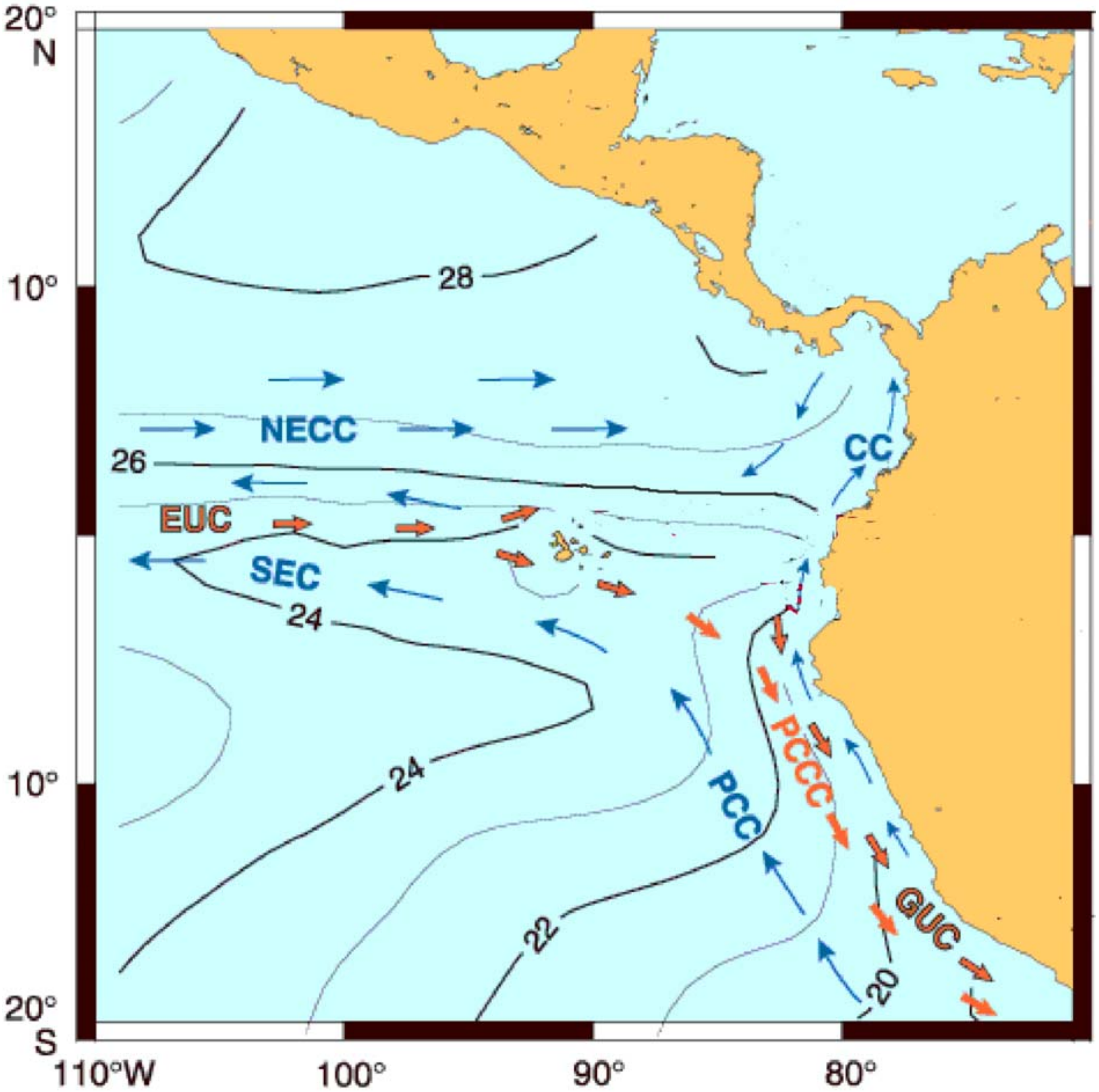

Fig. 1.6 Upper-ocean features off Peru and northern Chile during Southern Hemisphere winter after Strub et al. (1998). SEC = South Equatorial Current, NECC = North Equatorial Counter current, EUC = Equatorial Undercurrent, PCC = Peru-Chile Current, PCCC = Peru-Chile Counter current, CC = Coastal Current, GUC = Gunther Undercurrent.

waters into the Panama Bight (Strub et al., 1998, Leetma, 1982).
The Coastal Current (CC) **(Fig. 1.6)** as an extension of the Humboldt Current brings cool and salt rich water from the south of the Panama Bight into the Gulf of Panama.

1.7 Panama Bight

Recent studies show a distinct seasonal pattern in circulation, temperature, salinity and upwelling for the Panama Bight (Rodriguez-Rubio et al. 2003, D´Croz et al., 1991). In summer (May to November), the circulation in the Panama Bight is anti-cyclonic, with a coastal current to the south, whereas in winter (January to April), the circulation reverses and is cyclonic with a coastal current to the north, and an oceanic upwelling centre in the middle of the bight. In summer, SE trade winds dominate the region, but in winter NE trade winds of the North Atlantic, by means of the Panama Jet, enter the region via the Isthmus of Panama (Rodriguez-Rubio et al., 2003). Earlier work in the Gulf of Panama and Gulf of Chiriquí was mostly related to analyzing the hydrography of both bights or to investigate the parameters associated with upwelling in the Gulf of Panama (Schaefer et al., 1958; Forsbergh, 1963, 1969; Smayda, 1963, 1966; Legeckis, 1985; D`Croz, et al., 1991, 1997). The process of seasonal upwelling results in a change in temperature and nutrient level (D`Croz et al., 1991). The upwelling in the Gulf of Panama is induced by prevailing northern winds during the dry season forcing the surface water to drift southwards towards the shelf (Schaefer et al., 1958; D`Croz et al., 1991), bringing up the nutrient enriched waters from the extensions of the Humboldt Current and the EUC. In contrast to the Gulf of Panama, the Gulf of Chiriquí is far less affected by seasonal changes resulting in upwelling while this bight is protected by the high volcanic mountain range of the southern Cordillera de Talamanca, which blocks the NE trade winds.

1.8 Palaeontology

The closure of the Central American Seaway strongly influenced the fauna on the Caribbean and the Pacific side of the Isthmus of Panama. A series of studies

showed the response of the fauna to the stepwise closure of the Panama gateway (molluscs: Jackson et al., 1993, Todd et al., 2002; reef corals: Collins et al., 1996b; benthic foraminifers: Collins et al., 1996b, Culver and Buzas, 1999).
The diachronous first appearance of *Acropora palmata*, within the Gauss Chron (3.6-2.6 Ma) at Panama and at the Plio-Pleistocene boundary at the Bahamas (McNeill et al. 1997), displays the gradual spreading of this type of coral after the final closure of the Isthmus of Panama. Within Caribbean reef-corals accelerated extinction rates were observed for the period 2-1 Ma (Budd et al. 1996). Jackson (1997) registered an intense burst of extinction between 2.0 and 1.5 Ma when total diversity was reduced by nearly half. The increased reef-coral diversity (Jackson 1997) in the Late Pliocene probably reflects the closure of the Isthmus. Changing oceanographic conditions must have influenced the different trends in the evolution of size and larval development, as shown by a variety of biota (e.g., gastropods, shrimps, epibenthic foraminifera). Allmon (2001), however, suggested that changes in nutrient conditions played a dominant role in causing the observed patterns of origination and extinction in the Pliocene-Pleistocene (e.g., Budd et al. 1996, 1998; Jackson 1997), although changes in temperature might have been important. These nutrient changes might have destroyed habitat conditions to result in enhanced speciation and extinction.

1.9 Objective of this study

The geological situation around Panama opens up the possibility to study fossil - and recent carbonate systems on the Pacific and Caribbean side of the present-day Isthmus of Panama. The benthic carbonate ecosystems developed differently on both sides of the Isthmus after the closing of the Central American Seaway. For the interpretation of fossil facies pattern and their paleontological, mineralogical (e.g. aragonite, high-magnesium calcite, low-magnesium calcite), and sedimentological diversity (e.g. grain size, sorting) it is important to better understand the geological-biological relationships that exist in recent carbonate environments, with respect to the oceanography parameters like water temperature and salinity. A comparison between fossil and present-day carbonate ecosystems from the same paleolatitude opens up the possibility to document the evolution of these sedimentation systems through time.

The results of the recent carbonate ecosystems will be presented in detailed maps showing the occurrence of different biota groups, and many other parameters, in both gulfs, with respect to water temperature, salinity, nutrients and geographical aspects.

Numerous studies concentrated on a large variety of sedimentological, paleontological and geochemical aspects within reefs and tropical carbonates in the Caribbean region. The research presented in this thesis explores the variations within different carbonate regimes on the Pacific side of Panama in an upwelling (Gulf of Panama) and a non-upwelling setting (Gulf of Chiriquí). In addition, a comparison (Chapter 6) will be made between the present-day carbonate ecosystem (presented in Chapter 4 and 5) and the fossil environment (documented in Chapter 3) that existed in the study area shortly before the final closure of the Isthmus of Panama.

CHAPTER 2

METHODS

2. METHODS

The data used in this thesis were collected (1) during one fieldwork campaign in the Limon area in Costa Rica, which focused on Pliocene sediments and (2) during two cruises on the Pacific side of Panama in the Gulf of Chiriquí and the Gulf of Panama during which the recent sediment distribution was studied. Within both datasets the emphasis was placed on analyzing the carbonate fraction of the sediments.

2.1 Samples

2.1.1 Field study

More than 250 sediment samples were taken during the field expedition in March 2004 in the Limon region (Costa Rica). In total 10 locations southwest of Limon were sampled. The samples vary from whole rock samples to single corals, molluscs and other biota that were collected directly from the outcrops visited.

2.1.2 Cruise sampling

Grab and dredge samples were collected in May 2004 and February 2005 during cruises with the RV Urraca in the Gulf of Chiriquí and the Gulf of Panama. The majority of the samples were collected in shallow-water carbonate environments around the islands in both gulfs. In addition, three long transects were sampled with a grab sampler, crossing the gulfs from the shallow-water realm to water depths up to 300 m. The grab sampler was used for soft sediment collection whereas the dredge was used to obtain coarse-grained carbonate sediment and biota. This sampling strategy resulted in a total of 93 dredge samples and over 250 grab samples for the two cruises.

2.2 CTD

During the 2004-Cruise 118 CTD-Stations were measured. An Idronaut Ocean Seven 316 Probe was used with unattended data acquisition as a function of depth increments. The measured water depths ranged from 10 m, within the very shallow areas around the Islands, up to 236 m on the deeper-shelf. The standard sensors installed were a temperature sensor, in form of a platinum resistance thermometer with a time constant of 50ms; a flow conductivity sensor with a seven-ring quartz cell, which can be cleaned without re-calibrating; a pressure-compensated polarographic oxygen sensor, and an additional sensor for Chlorophyll-α measurements. The calculated parameters for the standard sensors are: salinity, sound velocity in sea water density (Sigma), pressure to depth conversion and potential temperature (Theta). The CTD has an internal memory with a possible storage of up to 32,000 data sets for each standard.
The unattended acquisition can be activated by means of a magnetic ON/OFF switch. The acquired data can be uploaded at the end of the measuring cycles. Extension of the internal battery life is obtained through an automatic power management procedure that switches the probe OFF between the data acquisitions.

In 2005 an SBE 37-SM MicroCAT was used for CTD-profiling, which is a high-accuracy conductivity and temperature (pressure optional) recorder with internal battery and memory. Designed for moorings or other long duration, fixed-site deployments, the MicroCAT includes a standard serial interface and non-volatile flash memory. Construction is of titanium and other non-corroding materials to ensure long life with minimum maintenance, and depth capability is 7000 meters (23,000 feet).
Calibration coefficients are stored in EEPROM, and uploaded data is presented in ASCII engineering units. The data always includes Conductivity and Temperature values a Pressure sensor was not installed. If desired, time can be added to each scan, and the MicroCAT can calculate and output salinity and sound velocity. Conductivity is acquired using an ultra-precision Wien-Bridge oscillator. A high-stability reference crystal with a drift rate of less than 2 ppm/year is used to count the frequency from the oscillator.

The MicroCAT communicates directly with a computer via standard RS-232 interface. Data can be uploaded at up to 38.4K baud. Real-time data can be transmitted at distances of up to 1600 meters (5200 feet) at 600 baud, simultaneously with recording.
Converted temperature and conductivity are stored 5 bytes per sample, time 4 bytes per sample, and optional pressure 2 bytes per sample; memory capacity is in excess of 185,000 samples. The MicroCAT is powered by a 7.2 Ampere-Hour (nominal) battery pack consisting of six 9-volt lithium. The pack provides sufficient internal battery capacity for more than 300,000 samples. During the 2005-Cruise it was not possible to lower the CTD with a constant speed. Therefore, it was problematic to calculate the exact salinity values because of the missing pressure sensor. The variance of the salinity values was too large and a mathematical correction was not possible.

2.3 Underwater Video camera survey

During our February 2005-Cruise an underwater video camera (UW-Video camera) was used. The video camera was towed and was in contact with the control-main unit and a VHS-Video recorder through a cable all the time. The UW-Video camera was used in water depths between 10 - 80 m to document the different carbonate production and accumulation areas in the two bays (i.e., coral reefs, coralline algae communities, large bivalve communities, carbonate sand and gravel accumulations and deep water banks).

2.4 Laboratory analysis

2.4.1 Fossil identification

In total 200 fossil samples were collected varying from corals, gastropods to bivalves. All were used to obtain a detailed overview of the biotic contents of the individual sedimentary units. The morphologic characteristics of the collected fossils were examined to determine the different genera and communities within the reefs.

The morphometric method in species recognition was used following the guidelines as discussed in Budd and Coates (1992).

2.4.2 Thin section analysis

The biota within the thin sections were counted and quantified as the individual percentage of the total amount of fossils present within one thin section. 49 thin sections of the carbonate-siliciclastic mixed sediments were analyzed. Determinations were made after Scholle and Ulmer-Scholle (2003). 200 counts were made per thin section and the following groups were distinguished: Foraminifera, bivalves, gastropods, red algae, coral fragments and terrigenous material.

2.4.3 Grain size analysis

The grab and dredge samples were washed with clean water and large organic pieces like wood, fish remains or leaves were removed. The washing residue of the grab samples was filled in 5 litre glass bottles for 4 days to allow the fine sediment to settle down. The over standing water was carefully removed avoiding loss of the fine fraction (<63µm). Subsequently the sediment was dried in a fan-assisted oven at 45°C for 48 hours. The bulk grab samples were weighted to determine the weight including the <63µm fraction. To avoid statistically failures during the following process of dry sieving because of agglutination of clays due to the drying process, the <63µm fraction was washed out and the remaining coarse grained sediments were dried in a fan-assisted oven at 45°C for 48 hours again. The samples were weighted again to achieve the sample-weight without <63µm. The samples were dry-sieved in a sieving tower for 10 min each to separate the samples into 6 different grain-size fractions: 63-125µm, 125-250µm, 250-500µm, 500-1000µm, 1000-2000µm and >2000µm. Subsequently, each fraction was weighted to determine the weight (g) and the weight-percentage of the individual grain-size fractions. Table 2.1 shows the formulas used for the calculation of mean, standard deviation, skewness, kurtosis and the table for the values for sorting.

Table 2.1. (after Blott and Pye, 2001)

Geometric Folk and Ward (1957) Graphical Measures

Mean	Standard Deviation
$M_G = \exp \frac{\ln P_{16} + \ln P_{50} + \ln P_{84}}{3}$	$\sigma_G = \exp\left(\frac{\ln P_{16} - \ln P_{84}}{4} + \frac{\ln P_5 - \ln P_{95}}{6.6}\right)$
Skewness	**Kurtosis**
$Sk_G = \frac{\ln P_{16} + \ln P_{84} - 2(\ln P_{50})}{2(\ln P_{84} - \ln P_{16})} + \frac{\ln P_5 + \ln P_{95} - 2(\ln P_{50})}{2(\ln P_{25} - \ln P_5)}$	$K_G = \frac{\ln P_5 - \ln P_{95}}{2.44(\ln P_{25} - \ln P_{75})}$

Sorting (σ_G)		Skewness (Sk_G)		Kurtosis (K_G)	
Very well sorted	< 1.27	Very fine skewed	$^-0.3$ to $^-1.0$	Very platykurtic	< 0.67
Well sorted	1.27 – 1.41	Fine skewed	$^-0.1$ to $^-0.3$	Platykurtic	0.67 – 0.90
Moderately well sorted	1.41 – 1.62	Symmetrical	$^-0.1$ to $^+0.1$	Mesokurtic	0.90 – 1.11
Moderately sorted	1.62 – 2.00	Coarse skewed	$^+0.1$ to $^+0.3$	Leptokurtic	1.11 – 1.50
Poorly sorted	2.00 – 4.00	Very coarse skewed	$^+0.3$ to $^+1.0$	Very leptokurtic	1.50 – 3.00
Very poorly sorted	4.00 – 16.00			Extremely leptokurtic	> 3.00
Extremely poorly sorted	> 16.00				

2.4.4 Component analyses

Groups of carbonate-producing organisms were distinguished during point counting. The groups distinguished were bivalves, gastropods, planktonic Foraminifera, benthic Foraminifera, echinoderms, serpulids, red algae, Bryozoa, corals, balanids, fish remains, ostracods, Porifera, organic material (wood, leaves) and unidentified fragments. The abundance of fish remains, Porifera and ostracods was very low, therefore they were not analysed in detail and were subsumed into the group “other biota”, together with the unidentified fragments. See Appendix for detailed list with values for all groups. Additionally, terrigenous material was counted and the percentage of quartz within the part of the mixed carbonate-siliciclastic sediments was estimated using visual comparison charts of Scholle and Ulmer-Scholle (2003).
Five fractions were used (125µm-250µm, 250µm-500µm. 500µm-1000µm, 1000µm-2000µm, >2000µm) for detailed analyses of the individual carbonate producers in each fraction. Thus 1500 sediment samples (300 samples, 5 fractions) from the sites were counted (100 points/sample in each fraction and an average of 60 points/sample in the fraction >2000 µm due to lack of sediment). A cluster analyses was performed to distinguish different facies types using the statistiXL 2006 Vers.

1.6 for Microsoft Excel (Roberts and Withers, 2006) with Ward`s method as linkage and Euclidian distances, because the complete or single linkage calculation tends to more extreme solutions than the Ward`s method does.

2.4.5 LECO analysis

Bulk samples (containing all fractions) from each site were freeze dried and ground in an agate-mortar for the LECO analysis, with the LECO C-200 analyzer at Leibniz Institute for Marine Geosciences IFM-GEOMAR (Kiel, Germany). The total carbon content of a sediment sample was determined by measuring the thermal conductivity of the gaseous products of pyrolysis of the sample. The analysis was also conducted on an acidified sample to determine the organic carbon content. The LECO analyzer was calibrated with pure carbon standards in-between the individual measurements.

Four samples of 20 to 30 mg sediment in each case were filled into china-containers, and weighted. Two of these four samples were treated with HCL (0.5%) to remove the calcium carbonate. The four samples were burned at 1.200°C in an inductive oven using copper as catalyst. The weight percentages of total carbon (TC), organic carbon (OC), and calcium carbonate (CaCO3) are related by the equation: (TC - OC) * 8.33 = CaCO3. If we assume that all the inorganic carbon is bound in calcium carbonate. Deviations of 0.5 % TC and 0.05 % TOC between the double-measurements were tolerated otherwise a third run was performed.

2.4.6 X-ray diffractometry (XRD)

Bulk samples (containing all fractions) from each site were freeze-dried and ground in an agate-mortar for X-ray diffractometry analysis. After freeze drying and grinding, the samples were filled in cavity mount holders. These were scanned in a Philips PW 1710 diffractometer with a cobalt K tube at 40 KV and 35 mA and with an angle from 2Θ to 70Θ. The computer-based program MacDiff Version 4.2.5 (Petschick, 1999) was used to process the X-Ray diffractograms and to calculate the peak areas of the individual minerals.

In-house calibrations were used to calculate the non-linear relationship between calcite and aragonite, because existing calibrations show low resolution and accuracy for aragonite percentages exceeding 70% (Milliman, 1974). The mineral quartz, with d= 3.343 A was used as an internal standard for peak correction in MacDiff. In samples with low quartz content or absence of quartz aragonite, with d=3.398 A was as standard for peak correction. The relative changes of the quartz peak areas in the diffractograms were interpreted as relative changes of quartz abundance in the individual samples.

2.5 Satellite Ocean Colour Data (NASA, GIOVANNI)

Satellite ocean colour data from the NASA were used to obtain chlorophyll values throughout the months May 2004 to April 2005 within the Gulf of Panama and the Gulf of Chiriquí.
The software of the web-based interface **G**ES-DISC **I**nteractive **O**nline **V**isualization and **A**nalysis **In**frastructure (Giovanni) was used to visualize the data. This software was developed by the GES DISC DAAC (http://reason.gsfc.nasa.gov) to provide users with an easy-to-use, web-based interface for the visualization and analysis of the Earth Science data. The data used were SeaWiFS ocean colour data, and MODIS Aqua ocean-colour and SST data (http://reason.gsfc.nasa.gov/Giovanni).

CHAPTER 3

Development of a mixed-carbonate siliciclastic reef-complex during the closure of the Central American Seaway (Pliocene, Limon, Costa Rica)

(submitted to Sedimentology)

3. Development of a mixed-carbonate siliciclastic reef-complex during the closure of the Central American Seaway (Pliocene, Limon, Costa Rica)

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(submitted to Sedimentology)

ABSTRACT

The Miocene to Lower Pleistocene Limon Group of Costa Rica is one of the best-preserved mixed carbonate-siliciclastic successions in the Central American region. It provides unique data to understand the physical and biotic changes in shallow-marine environments along the Caribbean coast associated with the emergence of the Central American Isthmus. Our study focuses on two Lower Late Pliocene reef units, the Las Islas roadcut and the newly discovered Contact Cut, which are located at the contact between the siliciclastic sediments of the Rio Banano Formation and the mixed reefal and coral bearing deposits and siliciclastic sediments of the Quebrada Chocolate Formation. The siliciclastic sediments were deposited in a thick, deltaic setting sourced by erosion of the Cordillera de Talamanca. These deposits preserve a sequence of progressively shallowing, near-shore sediments that were exposed by uplift during the early to middle Pleistocene.

The outcrop at Contact Cut shows extensive reef growth during a rise in sea level and a slight progradation during the following slowdown in sea-level rise. Within three stages of reef evolution the growth of the reef exceeds the increase in sea level and was nearly destroyed by a high input of siliciclastics. The Las Isla roadcut shows a rapid burial of the corals by siliciclastics. Differently than in the Contact Cut reef we first observe clays that in the later process change into silts and sands and

led to a comparable carbonate siliciclastic mixed sediment like the one in the Contact Cut.

Both time-equivalent reefs document a distinct facies diversification during the final stages of the closing of the Central American Seaway. The reefs developed in an environment stressed by siliciclastic input, which ultimately caused a decrease in coral diversity and abundance followed by a complete demise of the reefs. It will be discussed to what extents the facies differences and the ultimate reef demise was caused by variations in nutrients input, currents and wave action or if they resulted from environmental stress in response to the increased input of siliciclastics.

3.1 INTRODUCTION

The most extensive mixed carbonate-siliciclastic sequence in Costa Rica can be found in the Limon region (McNeill et al., 2000). It provides unique data for understanding physical and biotic changes in shallow-marine environments along the Caribbean coast associated with the emergence of the Central American Isthmus. The development of the Central American Isthmus during the Miocene and Pliocene and the emergence of the Cocos plate separated the Pacific Ocean and the Caribbean Sea and provided sedimentary sequences that recorded associated changes in the environment and evolutionary history during the separation (Coates et al., 1992). The formations of the Limon Group span this time interval. The deposits preserve a sequence of progressively shallowing; near-shore sediments that were exposed by uplift during the early to middle Pleistocene and are part of the Quebrada Chocolate Formation. Its base contains lenses of reefal debris, extensive coral deposits and individual reef build-ups (McNeill et al, 1997).

The objective of our study is to give a detailed description of early to late Pliocene reef evolution in an uplifted near-shore marine sequence. The evolution and coral community of the reef at Contact Cut outcrop is directly related to sea-level variations.

The project focused on two Locations within the Buenos Aires Reef Member of the Quebrada Chocolate Formation within the early late Pliocene. The newly discovered Contact Cut outcrop on top of the Rio Banano Formation shows the development of a Pliocene reef affected by sea-level variations and buried by siliciclastics. An outcrop at Route 32 (Las Islas), previously described by McNeill et al., (1997; 2000) shows a different evolution in the geologic record due to variations in siliciclastic input.

3.2 GEOLOGICAL SETTING

The final closure of the Central American Isthmus separated the Atlantic from the Pacific Ocean and the growth of the Central American volcanic arc was part of the geologic history of the formation of the Isthmus of Panama. During the late Cretaceous the development of the volcanic arc began and continued throughout the Cenozoic, as a result of subduction of the Farallon, Cocos and Nazca Plates (Coates and Obando 1996). This led to the rise of a magmatic arc, the Cordillera of Talamanca. The collision with South America led to the development of compressive forces that formed the Costa Rica-Panama microplate (Coates and Obando, 1996).

The aseismic crust of the Cocos Ridge produced major uplift of the basement and sedimentary basins on both sides of the Costa Rica - Panama microplate (Collins et al., 1995). Neogene forearc (Pacific) and backarc (Caribbean) sedimentary basins formed on both sides of the volcanic arc. During the late Miocene, restricted marine connections existed between the marine basins on both side of the arc (Coates et al., 1992, Coates and Obando, 1996) and the Central American archipelago developed and the southern Limon backarc basin became progressively shallower.

The Neogene of the southern Limon Basin is represented by the Limon Group that contains the Uscari, Rio Banano, Quebrada Chocolate and Moin Formation (Coates, 1999).

The sediments of the Limon Group reflect the regional emergence of the Isthmus of Panama in the transition from bathyal to middle-shelf depths in the lower and middle Miocene to marginal-marine and deltaic environments in the overlying lower Pliocene Rio Banano Formation. The sediments studied here were deposited in the southern Limon backarc basin.

Major streams to the north and south of Limon and river mouth migration controlled the deposition of boulder conglomerates and well developed channel cut-and-fill structures. Variations in the river systems control mainly the upper Neogene geologic history of Limon. The streams formed as a result of the uplift of the Cordillera de Talamanca and caused increasing shoaling of the depositional environments around Limon, but also caused the input of relative large amounts of sediment in the entire area (Taylor, 1973). Clastic deposition alternated with coral reefs as fairly broad sheets of sediment that smothered previously existing reef trends. In the vicinity of Limon, marine deposition continued until the early Pleistocene, forming shallow-water, brackish and normal marine claystone, sandstone and reef deposits that represent lagoonal, mangrove, and sea grass habitats, interfingering with a variety of tabular and patch reefs (Coates et al., 1992). After the late Cenozoic emergence of the Central American Isthmus several significant changes in the shallow-marine biotic communities around tropical America occurred (Coates et al., 1992) including increased speciation and extinction of molluscs (Allmon, 1992; Allmon et al., 1993; Jackson et al, 1996, 1999). In addition, changes in coral diversity and reef structure (Budd et al., 1996; Collins et al., 1996b) could be observed.

A detailed study by McNeill et al. (2000), combining litho- and biostratigraphy with palaeomagnetic analysis, of the upper Neogene sediments of the region immediately west of Limon, confirmed the Moin Formation as the youngest unit of the Limon Group. These authors also added a new unit, the Quebrada Chocolate Formation to the pre-existing formations defined by Coates et al. (1992) that conformably underlies the Moin Formation, containing the Buenos Aires Reef Member where this study focused on.

3.3 LIMON GROUP

3.3.1 Rio Banano Formation

The sediments of the Rio Banano Formation consist of blue-grey, mottled siltstones and sandstones with lenses rich in molluscs, bryozoans, sand dollars and Callianassa burrows (Cassel and Sen Gupta, 1989; Coates et al., 1992; McNeill et al., 2000). The formation is estimated to be about 750m thick. (Coates et al., 1992; McNeill et al., 2000).

3.3.2 Quebrada Chocolate Formation

The Quebrada Chocolate Formation crops out in the area west of Limon and south of Puerto Moin along Chocolate Creek and along Route 32 **(Fig. 3.1)**. The sediments are latest early Pliocene to earliest late Pliocene in age and deposits of the Quebrada Chocolate Formation overly the sediments of the Rio Banano Formation and underlie those of the Moin Formation.

McNeill et al. (2000) placed the contact between the Rio Banano Formation

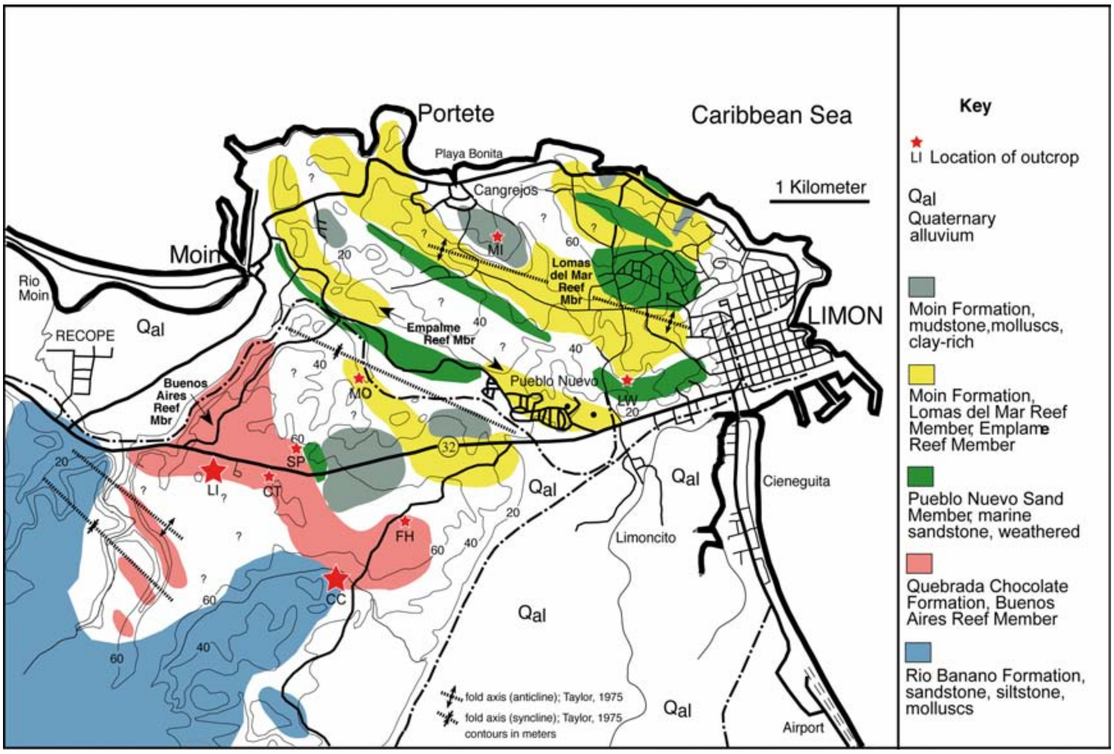


Fig. 3.1 Geology in the Area of Limon, Costa Rica. Studies focused on two outcrops within the Quebrada Chocolate Formation. The Las Islas (LI) roadcut along Route 32 and the newly discovered Contact Cut (CC). Map modified from McNeill et al. (2000).

and the overlying Quebrada Chocolate Formation at the waterfall within Chocolate Creek and stated that the contact between the Buenos Aires Reef Member and the Rio Banano Formation may be diachronous. The newly discovered Contact Cut outcrop is situated in the contact zone between the Buenos Aires Reef Member as the uppermost unit of the Quebrada Chocolate Formation and the Rio Banano Formation.

The contact between the Quebrada Chocolate Formation and the overlying Moin Formation can be observed along route 32, sometimes the Quebrada Chocolate

Formation is in contact with the Pueblo Nuevo Sand member or the Empalme Reef Member of the Moin Formation.

The Quebrada Chocolate Formation shows reef-derived carbonate debris ranging from branching corals to carbonate-reef build-ups with minor siliciclastics or reef patches with abundant siliciclastics.

A detailed description of the sediments within the Quebrada Chocolate Formation can be found in McNeill et al. (2000).

3.3.3 Buenos Aires Reef Member

The top of the Quebrada Chocolate Formation consists of a series of extensive tabular reefs and reef patches as described in this study that is separated as the Buenos Aires Reef Member. Several reef build-ups characterize this reef member. It is named after the village of Buenos Aires, on Route 32 six km west of Limon, where it forms a low but distinct topographic feature (Coates et al., 1992). The type section is located along route 32 from Buenos Aires to about 1.2 km east of where the Old Moin road meets Route 32. The Buenos Aires Reef Member is about 140 m thick and consists of a series of coral thickets with a silty claystone matrix, dominated by *Porites, Acropora, Stylophora, Caulastrea*, and *Avaricious.* Interbedded within the reefs are coral- and mollusc-rich carbonate sandstone and siliciclastics (Coates et al., 1992; McNeill et al., 2000).

3.4 METHODS

More than 250 sediment samples were taken during the field expedition in March 2004. In total 10 locations southwest of Limon were sampled. Over 120 samples originate from the newly discovered site Contact Cut and the Las Isla roadcut, previously described by McNeill et al. (1997, 2000) as Route 32 roadcut. 49 thin sections were analyzed of the carbonate-siliciclastic mixed sediments. The biota within the thin sections were counted and quantified as the individual percentage out of the total amount of fossils present within one thin section. In addition, 200 fossil samples were collected varying from corals, gastropods to bivalves. All were used to obtain a detailed overview of the biotic contents of the individual sedimentary units. The morphologic characteristics of the collected fossils were examined to determine the different genera and communities within the reefs. The morphometric methods in species recognition were used as discussed in Budd and Coates (1992).

3.5 RESULTS

The two locations within the Buenos Aires Reef Member of the Quebrada Chocolate Formation of the early late Pliocene that were analyzed in this study are the newly discovered Contact Cut outcrop on top of the Rio Banano Formation and an outcrop along Route 32 (Las Isla roadcut). Latter section was previously described by McNeill et al. (1997; 2000).

3.5.1 Contact Cut (CC)

The CC outcrop (09° 58.553'N / 83° 04.083'W) is located South-West of Limon on a construction site next to the road from Santa Rosa to Pueblo Nuevo. The newly excavated site revealed a reefal zone within the Buenos Aires Reef member. The sediments of the Rio Banano Formation found at the base of the outcrop consist of organic rich clayey siltstones that grade to siltstones, light grey to light brown at the base and blue-dark grey at the top. The siltstones are partly rich in fossils. Several horizons were found that contained different species of molluscs, shell fragments, and bryozoans. Burrows of *Callianassa sp.* and *Thalassinoides* are also present.

The facies is time equivalent to the facies present in the Quitaria section (3.7-3.5 Ma)(McNeill et al., 2000) within the Rio Banano Formation. The Quitaria section, sampled and dated by Coates et al. (1992), was redated by McNeill et al. (2000) using microfossils, palaeomagnetic and strontium-isotope measurements and the age date was revised to the timescale of Berggren et al. (1995) The age was defined as latest early Pliocene at about 3.8-3.6 Ma in the upper part of the Gilbert Chron (C2Ar) (McNeill et al., 2000).

The reef complex on top of the Rio Banano Formation shows different coral community zones through three different stages in the evolution of the reef. The excavation in the CC outcrop consists of carbonates interfingering with siliciclastics **(Fig. 3.2)**. The reef-front shows a zonation with a branching-coral zone and a massive-coral zone. *Stylophora ssp*. meadows were found within the branching-coral zone. The massive-coral zone shows a high diversity of

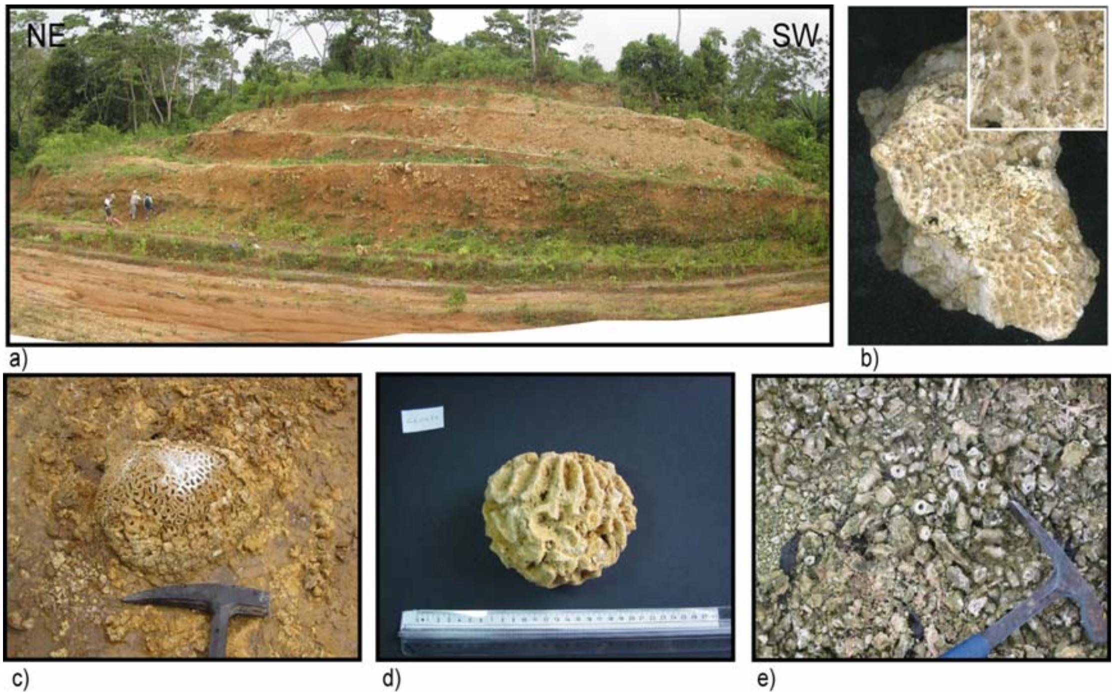


Fig. 3.2 Contact Cut outcrop (CC): Contact Zone between the Rio Banano Formation and the Buenos Aires Reef Member of the Quebrada Chocolate Formation a) Panorama view of CC outcrop b) Agaricia Agaricites c) Dichocoenia stokesi in the field d) Diploria labyrinthiformis e) Stylophora sp. Patch, first stage (CC).

head-corals (i.e. *Montastrea cavernosa, Diploria zambensis, Diploria sarasotana, Diploria labyrinthiformis, Dichocoenia stokes)*.

The reef-crest is dominated by *Dichocoenia stokesi, Porites sp. and Agaricia Agaricites*. Several species of gastropods and bivalves were found on the slope (*Bulla punctulata, Semele junonia, Hypponys sp, Chione compta, Macoma siliqua).* The back-reef consists of coral patches mixed with siliciclastics The patches consists of massive corals with mainly *Solenastrea bournoni, Siderastrea sidera, Manicia areolata, Dichocoenia stokesi and Diploria labyrinthiformis*. Common gastropods are *Conus (Ximeniconus) perplexus, Strombus graceilior* and *Vermitideae.* Bilvalves are few and low in diversity; mainly shell fragments

Table 3.1 Change in fossil communities at Contact Cut outcrop and Las Isla roadcut

CONTACT CUT

STAGE 1	Slope / Reef Front	Reef Crest	outer back-reef
Corals	Diploria labyrinthiformis	Agaricia agaricites	Dichocoenia sp.
	Diploria sarasotana	Dichocoenia stokesi	Dichocoenia stokesi
	Diploria zambensis	Porites ssp.	Diploria labyrinthiformis
	Montastraea cavernosa		Manicina areolata
	Stylophora ssp.		Siederastrea siderea
Gastropods	Bulla punctulata		Solenastrea bournoni
	Fossaridae; Hipponyx		
	Semele junonia		
Bivalves	Chione compta	Macoma siliqua	
	Macoma siliqua		

shallow reef environment, slope with fringing reef, max depth 30 m

STAGE 2	Slope / Reef Front	Reef Crest	outer back-reef
Corals	Dichocoenia stokesi	Dichocoenia stokesi	Dichocoenia stokesi
	Diploria labyrinthiformis	Dichocoenia eminens	Siederastrea siderea
	Montastraea cavernosa	Porites ssp.	Solenastrea bournoni
	Stylophora ssp.		Diploria clivosa
Gastropods	Cerithicum nicaraguense		Conus (Ximenic.) perplexus
	Conus (Lithoconus) archon		Strombus graceilior
	Murexiella keenae		
Bivalves	Chione compta		Glycymeris delessertii
	Ensis tropicalia		

shallow reef environment, beginning of siliciclastic input, transition fringing to barrier reef, close to coast, max depth 20 m

STAGE 3	Slope / Reef Front	Reef Crest	outer back-reef
Corals	n.a.	n.a.	Dichocoenia stokesi
			Diploria labyrinthiformis
			Manicina areolata
			Siederastrea siderea
			Solenastrea bournoni
Gastropods	n.a.		Strombus graceilior
			Conus (Ximenic.) perplexus
Bivalves	n.a.		Glycymeris delessertii
			Ensis tropicalia
			Vermetus

shallow reef environment, strong siliciclastic input, transition fringing to barrier reef, close to coast, max depth 20 m

of *Glycymeris delessertii* are found. In between these coral patches coral rubble and mixed siliciclastic-carbonate silts to sands occur which partly are clayey.

[1] The reef complex shows three different stages of reef evolution.

The first stage shows well-developed meadows of branching *Stylophora sp*. and a Montastrea – Diploria (Zlatarski and Estalella, 1982) coral community on the reef front and slope **(Table 3.1)**. The crest is characterized by *Porites sp*.,
Agaricia Agaricites and *Dichocoenia stokesi.* Patches dominate the outer back-reef facies with high diversity of massive corals. The reef patch measures 1m to 4m in the excavated outcrop. In between these patches some coral rubble is present with fragments of branching *Stylophora sp.* The sediment between the patches consists of carbonate mud to silt with less than 30 % siliciclastics. The quantity of siliciclastics in this facies decreases towards the second phase in reef development. Thin sections of the sediment between the patches show a small percentage (<5 % of total amount of fossils within thin section) of red algae, foraminifers, molluscs and echinoderms. A mollusc horizon with up to 55 % bivalves marks the end of this first reef phase **(Fig. 3.3)**.

[2] The second reef phase shows a well-developed reef. In addition, a slightly higher siliciclastic input can be observed at the end of phase 2. The branching *Stylophora sp*. meadows are no longer present and only a few species remain. The amount and diversity of head corals diminishes on the slope and within the reef patches. The coral community on the slope and reef front shows *Dichocoenia stokesi*, *Diploria labyrinthiformis, Montastrea cavernosa* and remnants of the branching *Stylophora sp*. meadows. The gastropods found *are Murexiella keenae, Conus (Lithoconus) archon and Cerithicum (Thericium) nicaraguense*, The bivalves are mainly represented by *Chione compta* and *Ensis tropicalia*. The reef crest is no longer characterized by *Agaricia Agaricites.* The massive coral *Dichocoenia ssp., and Porites ssp.* dominate the reef crest.

The facies in between the patches contains fragments of branching *Stylophora sp.* The siliciclastics show an upward increase from 10% to 40% and also contain small volcanic clasts with carbonate coatings. The coral patches decrease in size and the coral quantity diminishes. In the excavated outcrop the reef patch measures 1m to 3m. The corals found are *Solenastrea bournoni, Siderastrea sidera* and *Dichocoenia stokesi.* The thin sections only show a small percentage of molluscs and echinoderms (<5% to 15%). The percentage of red algae (20%) and foraminifers (10%) are higher in thin sections from sediment directly out of the patches.

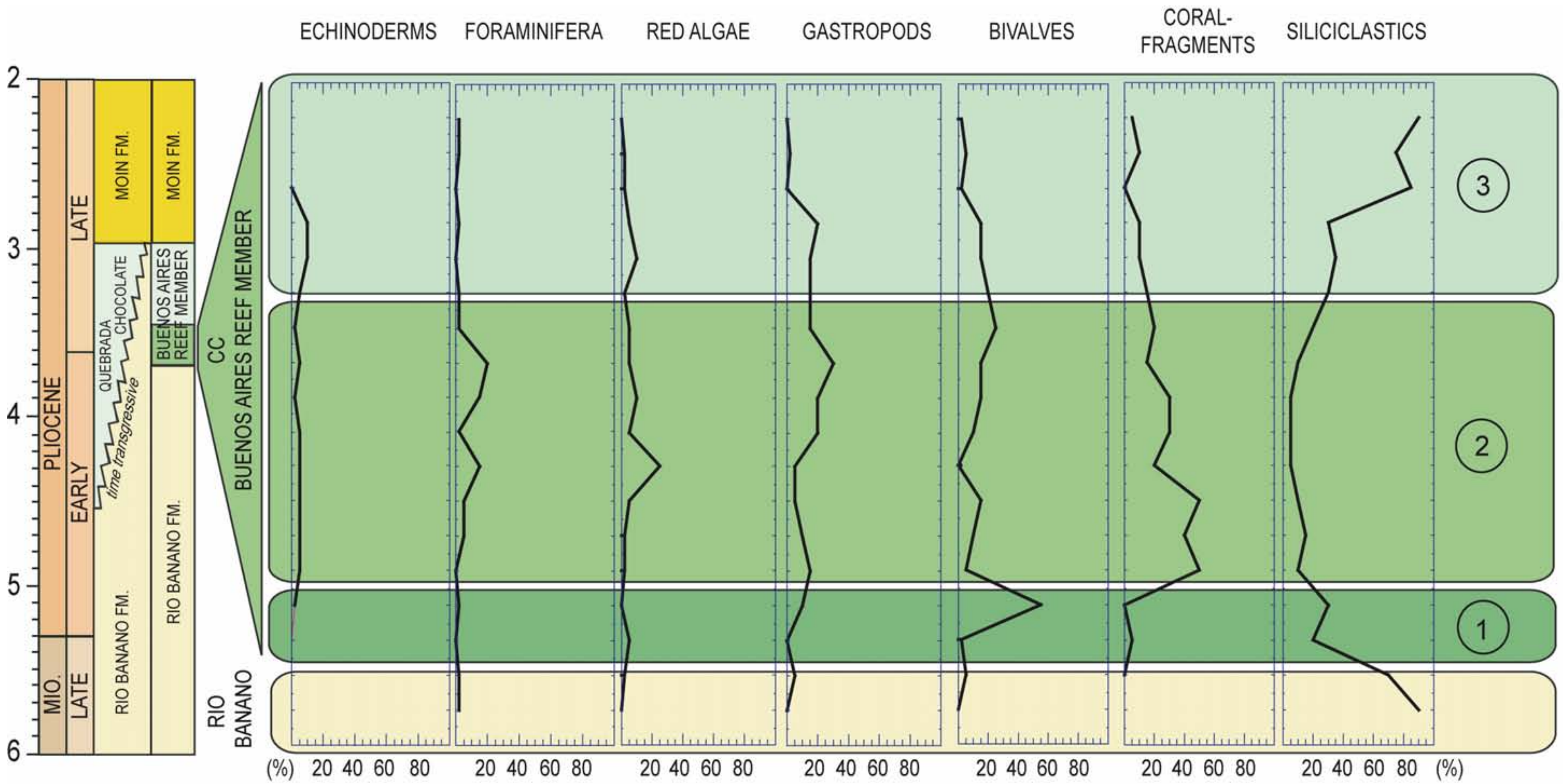


Fig. 3.3 Thin section results from the back reef of the Contact Cut outcrop and stratigraphy (timetable based on McNeill et al., 2000). (1) few silicicilatics and coral fragments, a mollusk horizon with higher abundance of siliciclastics. (2) increasing siliciclastics towards stage 3, high abundance of coral fragments. (3) reef is buried by siliciclastics, slight increase

The gastropod community shows mainly *Conus (Ximeniconus) perplexus, Strombus graceilior* and the bivalves found are *Glycymeris delessertii*.

[3] The third stage of the reef complex consists of a mixed carbonate-siliciclastic coral patch facies. In this stage only a few remnants of head corals, high in diversity but low in quantity, are left (*Solenastrea bournoni, Manicia areolata, Siderastrea sidera, Dichocoenia eminensi and Diploria labyrinthiformis)*. The thin sections show an upward increase in siliciclastics (40% to 90%).

3.5.2 Las Isla roadcut (LI)

The Las Isla roadcut (LI) is located (09° 59.066'N / 83° 05.306'W) west of Limon and was previously described by McNeill et al. (1997). Samples for thin section analysis were collected along the roadcut starting at the base of the Quebrada Chocolate Formation through the Buenos Aires Reef member. The reef complex described by McNeill et al. (1997) shows a fringing reef with slope, reef-front and reef-crest and a transition to barrier reef morphology. The sediments at the base directly overlying the top of the Rio Banano Formation consist of siliciclastics (silt to sand) with abundant benthic foraminifers, predominantly *Amphistegina sp.* and *Bolivina sp*. Red algae are also common and only a few fragments of corals were found. The thin sections show up to 40% foraminifers, mainly *Amphistegina sp.* and up to 40% red algae. On top of this unit the first reefal unit occurs, which is dominated by branching corals *Stylophora sp.* (McNeill et al., 1997). This interval is about 15m to 20m thick.

The succeeding main reef unit shows a high diversity in corals, i.e. *Diploria spp*., *Porites sp*., *Isastrea sp.*, *Mycetophyllia danaa, Montastrea sp.* and *Acropora palmata* on top of the reef-crest. McNeill et al. (2000) reports a mixed coral unit with a high coral diversity (39 coral species, 61.5% extant). The corals grow in large closely spaced colonies. The sediments in between the colonies are fine to coarse carbonate sands with some siliciclastics. The thin sections show only a few red algae and benthic foraminifers (5% to 25%). The gastropods show a divers composition. *Strombus granulatus* was found Common bivalves are *Chione ssp.* and *Trigoniocardia biangulata.*

Thin sections from the reef-crest show abundant corals embedded in clays to silt.

The excellent preservation of the fronds and little to no micro- or macro-boring suggests that the corals were rapidly buried (McNeill et al., 1997). The *Acropora palmata* on the reef-crest is embedded in siliciclastics. Red algae crusts occur frequently on these corals. One thin section showed up to 50% encrusting red algae. On top of the crest only remnants of corals and fragments were found. The facies changed into mixed carbonate-siliciclastic sediment with minor corals, with increasing siliciclastic content to the top from very coarse siliciclastic sand to gravel.

3.6 DISCUSSION

3.6.1 Coral depth zonation

A large variety of corals were present in the outcrops studied. In their study of 49 different recent reefs around Cuba, Zlatarski and Estalella (1980) very precisely described the depth zonations of a large series of coral species. Using the averaged depth values of the individual coral heads as indicated in that study **(Table 3.2)** allowed us to determine the individual growing zones of the coral communities in the Pliocene reefs of Costa Rica. The estimation of the precise palaeodepth also helped to understand the evolution in time of the reef types encountered.

Some differences exist between the species found in the Pliocene outcrop and the ones described in literature. For our depth and environmental analysis we have to assume that the same genus of corals in the Pliocene and at present, grow in similar and comparable water depths. The Pliocene communities were primarily dominated by *Stylophora ssp.* and *Goniophora ssp.* with some agariciid and poritid species. This reflects rather a modern Indo-Pacific coral community than a Caribbean one. Modern Caribbean reefs are dominated by *Diploria ssp.*, *Acropora ssp,* and *Montastrea ssp*.
During the Early Pliocene faunal turnover approximately 64% of all reef corals became extinct and a similar number of molluscs became extinct during the same time interval (Budd et al., 1994). The timing of this turnover is dated between 4-2 Ma whereby the turnover of corals started about 1 Ma earlier than those observed in the molluscs (Goreau, 1959; Budd et al., 1994).

Table 3.2 Average living depths of corals, habitat and their fossil record

Species	Average Depth**	Habitat	Tertiary to Quaternary Fossil record of Genus
Acropora Palmata	2-4	Shallow outer reef slopes exposed to wave action	Eocene - to this day
Agaricia agaricites	6-15	Shallow reef environments	Miocene - to this day
Dichocoenia caloosahatcheensis		Most reef environments	Pliocene - Pleistocene
Dichocoenia eminens		Most reef environments	Pliocene - Pleistocene
Dichocoenia stokesi	6-23	Most reef environments	Eocene - to this day
Diploria clivosa	2-6	Most reef environments, especially shallow slopes and lagoons	Eocene - to this day
Diploria labyrinthiformis	8-14	Shallow reef environments	Eocene - to this day
Diploria sarasotana		Shallow reef environments	Pliocene
Diploria zambensis		Shallow reef environments	Miocene - Pliocene
Manicina areolata	8-19	Subtidal sea grass beds where colonies are small and free-living, also shallow reef environments where colonies are attached and become hemispherical, lagoons	Oligocene - to this day
Montastraea cavernosa	9-32	All reef environments, especially lower slopes	Eocene - to this day
Mycetophyllia reesi	17-20	Lower reef slopes protected from wave action	Oligocene - to this day
Porites ssp.*	2-15	Most reef environments	Eocene - to this day
Siederastrea siderea	7-24	Shallow reef environments	Cretaceous - to this day
Solenastrea bournoni	2-5	Shallow turbid environments including sea grass beds and reef lagoons	Oligocene - to this day
Stephanocoenia duncani		Shallow reef environments	Pliocene - Pleistocene
Stephanocoenia ssp*	12-30	Shallow reef environments	Eocene - to this day
Stylophora ssp.		Most reef environments, sloping rock facies	Palaeocene - to this day

* identified in outcrop, impossible to retrieve sample

** average depth of recent corals ascertained after Zlatarski and Estalella (1982)

As extensively described in literature scleractinian corals are very sensitive to changes in light, temperature, salinity and nutrients and thus their distribution is limited to special habitats (e.g. Smith and Buddemeier, 1992). Our analysis shows that the Pliocene Contact Cut (CC) reef has a reefal community similar to the modern reef systems around Cuba. This may be slightly surprising with respect to the faunal turnovers that occurred in the Caribbean. In recent studies it was proposed that faunal change could start at different geographical locations at different times and in different ways (Budd et al, 1994). The CC reef exhibits a clear coral growth zonation with a branching and a massive coral zone at the reef slope/front and a reef crest.

3.6.2 Reef community

Bosence et al. (1994) describes computer model based processes of carbonate platforms based on a Miocene carbonate platform of Mallorca, Spain. The described reef flat and the early outer back reef to lagoonal facies characterized by skeletal, grainstones and patch reefs is similar to the facies found in back reef of CC. In between the coral patches some *Strombus sp.* could be found. The combination of gastropods and corals suggests a lagoonal setting with sea grass meadows between the coral patches. In recent coral reef systems *Diploria clivosa*, *Solenastrea bournoni* and *Manicia areolata* preferentially occur in lagoonal settings. *Strombus ssp.* occurs frequently in protected areas such as lagoons **(Table 3.3**) in community with *Thalassia* (Keen and McLean, 1971).

Silts dominate the siliciclastics. Abundant silts and skeletal components as molluscs, and echinoderms are an indicator for sea-grass (Pomar, 2001). It is hard to find direct evidence for sea-grass meadows in the fossil record and only can be deduced from the sedimentology and palaeontology within the individual environmental settings (Brasier, 1973, 1975). Perry and Beavington-Penney (2005) have shown that carbonate facies can be related to latitudinal and environmental-related shifts in the composition and character of sea grass related sediment facies. The biotic community of corals, gastropods and molluscs suggests a max. paleo-water depth of <30 m for the first stage of reef development. According to Bosence et al. (1994) the branching coral zone lies 15 m below the reef crest.

This suggests that the max. water depth for the reef top in the first stage is shallower than 15m. During the second stage of reef development a max water depth of <20m can be proposed for the branching coral zone on the reef front, which thus suggests a shallower reef top then for stage one. The frequent occurrence of *Diploria ssp.* on the reef front as well as primary reefbuilders *Agaricites agaricia* and *Porites ssp.* on the reef crest suggests a shallower environment, and if we keep in mind that the stated depths are max depth, we may assume a shallower palaeodepth. The comparison of the fossil coral community with recent reef communities (Zlatarski and Estalella, 1980) suggests a paleo-water depth of approximately 5-7 m for the reef crest. This agrees with the observations of a developing reef flat and back reef

Table 3.3 Living space of mollusks found at Contact outcrop and Las Isla roadcut

Species	Habitat
Bulla punctulata	offshore beyond low-tide limit, muddy ground
Cerithicum nicaraguense	intertidal and offshore to 37 m
Columbella major	under rocks, tidal zone
Columbellidae strombinformis	under rocks. tidal zone
Conus (Lithoconus) archon	mostly offshore to 26 m; and 400 m
Conus (Ximeniconus) perplexus	mostly on sandbars, also offshore to 37 m
Fossaridae; Hipponyx	
Murexiella keenae	intertidal and offshore to 33 m
Oliva polpasta	muddy
Semele junonia	offshore to 70 m
Strombus granulatus	muddy to sand in community with Thalassia
Strombus graceilior	offshore to 45 m, more protected environment, Thalassia, on sand flats and lagoons
Trivia radians	intertidal, muddy, soft sediment under rocks
Turitella ssp.	5 m to 130 m

Bivalves	
Cardids (Trogonioc.) biangulata	intertidal and depths to 115 m
Chione compta	mostly offshore 22 - 27 m
Chione mariae	mostly offshore in depths to 110 m
Ensis tropicalia	sandy bottom, 11 m to 25 m
Glycymeris delessertii	muddy to sandy ground, most offshore to 30m, occurrence of single shells very common in beach drift
Scaphopods	
Macoma siliqua	
Vermetideae	mostly cemented to rocks, sand to gravel

facies. The species occurring in latter environments, *Diploria clivosa* and *Solenastrea sp.* at present can be found in backreef settings with a water depth of approximately 2 -7 m.

During the 1st and 2nd phase of reef development the main carbonate producers and reefbuilders are the branching coral *Stylophora sp.* on the reef front, and *Porites ssp.* and *Agaricia agaricites* on the reef crest. Towards the reef flat lagoon the production rate decreases (Bosence and Waltham, 1990; McNeill, 2005). The increased reef growth accompanied by high carbonate production rates for the reef crest during the first reef phase led to a general shallowing of the reef. Through stage 1 to 3 the coral community changed. Thin sections reflect the development of the outer back reef facies. During stage 1 we found some small coral patches with only some rubble in between the patches mixed with some siliciclastics from the Rio Banano formation. Only small amounts of gastropods, bivalves, red algae and foraminifera could be found. The mollusc horizon at the end of stage 1 which is associated with a vast increase in coral rubble might indicate a storm event. The type of coral fragments might support this interpretation while it mainly consists of *Stylophora ssp.*, which preferentially occurs on the upper slope and thus was transported shoreward to the reef flat. The size of the reef patch and the amount of corals at first increases during stage 2 with the beginning of the developing back reef but then decreases again towards reef stage 3, which might be the response of the reef system to the increased input of siliciclastics. In stage 3 only few coral patches are left within an environment that is dominated by the high amount of siliciclastics.

3.6.3 Sea-level and increased siliciclastic input

A rise in sea level is proposed for the early/late Pliocene (Haq et al. 1987) followed by a sea-level highstand observed on “highstand-reefs” in the Moin Formation (McNeill, al. et, 2000). The 1st stage of the reef represents the catch-up phase of the reef (Schlager, 1981) in which reef growth exceeded sea-level rise. The succeeding slow rise in sea level gave the reef enough time to grow and during this time interval carbonate production exceeded sea level rise (Eberli and Ginsburg 1989), with the result that the reef nearly caught-up **(Fig. 3.4)**. The reef crest with the main carbonate producing organisms grow faster than the reef-front and reef flat, so that the outer back reef started to developed with a more lagoonal facies behind the crest. The 2nd and 3rd stage reflect a sea-level highstand and the observed reef progradation in the outcrop suggests an overproduction of the reef rapidly filling up the available accommodation space. Carbonate production was very efficient and with high productivity and accumulation rates vertical accommodation space may become limiting and led to progradation. The increased siliciclastic input starting in the 2nd stage and increasing vastly during stage 3, however, sheds a blanket over the back reef facies and finally the crest beginning to drown the reef.
The 2nd reef stage is characterized by the development of an outer back reef facies with a large diversity of coral patches. It evolves directly after the mollusc horizon. High input of coral rubble from the reef front as well as increase of siliciclastics with upwards-increasing grainsize towards the 3rd stage of reef development is observed.

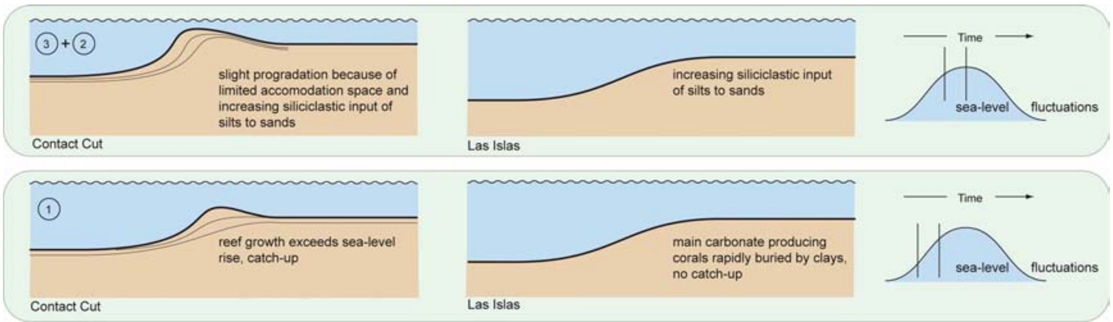


Fig. 3.4 Reef development correlated to sea-level. During the transgressive phase (sea-level rise) reef growth at Contact Cut exceeds sea-level rise (catch-up). At Las Islas a first siliciclastic input of clays buried the main carbonate producing corals (no catch-up). During the highstand phase (sea-level stillstand) slight progradation occurs at Contact Cut due to limited accommodation space. In addition increasing siliciclastic input at Contact Cut and Las Islas restricts reef growth.

The increased suspension of particles in the water through turbidity severely affected coral growth. As a supplier of the siliciclastics we propose river systems in the proximity of the reef, which were already described by Taylor (1973). River systems affect the entire Upper Neogene geologic history of the Limon area. The formation of the river systems was induced by the elevation of the Cordillera de Talamanca and transported siliciclastics including volcaniclasts to the river mouths (Coates et al., 1992; McNeill et al., 2000) The migration of the streams results in a sheet of clastics being deposited, smothering the reefs (Taylor, 1973). A precondition for increased turbidity is the availability of sufficient sediments that can be shifted into suspension. The shallowing caused by the extensive reef growth and thereby the increased wave energy as well as the tidal effect in proximity to the coast led to an increased suspension of particles in the water. The main reason for the turn off of many coral reefs in the west of the Atlantic is increased turbidity (Lighty et al., 1978; Macintyre, 1988). Tidal currents are able to move silt and sand and these flow rates are sufficient to keep these particles in suspension (Kleypas, 1996). The main factors that control the generation and distribution of turbidity are resuspension by waves, particle settling and vertically mixing (Larcombe and Wolf, 1999).

3.6.4 Reduced water clarity and its impact on reef diversity

On Puerto Rican reefs, which were affected by terrigenous input (Acevedo et al., 1989), the relationship of reduced water clarity and a decrease in the drowning depth of reef corals (Hallock and Schlager 1986) could be observed.
The amount of coral colonies, the decrease of the size of the corals as well as the absence of major framework builders might indicate the impairment of the reef growing conditions. Increased turbidity might be a reason for that. During an increase in sedimentation and turbidity and therefore an increase in sediment suspension concentration (SSC) in the water, we may expect a shift to smaller coral species because they are more efficient in sediment rejection contrary to larger grow-forms (Rogers, 1990). In addition, a smaller diversity is observed, particularly during the 3rd stage while under high turbidity stress less species exist that tolerate such conditions (Kleypas, 1996). With increase in the amount of siliciclastics from 10% on the reef flat in the middle of stage 2 to up to 90% on stage 3 we could observe the decrease of the amount of the main reefbuilder in the crest (*Porites ssp.*) and the reef front (*Stylophora sp.*)
The reef front as well as the crest is not visible in the outcrop but the development from stage 1 to 2 and the change in community and the reduced patch reefs in stage 3 support aforementioned developments. Many fragments of *Porites ssp.* and complete coral heads not in-situ live position were present on the reef flat of the 3rd stage
The run off from major reefbuilders and the change to more turbidity tolerant species in environments under high sedimentation and turbidity by the example of the Great Barrier Reef is described by Kleypas (1996) and Van Woesik (1992) and could be observed in the CC reef.

3.6.5 Coral rubble transport and building of patches

The reef flat and outer back reef facies are characterized by enormous amounts of coral rubble in between the reef patches. The rubble mostly contains small fragments of *Stylophora ssp.* and some rubble from other massive corals. During stage 3 the amount of *Diploria ssp.* fragments from the reef-crest increases. Only few studies focused on transport of coral fragments through wave-energy or tidal events. Most focused on episodic storm events (Ball et al., 1976; Baines et al., 1974; Dollar and Tribble, 1993; Scoffin 1993; Bourrouilh, 1998). Hughes (1999) focused on generation and movement of coral rubble down the reef slope and showed that fragments of more than 100g could be transported. Sixty-eight percent of the coral fragments of lithified *Stylophora ssp.* in our study area had a weight below 50g. If we keep in mind that the fragments were lighter in unlithified condition a shoreward transport of coral fragments to the reef flat would be feasible. The paleo-slope angle was very gentle below 10°. The co-occurrence of gentle slopes with reef-flats in shallow waters may result in shoreward transport of rubble (Woodleyet al. 1981; Scoffin 1993; Rasser and Riegel, 2002). Besides the transport of rubble through tidal waves the mollusc horizon at the end of stage 1 with the enormous increase in coral rubble from the reef front at the same time could be an indicator for a possible storm event. In the beginning of stage 2 the coral rubble may have provided a substratum for the settlement of coral larvae and thus the beginning of the development of more divers and bigger coral patches (Gilmore and Hall, 1976; Davies, 1983; Hughes, 1999 and Rasser and Riegel, 2002)

3.6.6 Las Islas and stratigraphic correlation

The Las Islas (LI) roadcut shows a different reef development. It shows a fringing reef with a pronounced *Stylophora sp.* branching zone at the reef front and a distinct carbonate producing area with various coral species growing very close to each other with *Porites ssp.* and *Acropora palmata* as primary reefbuildner (McNeill, et al., 1997). The outcrop shows a rapid burial of the corals by siliciclastics. Differently than in the CC reef we first observe clays that grade into silts and sands and led to a comparable carbonate siliciclastic mixed sediment like the one in the phase 3 of the CC reef. The thin sections show a steady increase in siliciclastics from 15% to 40%. No thin sections were made from the pure siliciclastics after the transition to the siliciclastic unit.

After a rapid sea-level rise in the transgressive stage, siliciclastics with primarily clays at the beginning buried the reef. In contrast to the CC reef the carbonate factory at the LI reef was turned-off by the siliciclastics. The well-preserved coral heads in live position as well as the lack of coral rubble on the slope or the inner reef suggest a fast burial and time-equivalent turn-off of carbonate production.

The Buenos Aires reef member as well as the Las Islas reef is very well dated using microfossils, palaeomagnetic and strontium-isotope measurements (McNeill et al., 2000). The age of the Quitaria section of the Rio Banano Formation is dated to 3.7 to 3.5 Ma. The Buenos Aires Reef Member of the Las Islas Reef is dated to 3.7 to 3.6 Ma. The stratigraphic position of the Contact Cut reef between well-dated Formations suggests an age comparable to that of the LI reef. A similar reef community as well as the process of the development of the reefs, and the timing of the burial of the carbonates strongly supports this interpretation.

3.7 CONCLUSION

The Early to late Pliocene facies around Limon is very strongly effected by an environment shortly before the closing of the Central American Seaway, with many coast lines, river processes, islands and currents in shallow (<30m) tropical waters. Examination of two reefs in this environment has shown that two reefs developing at the same time, in direct vicinity which shows similar communities, nevertheless can react very differently to siliciclastic input and thus leave different geologic records in the sediment. McNeill, et al., (1997) describes the Las Islas reef of the Buenos Aires formation as an in-situ mixed transgressive reef with stacked reefal build-ups. McNeill, et al., (1997) describes further the reefs of Moin Formation as highstand reefs with their lateral mixing of small patch reefs (2-7m and 5-30m wide) and the alternation of corals and siliciclastics.

In this study it was shown that with rapid sea-level rise in the transgressive phase followed by a slow rise of sea-level leading to the highstand phase, locally different siliciclastic input may turn off the carbonate factory (Las Islas) or may lead to an approximate “catch up” of the reef. Latter includes prograding and development of reef flats (Contact Cut) that led to the later dying of the reef community. The developed patch reefs under influence of the input of siliciclastics can leave a similar geologic record as the described highstand reefs of the Moin formation although it started to evolve during the transgressive phase.

CHAPTER 4

Sediment distribution in the Gulf of Panama and the Gulf of Chiriquí (E-Pacific)

4. Sediment distribution in the Gulf of Panama and the Gulf of Chiriquí (E-Pacific)

ABSTRACT

Up to now little is known on the sediment distribution in the Gulf of Panama and the Gulf of Chiriquí. Both, the Gulf of Chiriquí and the Gulf of Panama are mixed carbonate-siliciclastic systems. The sediment distribution in the Gulf of Panama displays a distinctive pattern, in which fine terrigenous material dominates along the coast. Sediment transport is mainly influenced by extensions of the Humboldt Current and the wind-induced Panama Current. The inherited glacial topography partly determines the sediment distribution. Some coarse sediment in the centre of the Gulf might represent glacial relict sediments. In the Gulf of Panama, coastal counter-clockwise currents related to extensions of the Humboldt Current, redistribute river-derived, fine terrigenous material towards the open shelf of the Gulf of Chiriquí. The Gulf of Chiriquí is characterized by a dominance of carbonate sediments around the islands within the gulf. Carbonate sediments are present in shallow-water areas surrounding the islands in the Gulf of Panama. The terrigenous sands present in both gulfs, predominantly consist of quartz, feldspar and volcanoclastic grains. Latter result from the weathering of the volcanic islands within the gulfs or are erosional products of the volcanic dominated mainland transported into the gulfs by rivers. Carbonate production mainly occurs in the shallow-water areas surrounding the small islands present in both gulfs and shows minor sediment transport.

4.1 INTRODUCTION

The Pacific coast of Panama can be divided into two parts, the Gulf of Panama and the Gulf of Chiriquí. The Gulf of Panama borders the southern side of the Isthmus of Panama and is located east of the Azuero Peninsula that divides the Pacific shelf region into the Gulf of Panama in the east and the Gulf of Chiriquí in the west **(Fig. 4.1)**. The shelf is 160 km long from west to east and 175 km in a north to south direction. The shallow-water area in the Gulf of Panama comprises in total approx

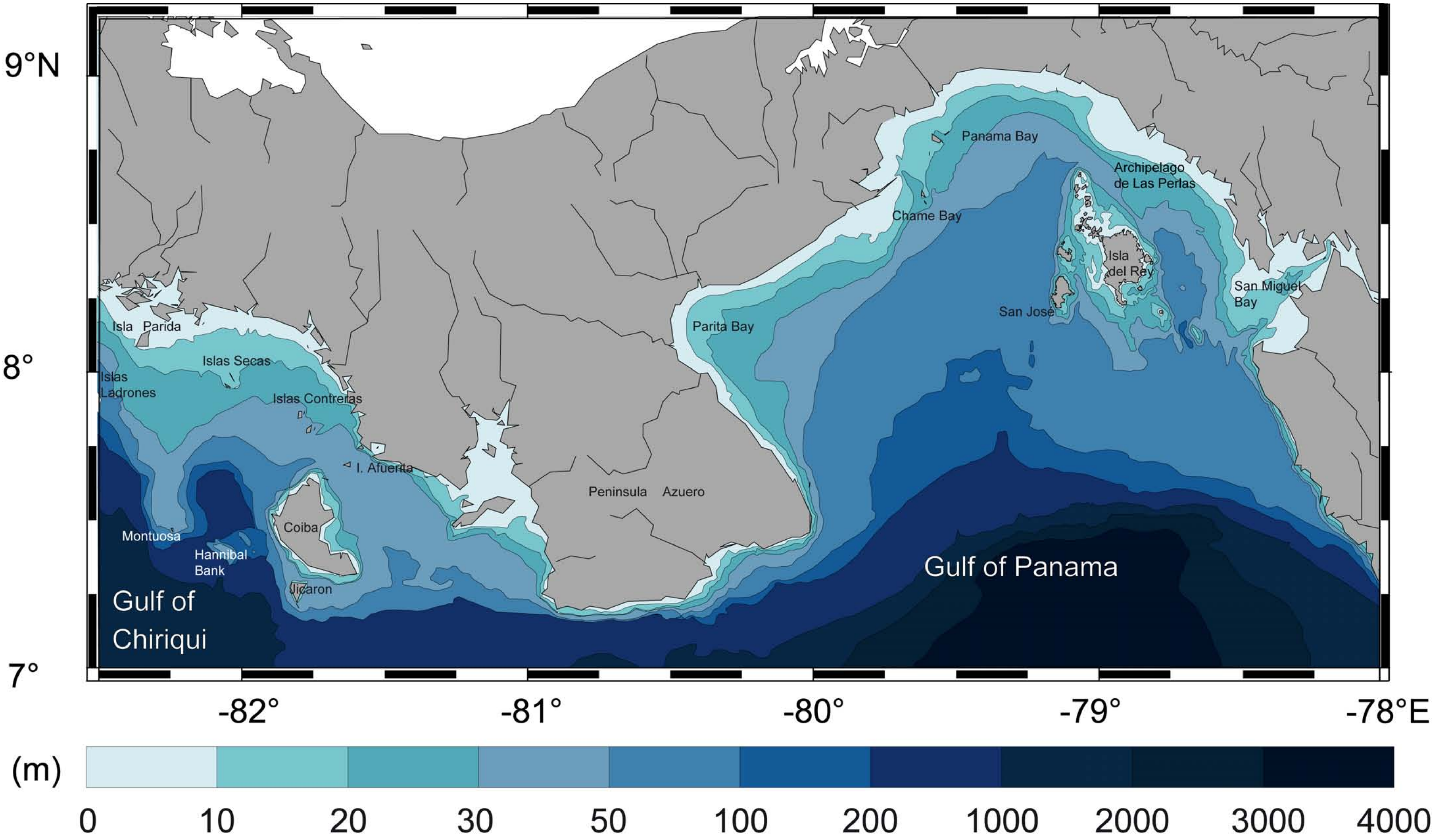


Fig.4.1 Map of the study area. Bathymetry data taken from hydrographic charts (UK Hydrographic Office UKHO) (Collins, 1973, Clark, 1998)

28000 km^2. Water depths are less than 75 m in most parts, with a mean water depth of 65 m (Fig. 4.1). The topography of the gulf is smooth and shallow except for a deeper valley starting northwest of the Archipelago de Las Perlas running south to the slope and a smaller southwest trending valley beginning at San Miguel Bay, ending at approx 50 m water depth (MacIlvaine and Ross, 1973).
The Gulf of Panama can be divided into three parts, Parita Bay as the western part, the Bay of Panama in the north and the Gulf of San Miguel in the east. The Archipelago de Las Perlas consists of over 100 small islands situated mainly west and north of the bigger Isla del Rey island in the eastern part of the gulf between Panama Bay and San Miguel Bay. The area around these islands has a diverse fish fauna and a large diversity of benthic biota like molluscs, echinoderms, balanids, red algae and corals. Freshwater enters the gulf in the bay of San Miguel, through the Panama Canal, into Panama Bay and through several rivers in Parita Bay.

The Gulf of Chiriquí is located west of the Azuero Peninsula and stretches west to the Costa Rican border. The shallow shelf area is smaller and deeper than in the Gulf of Panama. The average water depth in the Gulf of Chiriquí is 110 m, maximum water depths of 459 m are reached in the Hannibal Trench situated west of Coiba in the southern part of the gulf. There is one prominent valley in the centre of the gulf, which starts northwest of Islas Contreras and runs south to the Hannibal Bank and adjacent slope. The largest island in this region is Coiba. Some smaller islands are located along the mainland northwest of Coiba. The water depth is shallow (30m - 50m) between the Azuero Peninsula and Coiba, increasing to water depths of 50m – 400m west of Coiba (Fig. 4.1). The shelf edge lies closer to the mainland than in the Gulf of Panama. Isla Montuosa and the Hannibal Bank are located at the shelf edge.
The extensions of the Humboldt Current, coming from South America, meet the mainland of Panama in the area of the Azuero Peninsula and therefore influence the surface currents in both Gulfs. The extensions of the Humboldt Current enters both gulfs in the east, rotates counter-clockwise following the coastline and leaves both gulfs in south-western to western directions (Schaefer et al. 1958; MacIlvaine and Ross, 1973; Kwiecinski and Chial 1983).
The objective of this study is to determine the sediment distribution, mineralogy and grain size variations in the Gulf of Panama and the Gulf of Chiriquí as a first

approach to determine the differences in sediment input, sediment transport and current and wave regime within both gulfs.

Earlier work in that area was mostly related to the hydrography or upwelling in the Gulf of Panama (Schaefer et al., 1958; Forsbergh, 1963, 1969; Smayda, 1963, 1966; Legeckis, 1985; D`Croz, et al., 1991, D`Croz and Robertson, 1997). Some research on the sediments in the Gulf of Panama was done by Terry (1956); Golik (1968); Swift and Pirie (1970) and MacIlvaine and Ross, 1973).

4.2 METHODS

In total 250 grab samples were collected during two cruises in 2004 and 2005 with the RV *Urraca* in the shelf region of the Gulf of Chiriquí and the Gulf of Panama **(Fig. 4.2)**. The majority of the samples were taken in the shallow-water carbonate environments surrounding the islands present in both gulfs. In addition, two long

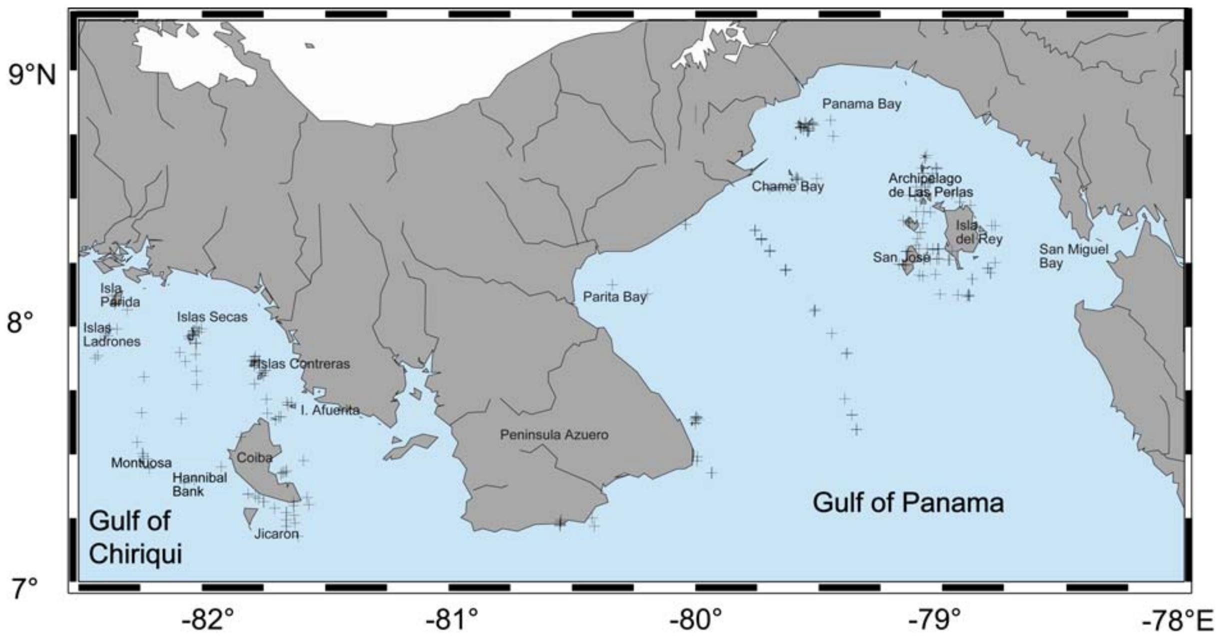


Fig.4.2: Map of the study area including grab sample locations from Cruise 2004 and 2005

transects were sampled. One transect in the Gulf of Panama that crosses the gulf from the shallow-water realm to water depth up to 300 m and one in the Gulf of Chiriquí from Islas Secas to Montuosa (Fig. 4.2).

4.2.1 Grain size analysis

The samples were washed and wood, leaves and fish remains were carefully removed. It was secured that the fine fraction attached to these fragments was returned to the sample during this cleaning process. The samples were dried in a hot stove at 45° for 48 hours and weighed in order to obtain the total weight of the sample including the fine fraction (<63µm). Subsequently the samples were wet sieved removing the <63µm fraction. The samples were dried again for 48 hours at 45 °C. Afterwards, the samples were dry sieved and the individual fractions, >63µm-125µm, 125µm-250µm, 250µm-500µm, 500µm-1000µm, 1000µm-2000µm and >2000µm) were weighed. The weight percentage of the individual fractions was calculated as percentage of the total sample. Using the weight percentages of the individual fractions the mean, mode, sorting (standard deviation), skewness, kurtosis were calculated. These grain size statistics were calculated using the methods of Folk and Ward (1957). The program GRADISTAT was used for these calculations.

Table 4.1 Udden-Wentworth grain-size classification scheme

Size range (metric)	**Aggregate name (Wentworth Class)**
16–32 mm	Coarse gravel
8–16 mm	Medium gravel
4–8 mm	Fine gravel
2–4 mm	Very fine gravel
1–2 mm	Very coarse sand
½–1 mm	Coarse sand
¼–½ mm	Medium sand
125–250 µm	Fine sand
62.5–125 µm	Very fine sand
3.9–62.5 µm	Silt
< 3.9 µm	Clay
< 1 µm	Colloid

(Wentworth, 1922)

It is a Microsoft Visual Basic program, which is integrated into a Microsoft Excel spreadsheet, allowing both tabular and graphical output (Blott and Pye, 2001). Grain sizes are given according to the Udden - Wentworth classification **(Table 4.1).**

4.2.2 LECO

Bulk samples (containing all fractions) from each site were prepared for LECO analysis with the LECO C-200 analyzer at IFM-GEOMAR – Leibniz Institute for Marine Sciences (Kiel, Germany). The weight percentages of total carbon (TC), organic carbon (OC), and calcium carbonate (CaCO3) are related by the equation: (TC - OC) * 8.33 = CaCO3. If we assume that all the inorganic carbon is bound in calcium carbonate. Deviations of 0.5 % TC and 0.05 % TOC between the double-measurements were tolerated otherwise a third run was performed.

4.2.3 XRD

Bulk samples (containing all fractions) from each site were freeze-dried and grinded in an agate-mortar for X-ray diffraction analysis. After freeze-drying and grinding by hand, the samples were filled in cavity mount holders. These were scanned in a Philips PW 1710 diffractometer equipped with a cobalt K tube at 40 KV and 35 mA and with an angle from 2Θ to 70Θ. The computer-based program MacDiff Version 4.2.5 (Petschick, 1999) was used to process the X-Ray diffractograms and to calculate the peak areas of the individual minerals.

In-house calibrations were used to calculate the non-linear relationship between calcite and aragonite, because existing calibrations show low resolution and accuracy for aragonite percentages exceeding 70% (Milliman, 1974). The mineral quartz, with d= 3.343 A was used as an internal standard for peak correction in MacDiff. In samples with low quartz content or absence of quartz aragonite, with d=3.398 A was as standard for peak correction. The relative changes of the quartz peak areas in the diffractograms were interpreted as relative changes of quartz abundance in the individual samples.

4.2.4 Point counting

The percentage of quartz within the terrigenous part of the mixed carbonate-siliciclastics sediments was estimated using visual comparison charts of Scholle and Ulmer-Scholle (2003).

The weight percentages of each individual grain size fraction were calculated from the dry sieve analyses and the amount of terrigenous material in the sediment derived from point–counting. Only the fractions 125µm to >2000µm were counted; 100 points were used to calculate the percentage of quartz, with respect to the terrigenous fraction and as percentage of the entire sediment sample, respectively.

4.2.5 Cluster analysis

A cluster analysis with the weight percentage of the individual fractions was performed using the program statistiXL 2006 Vers. 1.6 for Microsoft Excel (Roberts and Withers, 2006) with Ward`s method as linkage and Euclidian distances. The cluster analysis was necessary to prepare our data for the import of data from existing records. Our existing results for the fractions <63µm, 63µm-125µm, 125µm-250µm, 250µm-500µm, 500µm-1000µm, 1000µm-2000µm and >2000µm were processed, resulting in four clusters: (I) very coarse sand and above (1000µm>2000µm), (II) medium sands to coarse sand (250µm-1000µm), (III) very fine sand to fine sand (63µm-250µm) and (IV) clay to silt (<63µm).

4.2.6 Mapping program

The mapping software Surfer 7 by Golden Software (1999) was used to display the data and thus to visualize the grain size and mineralogy distribution maps. The Kriging gridding method was utilized for the construction of the maps.

4.3 RESULTS

4.3.1 Grain size distribution and sorting

Grain size distribution

The clays to very fine sands (<63µm to 125µm) In the Gulf of Panama are dark green-grey in colour. They appear along the coasts of the mainland. Their distribution is interrupted by two areas around Parita Bay and north of Chamé Bay with medium green-bluish sands (250µm to 500 µm; **Fig. 4.3)**. The clays to very fine sands (<63µm to 125µm) are also found west and east of the northernmost small islands of Archipelago de Las Perlas and along the east coast of the Azuero Peninsula. Due to the low sample resolution in the areas north of the Archipelago des Las Perlas along the coast of the mainland and east of the Azuero Peninsula along the coast, only an incomplete inventory can be made of the sediment distribution in the Gulf of Panama. Nevertheless the analyzed samples from these areas indicate that in the Gulf of Panama fine sediments appear along the mainland coast of Panama, whereas coarser sediments prevail towards the slope. This trend is interrupted by the occurrence of coarser grain sizes in the shallow waters near the Archipelago de Las Perlas. The regions around this archipelago predominantly contain carbonate sands except for the north and south passage west of Isla del Rey and a small muddy region northeast of Isla del Rey. In general the areas surrounding the small islands in this archipelago are characterized by pure carbonate sands or mixed siliciclastic carbonate sands. The carbonate fraction mainly consists of shell fragments, echinoderms, balanids, red algae and some corals.

The terrigenous fraction of the sediments contains minor amounts of quartz and feldspar and mainly consists of volcanoclastic debris derived from the adjacent volcanic islands. West of Isla del Rey and east of Isla Pedro Gonzales and Isla de San Jose two passages run north to south, the “North -“ and the “South - Passage”. Very fine sands (<63µm to 125µm) derived from the north dominate both passages. Additionally, fine sands (125µm to 250µm) prevail in the South Passage. The water depth in this channel (20m to 40m) is deeper than around the surrounding islands (5m to15m).

Two areas with a rocky bottom contain mean grain sizes exceeding >2000µm, one

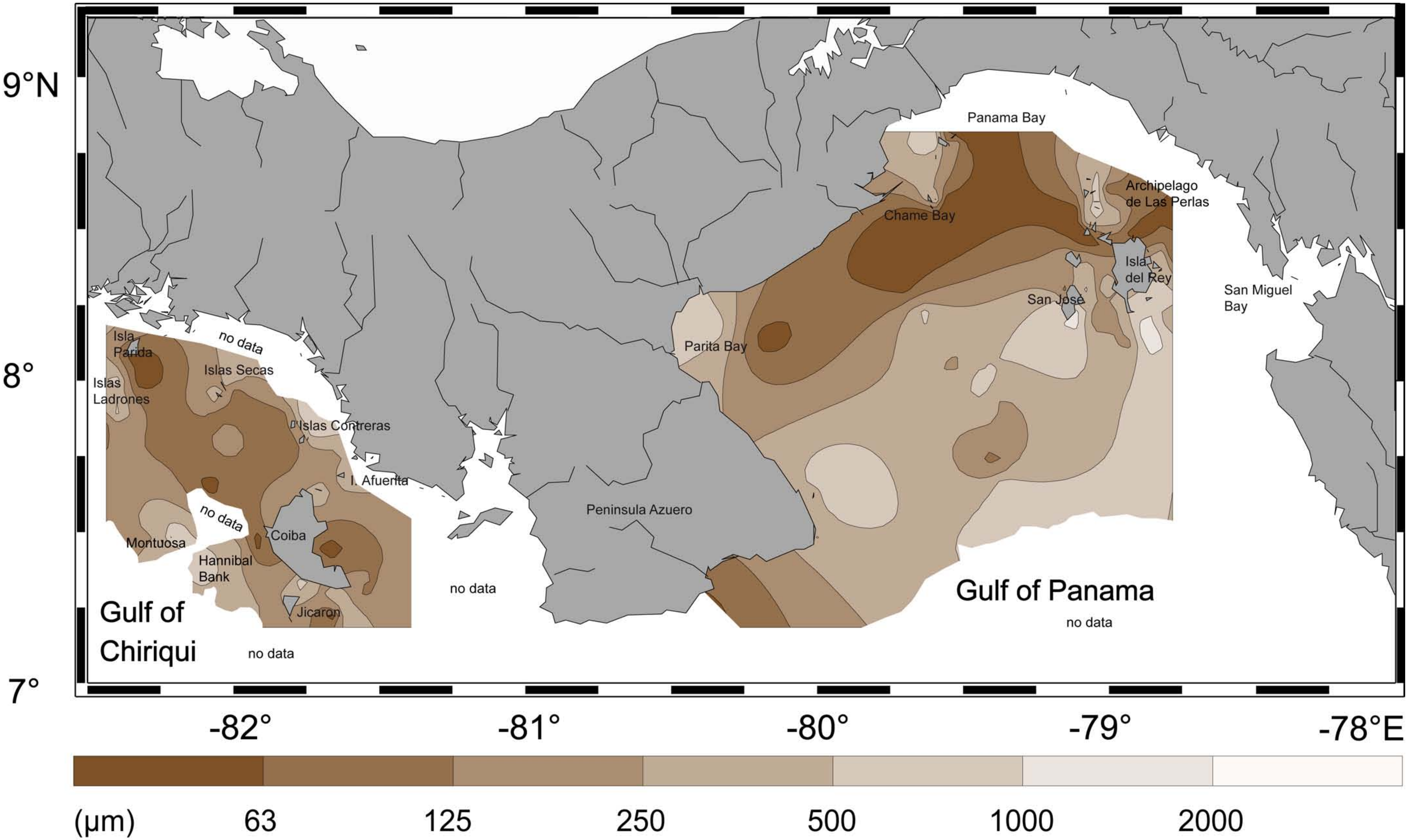


Fig. 4.3: Grain size distribution of surface sediments along the Pacific coast of Panama. In the Gulf of Panama finer sediments dominate along the coast. In the Gulf of Chiriqui finer sediments occur in the centre of the gulf. Coarse sediments prevail around the islands in both gulfs.

area south of Isla de San Jose in the Gulf of Panama located at U5120 (8.202; -79.091) with 2325.5µm and one close to Islas Contreras in the Gulf of Chiriquí located at U04113 (7.856; -81.783) with 2308.8µm. These areas are very small, and could not be shown on the map because of the large map scale covering the entire Gulf of Panama.

The shelf area near the coast in the Gulf of Chiriquí is dominated by slightly coarser sediments. They relate to the occurrence of carbonate producing biota that occurs in the shallow-water areas surrounding several small islands in this region. The sediments surrounding these islands consist of mixed carbonate-siliciclastic sands (250µm to 1000µm). The mid-shelf area is dominated by olive-green to medium-grey mud to very fine sand (<63µm to 125µm). The finest sediments can be found in the centre of the Gulf of Chiriquí. Northeast of Isla Montuosa and at the Hannibal Bank the sediments are coarser (500µm to 1000µm) and consist of mixed carbonate siliciclastic sands. No data are available for the sediment distribution in the very shallow coastal areas, but in analogy with the findings from the Gulf of Panama it is assumed that they contain fine-grained sediments.

In summary it can be said that in both gulfs the sediments are coarser around the islands (carbonate input). However, the overall sediment distribution in both gulfs still shows strong differences related to the local current patterns.

Sorting of grains

Table 4.2	Sorting
Very well sorted	<1,27
Well sorted	1,27-1,41
Moderately well sorted	1,41-1,62
Moderately sorted	1,62-2
Poorly sorted	2-4
Very poorly sorted	4-16
Extremely poorly sorted	>16

(after Folk and Ward, 1957)

The nomenclature of Folk and Ward (1957) was used to classify the sediment sorting **(Table 4.2)**. The Gulf of Panama mainly shows poorly sorted sediments with only four areas in which well sorted to moderately sorted sediments are present **(Fig. 4.4)**. These areas are located southeast of Chame Bay, southeast of Isla

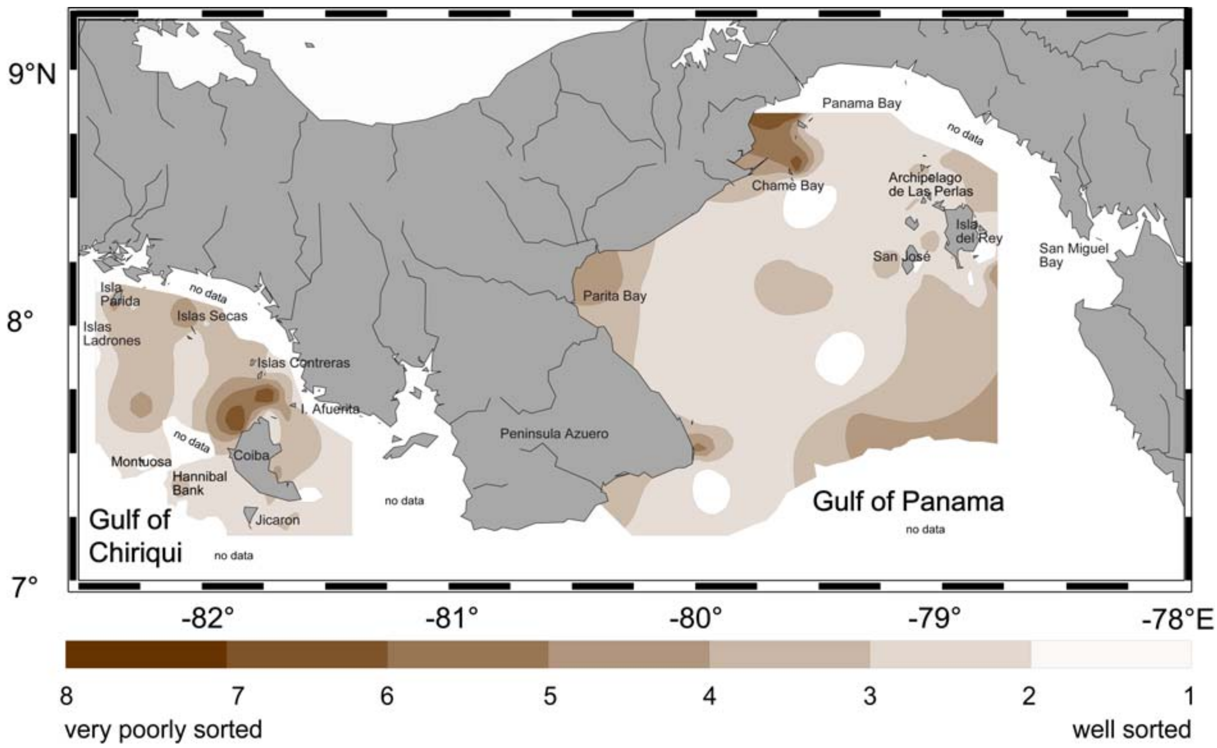


Fig. 4.4: Sorting of sediments in the Gulf of Panama and the Gulf of Chiriquí. The majority of the sediments in both gulfs are poorly sorted. Well sorted to moderately sorted sediments occur in areas with strong currents.

del Rey, in the centre of the Gulf of Panama and at the south-eastern edge of the Peninsula Azuero. The areas around Parita Bay and Chame Bay including the southern part of Panama Bay are dominated by very poorly sorted sediments.

The Gulf of Chiriquí also is dominated by poorly sorted sediments. Areas with well sorted to moderately sorted can be found at the south-eastern edge of Coiba and within two small areas west of Isla Parida and west of Montuosa. Two areas with very poorly sorted sediments are located northwest of Islas Secas and north and northwest of Coiba.

4.3.2 Mineral composition

The composition of the minerals in the Gulf of Panama and the Gulf of Chiriquí is similar. However, differences occur in the amount of anorthite and quartz between both gulfs. This study focuses on the major differences in the mineralogy in the surface sediments, with a detailed look at the quartz content and distribution in the individual fractions, the anorthite content and the carbonate content. The XRD analysis shows a dominance of clay minerals, mainly illite, montmorillonite, and kaolinite in the fine fraction of the sediments (<63µm; clay and silt).

Sediments with a grain size between 125µm to 2000µm are very different in mineral composition depending on the location and are characterized by varying carbonate content and some feldspar and quartz.

The grabs on latter locations were mostly empty and contained only some big fragments of molluscs, corals or basement rocks.

Close to the slope in the Gulf of Panama nearly no carbonates could be found and the XRD plots indicate a high amount of quartz and feldspar.

Anorthite

The difference in the anorthite amounts in both gulfs is not as pronounced as the ones for quartz, but in general anorthite contents are slightly higher in the Gulf of Panama. The highest values in the Gulf of Panama can be found in the central gulf area and southwest and southeast of Isla del Rey. The highest amounts of anorthite

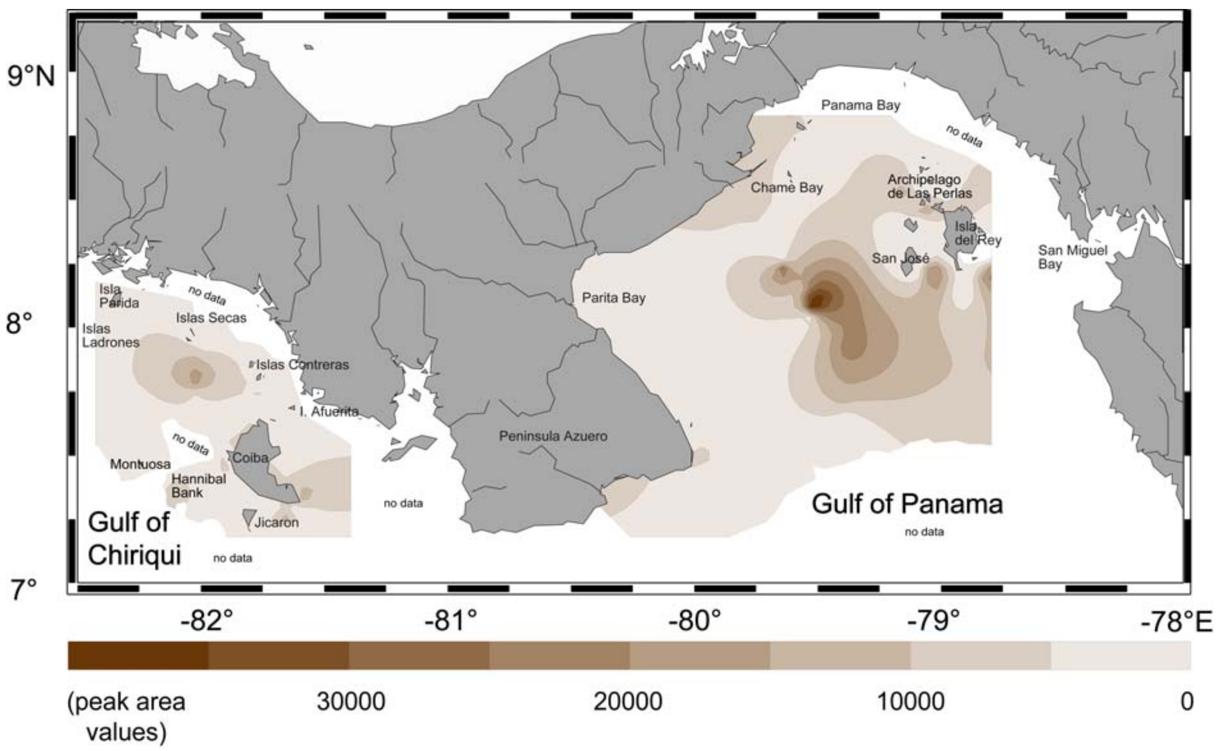


Fig. 4.5: Distribution of anorthite (peak area values) in the Gulf of Panama and Gulf of Chiriquí. Peak area values show only trends and do not provide the exact amount of anorthite. In general, the amount of anorthite in the Gulf of Panama is higher than in the Gulf of Chiriquí.

in the Gulf of Chiriquí are located south of Islas Secas towards the centre of the gulf, southwest of Hannibal Bank and at the south-eastern edge of Coiba **(Fig. 4.5)**.

Carbonates

High amounts of carbonates occur around the islands in both gulfs. The carbonate part of the sediments consists mainly of molluscs with higher amounts of balanids in the Gulf of Panama and corals in restricted areas in the Gulf of Chiriquí. The carbonate sands consist mainly of molluscs, echinoderms, foraminifera and at some locations contain red algae, corals and balanids. Benthic and planktic foraminifera dominate in areas with high terrigenous content.

The percentage of total carbonate (TC) derived from LECO analyses shows maximum values of 70-80%TC in the Gulf of Panama, in some restricted areas around Archipelago de Las Perlas **(Fig. 4.6)**. Areas with values of 60-70%TC occur northeast of Chame Bay around Isla Taboga and at the south-eastern edge of Peninsula de Azuero around Isla Iguana.

The Gulf of Chiriquí shows the highest values in TC (>90%) around the small islands near the mainland, Islas Secas and Islas Contreras and around other very small islands north of Coiba. The areas near the islands of Jicaron, Montuosa, Islas Ladrones and the area west of Hannibal Bank show values of 50%TC^{sed}-70%TC^{sed}. In general, the Gulf of Chiriquí shows higher mean values with 73.24TC^{sed} than the Gulf of Panama with 26.41TC^{sed} indicating a more carbonate dominated environment in the Gulf of Chiriquí.

Carbonate/Terrigenous Ratio (CTR)

The Carbonate content is derived from the LECO measurements performed on bulk samples. The terrigenous percentages of the total sediment derived from point counting, include only the fractions 125µm to >2000µm. Due to that fact the carbonate/terrigenous ratio (CTR) was determined using the carbonate percentages

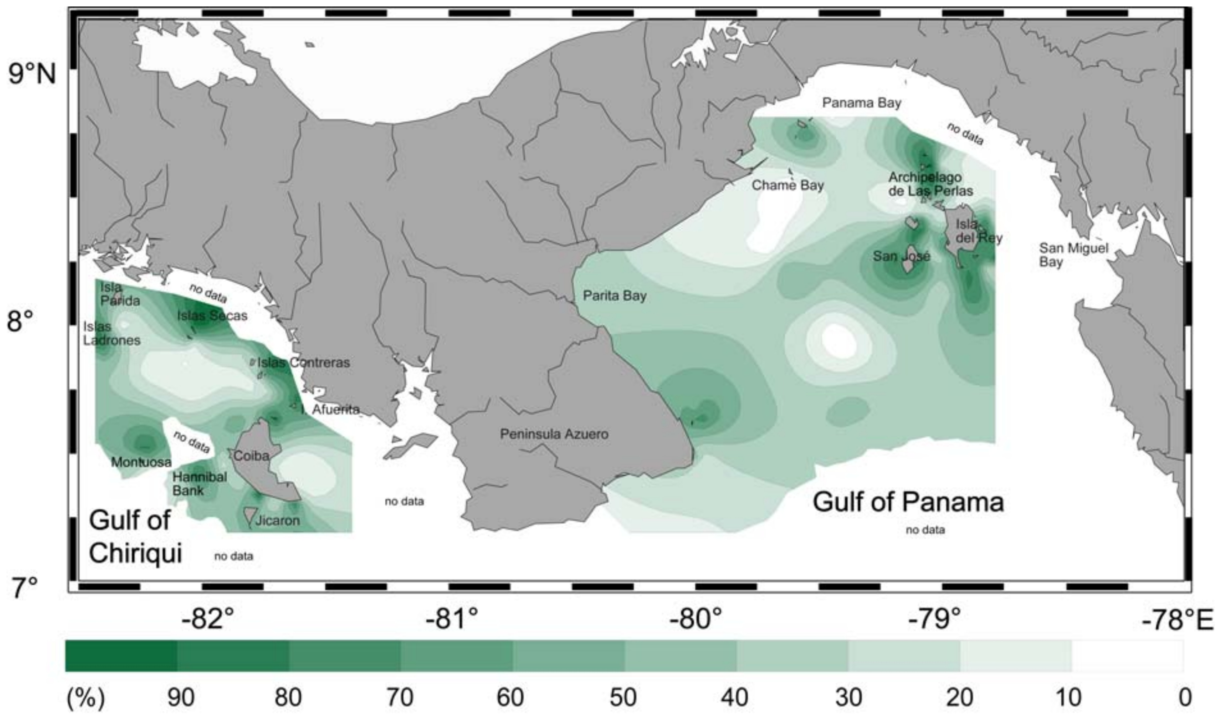


Fig. 4.6: Distribution of carbonates in the Gulf of Panama and the Gulf of Chiriquí. The total carbonate content (TC) is higher around the islands in both gulfs

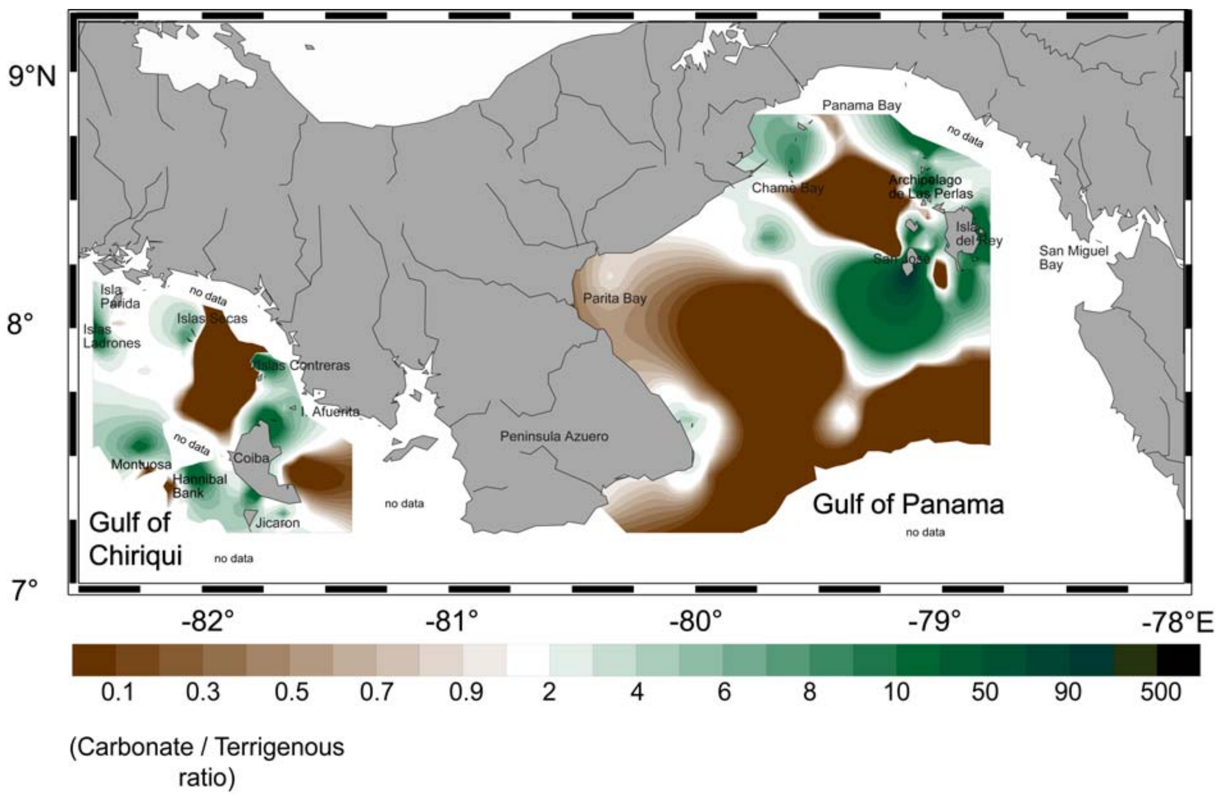


Fig. 4.7: Figure shows the Carbonate/Terrigenous ratio (CTR) of surface sediments in the Gulf of Panama and the Gulf of Chiriquí. Green: Areas with high carbonate content; brown: Terrigenous dominated areas. The Gulf of Panama is dominated by terrigenous sediments, whereas carbonates dominate around the islands in both gulfs and thus dominate within the Gulf of Chiriquí.

of the total sediment, derived from point counting. To calculate this ratio the carbonate content was divided by the terrigenous content.

The CTR distribution map of the surface sediments in both gulfs shows a detailed distribution of carbonate and terrigenous dominated areas **(Fig. 4.7)**. The Gulf of Panama shows large areas with values below 0.5CTR and thus shows the dominance of terrigenous material especially in parts of the centre of the Gulf of Panama and at Parita Bay. The lowest CTR (0.08) present in the Gulf of Panama is located in the centre of the gulf at U04004 (7.895; -79.384). The highest CTR was found at U05120 (8.202; -79.091) near the Archipelago de Las Perlas, with 237.10CTR. The high CTR values found in the Gulf of Panama southwest of Isla San José gradually decrease towards the centre of the gulf.

The Gulf of Chiriquí shows large areas that are dominated by carbonate sediments, especially around the islands, as expressed by CTR ratios of 10 to 30CTR. The highest ratio of 332.33CTR occurs near Islas Contreras at U04113 (7.856; -81.783) and the lowest ratio was found at U05035 (7.634; -82.091) positioned in the central Gulf of Chiriquí.

Quartz

Significant quartz amounts are present in the centre of the Gulf of Panama, comprising an area from the Archipelago de Las Perlas towards the slope in the southwest of the study area **(Fig. 4.8)**. For the Gulf of Chiriquí the XRD diffractograms show only low peak area values for quartz indicating a lower amount of quartz. The amount of quartz grains within the terrigenous part of each individual fraction varies between 60% and 70% of the total sediment (TQ^{sed}) in the central Gulf of Panama **(Fig. 4.9)**. Parita Bay and the South Channel between San José and Isla del Rey show quartz amounts of up to 40% TQ^{sed}. The area between Parita Bay and the central Gulf of Panama shows the highest values of quartz grains with an average of 20%TQ^{sed} to 30%TQ^{sed}. Close to Chame Bay the sediment show a low percentage of quartz (0%TQ^{sed}-10%TQ^{sed}). The highest values found in the Gulf of Chiriquí are 20%TQ^{sed}-30%TQ^{sed} and 40%TQ^{ter}-50%TQ^{ter} at the south-eastern edge of Coiba.

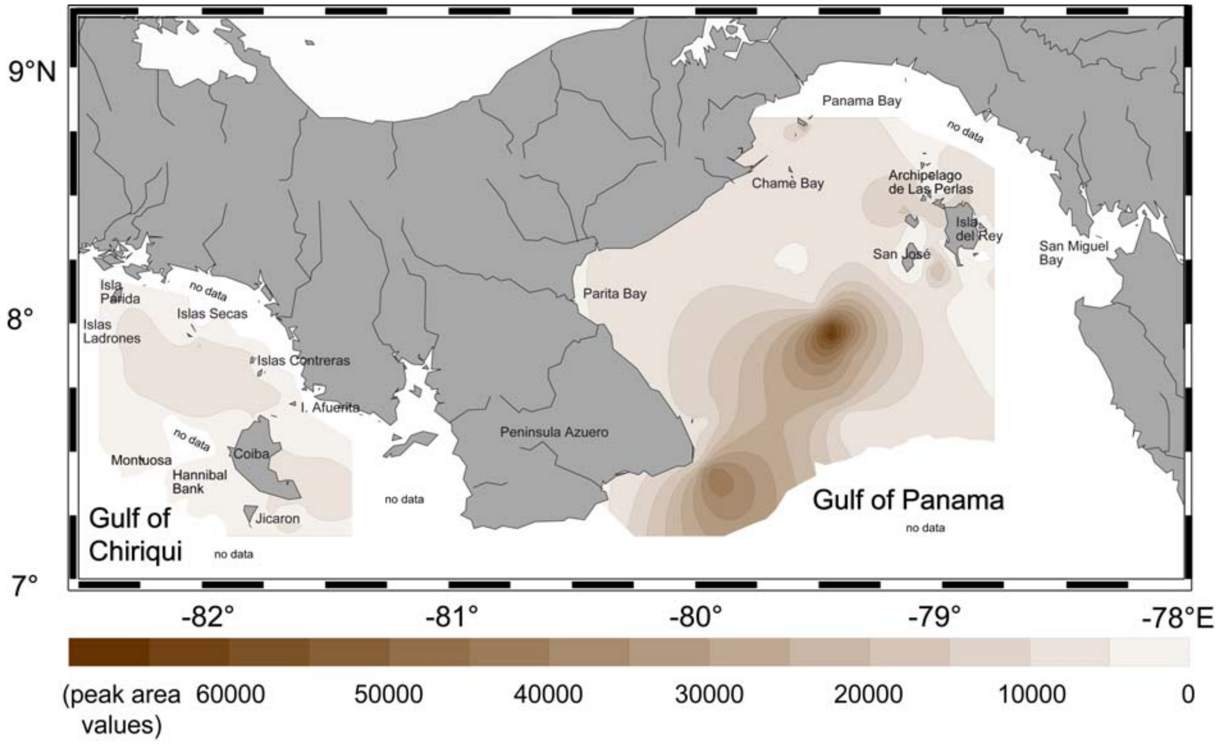


Fig. 4.8 Distribution of quartz (peak area values) in the Gulf of Panama and Gulf of Chiriquí. Peak area values show only trends and do not provide the exact amount of quartz. The quartz content in the sediments of the Gulf of Panama is higher than in the Gulf of Chiriquí. Highest values are present in the central part of the Gulf of Panama and continue towards the slope.

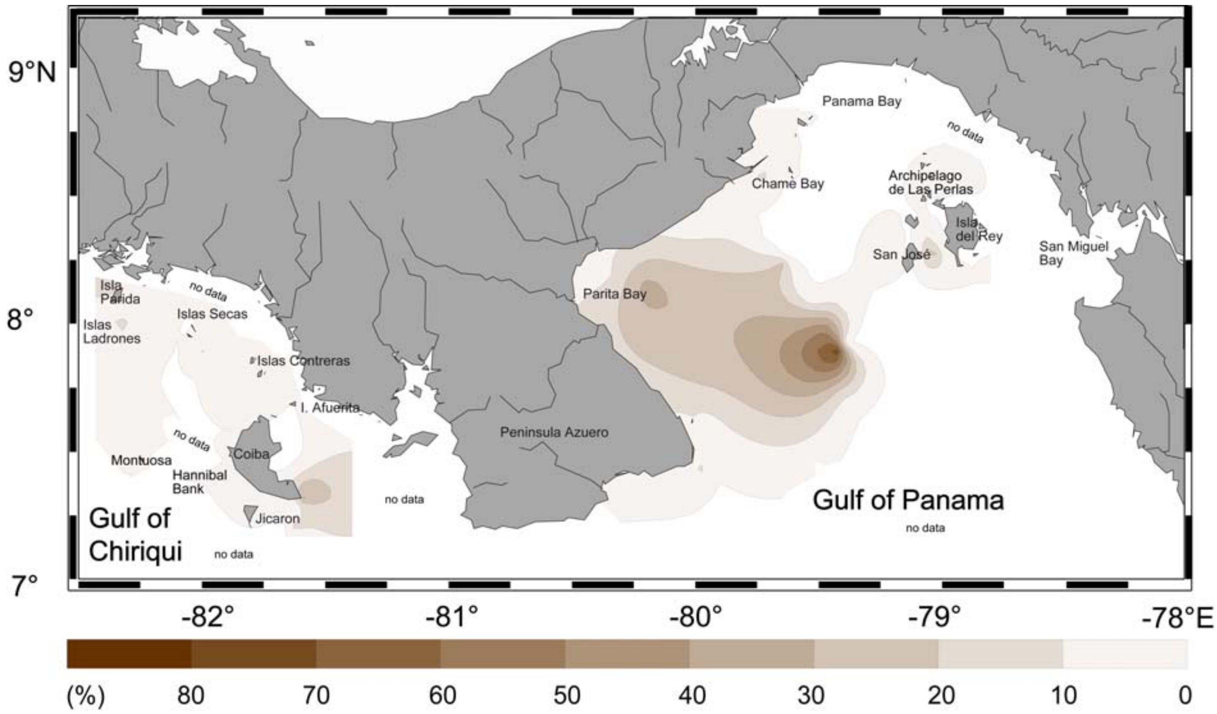


Fig.4.9: Total quantity of quartz in the sediment (TQ^{sed}). The Gulf of Panama shows higher amounts of quartz grains TQ^{sed} than those within the Gulf of Chiriquí.

4.3.3 Distribution of quartz grains

In the following section the contents of quartz grains in the individual sub-fractions (125µm->2000µm) were estimated using visual comparison charts of Scholle and Ulmer-Scholle (2003).

Fine Sands (125µm-250µm)

The fine sands in the Gulf of Panama show very high amounts of quartz grains within the 125µm-250µm fraction (TQ^{125}) and reach values of up to 90%TQ^{125} in the central gulf at location U05099 (7,892; -79,388). The area around Parita Bay shows quartz values of 40-60%TQ^{125}, the area of Chame Bay between 20 to 40%TQ^{125}. In the South Channel between San José and Isla del Rey they vary between 40-60%TQ^{125}, with slightly lower values southwest of San José. The Parita Bay area and the area southwest of Isla San José show similar values as found for the central Gulf of Panama **(Fig. 4.10)**.

The Gulf of Chiriquí shows the highest values of quartz grains at the south-eastern edge of Coiba with a maximum value of 60%TQ^{125} at location U05075 (7.251; -81.633) and north of Isla Parida with values of 20-40%TQ^{125}. On average the amount of quartz is lower in the Gulf of Chiriquí than in the Gulf of Panama with a mean of 4.79%TQ^{125} within the Gulf of Chiriquí and 12.80%TQ^{125} within the Gulf of Panama.

Medium Sands (250µm-500µm)

The medium sands (250µm-500µm) in the Gulf of Panama show very high amounts of quartz grains (TQ^{250}) in the central Gulf of Panama and northeast of Chame Bay close to Panama Bay, with up to 90%TQ^{250} at location U05099 (7,892; 79,388) and values up to 60-70%TQ^{250} northeast of Chame Bay **(Fig. 4.11)**. The area around Parita Bay shows quartz values of 20-40%TQ^{250}, while within the South Channel west of Isla del Rey and the area west of San José they vary between 30 - 50%TQ^{250}. The North Channel of the Archipelago de Las Perlas shows amounts of up to 50%TQ^{250}. The areas in the central Gulf and those around Parita Bay and north of Chame Bay contain the highest amount of quartz within the medium sands.

The Gulf of Chiriquí shows an overall low amount of quartz with a mean of

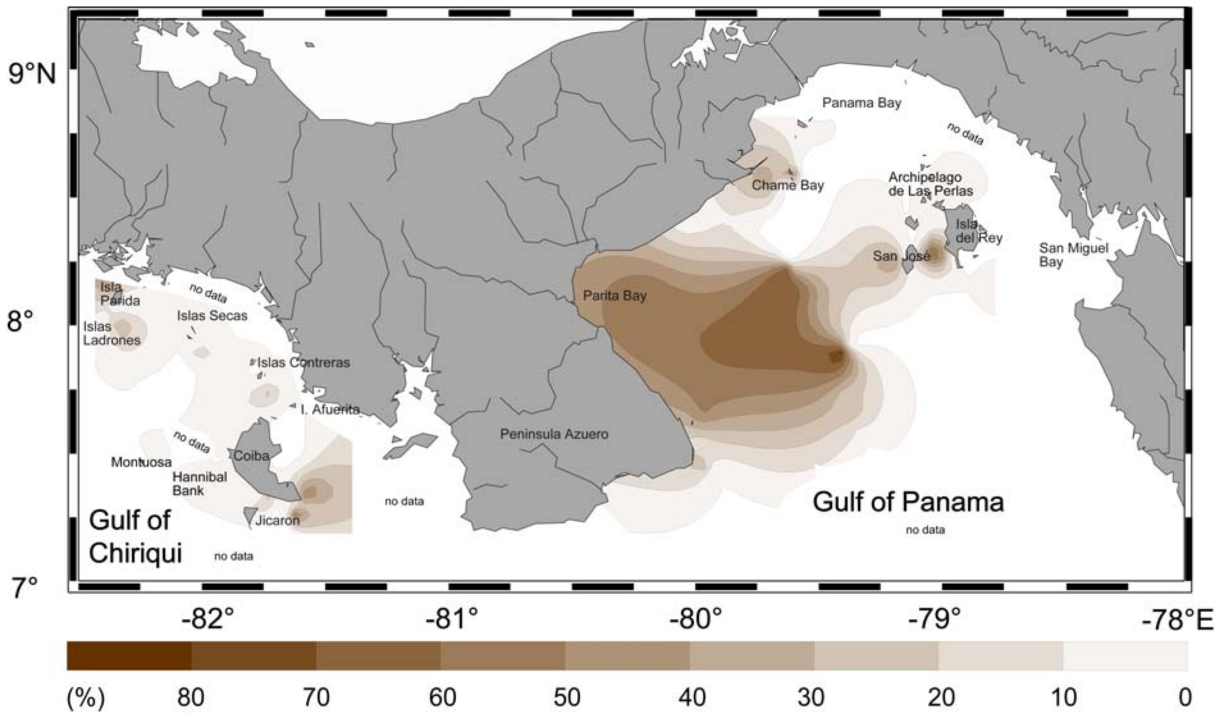


Fig.4.10: Total amount of quartz in the fine sediments (TQ^{125}). The areas of Parita Bay and southwest of Isla San José are connected with the area in the central Gulf of Panama with the highest quartz values. Gulf of Chiriquí shows a lower quantity of quartz grains in the fine sediments.

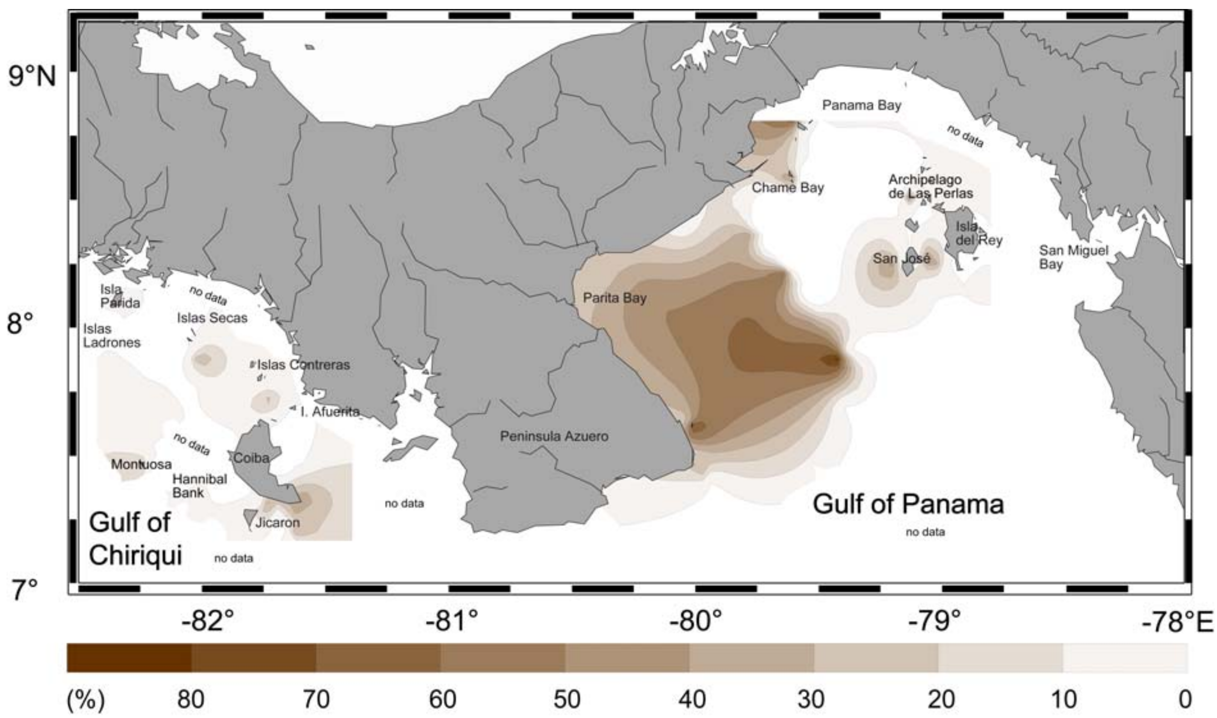


Fig.4.11: Total amount of quartz in the fraction medium sands (TQ^{250}). The areas around Parita Bay and north of Chame Bay show comparable high amounts of quartz within the medium sands, as found in the central Gulf of Panama. In the Gulf of Chiriquí a lower amount of quartz grains occurs in medium sand sized sediments.

4.4%TQ^{250} in comparison with the values known for the Gulf of Panama with a mean of 10.3%TQ^{250}. The maximum of quartz grains in the medium sand fraction, 40%TQ^{250}, within the Gulf of Chiriquí can be found at the south-eastern edge of Coiba. The overall percentage of quartz is very low in the Gulf of Chiriquí with values of 0%-10%TQ^{250} in most areas. Some small areas close to the islands of Isla Parida, southeast of Islas Secas, south of Islas Contreras and at Montuosa contain values of up to 30%TQ^{250}.

Coarse Sands (500µm to 1000µm)

In the Gulf of Panama the highest value of quartz in the coarse sands is located in the centre of the gulf at U05099 (7,892; 79,388) with a maximum amount of 90%TQ^{500} **(Fig. 4.12)**. The area east and northeast of Chame Bay shows values of 20%^{TQ500}-50%^{TQ500}. Two areas exist, Chame Bay and the centre of the gulf, in which high quartz values can be found >10%TQ^{500}. The South Channel between San José and Isla del Rey shows values of 20%-30%TQ^{500}.

The Gulf of Chiriquí shows the maximum quartz grain values within the coarse sands southeast of Coiba with 60%TQ^{1000}. Another area with high quartz amounts is located southeast of Islas Secas with values between 40%TQ^{500} and 50%TQ^{500}. The mean values for quartz grains within the coarse sands are only slightly higher in the Gulf of Panama (5.91%$TQ^{500)}$ than in the Gulf of Chiriquí (3.71%$TQ^{500)}$.

Very Coarse Sands (1000µm-2000µm)

The highest values of quartz within the very coarse sands can be found in the centre of the Gulf of Panama, 50%TQ^{1000} **(Fig. 4.13),** and northeast of Chame Bay, 70%TQ^{1000}. Parita Bay shows only 0%-10%TQ^{1000}. The North and the South Channel show no quartz grains in most parts except for some small areas of the South Channel west of San José showing values of <10%TQ^{1000}. The maximum values of quartz grains in the very coarse sand fractions (90%TQ^{1000} and 50%TQ^{1000}) can be found In the Gulf of Chiriquí, southeast of Islas Secas and at the south-eastern edge of Coiba, respectively. The mean of quartz grains within the very coarse sands shows slightly higher values in the Gulf of Chiriquí with 3.14%TQ^{1000} than those calculated for the Gulf of Panama with 2.35%TQ^{1000}.

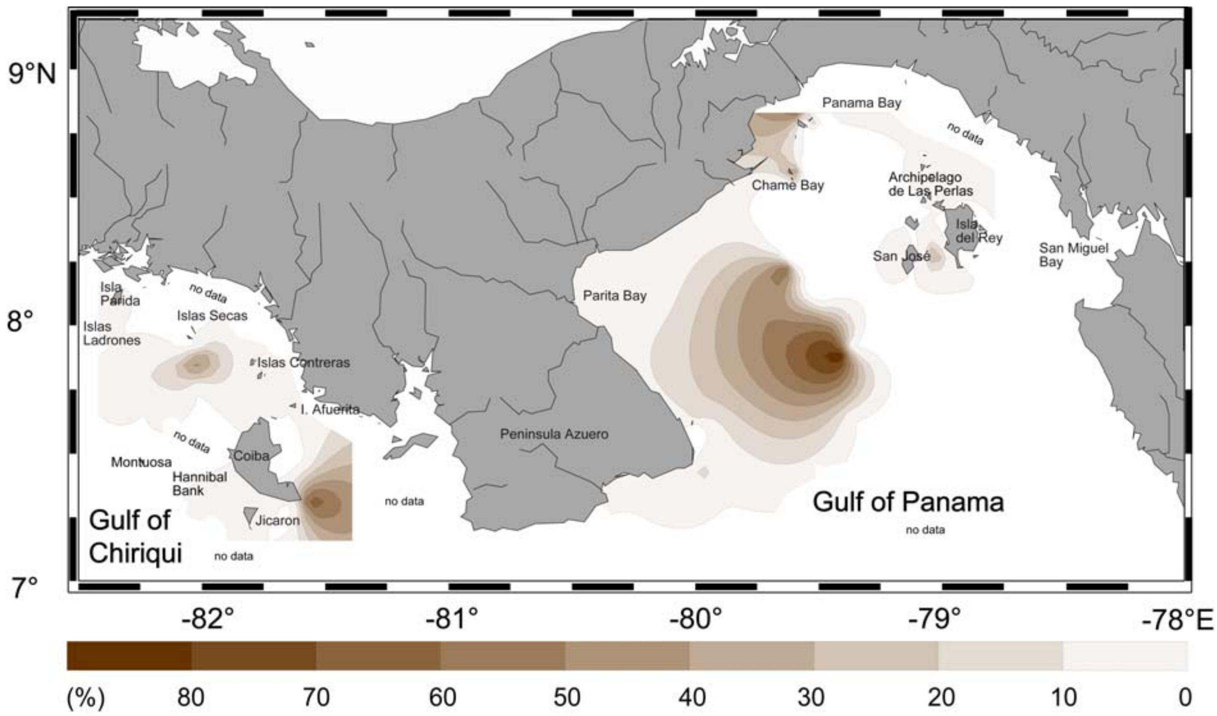


Fig. 4.12 Total amount of quartz within the coarse sands (TQ^{500}). The highest values occur in the centre of the Gulf of Panama and southeast of Coiba. The Gulf of Chiriquí shows a slightly lower amount of quartz grains in these coarse sediments.

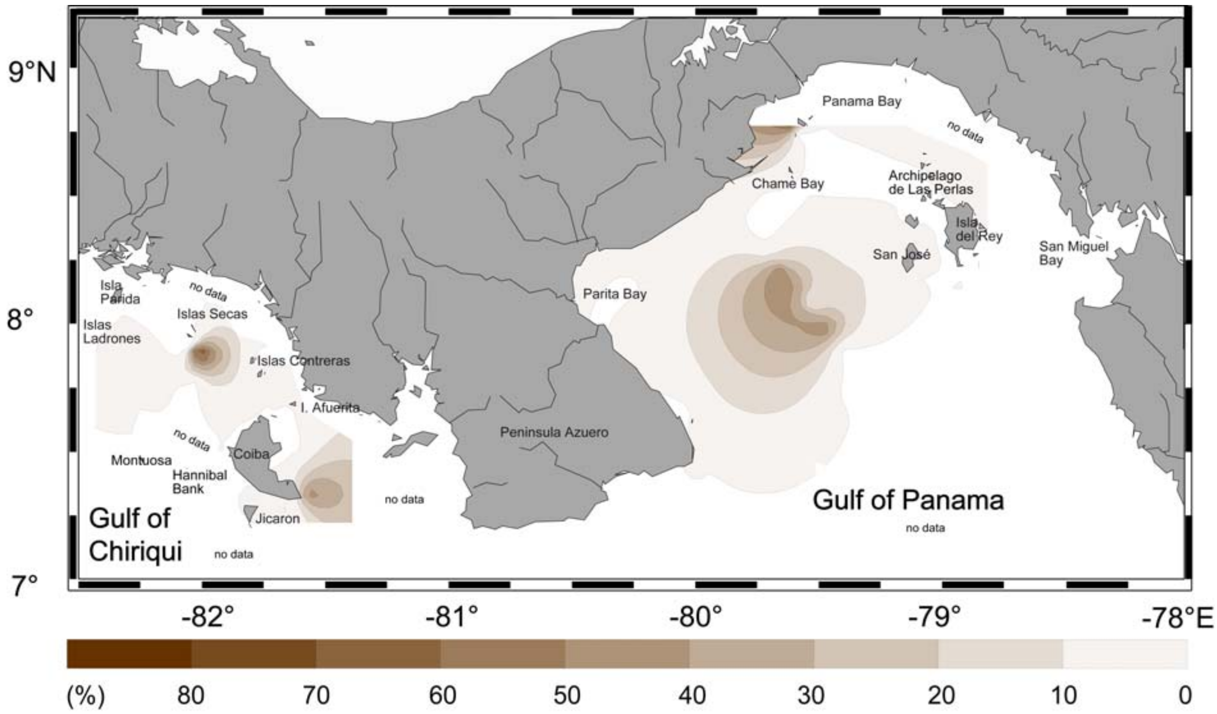


Fig. 4.13 Total amount of quartz in the very coarse sands (TQ^{1000}). Areas with high quartz values are located in the centre of the Gulf of Panama, Chame Bay, southeast of Coiba and south of Islas Secas. The Gulf of Chiriquí shows a slightly higher amount of quartz grains in the very coarse sediments.

Very Fine Gravel (>2000µm)

Quartz grains within the very fine gravels were only present at one location in the centre of the Gulf of Panama at U05098 (7.972;-79.447) with 50%TQ^{2000}. In the Gulf of Chiriquí no quartz was found within the very fine gravels.

4.3.4 Total organic carbon

The total organic carbon (TOC) values in the Gulf of Panama are high in the area of Panama Bay towards the south of Chame Bay and west of the Archipelago de Las Perlas. The highest values are south of Chame Bay with 2.24%^{TOC} **(Fig. 4.14)** at sample site U04125 (7.422; -81.673). A small area northeast of Isla del Rey also shows higher values of TOC with 0.8%^{TOC}-1.2%^{TOC}. The highest values in the Gulf of Chiriquí could be found in the central area at U04097 (7.737; -82.026) with 2.74%^{TOC} and with high values in the small bay area west of Coiba. The average

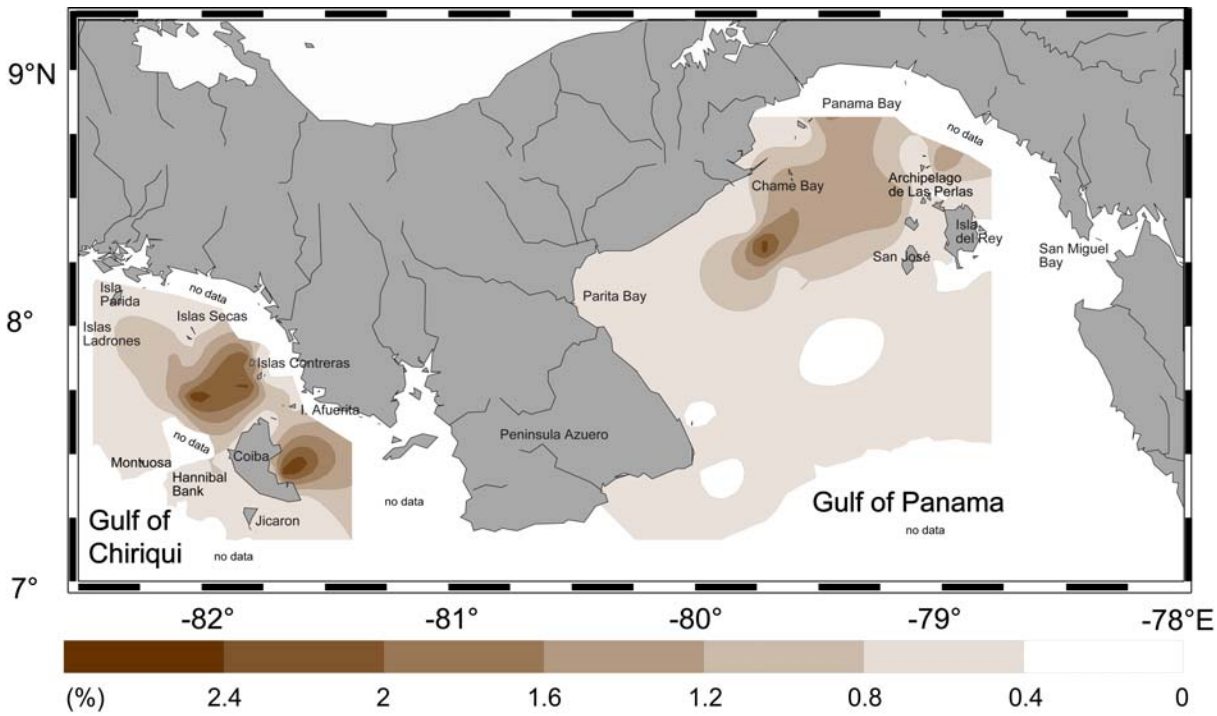


Fig. 4.14: Total organic carbon (TOC) content in the Gulf of Panama and the Gulf of Chiriquí. High values in the Gulf of Panama are present in a triangular area ranging from Panama Bay to Archipelago de Las Perlas towards south of Chame Bay. In the Gulf of Chiriquí highest values occur in an area parallel to the coast.

percentages are only slightly higher in the Gulf of Chiriquí with $0.62\%^{TOC}$ vs. $0.43\%^{TOC}$ in the Gulf of Panama.

4.4 DISCUSSION

4.4.1 Cluster analysis

MacIlvaine and Ross (1973) studied the surface sediments in the Gulf of Panama. They sampled the mid-shelf area along a dense grid of stations. Their dataset contains only a few stations close to the islands in the gulf **(Fig. 4.15)**.

The data provided by MacIlvaine and Ross (1973) comprise the precise sample locations and a detailed description of the sediments. In order to incorporate

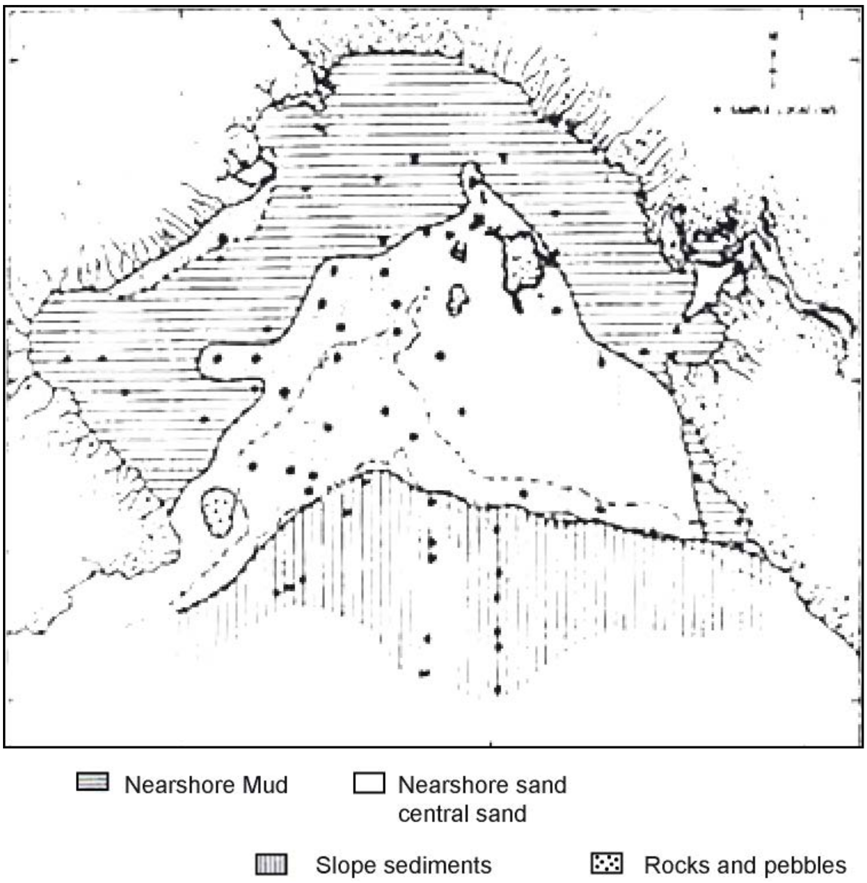
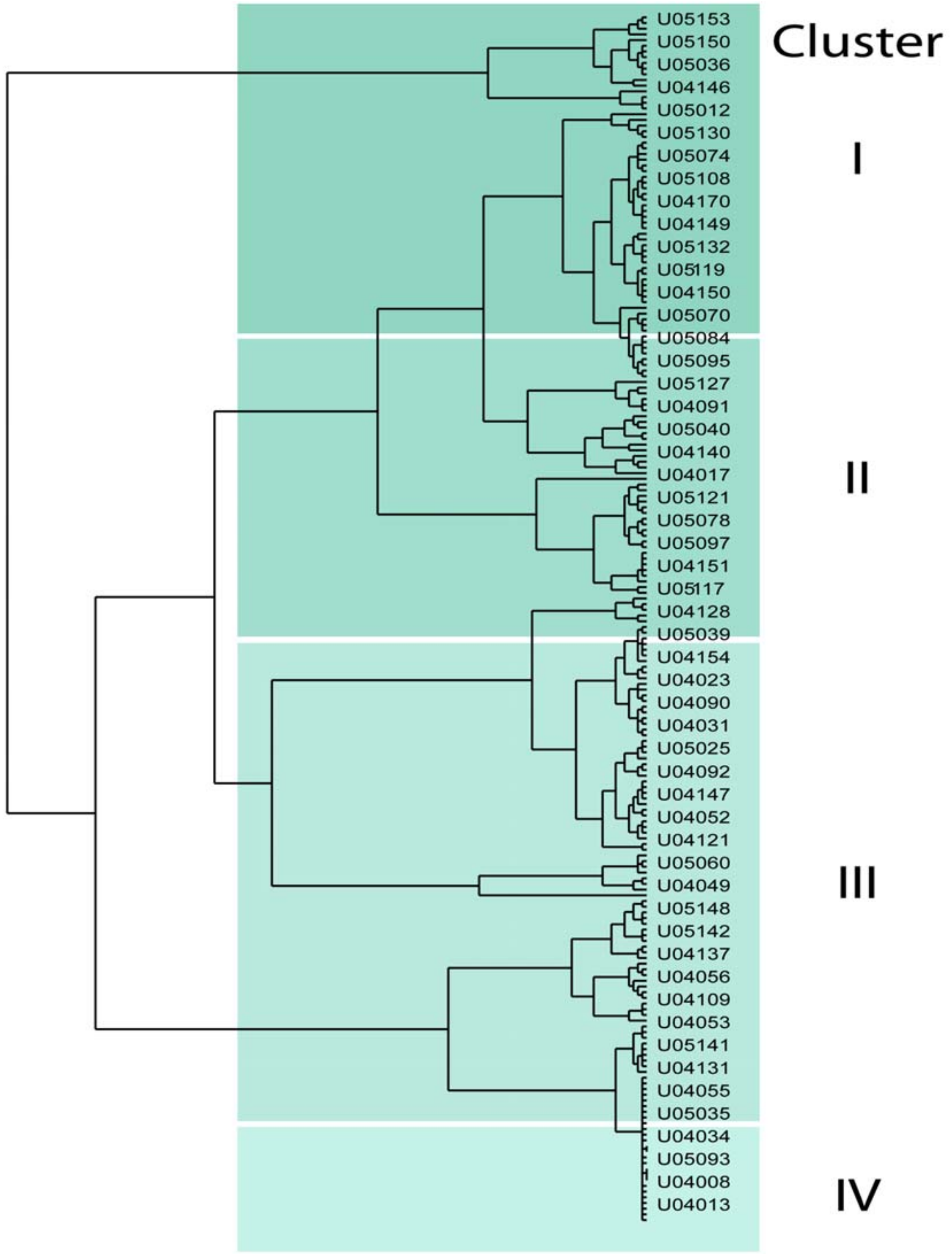


Fig. 4.15: Map from MacIlvaine and Ross (1973) showing distribution of surface sediments in the Gulf of Panama. Black dots indicate sampling stations.



Fractions included (µm)	<63µm	>63µm	>125µm	>250µm	>500µm	>1000µm	>2000 µm	Cluster	Mean
1000->2000	5,51	1,50	3,51	5,19	7,64	16,53	60,08	I	76,61
250-1000	5,39	2,71	14,50	29,06	24,02	14,32	10,08	II	53,08
63-250	10,65	16,76	45,82	14,24	6,38	3,80	2,62	III	62,59
<63	75,03	12,81	7,92	2,39	0,66	0,51	0,75	IV	75,03

Fig. 4.16: Upper panel: Cluster analysis of the grab sample grain-size data. Note that only every 4th sample number is shown in the graph. Lower panel: Table showing average and dominating grain sizes for each cluster.

aforementioned data into our dataset a cluster analyses was made using the weight percentage of the individual fractions of our samples. The cluster analyses showed four main clusters.

Cluster I represents the coarsest grain size and is dominated with a mean of 76.61% by very coarse sands to gravel (1000µm to >2000µm, **Fig. 4.16)**. Cluster II shows medium sands to coarse sands (52.49%; 250µm to 1000µm). Cluster III comprises the very fine sand to fine sands (62.59%; 63µm to 250µm) and cluster IV is dominated by clay and silt (75.03%; <63µm). The new map with the clustered dataset shows a similar grain size distribution as the original grain size map based on our own data. Fine sediments are present along the coast in the Gulf of Panama and coarser sediments in the centre of the Gulf. In the Gulf of Chiriquí finer sediments can be found in the centre of the gulf and in the small bay on the east side of Coiba **(Fig. 4.17)**, while coarser sediments occur around the islands.

Five locations were selected from the MacIlvaine and Ross (1973) dataset that lie close to our sampling locations. A comparison was made between the data obtained

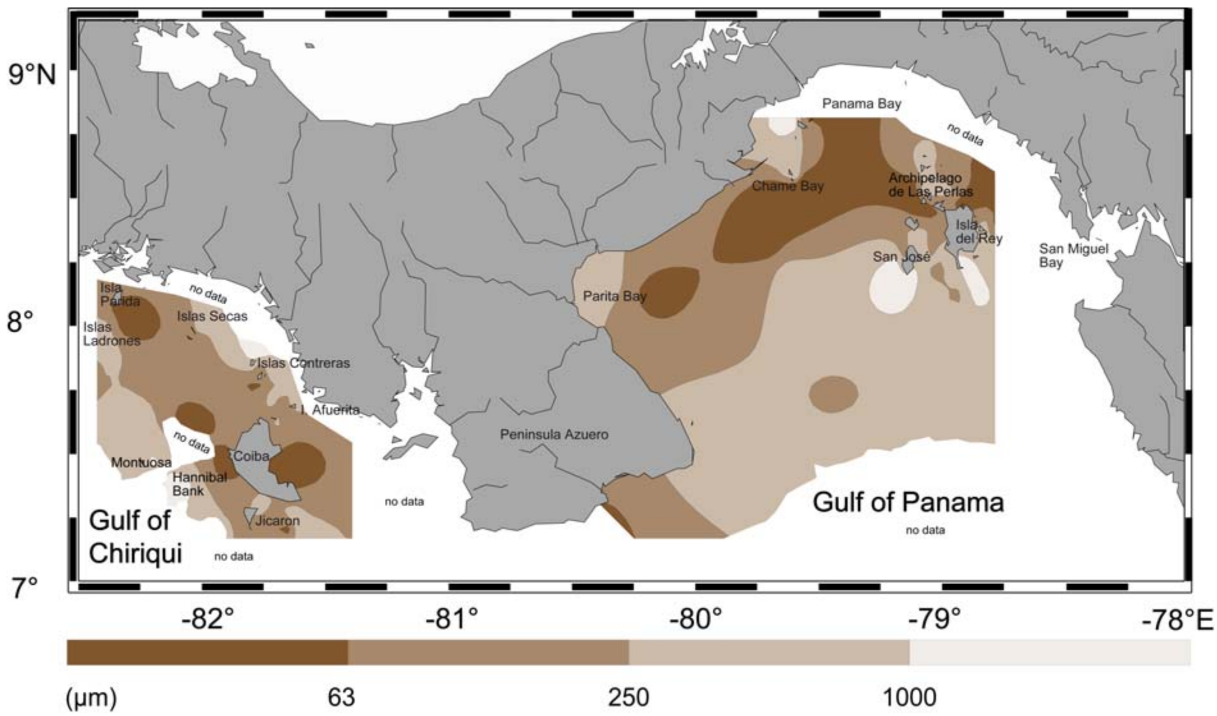


Fig. 4.17: Grain size distribution map of clustered data (this study). Fine sediments occur along the coast in the Gulf of Panama except for Parita Bay, Chame Bay and San Miguel Bay. Coarse sediments are present around the islands in the Gulf of Chiriquí. Defined clusters <63µm (IV); cluster 63µm-250µm (III); 250µm-1000µm (II); 1000µm->2000µm (I).

by MacIlvaine and Ross (1973) and the results of our study. MacIlvaine and Ross (1973) distinguished three main type of sediments; near shore mud, central sands and slope sediments. In areas were they described near shore sediments our study shows mud with clays to silt (cluster I). The central sands of MacIlvaine and Ross (1973) correspond with medium sands (cluster II) in our dataset. Based on this good correspondence, the near shore mud sediments of MacIlvaine and Ross (1973) were imported as cluster I sediments and the central sands were imported as sediments
representing cluster II. The slope sediment data of MacIlvaine and Ross (1973) were not used, because our dataset does not contain comparable data. All sample locations from the 2004 and 2005 cruises were located on the shelf and did not include the deeper water areas on the slope. The new sediment distribution map, including the data from MacIlvaine and Ross (1973), agrees very well with the sediment distribution map based on our own dataset. The new map shows that fine sediments, such as clay and silt (<63µm) can be found close to the coast all along the Gulf of Panama except for three regions: Parita Bay, Chame Bay and San Miguel Bay **(Fig. 4.18)**. The areas around Parita Bay, Chame Bay and parts of San Miguel Bay show coarser grain sizes varying from 250µm-1000µm. The coarsest grain size (1000µm to 2000µm) in these regions can be found southwest of Panama Bay with carbonate sands to gravel **(Fig. 4.19)** containing some large bivalves (*Megapitaria*, many Pecten), coralline red algae and a few open-branched red algae. The grab sample locations around Chame Bay are located close to the islands west of the shallow areas directly in Chame Bay.
The islands show higher carbonate production and therefore a higher terrigenous/carbonate ratio and a higher mean grain size (Fig. 4.11; Fig. 4.13).

4.4.2 Current pattern and river discharge

Sediment input in both gulfs is influenced by river discharge except for some areas along the coast in which strong tidal currents dominate. In those areas sands and rocks are present like in parts of San Miguel Bay (MacIlvaine and Ross, 1973) or Chame and Parita Bays.
The current pattern in the study area is greatly influenced by the extensions of the

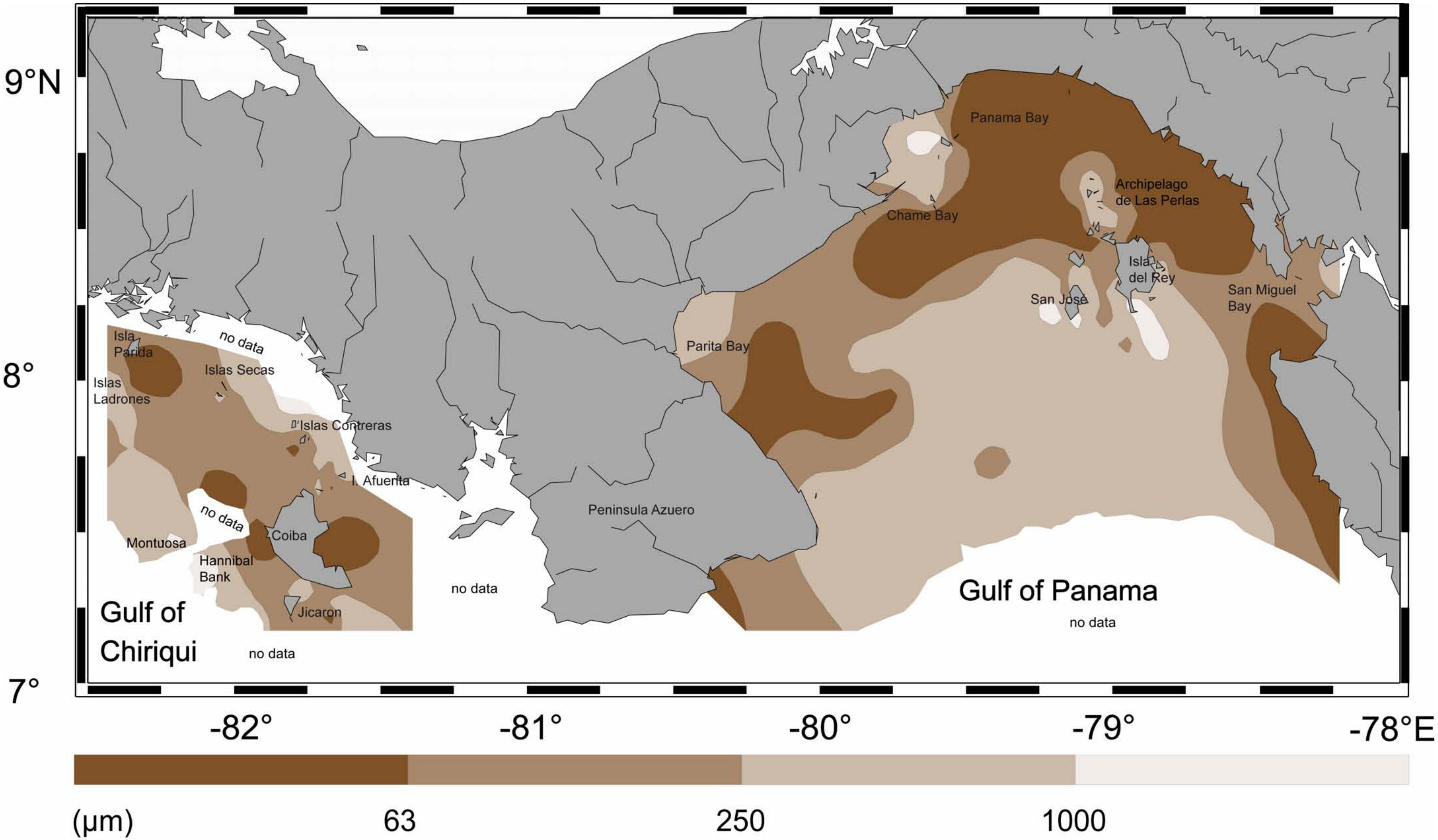


Fig. 4.18: Grain size distribution map showing own clustered data and literature data from MacIlvaine and Ross (1973). As for the data shown in Fig. 4.17, fine sediments occur along the coast in the Gulf of Panama except for Parita Bay, Chame Bay and San Miguel Bay. Coarse sediments are present around the islands in the Gulf of Chiriquí and the Gulf of Panama. Defined clusters <63µm (IV); cluster 63µm-250µm (III); 250µm-1000µm (II); 1000µm->2000µm (I).


U04008 Cluster IV


U04049 Cluster III


U04057 Cluster II


U04067 Cluster I

Sample	Latitude	Longitude	<63µm	>63µm	>125µm	>250µm	>500µm	>1000µm	>2000µm	Cluster
U04008	8,347	-79,732	100	0	0	0	0	0	0	IV
U04049	7,233	-81,665	22,73	46,08	28,89	1,92	0,16	0,05	0,10	III
U04057	7,971	-82,398	0,50	0,32	7,88	27,00	43,99	17,93	2,39	II
U04067	7,379	-82,079	7,77	2,10	4,78	7,08	8,38	20,54	50,18	I

Fig.4.19: (Photographs) Grab samples photos showing examples for each cluster. (Table) Grain-size distribution and corresponding clusters of samples shown in the photographs.

Humboldt Current. These coastal currents enter the Gulf of Panama in the southeast, rotate counter-clockwise following the coastline and leave the gulf in the west (Schaefer et al. 1958; MacIlvaine and Ross, 1973; Kwiecinski and Chial 1983). The seasonal wind driven Panama Current is influenced by northern winds, which are governed by the position of the Intertropical Convergence Zone (ITCZ; Forsbergh, 1969; D`Croz and Robertson, 1997). During the dry season, from January to April, these northern winds push the surface waters offshore (Schaefer et al., 1958) and cause upwelling. The distribution of clays to fine sands (<63µm to 250µm) is mainly influenced by the counter-clockwise current induced by the extensions of the Humboldt Current. The clays to fine sands are brought into the marine system at San Miguel Bay. Almost half of the river discharge into the Gulf of Panama passes through San Miguel Bay (Terry, 1956). The shallow area around San Miguel Bay is strongly influenced by tides and their currents, which prevent the deposition of clays in that region (Swift and Pirie, 1970). The clays to fine sands are transported in a counter-clockwise direction around Archipelago de Las Perlas, towards the Peninsula Azuero and leaves the gulf at the south-eastern edge of the following the coastline. The transport continues along Chame Bay and Parita Bay Peninsula. This current is strengthened by the prevailing northern wind that parallels the west coast.

4.4.3 Quartz

The amount of quartz in the Gulf of Panama increases from the shallow waters in the north towards the deeper areas of the central gulf region in the southwest. The same trend occurs moving from Parita Bay in the northwest towards the centre of the gulf (Fig. 4.4 to 4.8). This distribution is influenced by the inherited topography that was formed during the exposure of the shelf during the last sea-level low stand (Golik, 1968) and by streams, which distributed sediments towards the centre of the Gulf during that time (MacIlvaine and Ross 1973).

At present, fine and coarse quartz grains accumulate in the central Gulf of Panama. The distribution pattern of the fine quartz grains between Parita Bay and the centre of the gulf shows that the source of these fine quartz grains must be the rivers that enter the Gulf of Panama in Parita Bay. The dominance of fine terrigenous material between Parita Bay and the central gulf, the accumulation of fine quartz grains in the same area and the counter-clockwise directions of currents demonstrate the redistribution of these sediments. Coarser quartz grains are found in the trench in the middle of the gulf at water depths varying between 100 and 200m. The wind-driven Panama Current is not able to transport these coarser quartz grains.

The origin of the coarse quartz grains could not be explained by recent sediment transport processes, while no coarse grained sediments are present between river mouth and the area in the middle of the gulf. This suggests that these sediments represent a relict sediment accumulation that formed during the last transgression as proposed by Golik (1968).

Strong tidal currents also influence the shallow region around Chame Bay and Parita Bay. The amount of medium sands (250µm to 500µm) at Parita Bay and Chame Bay suggest that these areas are important suppliers of medium sand into the Gulf of Panama (Fig. 4.13). This observation agrees with MacIlvaine and Ross (1973) who proposed that Chame Bay is presently an important source of sand. The rivers discharging into Parita Bay and Chame Bay predominantly transport fine to medium-grained siliciclastic sands into the Gulf of Panama. Through Parita Bay fine to medium grained 125µm to 500µm (Fig. 4.5/4.6) siliciclastic sediments are transported into the gulf as shown by the occurrence of fine quartz grains in this area and the very poor sorting of the sediment. For example sample U04002 close to Parita Bay shows 41.64% medium to coarse sand, 12.75% fine sands and 11.60% clays to silt. Parita Bay also contains mangrove forests. Two principal zones can be distinguished: an external and an internal zone. The external areas are directly exposed to estuarine waters; the internal areas are relatively isolated and are only inundated during high tides (D`Croz, 1993). Mangrove forests form excellent sediment traps for very fine sediments. The terrigenous material present around the Archipelago de Las Perlas is mostly derived from weathering of the volcanic material from the small islands around Las Perlas (MacIlvaine and Ross, 1973). Within the North and South Channel fine terrigenous material is transported in a southward direction. This process is probably driven by the prevailing northerly winds, transporting minor amounts of terrigenous material from the north towards the central gulf. The channels within the Archipelago de Las Perlas are the only region in that area dominated by terrigenous material. The sediments around the archipelago predominantly consist of carbonates, which generally show coarser grain sizes. The carbonate fraction in the mixed carbonate siliciclastic sediments south of the Archipelago de Las Perlas is dominated by benthic and planktic foraminifera. This suggests that only limited to no transport of carbonates through currents or waves occurs in this region.

4.4.4 Sorting of grains

Sorting of sediments predominantly results from currents transporting the grains. The major currents in the Gulf of Panama are (A) the counter-clockwise current driven by the Humboldt Current entering the gulf from the southeast and (2) the seasonal wind-driven Panama Current towards the northwest. Areas in both gulfs, which show well to moderately sorted sediments, are at present influenced by strong currents. The nautical charts of the Gulf of Panama (Clark, 1998) show strong currents in this region with 1 knot most of the time, but they can reach up to 2-5 knots. Strong currents prevail at the south-eastern edge of Peninsula Azuero with current speeds of 1 to 5 knots. The majority of the surface sediments in the Gulf of Panama at present are influenced by the weaker counter-clockwise current as shown by the distribution of fine sediments (Fig. 4.17). The counter-clockwise current reaches speeds up to 1 knot (Clark, 1998), the maximum speeds of the Panama Current are varying.

For the Gulf of Chiriquí the nautical maps do not provide any data regarding current strengths. Assuming that the same relation exists between the currents and sediment distribution as for the Gulf of Panama, then the sediment distribution should indicate strong currents coming from the southeast driven by the extensions of the Humboldt Current and weaker currents towards the south running from southeast of Islas Secas to the Hannibal Bank towards the shelf. The Gulf of Chiriquí is not as strongly influenced by prevailing northern winds as the Gulf of Panama while the mainland mountain chain protects this area.

4.4.5 Sediment distribution

In the Gulf of Panama the distribution pattern is strongly influenced by counter-clockwise currents driven by the extensions of the Humboldt Current and the Panama Current driven by the prevailing northern winds. Long shore currents seem to play an important role in the Gulf of Panama, especially along the western coastline, where the coastal currents running south are strengthened by prevailing northerly winds. The wave energy is a major factor controlling the development and changes in the beach area (King, 1972). The longshore currents, rip currents and coastal currents remove the fine material from the beach environment and thus are the major influencing factors in sediment distribution close to the coast (Wiegel, 1964; Ingle, 1966). Due to the volcanic hinterland the river input mainly consists of coarse to fine-grained siliciclastics.

In the Gulf of Chiriquí the sediment distribution map based on the clustered data shows an accumulation of clay-silts (<63µm) southeast of Parida Island on the western side of the Gulf probably derived from the north. This also holds for the deeper water region north of the Hannibal Bank and the shallow bay area on the western side of Coiba. The clays to very fine sand (<63µm to 125µm) found in the small bay east of Coiba probably are erosional products derived from Coiba and possibly from the large bay area west of the Peninsula Azuero . No samples were collected near the mainland coast and the map of the Gulf of Chiriquí region was completed following the data known from the Gulf of Panama **(Fig. 4.20)**.

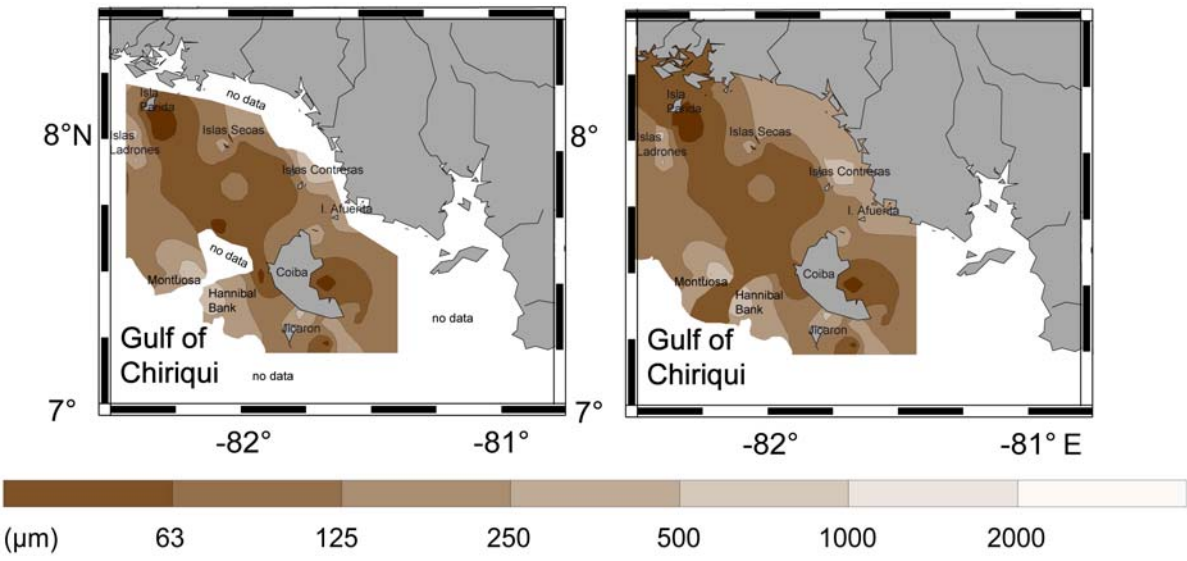


Fig. 4.20: Left figure shows original own data. Right figure shows possible grain size distribution analogous to the findings in the Gulf of Panama. The bay north of Islas Parida acts as the main supplier for very fine to fine sands.

It is assumed that fine to medium sands are located along the coastline, which are transported by rivers carrying erosional products from the same hinterland as the sediments found in Parita Bay in the Gulf of Panama. The area northwest of Isla Parida is one of the areas along the Pacific Coast in which a large concentration of mangrove forests can be found (Osorio 1994). Thus, a similar sediment distribution is assumed as found in the mangrove areas known from the Gulf of Panama. The internal zones of the mangrove forests act as clay traps and the external zones exposed to tidal fluctuations supply limited amounts of clay into the Gulf of Chiriquí. The clays that occur in the deeper water in the centre of the gulf north of the Hannibal Bank are slope sediments. These clays were most likely transported from the shallow-water mangroval areas by currents towards the shelf break. MacIlvaine and Ross (1973) characterized the slope sediments in the Gulf of Panama as dominated by clays, with a similar composition as those found in the near shore areas. The sediment sorting distribution pattern supports the interpretation that a north-south current transports fine material from the coastal areas towards the shelf towards the Hannibal Bank.

In the Gulf of Panama there is a tendency to finer grained sediment along the coastline of the mainland, whereas coarser material occurs in more open shelf settings. In contrast, the open shelf in the Gulf of Chiriquí seems slightly finer-grained with muddy silts down to greater water depths. In both gulfs the shallow water areas around the islands are coarser grained, due to the carbonates (e.g. large fragments of shells) in the samples. The areas close to the coast with 0m to 20m water depth thus show primarily sands in both gulfs. This is the normal pattern in coastal areas with sands above the wave base and absence of mud layers (Reineck and Singh, 1986). The fine material is washed out by waves and transported towards the shelf accumulating in the deeper areas. Both gulfs show clays in water depths at approx. 30m to 50m on the shelf. This is also conform with Reineck et al. (1968) describing silts to sands in the coastal areas from 0-15m and clays to silt and fine sands at depth about 15m to 40m around high energy coasts.

4.5 CONCLUSIONS

The Gulf of Chiriquí shows a normal distribution pattern of surface sediments in which all grain size fractions are represented. The sediment distribution is influenced by sediment input by rivers, redistribution by waves and currents, and the inherited pre-Holocene shelf bathymetry. Coarser sediments are found along the coast of the mainland and finer material occurs below the wave base and towards the slope in deep water areas below 200m. The distribution pattern of terrigenous input is only interrupted by carbonate sands that are present around the islands. Bivalves, gastropods, red algae and in some areas coral reefs are the major producers of carbonate sediments. The carbonate production in both gulfs is mainly limited to shallow water areas surrounding the islands. The carbonates are hardly transported by the currents and remain in their production area; therefore, the carbonates have only limited distribution on the shelf.

The sediment distribution pattern in the Gulf of Panama is strongly influenced by strong currents related to seasonal variations. The prevailing northern winds induce currents that transport fine material towards the shelf. The clays transported by rivers predominantly into San Miguel Bay subsequently are transported by currents in a counter-clockwise direction within the Gulf of Panama. These counter-clockwise currents are driven by extensions of the Humboldt Current and tend to transport the fine material off the shelf towards the coast, whereas the Panama Current tends to transport the clays to the central gulf towards the shelf.

CHAPTER 5

Facies patterns in upwelling vs. non-upwelling environments (E-Pacific)

5. Facies patterns in upwelling vs. non-upwelling environments (E-Pacific)

ABSTRACT

The Gulf of Chiriquí (non-upwelling) and the Gulf of Panama (upwelling) display significant differences in their main carbonate producing biota. The Gulf of Chiriquí mainly shows photozoan (coral-, rhodolith-facies) assemblages within the shallow-water areas surrounding the islands and a mollusc-dominated facies in deeper waters towards the shelf. The Gulf of Panama is influenced by seasonal upwelling and shows mainly heterozoan assemblages around the islands, dominated by balanids, echinoderms and/or molluscs. This assemblage differentiation suggests oligotrophic to mesotrophic conditions in the Gulf of Chiriquí, whereas mesotrophic to eutrophic conditions prevail in the Gulf of Panama. Both gulfs show warm and temperate carbonate-producing biota, with carbonate producers that occur in tropical environments (e.g. Corals), as well as carbonate producers known for cool-water environments (e.g. Bryozoa).

5.1 INTRODUCTION

Numerous studies exists on carbonate production in oligotrophic tropical environments such as the Caribbean or on warm-temperate to cool water carbonates in mesotrophic to eutrophic conditions (e.g. James, 1997, Fornos and Ahr, 1997; Henrich et al., 1995; 1996; 1997; Schäfer et al, 1996; Halfar et al., 2000, 2001, 2005).

Numerous studies concentrated on reefs and tropical carbonates in the Caribbean region, but only limited work has been done on surface sediments and carbonate factories in the tropical Pacific region of Panama. The majority of the studies in the Pacific region of Panama concentrated on analysing the biotic content of coral reefs (Glynn et al., 1972; Glynn and MacIntyre, 1977; Wellington and Glynn, 1983; Linsley et al., 1994).

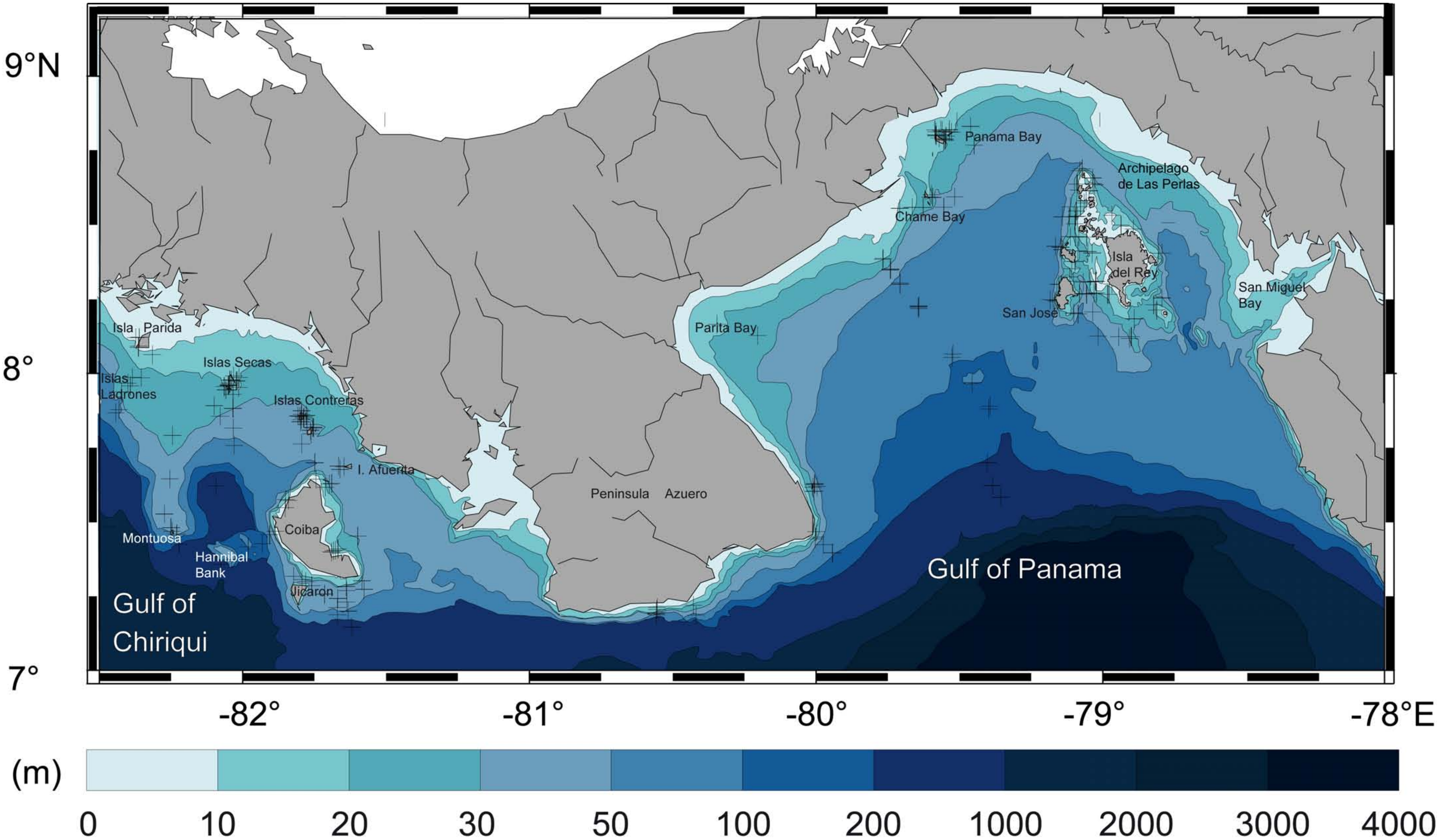


Fig.5.1 Map of the study area. Bathymetry data taken from hydrographic charts (UK Hydrographic Office UKHO) (Collins, 1973, Clark, 1998). Also shown are the sample locations of the May 2004 and February 2005 campaigns.

Carbonate producing organisms within the geographical position of the tropics, that normally occur in cold water environments are a distinctive feature of the Gulf of Panama. All studies describing such a phenomenon are known from the fossil record (James, 1997). In addition the direct vicinity of two different environments (Gulf of Chiriquí, non-upwelling and Gulf of Panama, upwelling) provide the opportunity to study two different carbonate producing regimes, located in direct geographical vicinity located on the same latitude (7°N to 9°N) in the tropics.

On the Pacific shelves of North, Central and South America carbonate environments are rare because of the mostly narrow shelves and high terrigenous input associated with the tectonically active margins and to regional upwelling effects (Halfar et al., 2000). The Gulf of Chiriquí, however, shows high productive carbonate environments with coral reefs and rhodoliths facies around the islands (Glynn et al., 1972; Glynn and MacIntyre 1977; Linsley et al., 1994). The Gulf of Panama shows different carbonate producing biota due to seasonal upwelling in the dry season. Here, coral reefs occur only in protected bays, in northern parts of the Archipelago de Las Perlas (Glynn et al., 1972). Previous work in the Gulf of Panama was mostly related to the hydrography or upwelling dynamics (Schaefer et al., 1958; Forsbergh, 1963, 1969; Smayda, 1963, 1966; Legeckis, 1985; D`Croz, et al., 1991, 1997). An important effect of seasonal upwelling is frequent changes in temperature and nutrient level (D`Croz et al., 1991). The upwelling in the Gulf of Panama is induced by northerly prevailing winds forcing the surface water to drift southwards towards the shelf (Schaefer et al., 1958; D`Croz et al., 1991). The aim of this study is to examine the different carbonate regimes in an upwelling (Gulf of Panama) and non-upwelling setting (Gulf of Chiriquí) on the Pacific side of Panama. The results will be presented in detailed maps showing the occurrence of different biota groups in both gulfs, with respect to water temperature, salinity, nutrients and geographical aspects. The data presented in this study result from point counting grab samples collected during the years 2004 and 2005 along a dense grid of locations positioned in both gulfs **(Fig. 5.1).** The 2004 campaign took place during the beginning of the rain season, whereas the February 2005 campaign covered the dry season, when active upwelling occurs in the Gulf of Panama.

5.2 METHODS

5.2.1 Sampling

This study is based on point counting grab samples obtained during two cruises in May 2004 (onset of wet season) and February 2005 (dry season) with the *RV Urraca*. The majority of the samples were collected in shallow-water carbonate environments around islands in the Gulf of Panama and the Gulf of Chiriquí. In addition, three long transects were sampled that cross the gulfs from the shallow-water realm to water depths of up to 300 m. Grab sampling was used to sample soft bottom sediment areas (230 bulk samples, see also Appendix).

5.2.2 Component analyses

The bulk samples were divided into grain-size fractions for detailed analyses of the different carbonate producers in the individual fractions. Five fractions were studied: 125µm-250µm, 250µm-500µm. 500µm-1000µm, 1000µm-2000µm, and >2000µm. Because of the large amount of samples that were analysed (230 samples, 5 fractions each sample) only 100 points in each fraction were classified. However, in the >2000 µm fraction an average of 60 points/sample was counted due to the limited amount of grains within this subfraction. The groups distinguished were bivalves, gastropods, planktonic Foraminifera, benthic Foraminifera, echinoderms, serpulids, red algae, Bryozoa, corals, balanids, fish remains, ostracods, *Porifera*, organic material (wood, leaves) and unidentified fragments. The abundance of fish remains, *Porifera* and ostracods was very low, therefore they were not analysed in detail and were subsumed into the group “other biota” together with the unidentified fragments. See Appendix for detailed list with values for all groups. Additionally, terrigenous material was also counted.
For each biota the mean percentage of the all individual samples (including all fractions) was calculated. A cluster analyses was performed to distinguish different facies types using the statistiXL 2006 Vers. 1.6 (Roberts and Withers, 2006) with Ward`s method as linkage and Euclidian distances. The complete or single linkage calculation tends to more extreme solutions than the Ward`s method does.

5.2.3 Carbonate analyses (LECO)

Bulk samples (containing all fractions) from each site were freeze dried and ground in an agate-mortar for LECO analysis, with the LECO C-200 analyzer at IFM-GEOMAR - Leibniz Institute for Marine Geosciences (Kiel, Germany). The total carbon content of a sediment sample was determined by measuring the thermal conductivity of the gaseous products of pyrolysis of the sample. The analysis was also conducted on an acidified sample to determine the organic carbon content. The weight percentages of total carbon (TC), organic carbon (OC), and calcium carbonate ($CaCO_3$) are related by the equation: (TC - OC) * 8.33 = $CaCO_3$, if we assume that all the inorganic carbon is bound in calcium carbonate.

5.2.4 X-Ray Diffractometry (XRD)

Bulk samples (containing all fractions) from each site were freeze-dried and ground in an agate-mortar for X-ray diffraction. These were scanned in a Philips PW 1710 diffractometer with a cobalt K tube at 40 KV and 35 mA**.** The computer-based program MacDiff Version 4.2.5 (Petschick, 1999) was used to process the X-Ray diffractograms and to calculate the peak areas of the individual minerals.

In-house calibrations were used to calculate the non-linear relationship between calcite and aragonite, because existing calibrations show low resolution and accuracy for aragonite percentages exceeding 70% (Milliman, 1974). The mineral quartz, with d= 3.343 A was used as an internal standard for peak correction in MacDiff. In samples with low quartz content or absence of quartz aragonite, with d=3.398 A was as standard for peak correction. The relative changes of the quartz peak areas in the diffractograms were interpreted as relative changes of quartz abundance in the individual samples.

5.2.5 Satellite Ocean Colour Data (NASA, GIOVANNI)

Satellite ocean colour data from the NASA were used to obtain chlorophyll values throughout the months May 2004 to April 2005 within the Gulf of Panama and the Gulf of Chiriquí.

The software of the web-based interface **G**ES-DISC **I**nteractive **O**nline **V**isualization and **A**nalysis **In**frastructure (Giovanni) was used to visualize the data. This software was developed by the GES DISC DAAC (http://reason.gsfc.nasa.gov) to provide users with an easy-to-use, web-based interface for the visualization and analysis of the Earth Science data. The data used were SeaWiFS ocean colour data, and MODIS Aqua ocean-colour and SST data (http://reason.gsfc.nasa.gov/Giovanni).

5.2.6 CTD

During the 2004-Cruise 118 CTD-Stations were measured. An Idronaut Ocean Seven 316 Probe was used. The measured water depths ranged from 10 m, within the very shallow areas around the Islands, up to 236 m on the deeper-shelf. The standard sensors installed were a temperature sensor, a flow conductivity sensor, an oxygen sensor, and an additional sensor for Chlorophyll-a measurement was used.

In 2005, an SBE 37-SM MicroCAT was used for CTD-profiling, which is a high-accuracy conductivity and temperature (pressure optional) recorder with internal battery and memory. Designed for moorings or other long duration, fixed-site deployments, the MicroCAT includes a standard serial interface and non-volatile flash memory. The data include conductivity and temperature values, but a pressure sensor was not installed.

During the 2005-Cruise, it was not possible to lower the CTD with a constant speed. Therefore, it was problematic to calculate the exact salinity values because of the missing pressure sensor. The variance of the salinity values is too large and a mathematical correction was not possible to get trustworthy CTD data from the 2005 campaign.

5.2.7 Underwater video camera survey

During our February 2005-Cruise an underwater video camera (UW-video camera) was used. The video camera was towed and was in contact with the control-main unit and a VHS-Video recorder through a cable all the time. The UW-Video camera was used in water depths between 10 – 80 m to document the different carbonate production and accumulation areas in the two bays (i.e. coral reefs, coralline algae communities, large bivalve communities, carbonate sand and gravel accumulations and deep water banks).

5.3 RESULTS

5.3.1 Temperature

The Sea Surface Temperature (SST) shows significant differences in both gulfs during different seasons (May 2004, onset rain season / February 2005, dry season).

In May 2004 similar high SST´s were present in the Gulf of Chiriquí and the Gulf of Panama. The average SST in the Gulf of Panama was 27.23°C and in the Gulf of Chiriquí 27.45°C **(Fig. 5.2 / 5.3)**. In the Gulf of Panama own measurements with an Idronaut Ocean Seven 316 Probe show slightly different values with 27.90°C (mean), versus 28.6°C (mean) in the Gulf of Chiriquí. The data show slight mixing of the water masses in the Gulf of Panama resulting in a shallower and less pronounced thermocline in May 2004. The temperature change to 22.50°C in the Gulf of Panama lies between 40m and 50m water depth vs. 50m to 60m water depth within the Gulf of Chiriquí. During the dry season the northern trade winds press the surface waters southwards resulting in upwelling of relatively cold waters. The average SST derived from satellite imagery in the Gulf of Chiriquí (non-upwelling) is 28.14°C and in the Gulf of Panama 24.79°C (upwelling). Own SST data from an SBE 37-SM MicroCAT shows more pronounced differences in the SST with 20.09°C (mean) in the Gulf of Panama and a 28.5°C average SST in the Gulf of Chiriquí.

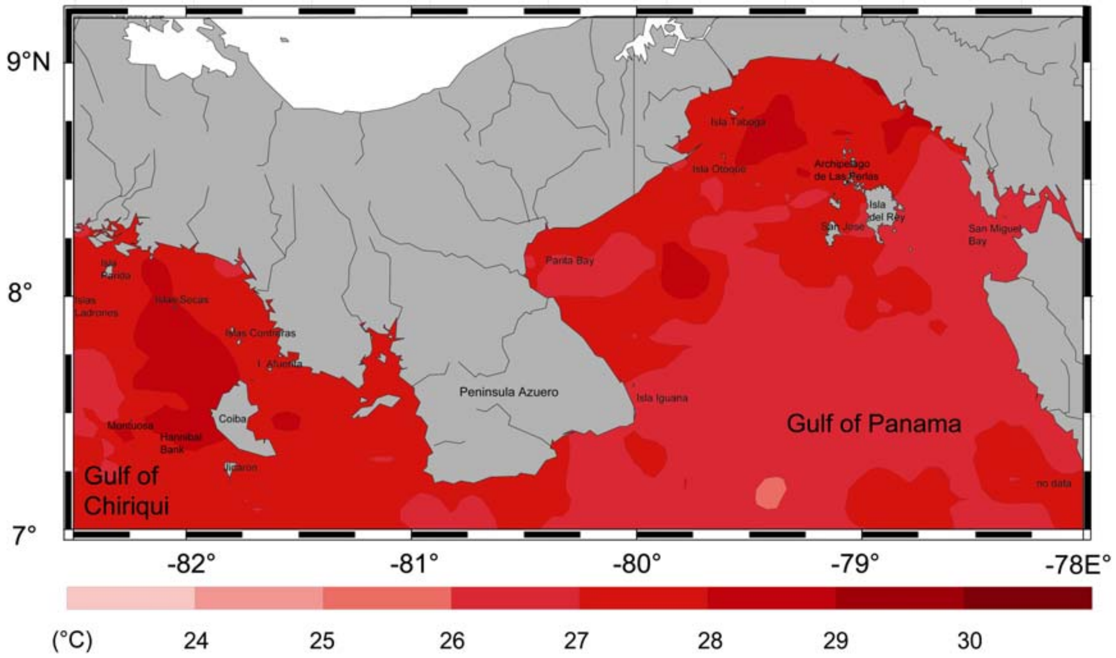


Fig. 5.2 The SST ocean colour data (GIOVANNI) of May 2004 show similar temperatures in both gulfs.

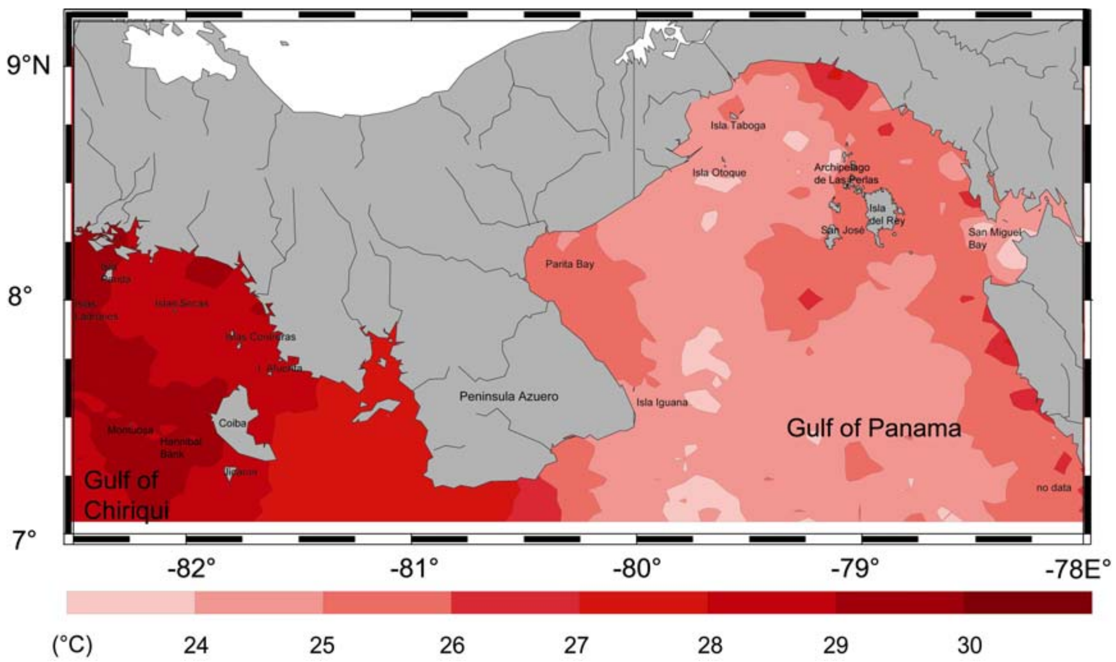


Fig. 5.3 The SST February 2005 shows distinct differences in temperature between the Gulf of Chiriqui and the Gulf of Panama. The Gulf of Panama shows lower temperatures due to upwelling in the dry season. Data from ocean colour data (GIOVANNI).

5.3.2 Salinity

The salinity in both gulfs varied around 33.50 psu in May 2004 except for a small lens in the Gulf of Panama with a lower salinity of approx. 33 psu. This might be a regional effect resulting from freshwater discharge from the Azuero Peninsula and/or from the beginning of the wet season bringing more rain into the Gulf of Panama than into the Gulf of Chiriquí, because the Gulf of Chiriquí is protected by mountain ranges. Due to technical problems no salinity data are available for February 2005.

5.3.3 Chlorophyll-α and Oxygen

During May 2004 to November 2004 **(Fig. 5.4)** both gulfs show similar values of chlorophyll with values ranging from 0.1mg/m^{-3} to 0.7mg/m^{-3} in the Gulf of Panama to 0.2mg/m^{-3} to 0.7mg/m^{-3} in the Gulf of Chiriquí in the centre of both gulfs. Higher values in both gulfs prevail close to the coast or individual islands within the gulfs and probably are generated by nutrient influx from rivers.

During December 2004 to April 2005 **(Fig. 5.5)** both study areas show distinct differences in chlorophyll values. The Gulf of Panama shows values ranging from 0.7mg/m^{-3} to >10mg/m^{-3}. Lower values appear towards the open shelf in the south-eastern sector of the gulf and close to the Azuero Peninsula. The Gulf of Chiriquí shows values ranging from 0.1mg/m^{-3} to 0.4mg/m^{-3}, higher values only appear close to the coast in large bays (>2.5 mg/m$^{-3)}$ north of Isla Parida and along the bay on the west side of the Peninsula Azuero (Bahia Montijo). Oxygen measurements with the Idronaut Ocean Seven 316 Probe show higher values in <100 m water depth, where highest concentrations occur in 10 – 30 m. This is explained through uptake of oxygen through waves and mixing of the surface water combined with photosynthesis of planktic algae.

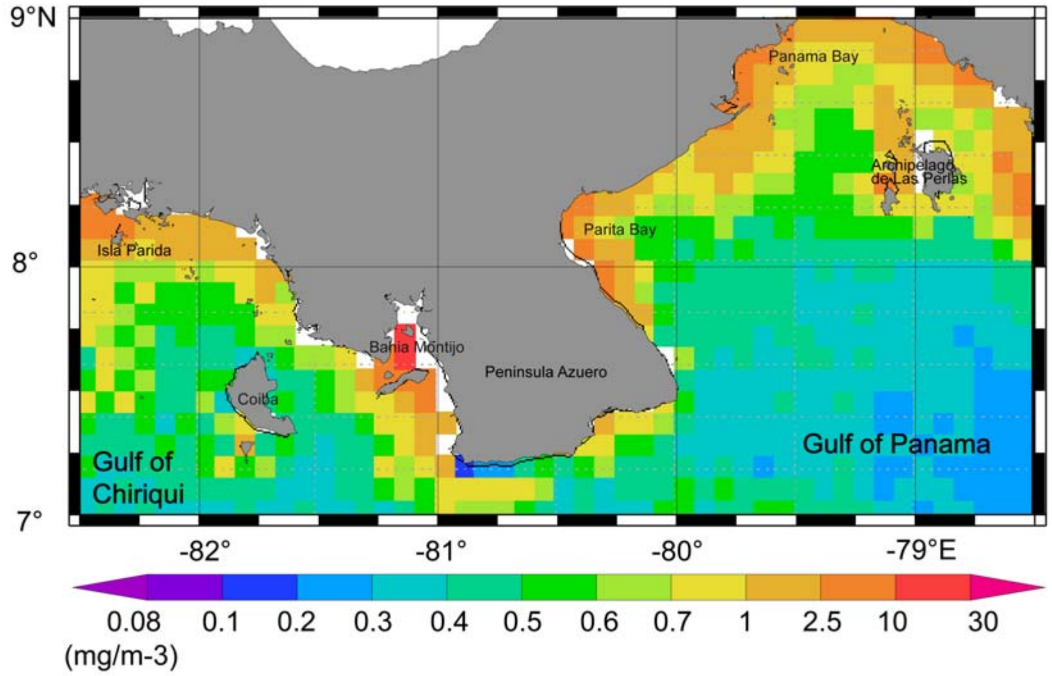


Fig. 5.4 Chlorophyll values for the period May 2004 to November 2004 (wet season) derived from ocean colour data. No distinct differences exist between the gulfs, with low values in both the Gulf of Panama and the Gulf of Chiriqui.

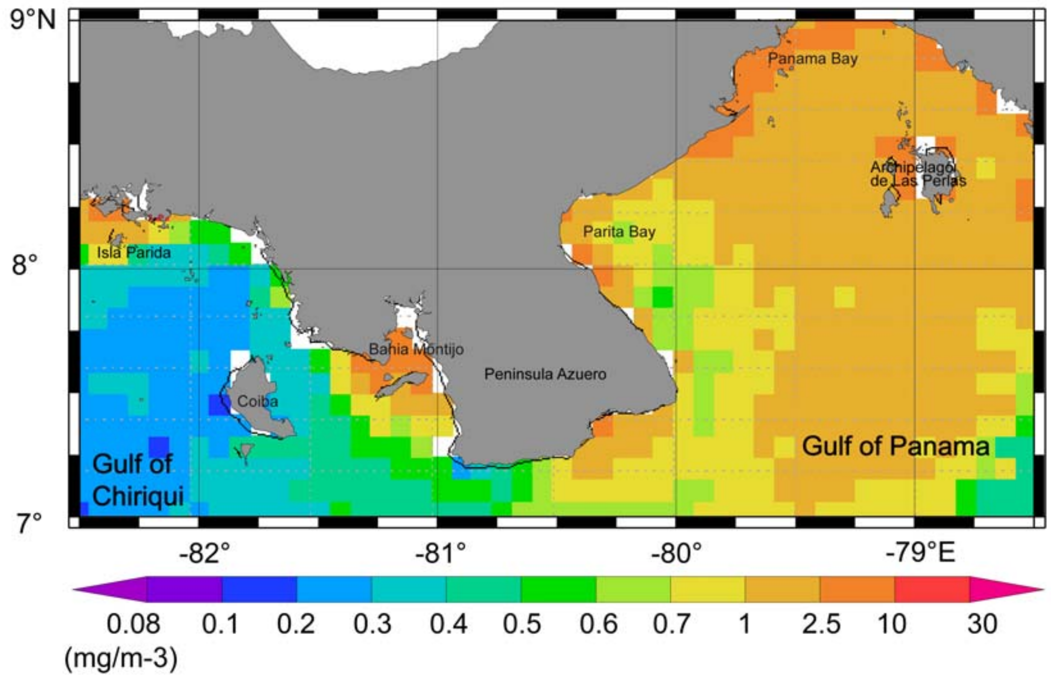


Fig. 5.5 Chlorophyll values for the period between December 2004 and April 2005 (dry season) derived from ocean colour data. The Gulf of Panama shows higher values during this period because of upwelling conditions caused by northerly winds crossing the Panamanian Isthmus.

5.3.4 Distribution of organic particles in the sediment

In the following section the amount of organic particles from different biota groups in the sediment within the individual sub-fractions (125µm->2000µm) were obtained by point counting.

Bivalves

Fragments of bivalves are common in the Gulf of Panama and the Gulf of Chiriquí. They occur in nearly all sediment types and water depths, although they are less abundant in deeper waters. In the Gulf of Panama the highest percentage of bivalves of the counted fractions (CF^{Biv}) was found northwest of Isla Taboga with 76.82%CF^{Biv} and northeast of the northernmost small islands of the Archipelago de Las Perlas with 50%CF^{Biv}-60%CF^{Biv} **(Fig. 5.6)**. Values of 30%CF^{Biv} to 40%CF^{Biv} occur also along the coastlines with exception of Parita Bay with lower values around 20%CF^{Biv} to 30%CF^{Biv}. The average percentage of bivalves in the Gulf of Panama is 21.65%^{CFBiv}. The Gulf of Chiriquí shows a similar bivalves distribution. The highest values occur around the northern small islands along the coast with values averaging 30%CF^{Biv} to 40%CF^{Biv}. The highest value with 43.78%CF^{Biv} was found at U04078 (7.995; -82.029) located at Islas Secas. The abundance of bivalves is lower in the central gulf and towards Hannibal Bank. The average percentage of bivalves in the Gulf of Chiriquí is slightly lower than in the Gulf of Panama with 20.45%CF^{Biv}.

Gastropods

In the Gulf of Panama the gastropods are dominant around the islands and in shallower waters on the shelf. No significant amounts of gastropods were found below 100m of water depth except for a limited area at U05101 (7.635; -79.374) with an accumulation of gastropods with an amount of 16.08%CF^{Gas} **(Fig. 5.7)**. The sediment at this location consists mainly of shell hash and many planktonic

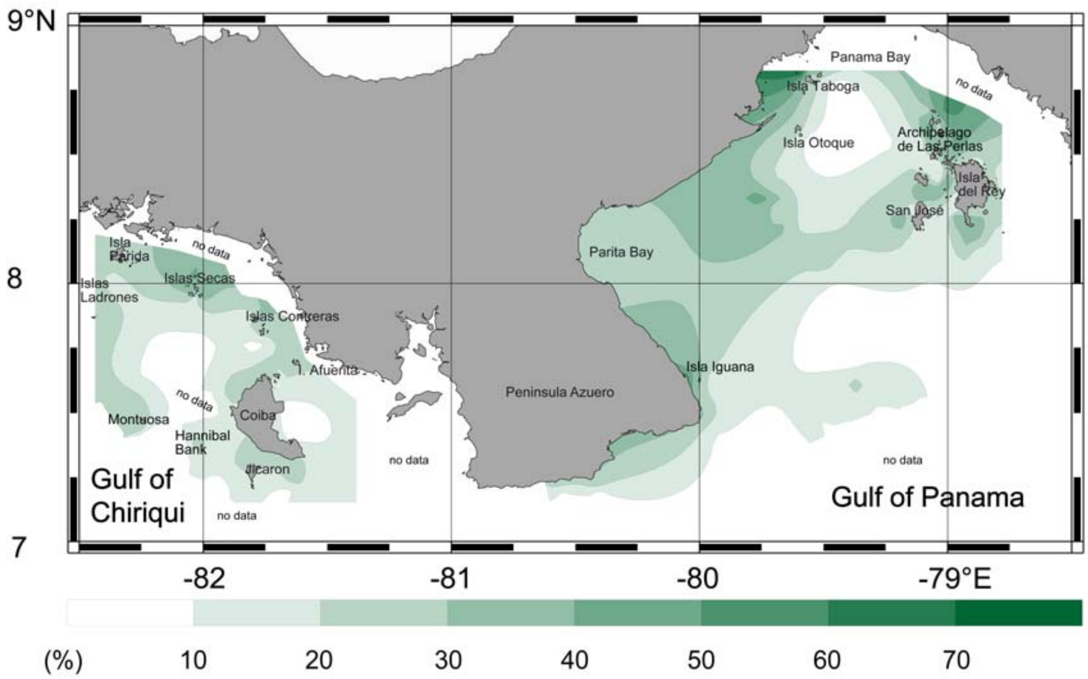


Fig. 5.6 The distribution of bivalves, (percentage of bivalves as total of the point counted fractions, CF^{Biv}) shows that they occur abundant in both gulfs without major differences.

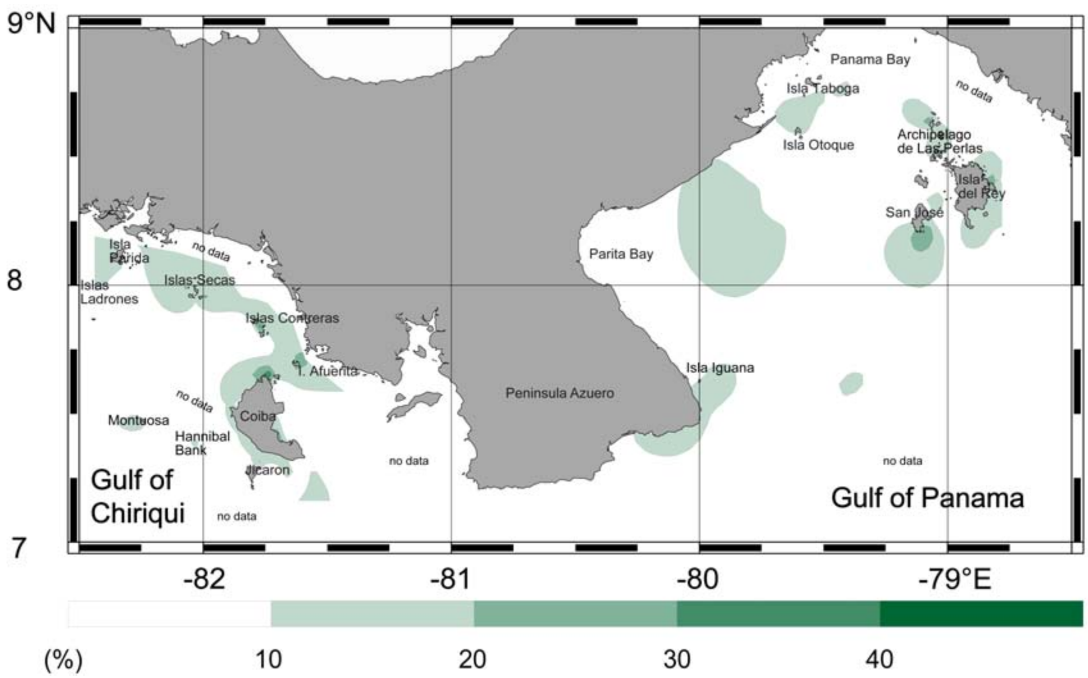


Fig. 5.7 The distribution of gastropods (percentage of gastropods as total of the point counted fractions, CF^{Gas}) shows a dominance around the islands in both gulfs.

foraminifers. The sands have a brownish colour as well as the gastropods and bivalve fragments (Fe-stained). The water depth is 301m. In the shallower waters and around the islands the amounts of gastropods vary between 10%CF^{Gas} and 20%CF^{Gas}. The highest values were present at location U05120 (8.202; -79.091) located south of Isla San José with 34.65%CF^{Gas}. The average percentage of gastropods in the Gulf of Panama is 7.02%CF^{Gas}. The Gulf of Chiriquí shows overall higher values of gastropods with an average amount of 11.05%CF^{Gas}. The gulf shows no significant amount of gastropods below 100m water depth. The gastropods are located on a small band around the shallow waters of the islands along the coast and around Coiba. Higher values are also present around the islands of Montuosa and at Hannibal Bank. The highest values of gastropods could be found at U04113 (7.856; -81.783) located at Islas Contreras with 64.06%CF^{Gas}.

Balanidae

Cirripedians are common in the sediment samples of the Gulf of Panama around the Archipelagos de Las Perlas with higher amounts south of Isla San José and Isla del Rey. Isla Taboga, Isla Otoque with values of 40%CF^{Bal} to 50%CF^{Bal}. Isla Iguana and Parita Bay also show slightly lower amounts, 30%CF^{Bal} to 40%CF^{Bal} **(Fig. 5.8)**. The highest values were found at location U05107 (8.306; -79.013) south of Isla San José with 51.90%CF^{Bal}. The average amount of Balanidae in the Gulf of Panama is 9.92%CF^{Bal}. In the Gulf of Chiriquí Balanidae are very rare. The highest value with 24.39$^{\%CFBal}$ was found south of Islas Secas (U04091; 7.949; -82.056) towards the open shelf and is relatively low compared to the values found for the Gulf of Panama. Balanidae occur only in small limited areas on the west coast of Coiba, at Islas Contreras and Islas Secas, all other areas in the Gulf of Chiriquí show no significant amounts of Balanidae.

The average amount of Balanidae in the Gulf of Chiriquí is only 2.90%CF^{Bal}, which is less than 1/3 of the values found in the Gulf of Panama.

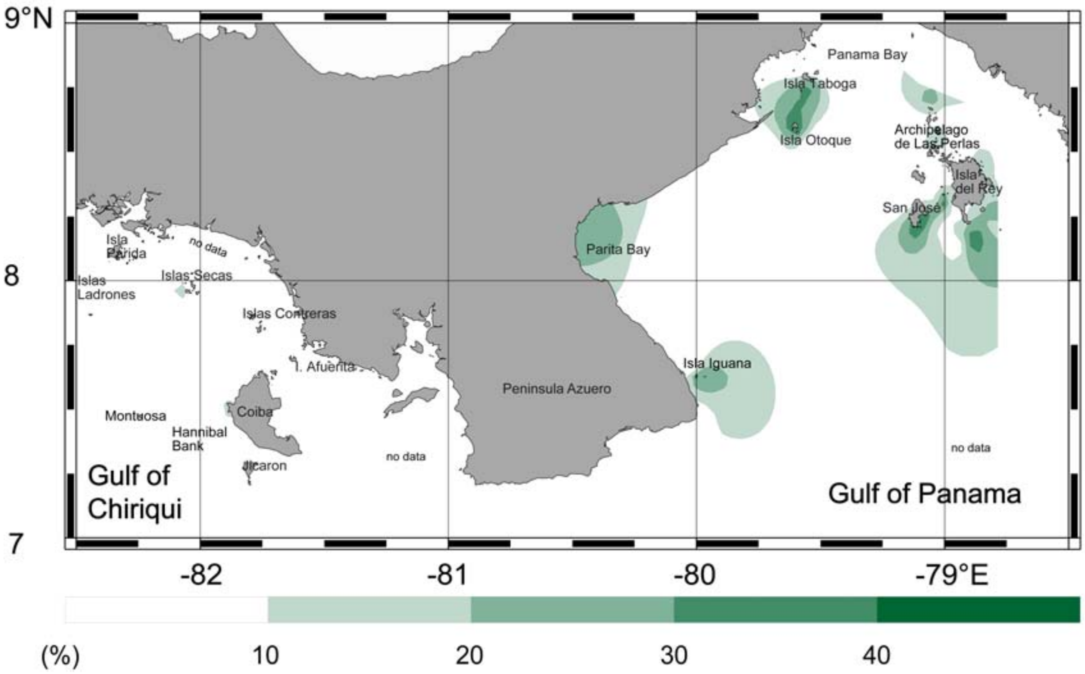


Fig. 5.8. Balanidae occurrence (percentage of balanids as total of the point counted fractions, CF^{Bal}). The Balanidae prevail in the Gulf of Panama and are nearly absent in the Gulf of Chiriqui.

Planktonic Foraminifera

Planktonic foraminifera are common in both gulfs, with higher values in areas with a dominance of terrigenous material or with only minor dominance of carbonate material. In the Gulf of Panama planktonic foraminifera are common in an area between Isla Otoque and the Archipelago de Las Perlas, in which fine sediments are common. They also occur in the central gulf towards the open shelf in an area with coarse, relict sands **(Fig. 5.9)**. The highest amount of planktonic foraminifera is found at location U05134 (8.399; -78.783) with 46.24%CF^{Pla}. It is important to mention that within this sample the counted fractions (125µm to >2000µm) represent only 2.14% of the total sediment. This is due to the fact that the sediment is coarse silt with a mean grain size of 21.82µm and thus the majority of the sediment was not counted. The second highest value of planktonic foraminifera is located at U05094 (8.297; -79.699) south of Isla Otoque with 21.09%CF^{Pla}. The total amount of counted sediment there is 85.94%. The mean percentage of planktonic foraminifera in the Gulf of Panama is 3.89%CF^{Pla}. In the Gulf of Chiriquí planktonic foraminifera are common, similar to the Gulf of Panama, and occur mainly in areas towards the centre of the shelf at some distance from the islands. The sample with one of the highest values was found at location U05025 (7.862; -82.076) with 38.08%CF^{Pla} out of 63.98% of the total sediment. This sample shows only few benthic foraminifers and a dominance of planktonic foraminifera in the fractions 125µm-250µm and 250µm-500µm. In the fraction 500µm-1000µm the amount of planktonic foraminifera is still high with 25%. In both gulfs the planktonic foraminifera show the highest values in the fractions 125µm-250µm followed by the fraction 250µm-500µm. The average value for planktonic foraminifera is 6.58%CF^{Pla} in the Gulf of Chiriquí.

Benthic Foraminifera

In the Gulf of Panama the benthic foraminifera are common in areas where the sediment is dominated by terrigenous material as in the centre of the gulf and between Isla Otoque and the Archipelago de Las Perlas **(Fig. 5.10)**. The benthic foraminifera show the highest amounts in the fractions between 125µm and 500µm like the planktonic foraminifera. The highest value for benthic Foraminifera in the Gulf of Panama is U05094 (8.297; -79.699) with 29.41%CF^{Ben}. The average percentage in the gulf is 2.93%CF^{Ben}. In the Gulf of Chiriquí benthic foraminifera are very rare except for a small area west of Jicaron with 24.91%CF^{Ben}. The average percentage of benthic foraminifera in the Gulf of Chiriquí is similar to the Gulf of Panama with 2.55%CF^{Ben}.

Bryozoa

Bryozoa are not common in the sediment of the grab samples in the Gulf of Panama **(Fig. 5.11)**. The only area with slightly elevated values occurs south of the Archipelago de Las Perlas with 11.94%CF^{Bryo}. The average amount of Bryozoa in the Gulf of Panama is 1.38%CF^{Bryo}. The Gulf of Chiriquí shows higher average

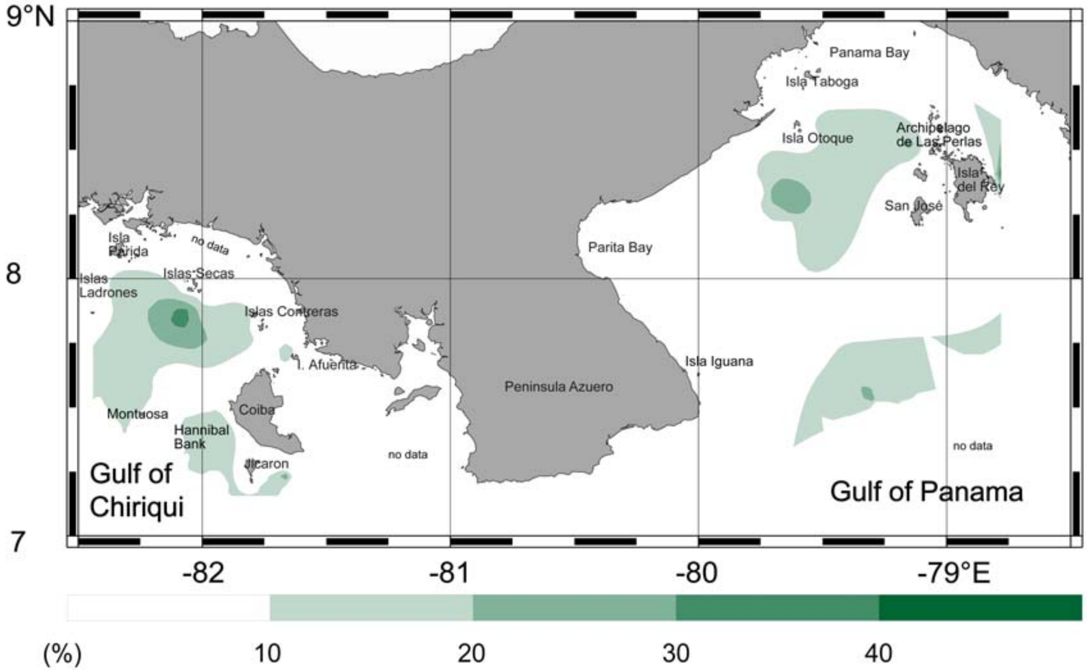


Fig. 5.9 Occurrence of planktonic foraminifera in percentage of total count CF^{Pla} Planktonic foraminifera occur mainly towards the open ocean influenced centres of both gulfs.

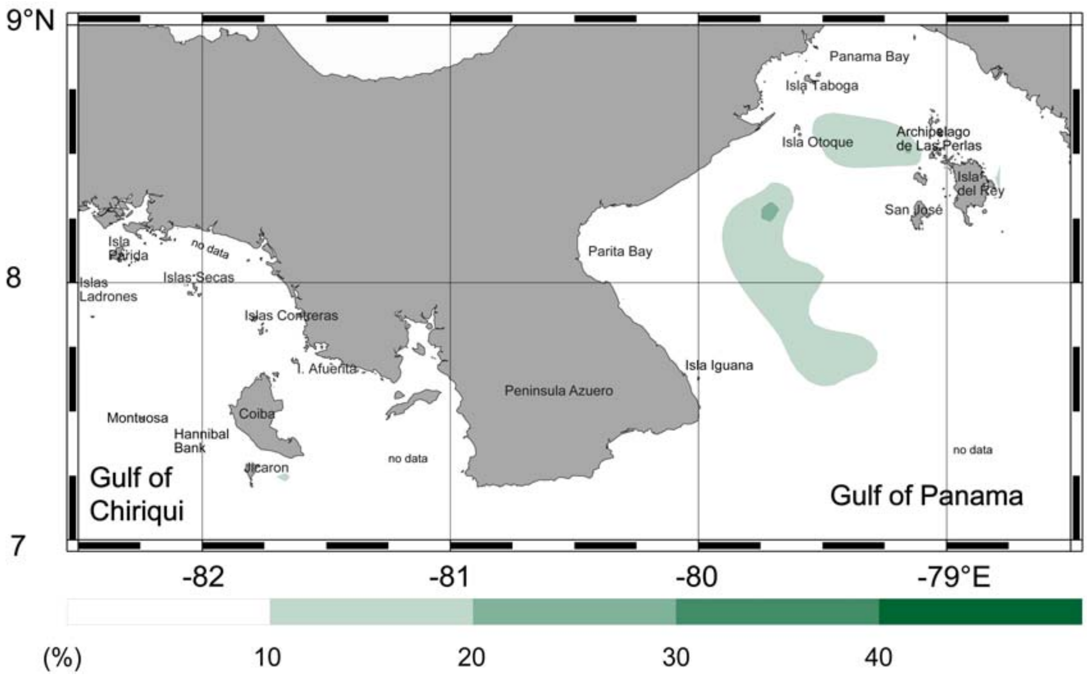


Fig. 5.10 Benthic foraminifera, percentage of the counted fraction CF^{Ben}, in the Gulf of Panama occur in low abundances in the center of the gulf. In the Gulf of Chiriqui they occur also around the islands but also with minor abundance.

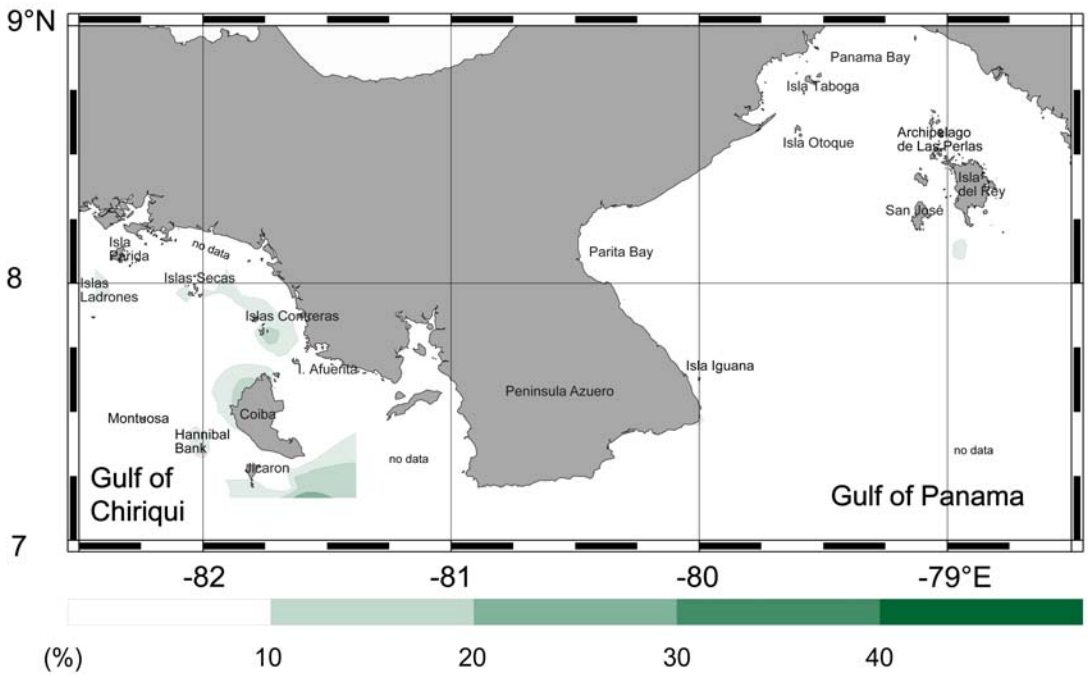


Fig. 5.11 Bryozoa, percentage of the counted fraction CF^{Bryo}, are not abundant in the sediment samples of both gulfs. They occur in higher quantities (50% more) in the Gulf of Chiriquí, where they occur around the islands and southeast of Cobia.

values with 3.91%CF^{Bryo}. The highest amount is found at U05078 (7.168; -81.616) with 27.92%CF^{Bryo} located south of Coiba. The Bryozoa occur mainly as fragments in this sample. They are dominant in the fraction 250µm - >2000µm. The fraction 1000µm - 2000µm shows the highest amount of Bryozoa with 44%. In the Gulf of Chiriquí Bryozoa are common in the area of Islas Secas and Islas Contreras, as well as Islas Ladrones, Hannibal Bank, northwest coast of Coiba and south and southeast of Coiba.

Echinodermata

Echinoderms occur as spines or fragments within the sediments in both gulfs. Around Archipelago de Las Perlas, especially the southern part, southwest of Isla Otoque and at a limited location at the south-eastern edge of the Azuero Peninsula are the locations in which Echinodermata occur with values between 5%CF^{Echi} to 10%CF^{Echi}. The highest relevant values are located at U05130 (8.299; -78.812) with 11.35%CF^{Echi} **(Fig. 5.12)** out of 97.94% of the total sediment. The high values of

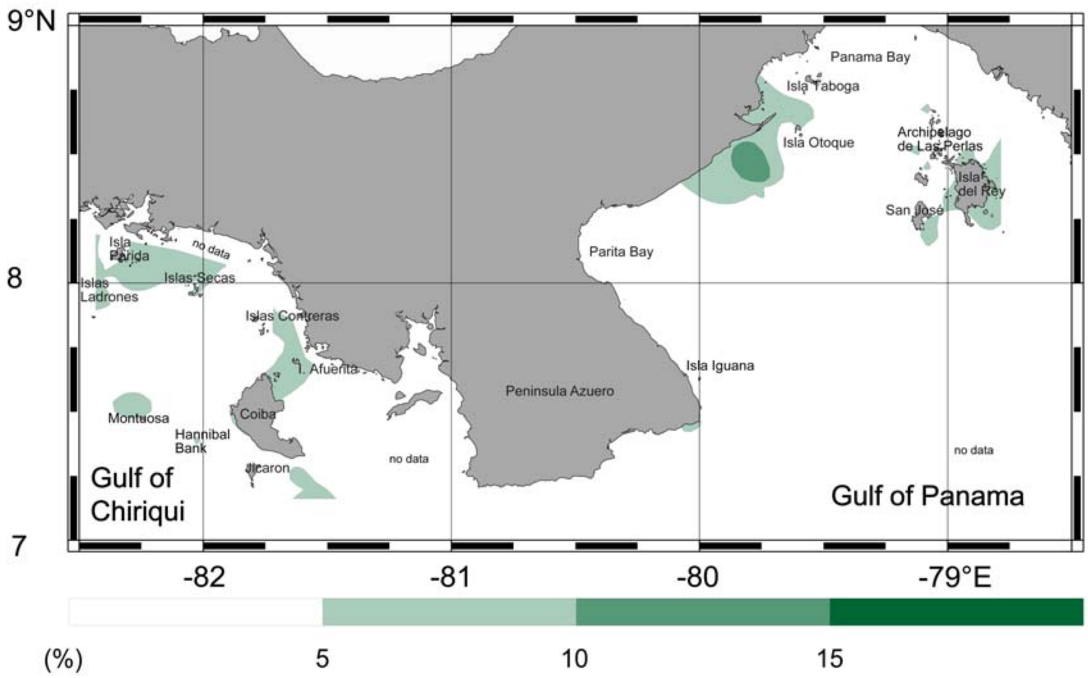


Fig. 5.12 Echinodermata show only minor amounts in both gulfs with a dominance in the Gulf of Chiriqui around the islands, where also corals and rhodoliths prevail. Scale percentage of total counts CF^{Echi}.

>15%CF^{Echi} southwest of Isla Otoque are related to a very fine sediment where only 0.27% out of the total sediment fell within the range of 125µm to >2000µm that was counted. The sample was U04009 (8.382; -79.758) a poorly sorted silt with a mean grain size of 15.02µm. In the Gulf of Chiriquí the Echinodermata occur on a small band close to the islands along the coast, northeast and southeast of Coiba, at Montuosa and Hannibal Bank, with values of 5%CF^{Echi} – 10%CF^{Echi}. They follow the same distribution pattern as the gastropods in the Gulf of Chiriquí except for the area between Islas Secas and Islas Contreras. The average percentage of echinoderms in the Gulf of Chiriquí is 3.79%CF^{Echi} and is similar to the amount in the Gulf of Panama with 3.24%CF^{Echi}. The highest amount of Echinodermata in the Gulf of Chiriquí is 13.71%CF^{Echi} located at Islas Ladrones (U0460; 7.942; -82.421).

Serpulids

Serpulids occur only in small amounts in the sediments of both gulfs. Serpulids were found between Isla Otoque and Isla Taboga as well as in the area around the Archipelago de Las Perlas, especially on the southwest coasts of the southern islands and at Isla Iguana and around the south-eastern edge of Peninsula Azuero

(Fig. 5.13). The amounts in the Gulf of Panama fall below 10%CF^{Ser} in all samples. The average lies at 1.45%CF^{Ser}.

The highest amount in the Gulf of Chiriquí is 12.24%CF^{Ser} and was found at U04050 (7.263; -81.655) south of Coiba. All other values are below 7%CF^{Ser} with an average of 1.75%CF^{Ser} similar to those of the Gulf of Panama.

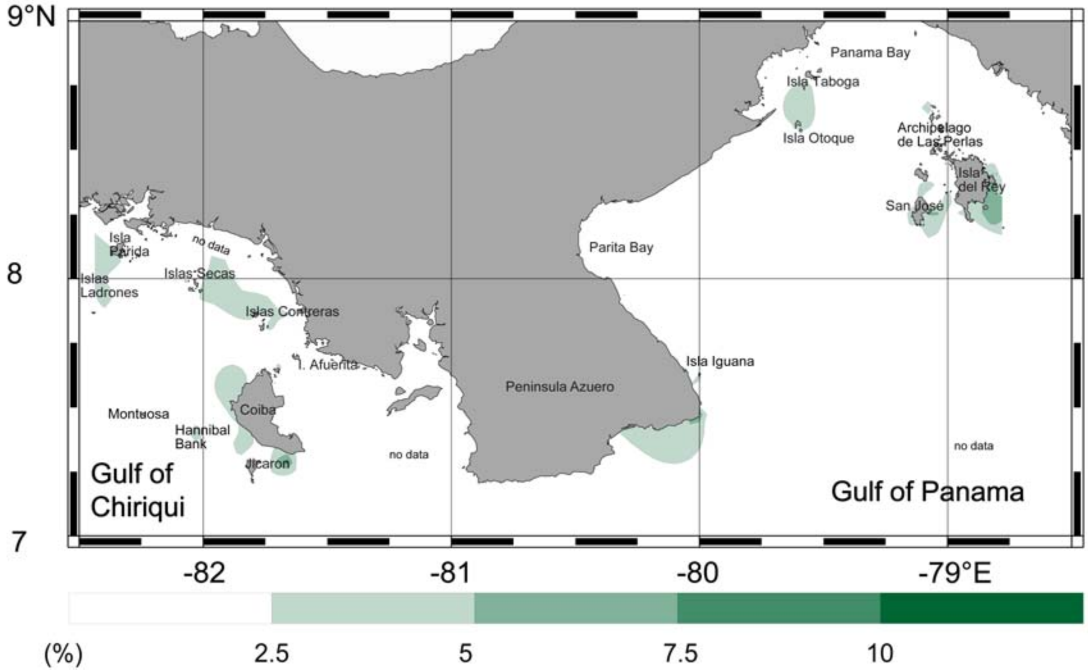


Fig. 5.13 Serpulids, in percentage of total count (CF^{Ser}), show only minor abundance in the sediments of both gulfs.

Coralline red algae

Red algae occur only in limited areas in both gulfs and occupy the same habitat as the corals. Red algae occur only in 21 of 132 sample locations in the Gulf of Panama in most of them with below 10%CF^{RAlg}. The highest amount was found southeast of Isla del Rey **(Fig. 5.14)**(U05127; 8.124; -78.890) with 32.66%CF^{RAlg}. The red algae occur as encrusting forms covering rock fragments in both gulfs. Articulate forms (rhodoliths) dominate in the Gulf of Chiriquí. The highest amount of red algae occurs at U04067 (7.475; -82.228) close to Montuosa with 48.65%CF^{RAlg}, and comprise encrusting forms and rhodoliths. The area around Islas Ladrones is dominated by rhodoliths as major carbonate producer with values around 30.07%CF^{RAlg} (U04060; 7.942; -82.421). High quantities of rhodoliths fragments in the sediment can also be found around Islas Secas and Islas Contreras, where they are not always the dominant carbonate producer. The average percentage of red algae of all stations in the Gulf of Chiriquí is 3.88%CF^{RAlg} and in the Gulf of Panama it is 1.60%CF^{RAlg}. These very low average percentages result from the fact that red algae only occur in higher amounts in limited areas around the islands in both gulfs.

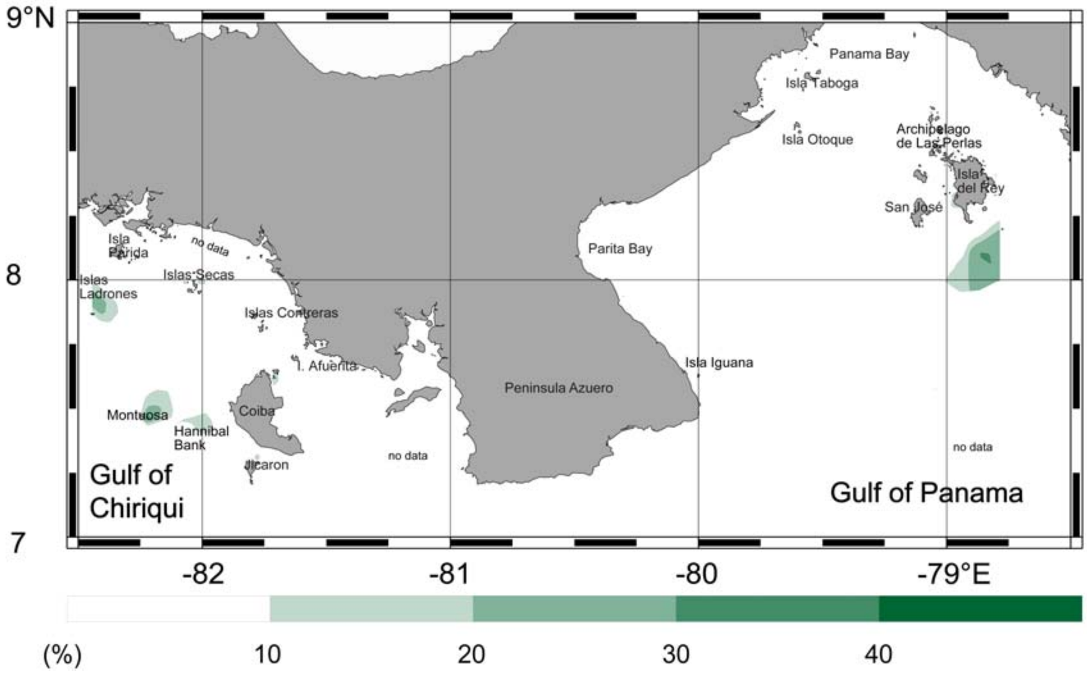


Fig. 5.14 Red algae, in percentage of counted fraction, occur mainly in the Gulf of Chiriquí around the islands. In the Gulf of Panama they occur only around the Archipelago de Las Perlas and south of Isla del Rey, together with Balanidae.

In the Gulf of Chiriquí red algae occur in 44 of 97 grab samples, but only 5 samples show percentages over 20%CF^{RAlg}.

Corals

Similar to red algae, corals occur only in small habitats, but can be the dominant carbonate producer when living conditions are ideal. In the Gulf of Panama corals are not very common and only occur in very small amounts below 1%CF^{Cor} around Isla Taboga and Isla Iguana and with values below 5%CF^{Cor} at the Archipelago de Las Perlas **(Fig. 5.15)**. The average percentage of corals in the Gulf of Panama is 0.09%CF^{Cor}. In the Gulf of Chiriquí the average amount of corals is higher with

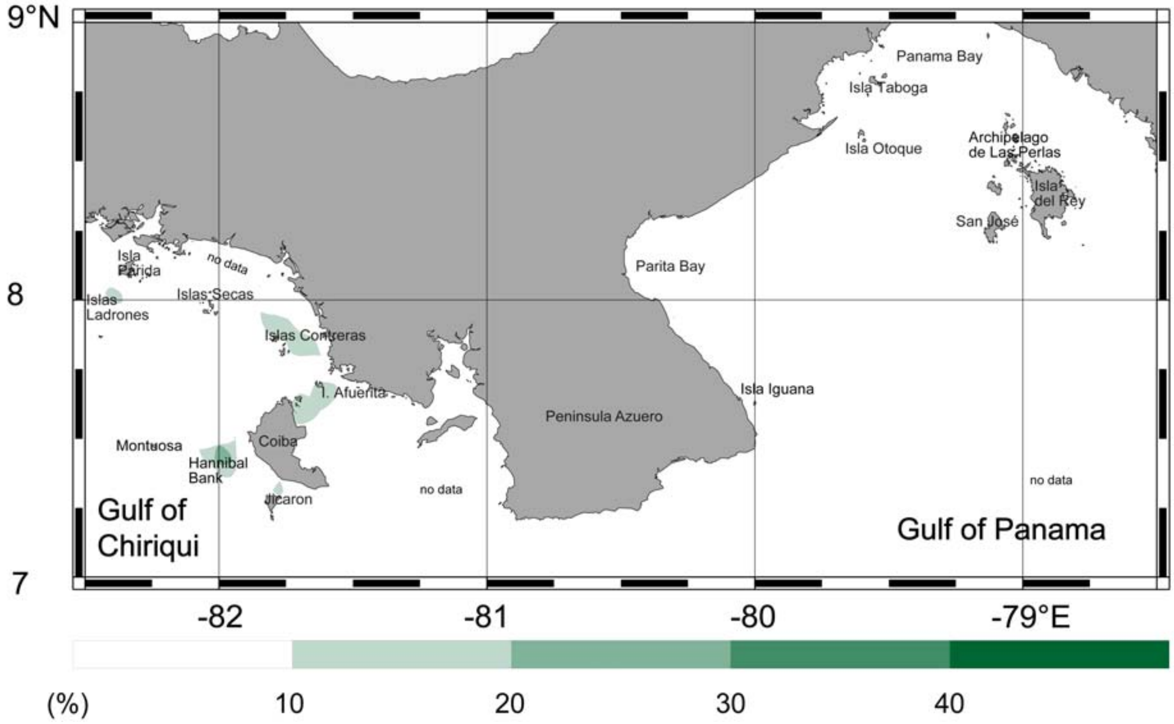


Fig. 5.15 Corals, in percentage of counted fraction, occur mainly in the Gulf of Chiriquí around the islands. In the Gulf of Panama they occur only around the Archipelago de Las Perlas and south of Isla del Rey In small amounts.

3.73%CF^{Cor}. Corals occur around all islands in the Gulf of Chiriquí and at Hannibal Bank. The highest amount of corals was found around Islas Contreras with 37.94%CF^{Cor} at U05037 (7.868; -81.792) and at Hannibal Bank with 35.63%CF^{Cor}.

5.3.5 Terrigenous and Carbonate Distribution

The percentage of terrigenous material in the sample was obtained by point counting all the grain-size fractions between 125µm to >2000µm. The carbonate content was achieved through LECO analyses of bulk samples containing all grain-size fractions. The maps of both parameters **(Figs. 5.16** and **5.17)** agree very well. High carbonate contents are found around the islands, whereas high terrigenous values mainly can be found in the centre of the gulfs but also in areas with high terrigenous input from river discharge or bottom currents. One area south of Chame

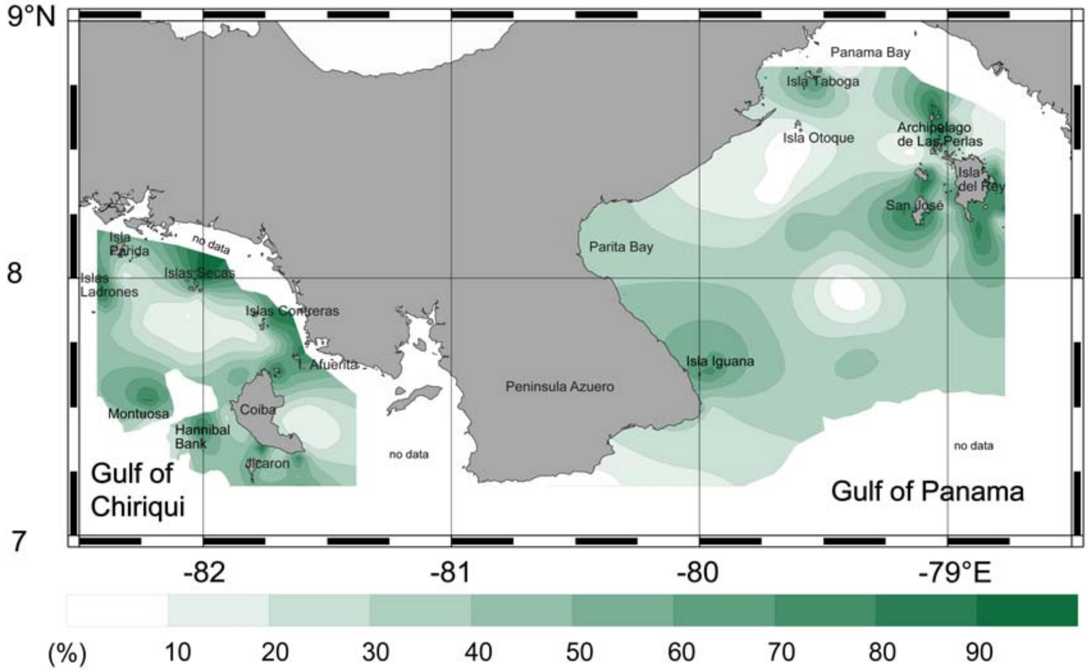


Fig. 5.16 The percentage of carbonates derived from LECO analyses shows slight dominance in the Gulf of Chiriquí and dominance of carbonates in the shallow water surrounding the islands in both gulfs.

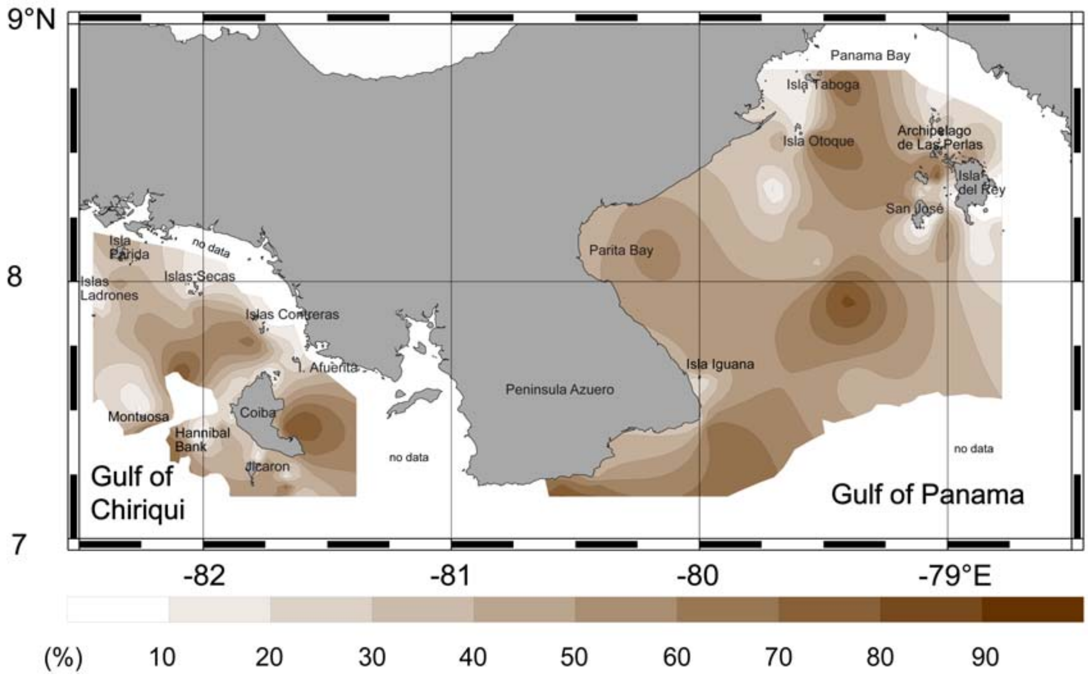


Fig. 5.17 Distribution of terrigenous material derived from point counting. Scale in percentage of total sediment. Abundancy of terrigenous material increases towards the center of the Gulf of Panama.

Bay in the Gulf of Panama shows low values of terrigenous material in the fractions 125µm to >2000µm and low carbonate content in the whole sediment. This probably relates to the very fine grain size at this location (see Chapter 4).

5.3.6 Carbonate Mineralogy

Aragonite

Aragonite is abundant within both gulfs. A mean amount of Aragonite of 19.54% was found in the Gulf of Panama **(Fig. 5.18)**. Aragonite is absent within areas close to the west coast and in the centre of the gulf or values are less than 10%. The highest

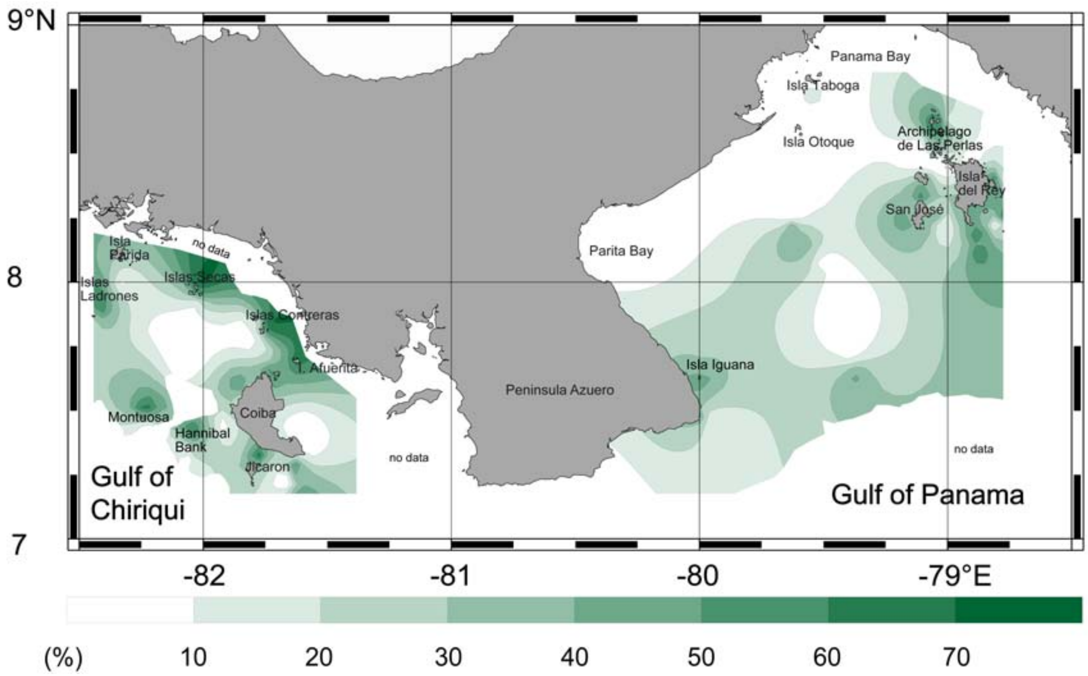


Fig. 5.18 Aragonite is present throughout both gulfs with a slight dominance in the Gulf of Chiriquí around the islands because of the occurrence of corals. Scale percentage from the carbonate fraction measured by X-ray diffraction.

values occur around the islands with a maximum amount of 65.74% at location U05129 (8.183; -78.880) positioned south of Isla del Rey. The Gulf of Chiriquí shows higher values with 78.67% as maximum amount of aragonite within the sediment, a sample taken at U04078 (7.995; -82.029) near Islas Secas. Similar high values can be found around Islas Contreras. The mean amount of aragonite in the Gulf of Chiriquí is 35.67%.

Calcite (High-magnesium and low-magnesium calcite)

The amount of calcite (HMC and LMC) was achieved through XRD analysis of bulk samples. The Gulf of Panama and the Gulf of Chiriquí show similar values ranging from 0% to 40% Calcite **(Fig. 5.19)**. In the Gulf of Panama nearly no calcite was found in the central gulf and near the coastline between Chame Bay and Parita Bay. The calcite in the Gulf of Chiriquí is more uniformly distributed with only small areas without calcite that is located in the central gulf and southeast of Coiba where fine terrigenous sediments prevail. The highest values of calcite in the Gulf of Panama are 57.43% located at U05144 (8.521; -79.078) and around archipelago de Las Perlas with an average of 14.39%. In the Gulf of Chiriquí the highest value is 43.29% located at U04091 (7.949; .82.056) near Islas Secas. The Gulf of Chiriquí shows a slightly higher calcite average of 16.56%.

***High Magnesium Calcite (HMC*)**

In the Gulf of Panama the amount of **H**igh **M**agnesium **C**alcite (HMC) is very low. HMC only occurs in an area south of Isla del Rey where large amounts of Balanidae were found and in a restricted area around small islands in the northern part of Archipelago de Las Perlas. The average amount of HMC in the Gulf of Panama is 3.17%, with a maximum amount of 29.97% as found south of Isla del Rey at location U05128 (8.111; -78.890; **Fig. 5.20)**.

The Gulf of Chiriquí shows higher values of HMC especially around the islands and Hannibal Bank. The maximum amount of HMC in the Gulf of Chiriquí can be found at U05043 (7.851; -81.793) near Islas Contreras with 37.05% HMC in the sediment. The average amount of HMC in the Gulf of Chiriquí is 10.14% and thus 3 times higher than the mean value found in the Gulf of Panama.

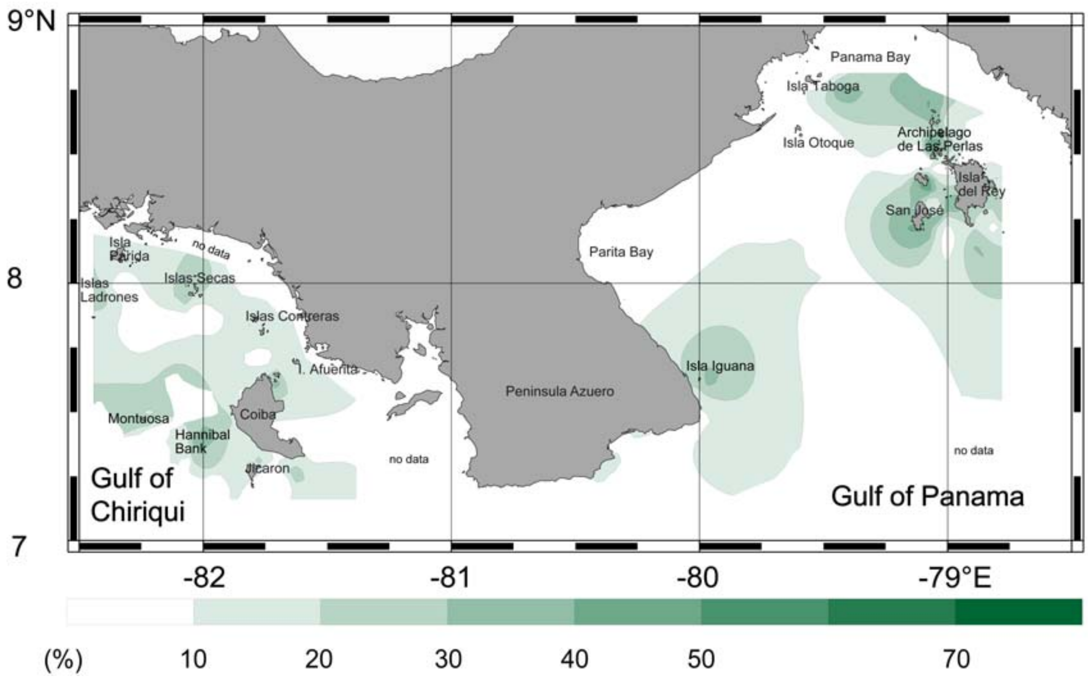


Fig. 5.19 Carbonate (HMC and LMC) shows a slight increase around the islands in both gulfs but is also abundant in the center of the gulfs. Scale percentage from the carbonate fraction measured by X-ray diffraction.

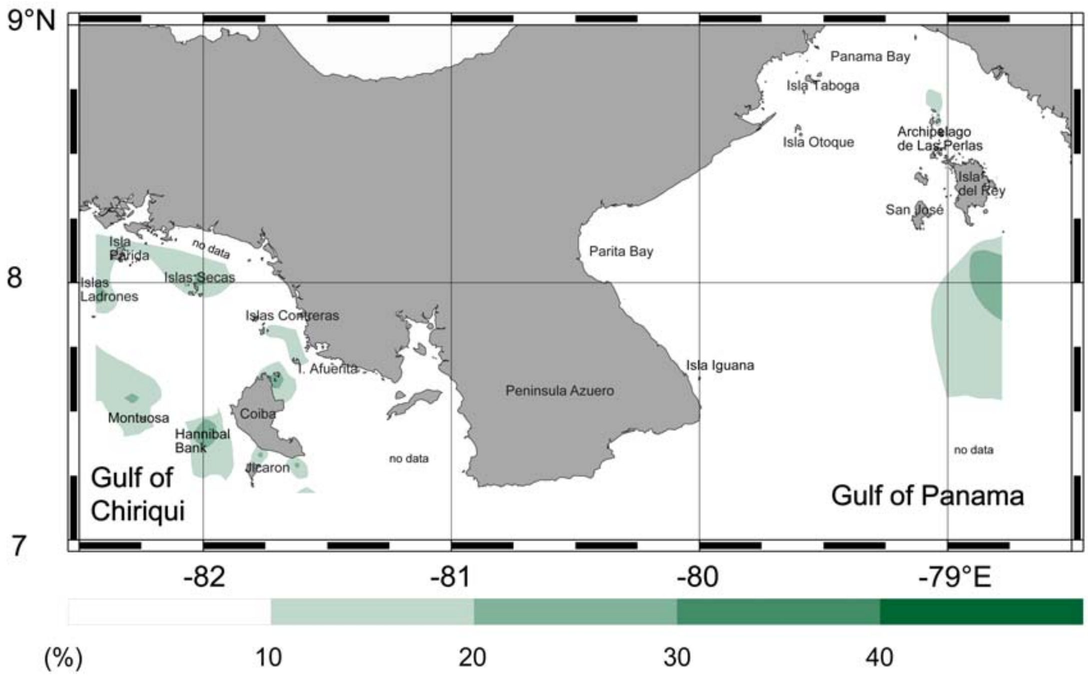


Fig. 5.20 High Magnesium Calcite occurrence (HMC) is higher in the Gulf of Chiriquí than in the Gulf of Panama. Scale percentage from the carbonate fraction measured by X-ray diffraction.

Low Magnesium Calcite (LMC)

The distribution of **L**ow **M**agnesium **C**alcite (LMC) also shows significant differences in both gulfs. The highest values of LMC in the Gulf of Panama can be found northwest of the Archipelago de Las Perlas towards Panama Bay, southwest of Archipelago de Las Perlas towards the central gulf and in an area around Isla Iguana towards the northeast with values of up to 50% LMC. The highest amount of LMC were found in the northern part of Archipelago de Las Perlas at sampling point U05144 (8.521; -79.078) with 51.63%. The average amount of LMC in the Gulf of Panama is 11.22% **(Fig. 5.21)**.

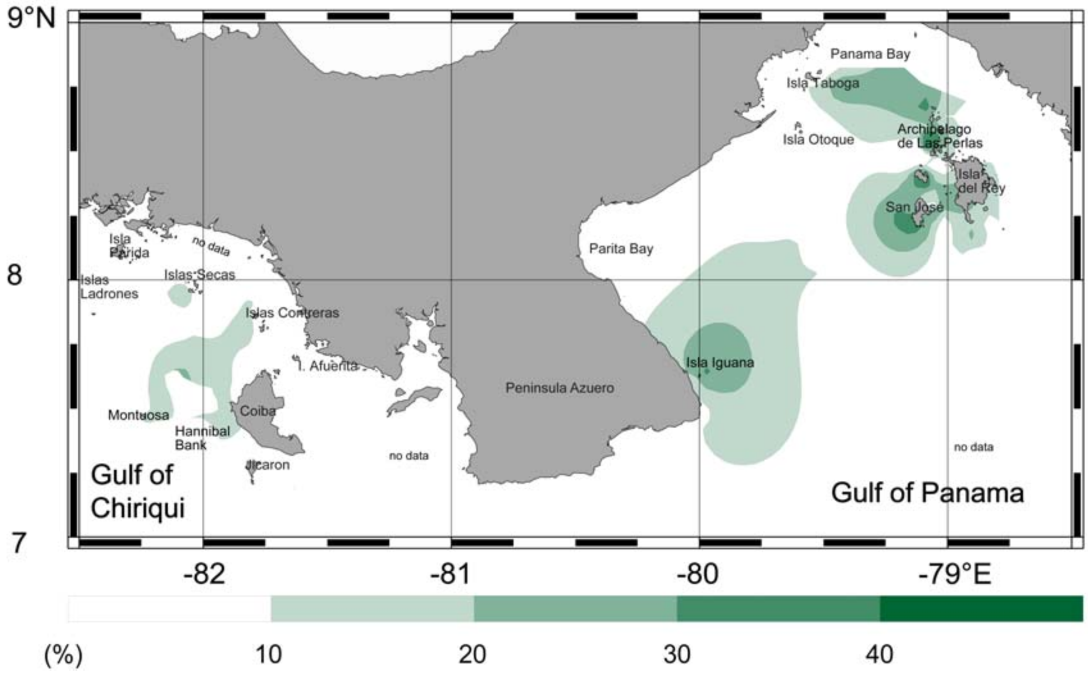


Fig. 5.21 Low Magnesium Calcite occurrence shows preferences towards the centre of the Gulf of Chiriquí and also can be observed in the Gulf of Panama, where it also occurs around the islands. Scale percentage from the carbonate fraction measured by X-ray diffraction.

The Gulf of Chiriquí shows an overall lower amount of LMC with an average of 6.41%, which is about the half of the amount found in the Gulf of Panama. The only areas with a higher amount of LMC are situated in the central gulf between the islands with values below 20%. The highest values of LMC can be found at location U04091 (7.949; -82.056) south of Islas Secas with 36.21%.

5.4 DISCUSSION

5.4.1 Oceanographic parameters

The Gulf of Panama (GoP) and the Gulf of Chiriquí (GoC) show distinct differences in their oceanographic parameters, such as temperature, salinity and nutrients. During the beginning of the rain season in May 2004 the temperature in both gulfs was similar with a mean in the GoP of 27.23°C (GIOVANNI database) or 27.90°C (own data); mean values for the GoC were 27.45°C (GIOVANNI), and 28.6°C /own data). In the dry season pronounced differences in SST occur (mean GoP 24.79°C GIOVANNI / 20.09°C own data; mean GoC 28.14°C GIOVANNI / 28.5°C own data). The fact that our data were obtained at the beginning of the rain season most likely explains the less pronounced difference in temperatures between the rain season and the dry season in the Gulf of Panama. Glynn and MacIntyre (1977) state that the sea surface temperature in the GoP varies from 26°C to 28°C in the rain season, with a maximum measured SST of 29.8°C (D´Croz, et al., 1991). The dry season shows SST´s between 18-20°C with increased productivity, and nutrient enrichment (Glynn and MacIntyre, 1977). The lowest measured temperature was 16.75°C (D`Croz et al., 1991). These low SST in the Gulf of Panama during the dry season is related to upwelling and a result of northerly wind stress displacing the surface water masses (Fleming, 1939; Schaefer et al., 1958; Forsbergh, 1963, 1969; D`Croz et al., 1991). The SST and associated parameters like salinity or nutrients show interannual variations. They are caused by changes in the upwelling intensity and in the origin of upwelling waters and thus relates to the regional Eastern Pacific climatology (D`Croz et al., 1991). One of the most important factors controlling shallow-water carbonate formation is water temperature (Lees and Buller, 1972; Carannante et al., 1988; Nelson, 1988; James, 1997). Temperature fluctuations associated with upwelling thus may put intensive stress on temperature-sensitive groups of carbonate producers like corals (Halfar et al., 2005). No significant differences in SST were observed in the Gulf of Chiriquí between the seasons. This might be explained by the geographic position of this gulf on the leeward side of the Panama mountain range which protects it from the seasonal northerly winds.

The observed salinity in both gulfs was comparable with values around 33 psu at the beginning of the rain season,. Forsbergh (1969) described that the salinity in the

Gulf of Panama is related to a high dilution from rainfall and freshwater runoff especially in the rain season. This results in salinities below 30psu. The lowest values of <25psu occur during the rain season from September to November (D`Croz et al., 1991). Like temperature, salinity often is a major factor controlling carbonate production (Lees, 1975). However, Halfar et al. (2005) showed that it had only less influence on the carbonate environments in the Gulf of California.

Besides temperature and salinity, nutrients are an important factor influencing the biogenic composition within carbonate environments (Littler and Littler, 1985; Hallock and Schlager, 1986; Birkeland, 1987; Carannante et al., 1988; Hallock 1988, 2001; Mutti and Hallock, 2003; Vecsei, 2003; Halfar et al., 2005; Wilson and Vecsei, 2005; Halfar et al., 2005). D´Croz et al., (1991) reports low chlorophyll (0.5 mg/m^3) and low density of phytoplankton (20.30 cells/ml) for the rain season in the GoP and high chlorophyll 3mg/m^3 and abundance of phytoplankton (100-300 cells/ml) during the dry season. Smayda (1963; 1966) already suggested that the phytoplankton occurrence in the GoP was steered by seasonal climate variations. Estrada and Blasco (1979) described dinoflagellate blooms during the dry season that resulted from nutrient enrichment caused by upwelling.

The growth of phytoplankton is related to nutrient availability, which might result in reduced water transparency and therefore reduced phototrophic carbonate production because of the limited depth ranges of zooxanthellate corals and calcareous algae (Hallock and Schlager, 1986). In addition, nutrients are food resources for fast growing species like Balanidae, which can occupy the same habitat as corals (Birkeland, 1987). During the rain season typical warm and nutrient-poor seawater conditions could be observed in the Gulf of Panama (D`Croz et al., 1991).

5.4.2 Carbonate production

The oceanographic differences between upwelling and non-upwelling conditions in the Gulf of Panama and the Gulf of Chiriquí, respectively, influence the carbonate environment as shown by the distribution of the different biota groups in the sediment. Molluscs are the most abundant biota in both gulfs. Molluscs do not photosynthesize and do not rely on high light levels like corals (Halfar et al., 2000) and thus will be less influenced by upwelling and non-upwelling conditions. Therefore they show a rather uniform distribution with not much difference between both gulfs (compare Fig. 5.6 and 5.7). The bivalve occurrence in the GoP and the GoC shows only a very small difference of 1.2%CF^{Biv} in their mean values (Fig. 5.6). Gastropods show a slightly larger difference of 4.03%CF^{Gas} in their mean values. This difference is probably caused by the island distribution in both gulfs, which shallow-water areas form the main habitat of the gastropods. In the Gulf of Chiriquí the islands show a rather uniform distribution throughout the entire gulf with dominance along the northern coastline. In the Gulf of Panama, however, most of the islands are part of the Archipelago de Las Perlas in the north, leaving large areas in the GoP without islands especially in the central part of the gulf. Hence this variation in island distribution results in varying CF^{Gas} values. The gastropods that were found in the deep water areas of the Gulf of Panama were classified as fossil species possibly of the same origin (last Holocene transgression) as the "central-sands" classified by MacIlvaine and Ross (1973). The gastropods found in this area might be deep dwellers but their abraded appearance and Fe-staining supports the interpretation as fossil specimens.

The Balanidae prefer mesotrophic environments but are also common in eutrophic environments. The highest values are found south of the Archipelago de Las Perlas in the Gulf of Panama in areas exposed to upwelling. The Gulf of Chiriquí also shows Balanidae but less pronounced. They were present around the islands like Islas Secas and Islas Contreras at sites at which corals also occur that prefer oligotrophic conditions. Living barnacles were found on dead but still in situ coral heads and on skeletal debris located at some distance from the reef (Glynn et al., 1972).

Corals are mainly found in the Gulf of Chiriquí and the average amount of corals (CF^{Cor}) is eleven times higher than those found in the Gulf of Panama, which might be caused by high stenothermic conditions characteristic for this region (Glynn et al., 1972). The corals predominantly occur around the islands in shallow-water environments. The largest amounts of corals in the Gulf of Chiriquí were found at Uva Island (Islas Contreras) and around Islas Secas, smaller reefs were also present at Islas Parida. This distribution agrees with the detailed study of Glynn et al. (1972). This restricted distribution is caused by the fact that hermatypic corals need photosynthesizing algal symbionts (Halfar et al., 2000) and require a shallow depth for prolific growth (Halfar et al., 2001). Dominating corals found are *Poccilopora*, *Porites, Millepora and Pavona. Poccilopora* forms fringing reefs and usually predominates in shallow depth (Glynn et al., 1972); a fringing reef with similar coral assemblages in Islas Secas nearly 500m in length, was studied in detail by Glynn et al. (1972). Our database did not include samples taken close to the coastline and thus is restricted to the description of the coral distribution around the islands. Glynn et al. (1972), however, described rich corals communities along the coast, for example Bahia Honda. In the Gulf of Panama only very limited amounts of corals were found (0.09%CF^{Cor}; Fig. 5.15) which is caused by the upwelling regime during the dry season resulting in unfavourable living conditions for corals.

Another factor controlling reef growth is stress through terrigenous input, freshwater influx and industrial effluents like at the islands around Taboga northeast of Chame Bay (Glynn and MacIntyre, 1977). The terrigenous material is mainly found in the smaller grain sizes (<63µm to 250µm) and therefore easily transported by currents and waves. Sediments with dominating carbonate content (carbonate sands and mixed carbonate-siliciclastic sands) are restricted to larger grain-sizes (>500µm) and these mostly remain at the places where they are produced.

The coral reef found in a bay on the west side of Isla del Rey is protected from upwelling. This agrees with Glynn et al. (1972) who describes that the reef formations in the GoP are preferentially located on the north-eastern sides of the Archipelago de Las Perlas protected from upwelling. For the Gulf of California Halfar et al. (2000) showed that carbonates mainly accumulated in shallow sheltered pocket bays. Those pocket bays could also be found around the small islands of the Archipelago de Las Perlas in the GoP. These protected areas generally are not subject to intense cooling through periodic upwelling. However, latter process may result in widespread coral mortality even in sheltered areas and could interrupt reef growth and thus may be partly responsible for the differences in coral reef development in the Gulf of Chiriquí and the Gulf of Panama (Glynn and MacIntyre, 1977). In the Gulf of Chiriquí the distribution of corals around the islands shows no difference regarding their position on the seaward or windward sides of the islands. Coral fragments and reef derived sediments like bioclastic calcareous sands can be found in deeper water and are scattered widely around the reef base and beyond (Glynn et al., 1972) as observed in Islas Contreras, north of Islas Ladrones, northeast of Coiba and at Hannibal Bank. The reef growth determined in the Gulf of Chiriquí and the Gulf of Panama by Glynn and MacIntyre (1977) showed values that range from 1.3–4.2m /1000yr, with a maximum reef frame thickness of 8.3m in the GoC and 4.2m in the GoP. These values are comparable to the rates calculated for the Galeta fringing reefs (0.6–3.9m/1000yr) situated on the Caribbean Side of Panama.

5.4.3 Coralline Red Algae

Coralline Red Algae occur as attached (encrusting) or unattached (maerl, rhodoliths) forms. The term rhodoliths is described and discussed extensively in the literature (Barnes et al., 1970; Bosellini and Ginsburg, 1971; Ginsburg and Bosellini, 1973; Adey and MacIntyre, 1973; Bates and Jackson, 1983; Bosence, 1983a, 1983b; Prager and Ginsburg, 1989). Some authors describe unattached branched forms of coralline red algae as “maerl” (Alexandersson, 1977; Bosence, 1977; Ginsburg and Bosellini, 1973). In this study we refer to the term “rhodolith” as described by Bosence (1983a/1983b) whereas maerl is a type of rhodolith.

In the Gulf of Panama coralline red algae occur mostly as encrusting forms surrounding or attached to rock fragments. Around Archipelago de Las Perlas articulate branching forms also were present. The reason for the dominance of encrusting forms in the GoP might be that rhodoliths are less tolerant to mixing with terrigenous material (Halfar et al., 2005) and that large parts of the Gulf of Panama are dominated by terrigenous input (see Chapter 4). The upwelling in the Gulf of Panama seems to have only minor influence as red algae are adapted to a wide range of salinity and can thrive under wide temperature ranges (Bosence, 1983b). In the Gulf of Chiriquí predominantly rhodoliths occur. They occur in the same habitat as the corals but also at greater water depths. Red algae can live at water depth levels with low light levels and thus can be found in water depths of up to 80m (Halfar, 1999) or even up to 250m (Bosence, 1983b). In both gulfs the coralline red algae occur mainly in shallower water depth. The distribution of coralline red algae is mainly dependent on sufficient current or wave energy to inhibit siltation (Marrack, 1999; Foster et al., 1997). Coralline red algae are dominant carbonate producers in some areas, for example around Islas Secas in the Gulf of Chiriquí thick beds of rhodoliths were found covering large areas of the seafloor.

The rhodoliths beds were located at U05014 (7.955; -82.012) in about 15m water depth and were researched with an Underwater Camera and during snorkelling **(Fig. 5.22)**. Such beds of rhodoliths are sometimes classified as algal-gravels or maerl (Schlanger and Johnsen, 1969; Freiwald, 1995; Halfar et al., 2000). Accumulations of unattached coralline algae have been recorded from the Gulf of California and the Gulf of Mexico (Johansen, 1981; Bosence and Pedley, 1982; Woelkerling, 1988; Steller and Foster, 1995) and are described as major sources of carbonate, but may also represent areas with high biodiversity (Foster et al., 1997).

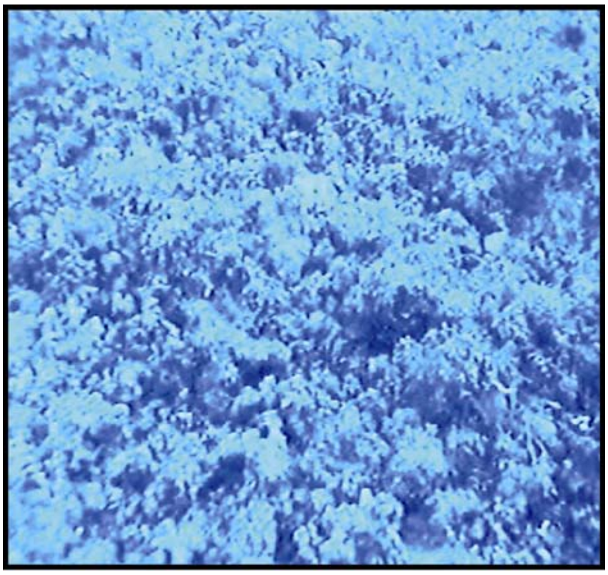


Fig. 5.22 Rhodolith bed, snapshot from video survey with under-water camera. Location U05014

The dredge samples (Scha355/24, unpubl. Data) show a dominance of rhodoliths in this area around Islas Secas. Dredge sample U05029D (7.957; -82.010) shows 82.72% (weight percentage of total fraction) rhodoliths in fraction >20mm, 86.77% in 20mm-6.3mm and 69.32% in 6.3mm-2mm. The grab samples close to this area show only very limited amounts of rhodoliths. The videos from the UW-Camera survey show that the distribution of the rhodoliths beds is patchy. In between these patches finer sands occur. This suggests that the grab samples obtained from these areas and described in this study were located in between the rhodoliths patches and therefore contain a different sediment type than the dredge sample. Thus, it is important to mention that dredge and grab samples may show different findings due to the different sampling method. Whereas dredge samples catches all macro-fauna living on the substrate but loose all the fine sediment during the sampling process, grab samples are not able to catch the bigger components and thus only sample the fine sediment. However, most of the dredge samples could be easily correlated with the grab samples. In the Gulf of

Panama most dredge samples show dominance of Cirripedia and in the Gulf of Chiriquí rhodoliths prevail, but mollusc are also abundant in both gulfs.

5.4.4 Competition within the Reefs

The coexistence of red algae and corals is common in modern shallow-water environments and can also be found at several other locations like the Yucatan Shelf of the Gulf of California (Logan et al., 1969; Carannante et al.; 1988; Halfar et al., 2000).

Coralline algae are an important constructional component of reefs regarding their abundance and binding properties (Glynn, et al., 1972). Rhodoliths in the Gulf of Panama and the Gulf of Chiriquí are mostly of the genus *Lithophyllum*, which dominates most modern shallow-water environments (Foster et al., 1997; Riosmena-Rodriguez, 1999; Halfar et al.; 2000). Several studies documented the competition between red algae and corals within reef environments, especially the process in which coral reefs become dominated by algae (Littler and Litter 1984; Lapointe 1989; Lang and Chornesky, 1990; Done 1992: Hughes 1994; Miller 1998; Karlson 1999; McCook et al., 2001). There is little evidence that algae actively conquer reef areas resulting in coral reefs becoming dominated by algae. It is postulated that they occur as a consequence of coral mortality (McCook et al., 2001), for example due to herbivore activity as a key factor mediating the effects of algae on corals (Carpenter, 1997; McCook 1999; McCook et al., 2001). In the Gulf of Chiriquí several starfish were present in the dredges. Glynn et al. (1972) reports that *Acanthaster planci* acts an important predator of corals and hydrocorals in the Gulf of Chiriquí at many locations. Feeding activity is also important as bioerosion process related to sediment production of carbonate sands (Chazottes et al., 1995, 2002). Glynn et al. (1972) and Chazottes et al. (2002) showed that predator-induced erosion can amount to one-third of the annual coral growth and that large quantities of sediment can accumulate from this cause alone next to the influence of high energy physical processes, such as strong wave action or tropical storms.

5.4.5 Carbonate Mineralogy

The distribution of aragonite and calcite (Low-magnesium calcite (LMC) and high–magnesium calcite (HMC) reflects the distribution of the different biota producing these carbonate mineralogies. Aragonite shows high values in nearly all carbonate-dominated areas in both gulfs especially in the areas around the islands in the Gulf of Chiriquí. This is not only related to the distribution of corals but also to the very abundant occurrence of bivalves and gastropods (Fig. 5.5/5.6). Aragonite is present in the inner layers of mollusc shells while calcite occurs in the generally prismatic outer layers (Milliman, 1974). Most marine gastropods are aragonitic (Milliman, 1974). The high-magnesium calcite values are higher in the Gulf of Chiriquí, which might be an effect of the abundant rhodoliths (Milliman, 1971). Low-magnesium calcite is produced by coccoliths, planktic and benthic foraminifera and ostracods (Scholle and Ulmer-Scholle, 2003). Areas with higher LMC content in the Gulf of Panama overlap with areas in which the amount of this biota is higher. However, the average amount of planktic and benthic foraminifera is slightly higher in the Gulf of Chiriquí and therefore cannot explain the higher values in the Gulf of Panama. Coccolithophorids are producing LMC and might be an explanation for the higher LMC values in the Gulf of Panama. Coccolithophorids are commonly found in near-surface waters (Yang et al., 2001). Berger (1976) showed that they are primary producers of oceanic phytoplankton biomass. Several species thrive in upwelling areas and continental shelf settings (Yang et al., 2001).

5.4.6 Facies Distribution

To distinguish different sediment facies types in the Gulf of Panama and the Gulf of Chiriquí a cluster analysis was performed using Ward`s Method with Euclidian distances. The Cluster analysis shows five different facies types that occur in both gulfs. Facies I to III are carbonate dominated, whereas facies IV and V have abundant terrigenous material **(Fig. 5.23)**. Facies I includes all samples with a photozoan assemblage.

Facies Ia represents a Coralgal facies, dominated by corals (37%), red algae (18%) and bivalves (11%). Facies Ib shows a Rhodmol facies, dominated by red algae

(34%), bivalves (21%) and corals (6%). Facies II is shows a Balamol facies with a dominance of Balanidae (36%), followed by bivalves (21%) and gastropods (11%). Facies III is a Mollusc facies with bivalves (35%) and gastropods (15%). Facies IV is a Foramol facies with abundant terrigenous material. The composition of the Foramol facies is similar to the mollusc facies with abundant bivalves (22%) and gastropods (9%), but also shows higher amounts of planktonic foraminifera (9%) and benthic foraminifera (5%). The terrigenous part of the Foramol facies is very high with 40%. Facies V is a bivalve terrigenous rich facies dominated by terrigenous material with a mean of 68%. The carbonates within facies V mostly are bivalves (13%). The Coralgal and Rhodmol facies, dominated by corals or red algae only exists in the Gulf of Chiriquí around Islas Ladrones, Hannibal Bank, Islas Secas, Islas Contreras and at the northeast edge of Coiba. Around Isla Parida and Montuosa facies I exist only at very limited areas (not shown in the maps because of their very limited extent). The Coralgal facies is found mostly in protected bays of Islas Secas and Islas Contreras, as well as Hannibal Bank and north of Coiba**.** Reefs around Islas Secas and Islas Contreras were also reported by Glynn et al. (1972) and Glynn and MacIntyre (1977). The Rhodmol facies occurs close to locations with the Coralgal facies, but also occurs at greater water depths. The Rhodmol facies is most abundant around Islas Ladrones. The northern parts of the islands are not very protected from currents bringing in fine terrigenous material from the north (Chapter 4 / Fig.4.20), what might be a reason for the absence of the Coralgal facies. The Rhodmol facies also exists in the same habitat as the Coralgal facies, like in Islas Secas, Islas Contreras, Hannibal Bank or northeast of Coiba.

The Balamol facies exits only in the Gulf of Panama with a preference for the areas around the Islands Isla Iguana, Isla Otoque towards the north and Isla del Rey in the Archipelago de Las Perlas. Smaller areas also occur around Isla Taboga and the Archipelago de Las Perlas in the north and south of Isla San Juan. The mollusc facies III occurs in both bays and shows the importance of molluscs as carbonate producer in both gulfs. The Foramol facies is influenced by terrigenous material in both gulfs and mainly occurs in the centre of both gulfs. The bivalve terrigenous rich facies occurs in both gulfs in areas with fine grain sizes (Chapter 4) or in areas with terrigenous input associated with rivers like in Parita Bay. The facies distribution **(Fig. 5.24)** shows that the Gulf of Panama is dominated by terrigenous material

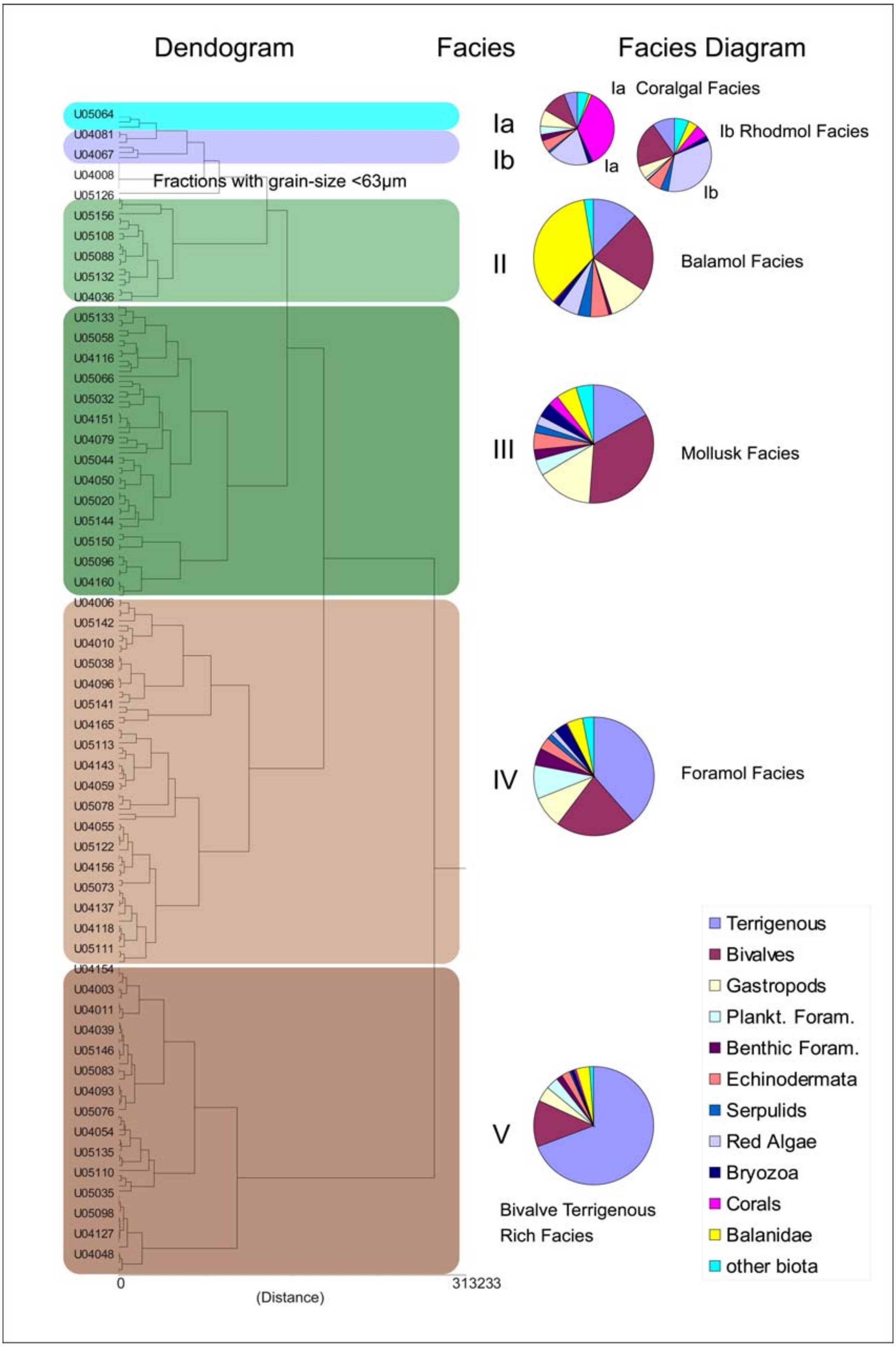


Fig. 5.23 Dendrogram showing each cluster with pie charts showing the mean percentage for each biota group in the individual facies types. Note that only every fourth sample number is shown, due to limited space. Facies I to III are carbonate dominated. Facies IV and V are strongly influenced by terrigenous material. Samples with 100% weight percentage <63µm (pure mud) were not taken into account for facies analyses.

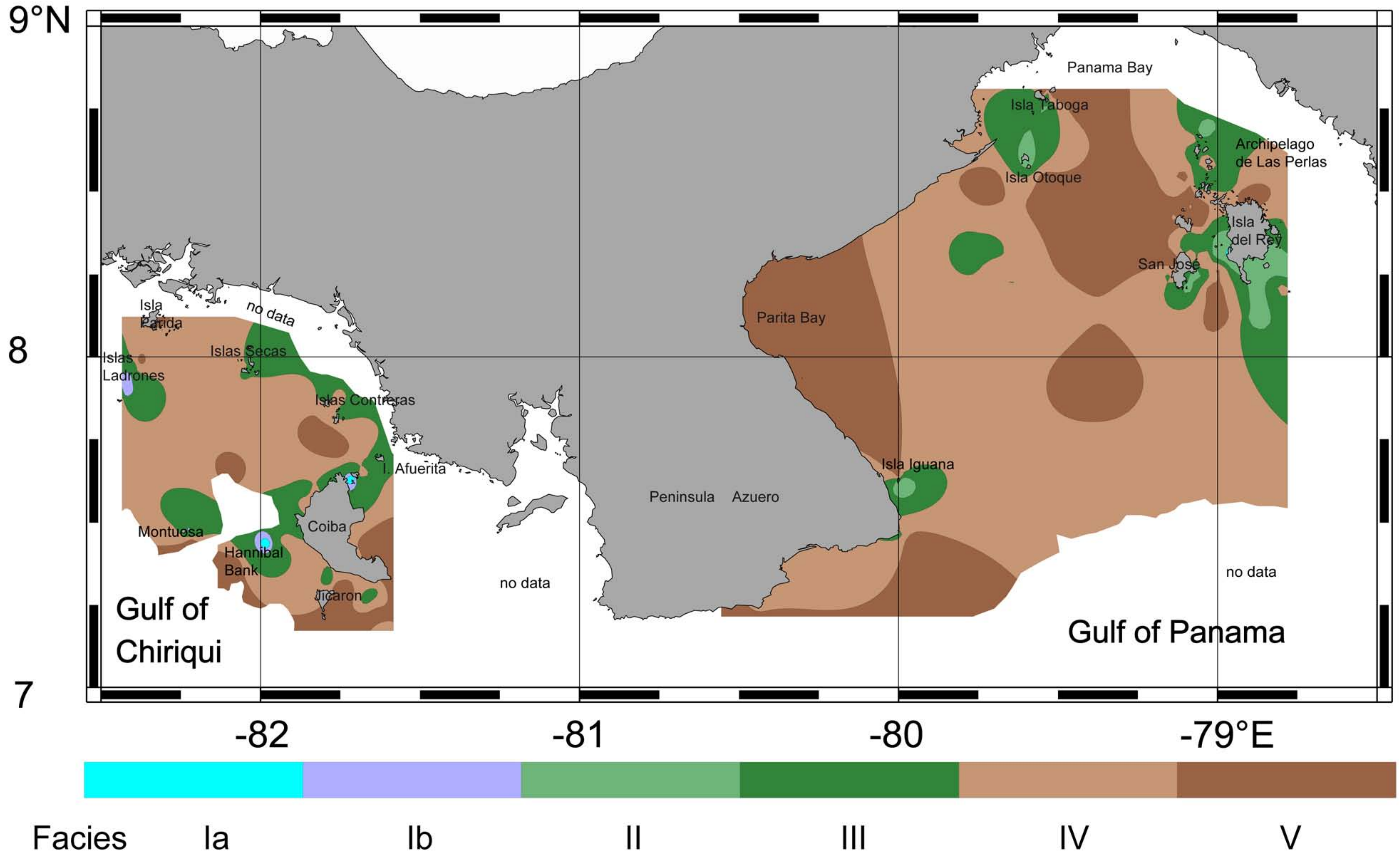


Fig. 5.24 Facies distribution in the Gulf of Chiriqui (GoC) and the Gulf of Panama (GoP). Facies I to III represent carbonate dominated facies, see text for explanation. Facies I occurs only in the GoC, whereas Facies II is restricted to the GoC. Facies IV and V (brownish colour) represent terrigenous dominated facies .

(Facies IV and V), while the Gulf of Chiriquí is dominated by carbonates (Facies I to III). This difference may be caused by the unevenly distribution of islands providing environments in which carbonate biota can develop and the difference in oceanographic conditions in both gulfs (see next paragraph). Islands with carbonate production areas only exist in the northern part of the Gulf of Panama. They are mainly located around the Archipelago de Las Perlas and small islands (Isla Iguana) at the south-eastern edge of Peninsula Azuero and north of Chame Bay (Isla Taboga and Isla Otoque). In the Gulf of Chiriquí numerous islands can be found, which are spread throughout the entire gulf (Fig. 5. 24) and allow abundant carbonate production.

5.4.7 Classification of carbonate environment

Carbonate production occurs in different trophic environments. Photozoan assemblages develop under tropical oligotrophic to slightly mesotrophic conditions, heterozoan carbonates prevail in polar to warm-temperate and mesotrophic to eutrophic conditions (Halfar et al., 2005). Carbonate production can take place in tropical and cool water conditions, but with different rates. However, numerous authors have shown that significant carbonate production can take place within present-day warm-temperate environments, which form the transition between aforementioned end members (Fornos and Ahr, 1997; Henrich et al., 1995, 1996; Halfar et al., 2000; 2001; 2005). The same holds for fossil warm-temperate environments (Manker and Carter, 1987; Carannante et al., 1995; Brachert et al., 1998; Carannante et al., 1998; Gischler et al. 1994; Vecsei and Sanders; 1999).
In the Gulf of Panama and the Gulf of Chiriquí the sediment components within the facies types were classified with respect to the environments in which they occur. Corals are characteristic for tropical carbonates, whereas high percentages of bryozoans, molluscs, echinoderms and foraminifers are typical for cool-water carbonates (Lees, 1975; Nelson, 1988; James, 1997; Halfar et al., 2000; 2001; 2005). The occurrence of the Coralgal facies, including molluscs and echinoderms, the absence of green algae and occurrence of the Rhodmol facies, including bryozoans, as well as the presence of the molluscs facies clearly suggest that oligotrophic to mesotrophic conditions prevail in the Gulf of Chiriquí

(Fig. 5.25). Zooxanthellate corals are substituted by coralline red algae with increasing nutrient condition. The Gulf of Panama shows mesotrophic to eutrophic conditions due to upwelling, which is shown by the Balamol facies. Latter facies only occurs in the Gulf of Panama and represents a heterozoan assemblage with balanids and echinoderms as well as molluscs. Halfar et al. (2005) showed that the dominance of balanids and echinoderms in parts of the warm-temperate Gulf of California indicate

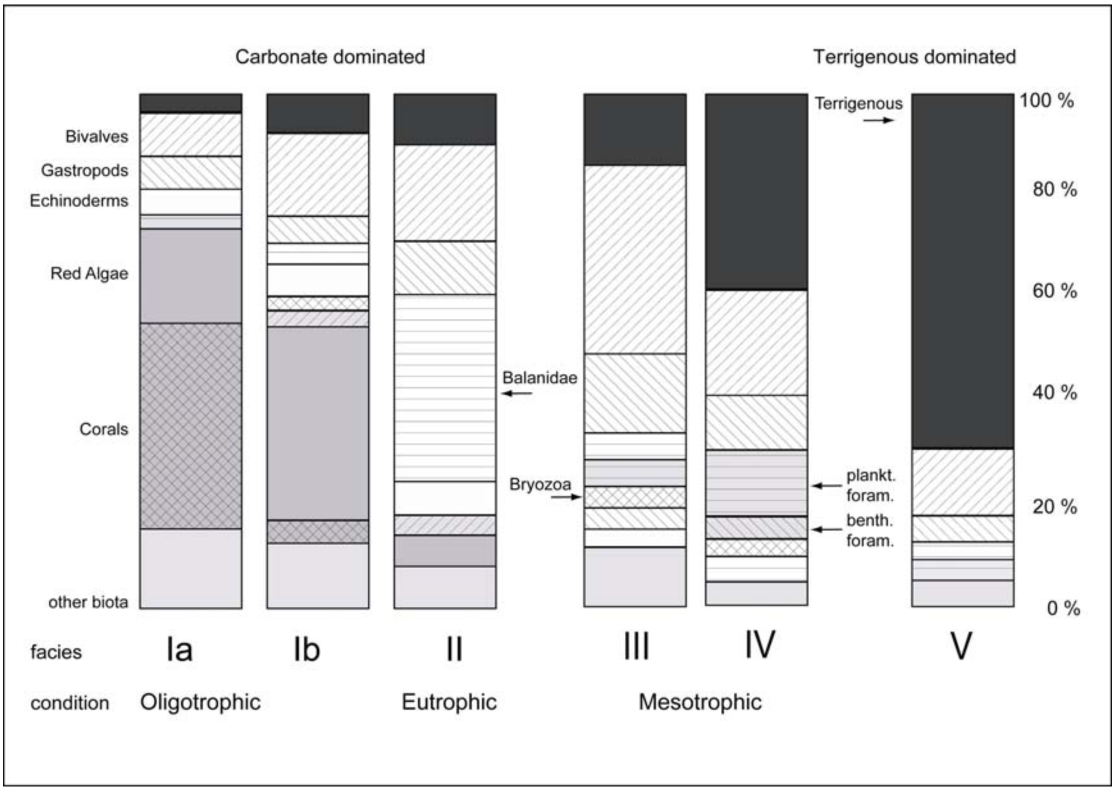


Fig. 5.25 Sediment facies found in the Gulf of Panama and the Gulf of Chiriquí, Facies I to III are carbonate dominated whereas facies IV and V are dominated at different levels by terrigenous material. Bottom of the graph shows the different environmental conditions related to the distinguished facies types. Facies I shows a photozoan assemblage which indicates oligotrophic conditions. Facies II (heterozoan) indicates eutrophic conditions whereas the mollusc dominated facies relates more to mesotrophic conditions.

eutrophic conditions. Corals (photozoan) do primarily occur in oligotrophic conditions, whereas coralline red algae are abundant in mesotrophic conditions. Balanids and echinoderms (heterozoan) are abundant in eutrophic conditions (Littler and Littler, 1985; Hallock and Schlager, 1986; Hallock, 1988, 2001; Halfar et al., 2000; 2005). In the Gulf of California similar conditions exists (Halfar et al., 2005) as those found in the Gulf of Chiriquí with a dominance of corals in oligo-mesotrophic conditions, and rhodolith dominance in more mesotrophic conditions.

5.5 CONCLUSIONS

Seasonal upwelling conditions in the Gulf of Panama have a major influence on the distribution of carbonate producing biota. In addition, carbonate production and distribution is influenced by the distribution of islands in both gulfs and by terrigenous input. The terrigenous material is mainly found in the smaller grain sizes (<63µm to 250µm) and therefore easily transported by currents and waves. Sediments with dominating carbonate content (carbonate sands and mixed carbonate-siliciclastic sands) are restricted to larger grain-sizes (>500µm) that mostly remained located near the places where they were produced. Fossil shells were only found in deeper water areas in the central Gulf of Panama. They could easily be distinguished from their recent counterparts, because of their brownish colour (Fe-stained).

Upwelling in the Gulf of Panama has only limited influence on the amount of carbonate produced, but has a major impact on the groups of carbonate producing biota. The carbonate assemblages around the islands within both gulfs differ significantly. Whereas photozoan assemblages prevail in the Gulf of Chiriquí, more heterozoan assemblages dominate in the Gulf of Panama. Both gulfs show neither pure tropical carbonates nor cool-water carbonates sensu stricto. The Gulf of Panama and the Gulf of Chiriquí actually contain carbonate-producing biota that may occur in both aforementioned environments. The shallow-water areas around the islands in the Gulf of Chiriquí show a dominance of coral- or rhodolith facies indicating oligotrophic to mesotrophic conditions. A mainly Balanidae-molluscan facies occurs around the islands within the Gulf of Panama suggesting mesotrophic to eutrophic conditions related to upwelling in the dry season (December to April).

CHAPTER 6

CONCLUSIONS

CHAPTER VI

6 CONCLUSIONS

The geological setting of Panama not only opens up the possibility to study fossil carbonate systems that developed before and during the formation of the Isthmus of Panama as we know it today, but also provides insight in the sedimentary environment of recent carbonate systems that at present can be found on the Pacific and Caribbean side of this Isthmus. The main objective of this study is to determine the impact of gateway closure on the diversification of carbonate ecosystems.

The closure of the Central American Seaway around 3.6 Ma not only resulted in changes in the Caribbean, the gradual development of the West Atlantic warm pool (e.g. Haug & Tiedemann, 1998), but also on the Pacific side of the Isthmus. Along the Pacific coast of Panama upwelling conditions regionally developed that is

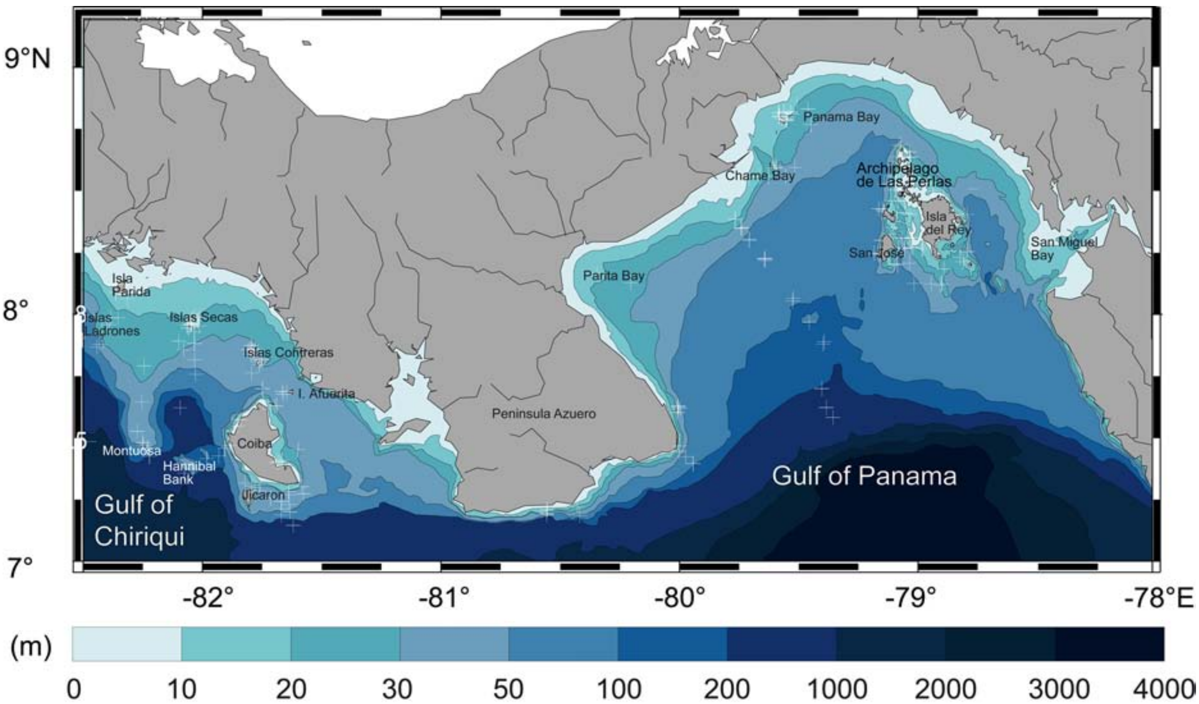


Fig.6.1: Map of the study area includes all sample locations. Bathymetry data taken from hydrographic charts (UK Hydrographic Office (UKHO) (Collins, 1973; Clark, 1998).

driven by the northeast-bound trade winds. In the Gulf of Panama, the carbonate producing benthic ecosystem has adapted itself to this new situation governed by increased nutrient supply through upwelling. In the Gulf of Chiriquí non-upwelling conditions still exists that are thought to be comparable to the setting existing in the region before the closure of the Central American Seaway **(Fig. 6.1).**

6.1 Pliocene sedimentation system (Chapter 3)

The study area near Limon comprises the most extensive mixed carbonate-siliciclastic sequences in Costa Rica (McNeill et al., 2000). The Early to late Pliocene facies around Limon is characterized by an environment with a diverse coast line with islands, varying sediment input through rivers, and sediment transport through

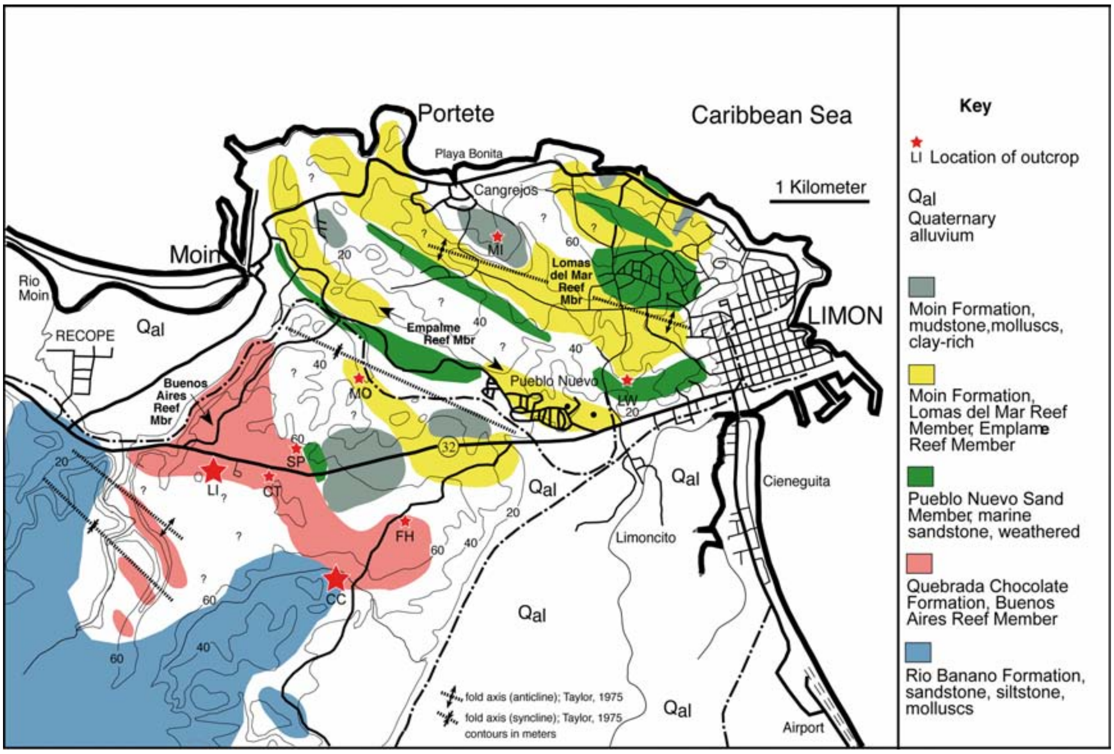


Fig. 6.2 Geology in the Area of Limon, Costa Rica. Studies focused on two outcrops within the Quebrada Chocolate Formation. The Las Islas (LI) roadcut along Route 32 and the newly discovered Contact Cut (CC). Map modified from McNeill et al. (2000).

currents in shallow tropical waters that existed in this region shortly before the final closure of the Central American Seaway. The Limon study area shows an early to late Pliocene reef evolution in an uplifted near-shore marine sequence. Neogene forearc (Pacific) and backarc (Caribbean) sedimentary basins formed on both sides of the volcanic arc. Only restricted marine connections existed between the marine basins on both side of the arc (Coates et al., 1992, Coates and Obando, 1996). The Central American archipelago developed and the southern Limon backarc basin became progressively shallower. The two different reef systems studied (Chapter 3) that existed shortly before the closure of the seaway (McNeill et al., 2000), showed this basin development through their shallow-water reef community. The stratigraphic position of the Contact Cut Reef **(Fig. 6.2)** lies close to well dated known formations (McNeill et al., 1997, 2000) and the well dated Las Islas Reef. Age of the Rio Banano Formation located at the base of the Contact Cut reef is dated at 3.5 to 3.7 Ma. The Buenos Aires Reef Member of the Las Islas Reef is dated at 3.6 to 3.7 Ma. The comparable ages of the reef systems is also strongly supported by (A) the similarity of their reef communities, (B) the comparable stacking pattern in the development of the reefs, as well as (C) the timing of the burial of the carbonates. The comparison of the coral communities with recent Caribbean Coral Reefs (Table 3.1/3.2) shows a similar community with fringing reefs, reef flats and outer back reef to lagoonal facies in a shallow environment close to the coast.

6.2 Modern day carbonate-siliciclastic systems (Chapter 4 and 5)

The Gulf of Chiriquí and the Gulf of Panama located on the Pacific side of Panama show two mixed carbonate-siliciclastic systems that exist under different oceanographic conditions. The present-day Pacific coast of Panama is influenced by the West Atlantic climate system and the tropical Pacific climate (El Niño, La Niña) and thus holds a key position connecting both systems. Different carbonate benthic ecosystems developed under upwelling (Gulf of Panama) and non-upwelling (Gulf of Chiriquí) conditions. The sedimentological comparison between these carbonates factories occurring under upwelling and non-upwelling conditions will help

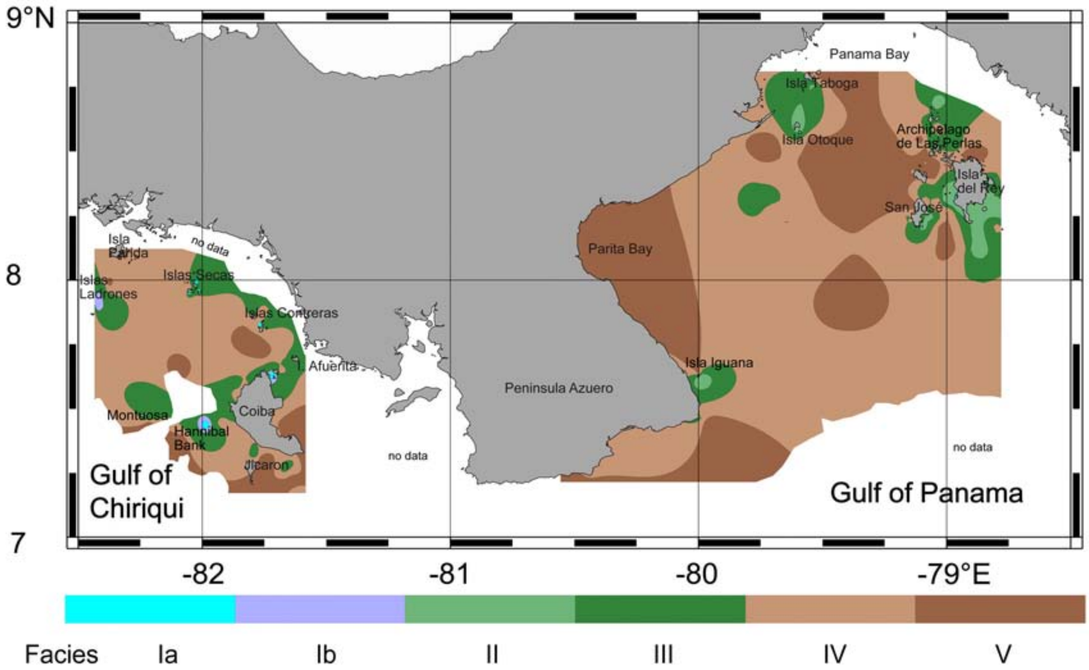


Fig. 6.3 Facies distribution in the Gulf of Chiriqui (GoC) and the Gulf of Panama (GoP). Facies I to III represent carbonate dominated facies, see text for explanation. Facies I occurs only in the GoC, whereas Facies II is restricted to the GoC. Facies IV and V (brownish colour) represent terrigenous dominated facies.

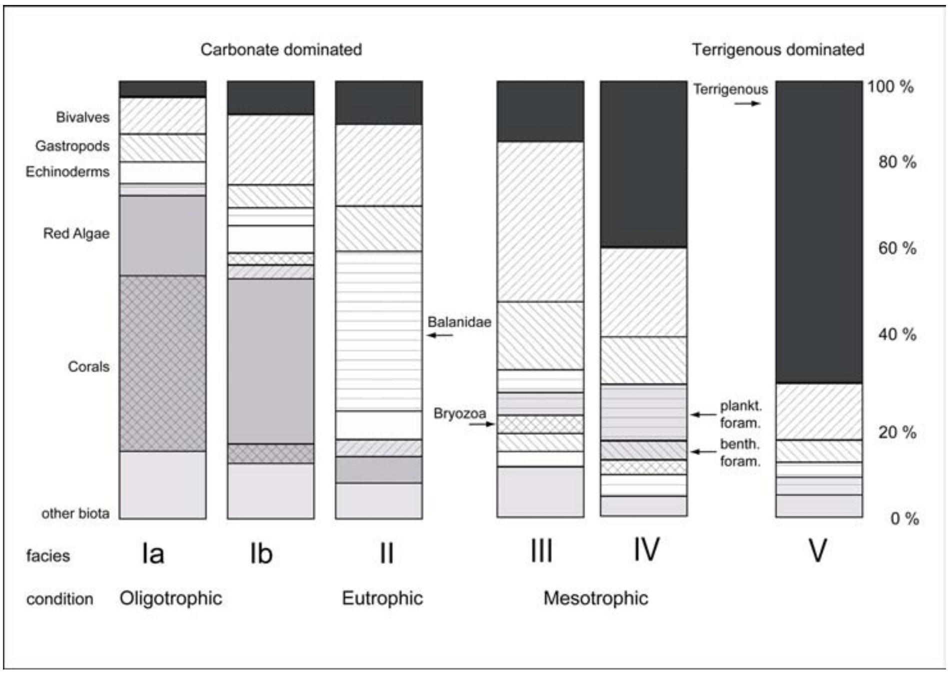


Fig. 6.4 Sediment facies found in the Gulf of Panama and the Gulf of Chiriquí, Facies I to III are carbonate dominated whereas facies IV and V are dominated at different levels by terrigenous material. Bottom of the graph shows the different environmental conditions related to the distinguished facies types. Facies I shows a photozoan assemblage which indicates oligotrophic conditions. Facies II (heterozoan) indicates eutrophic conditions, whereas the mollusc dominated facies relates more to mesotrophic conditions.

to determine the interaction between the ocean environment, river input and facies patterns. The Gulf of Chiriquí mainly shows photozoan (Coralgal) assemblages within the shallow water areas surrounding the islands and contains mollusc-dominated facies in deeper waters towards the shelf. The Gulf of Panama influenced by seasonal upwelling mainly shows heterozoan assemblages around the islands dominated by Balanidae, Echinodermata and/or molluscs **(Fig. 6.3/6.4)**. These assemblages suggest oligotrophic to mesotrophic conditions in the Gulf of Chiriquí, whereas mesotrophic to eutrophic conditions prevail in the Gulf of Panama. Both gulfs show warm-temperate carbonate-producing biota, with assemblages that occur in tropical carbonate producing environments (e.g. corals), as well as in cool-water carbonate producing environments (e.g. bryozoa).

6.3 Stressed carbonate environments (siliciclastic input, upwelling)

The carbonate environment in the Gulf of Panama and the Gulf of Chiriquí shows facies types, which include biota that are characteristic for tropical carbonates (e.g. corals) and biota that characterize cool-water carbonates (e.g. Echinodermata, Balanidae, bryozoans). The warm temperate environment on the Pacific coast of Panama shows a diverse pattern with photozoan assemblages that prevail in the Gulf of Chiriquí and more heterozoan assemblages that dominate in the Gulf of Panama and thus neither show pure tropical nor pure cool water carbonate depositional systems. The prevailing heterozoan assemblages in the Gulf of Panama evolved in response to the upwelling conditions that developed in the Gulf of Panama after the closure of the Central American Seaway but is also influenced by the high terrigenous input from the rivers. However, the photozoan assemblage in the Gulf of Chiriquí developed in a comparable tropical environment with significant siliciclastic input as found in the Pliocene reef communities studied in Costa Rica.

The analysis of the sediment distribution, mineralogy and grain-size variations in the Gulf of Panama and the Gulf of Chiriquí shows the differences in sediment production, sediment transport and the current and wave regime within both gulfs resulting in different sediment facies. The distribution of clays to fine sands In the Gulf of Panama is mainly influenced by the counter-clockwise current in the gulf which is induced by the extensions of the Humboldt Current. The sedimentation pattern observed in the channels within the Archipelago de Las Perlas, which show terrigenous sediment transport, are comparable with the environment as found in the Limon study area (Chapter 3) shortly before the final closure of the Central American Seaway, with rivers and channels transporting terrigenous material towards the carbonate producing bays around the islands. Carbonates in the Pliocene setting around Limon and in the modern day setting of the Gulf of Panama, are stressed by terrigenous input **(Fig. 6.5/**Fig. 3.3**)**

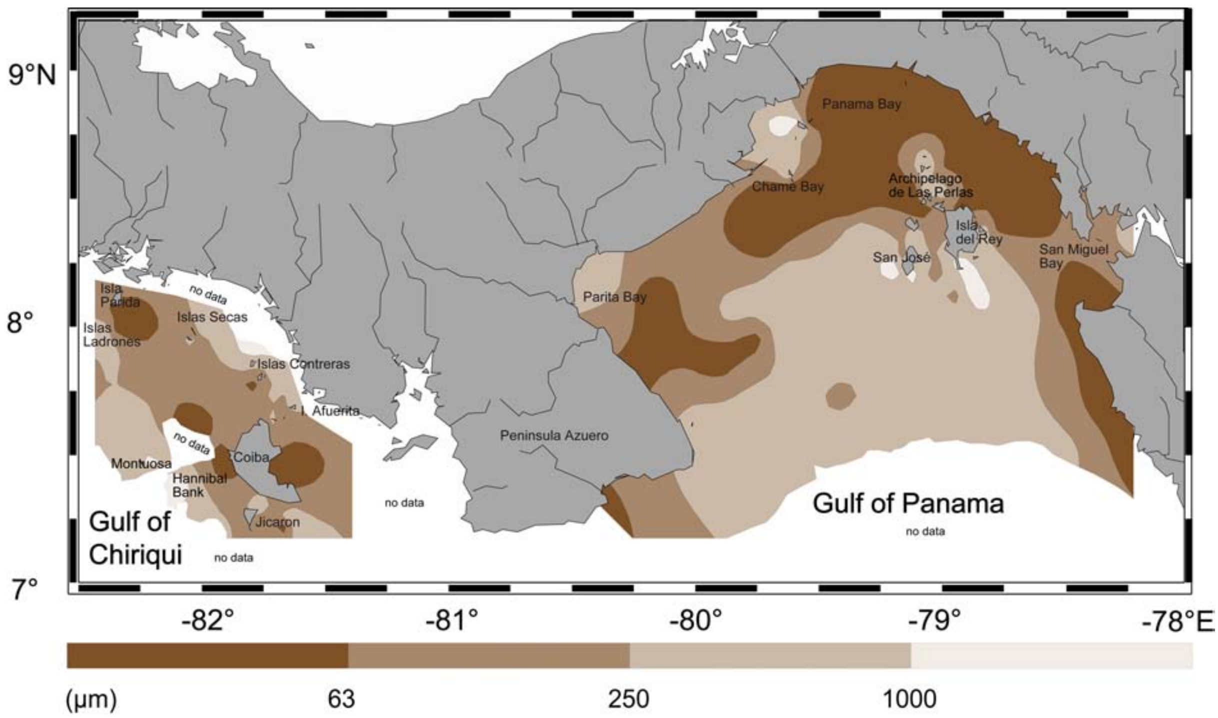


Fig. 6.5: Grain size distribution map showing own clustered data and literature data from MacIlvaine and Ross (1973). As for the data shown in Fig. 4.17, fine sediments occur along the coast in the Gulf of Panama except for Parita Bay, Chame Bay and San Miguel Bay. Coarse sediments are present around the islands in the Gulf of Chiriqui and the Gulf of Panama. Defined clusters <63µm (IV); cluster 63µm-250µm (III); 250µm-1000µm (II); 1000µm->2000µm (I).

Encrusting forms of red algae prevail, and the coral abundance and diversity diminishes because of upwelling (Gulf of Panama) and terrigenous input (Gulf of Panama; Gulf of Chiriquí; Pliocene, Limon). In the Gulf of Panama upwelling actually is the major factor influencing the carbonate biota that develop in this

environment. However, the large amount of terrigenous material that is introduced in the sedimentary systems of the Gulf of Panama and the Gulf of Chiriquí also contribute to the stressful situation in which the carbonate biota developed.
The terrigenous material is mainly present as sediment with small grain sizes from <63µm to 250µm (except of sands derived from river input in Parita Bay and Chame Bay in the Gulf of Panama) and therefore easily can be transported by currents and waves. The sediment distribution pattern in the Gulf of Panama is strongly influenced by strong currents related to seasonal variations. The prevailing northern winds induce currents that transport fine material towards the shelf. The clays to silts are transported by currents in a counter-clockwise direction within the Gulf of Panama. These counter-clockwise currents associated with the Humboldt Current tend to transport the fine material off the shelf towards the coast, whereas the wind forced Panama Current tends to transport the clays to the central gulf towards the shelf.

The Gulf of Chiriquí shows a normal distribution pattern of surface sediments in which all grain size fractions are represented. Coarser sediments are found along the coast of the mainland and finer material occurs below the wave base and towards the slope in deep water areas below 200m. Exceptions to this distribution pattern are clays to very fine sands that are located close to the coastline in areas with mangrove forests. The distribution pattern of terrigenous input is only interrupted by carbonate sands that are present around the islands.

In both gulfs sediments with a high carbonate content (carbonate sands and mixed carbonate-siliciclastic sands) show a dominance of large grain-sizes (>500µm) and a limited lateral extent, which shows that the majority of these carbonate sediments remain within the area where they were produced. Fossil shells were only found in deeper water areas in the central Gulf of Panama.

6.4 Reef communities

The Pliocene reef communities were primarily dominated by *Stylophora ssp.* and *Goniophora ssp.* with *Poritidae and Agaricitidae*. The studied early late Pliocene Buenos Aires Reef Member was dominated by *Stylophora ssp., Diploria ssp.* and

Montastrea ssp. that occurred on the reef front and *Dichocoenia ssp*., *Poritidae and Agaricitidae*, which occupied the reef crest (Table 6.1). Present-day Caribbean reefs are dominated by *Diploria ssp.*, *Acropora ssp,* and *Montastrea ssp*. Coral communities in the Gulf of Chiriquí show a dominance of *Pocciloporidae, Poritidae, Agaricitidae and Milleporidae.*

The tropical coral communities of the Caribbean; on the Pacific side and during the Pliocene in the Limon region are dominated by different coral families, genera and species. However, the studied Pliocene coral communities show families which appear on modern day Caribbean reefs (e.g. *Diploria* and *Montastrea*) and families that appear in modern reefs on the Pacific side of Panama (e.g. *Poritidae and Agaricitidae*. This is due to the fact that the modern-day reef ecosystem in the Caribbean and on the Pacific side of Panama evolved from the population thriving in this region before the closure of the Panamanian Isthmus.

The Early to late Pliocene facies around Limon (Costa Rica) and the present day sediments in the Gulf of Chiriquí and the Gulf of Panama, all show a mixed carbonate-siliciclastic sedimentation system in which carbonate benthic ecosystems developed in an environment stressed by terrigenous input.

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PERSONAL INFORMATION

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Address	Leibniz Institute of marine sciences IFM - GEOMAR Dienstgebäude Ostufer Wischhofstr. 1-3, Geb. 4, Raum 226 D- 24148 Kiel; Germany
Telephone Fax	0049 431 600-2866 0049 431 600-2949
E-mail	tbauch@ifm-geomar.de info@thbauch.de
Date of birth	20.09.1975, Lüneburg, Germany
Nationality	german

EDUCATION

since 2003	Ph.D. within the Research Unit "Impact of Gateways on Ocean Circulation, Climate, and Evolution"
1999-2002	Diploma (M.Sc.) at the Christian-Albrechts-Universität of Kiel Main courses: Marine Geology and Paleontology Mapping*:* Geologische Kartierung des Gebietes NW von Villamanín, Provinz Castilla y León (NW Spanien) Diploma Thesis: Sedimentation cycles on a Pliocene carbonate slope (Site 1006, ODP Leg 166, Bahama Transect)
1996-1999	B.Sc. in Geology at the Rheinischen Friedrich-Wilhelms-Universität of Bonn

WORK EXPERIENCE

since Oct. 2003	Carbonate sedimentologist, current Ph.D.; Christian Albrechts University of Kiel and IFM-GEOMAR Leibniz Institute for Marine Geosciences.
Jul.–Sep. 2003	Security Officer: inter-SAFE GmbH
Mar.-Jun. 2003	Contract Web Content Coordinator; Christian Albrechts University of Kiel.

Nov. 2002	Contract Web Designer / Web Application Developer (part-time); KOGGE - Setting up of self-employed premium.
Nov. 1999 – Feb. 2003,	Marine Geological Research Assistant; IFM-GEOMAR Leibniz Institute for Marine Geosciences.
Apr. 1998 – Oct. 1999,	Project Geologist Assistant / Geotechnical Engineer Assistant; Kühn Geoconsulting GmbH.

SHIPBOARD EXPERIENCE

2005 RV Urracá, Gulf of Panama and Gulf of Chiriquí
Facies mapping of Gulf of Panama and Gulf of Chiriqui

2004 RV Bellows, Great Bahama Bank
Facies mapping of the Great Bahama Bank

2004 RV Urracá, Gulf of Panama and Gulf of Chiriquí
Paleoceanography and carbonate sedimentology in upwelling vs. non.-upwelling areas

FIELDWORK EXPERIENCE

2004 Panama
2004 Costa Rica, Limon Basin
2002 Spain, Villamanin (Mapping)

LANGUAGES

Mother tongue	German		
Other languages	English	French	Spanish
Reading/writing/verbal skills	Excellent	High school level	Basic

ANNEX

MEMBERSHIP IN SCIENTIFIC SOCIETIES

SEPM Society for Sedimentary Geology
International Association of Sedimentologists (IAS)
National Geographic Society

PUBLICATIONS, DIPLOMA THESIS AND CONFERENCE CONTRIBUTIONS

Bauch, Th., Reijmer, J. J. G., Schäfer, P., Bader, B, Fortunato, H.: Facies patterns in upwelling vs. non-upwelling environments (E-Pacific); (in prep.).

Bauch, Th., Reijmer, J. J. G., Schäfer, P. Bader, B., Fortunato, H.: Sediment distribution in the Gulf of Panama and the Gulf of Chiriquí (E-Pacific); (in prep.)

Bauch, Th., Reijmer, J. J. G., Schäfer, P., McNeill, D. F.: Development of a mixed-carbonate siliciclastic reef-complex during the closure of the Central American Seaway (Pliocene, Limon, Costa Rica); (subm.).

Reijmer, J.J.G., Swart, P.K., **Bauch, Th.**, Reuning, L., Roth, S., Otto, R., Zechel, S. (2006); A new facies map of Great Bahama Bank. IAS Special Publication.

Reuning, L. , Reijmer, J. J. G. , Betzler, C. , Swart, P.K. , **Bauch, Th.**: The use of paleoceanographic proxies in carbonate platform settings - opportunities and pitfalls .In: ; (2005) Sedimentary Geology Special Issue "Sedimentology in the 21st Century - A Tribute to Wolfgang Schlager 175, S. 131-152.

Diploma Thesis:

Bauch, Th., Sedimentation cycles on a Pliocene carbonate slope (Site 1006, ODP Leg 166, Bahama Transect), unpubl. Diploma thesis, Christian-Albrechts-Universität zu Kiel, IFM-GEOMAR, pp. 58; (2002).

Bauch, Th., Geologische Kartierung des Gebietes NW von Villamanín, Provinz Castilla y León (NW Spanien), unpubl. Diploma thesis mapping, pp. 82; (2002).

Poster

Bauch, Th., Bader, B, Reijmer, J. J. G., Schäfer, P., Fortunato, H Upwelling vs. non-upwelling carbonate depositional settings on the modern tropical shelves of Panama (E-Pacific); Sediment 2005

Reuning, L., **Bauch, Th.**, Reijmer, J. J. G., & Betzler, C.: Semi-precession cycles at the slope of the Early Pliocene Great Bahama Bank. In: Sediment 2002, Vol. 17 (Ed. by H. Hüssner, M. Hinderer, A. E. Götz and R. Petschick). Schriftenreihe der Deutschen Geologischen Gesellschaft, Frankfurt a. M. - Darmstadt, Germany.

Reuning, L., Reijmer, J. J. G., **Bauch, Th.** & Betzler, C.: Evolution of Sedimentation Cycles on the Slope of a Carbonate Ramp with Changing Morphology (Bahamas, ODP Leg 166); SEPM Meeting at the 2002 AAPG Annual Convention, Houston, Texas.

Ich erkläre hiermit, daß es sich um meinen ersten Promotionsversuch handelt.
Ich erkläre ebenfalls, daß ich die Dissertation, abgesehen von den ausdrücklich bezeichneten Hilfsmitteln und den Ratschlägen von den jeweils namentlich aufgeführten Personen, selbständig verfaßt habe.

Kiel, den 25.09.2006

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(Thorsten Bauch)