COASTAL GEOMORPHOLOGY
PLAYA GUIONES, GUANACASTE PROVINCE COSTA RICA

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PLAYA GUIONES, GUANACASTE PROVINCE COSTA RICA

AARON MICHAEL BERTRAM, Hons. B.Sc.

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AUTHOR: Aaron Michael Bertram, Hons. B.Sc.

SUEPRVISOR: Susan Vajoczki

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ABSTRACT

This research provides the first detailed study of the coastal geomorphology of Playa Guiones, Guanacaste Province Costa Rica. Playa Guiones is located within a tropical wet/dry climate necessitating that field work is completed in both seasons to ensure a broad understanding of the coastal characteristics. The research commenced February 2005 with site selection and preliminary field work. During June 2005 a detailed real-time kinematic GPS survey and beach inventory (sediment, rock and vegetation) was conducted. During a third field session a comparison was made between the current observed coastal characteristics and those observed during the two other field seasons.

Playa Guiones is composed of primarily fine grained sand and carbonate shell material. Rock samples collected adjacent to the southern headland on the rocky shore platform consisted of limestone and finely grained, interbedded sandstone and siltstone. Adjacent to the northern headland on the rocky shore platform the rock consisted of sandstone.

Playa Guiones displays some temporal variability which may be linked to the wet and dry seasons. On initial inspection Playa Guiones appears to have the characteristics of an embayed beach but more detailed inspection illustrates that Playa Guiones has many characteristics that are contradictory to a typical embayed beach. Although Playa Guiones lies on a convergent margin it has many characteristics of a divergent margin coast.

This study is significant because it provides important baseline information for future work. Playa Guiones is located on the Nicoya Peninsula where a large seismic gap, which last fully ruptured in 1950, is known to exist. The baseline data will be very useful subsequent to any future earthquake event for measuring change that occurs along this rapidly developing coastline.

The methodologies employed in this study provide much more detail information than is typically collected in geo-indicator studies which often only measure several profiles along a beach to create a digital elevation model rather than the 3 m gridding distance used in this study.

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CHAPTER 1: INTRODUCTION

1.1 Overview

This study focused on the coastal geomorphology of Playa Guiones, Guanacaste Province Costa Rica (Figure 1.1). Costa Rica, a tectonically active region, is centered at 10°N 84°W. It forms the southern province of Central America and lies within the Caribbean Plate, adjacent to the subducting Cocos Plate at the Middle American Trench (Escalante, 1990). Playa Guiones comprises the southern portion of the Ostional Wildlife Refuge which extends for approximately 11 km along the Pacific coast of the Nicoya Peninsula (Campbell, 1998). The northern portion of this Refuge is one of the most important olive ridley (*Lepidochelys olivacea*) nesting sites in the world (Campbell, 1998). Playa Guiones has few turtle nesting sites but is under considerable land use pressure from tourism development.

1.2 Aims of the Thesis

This research project provides the foundation for a series of studies which are being undertaken along this section of coastline. The primary aim of this study was to establish a thorough understanding of the current coastal conditions on Playa Guiones as a baseline for future studies. A secondary aim was to measure qualitative shoreline change during the period 1940 to 2005 at Playa Guiones, Gaunacaste, Costa Rica. The analysis for the primary aim of the thesis involved collection of current sediment, rock and vegetation

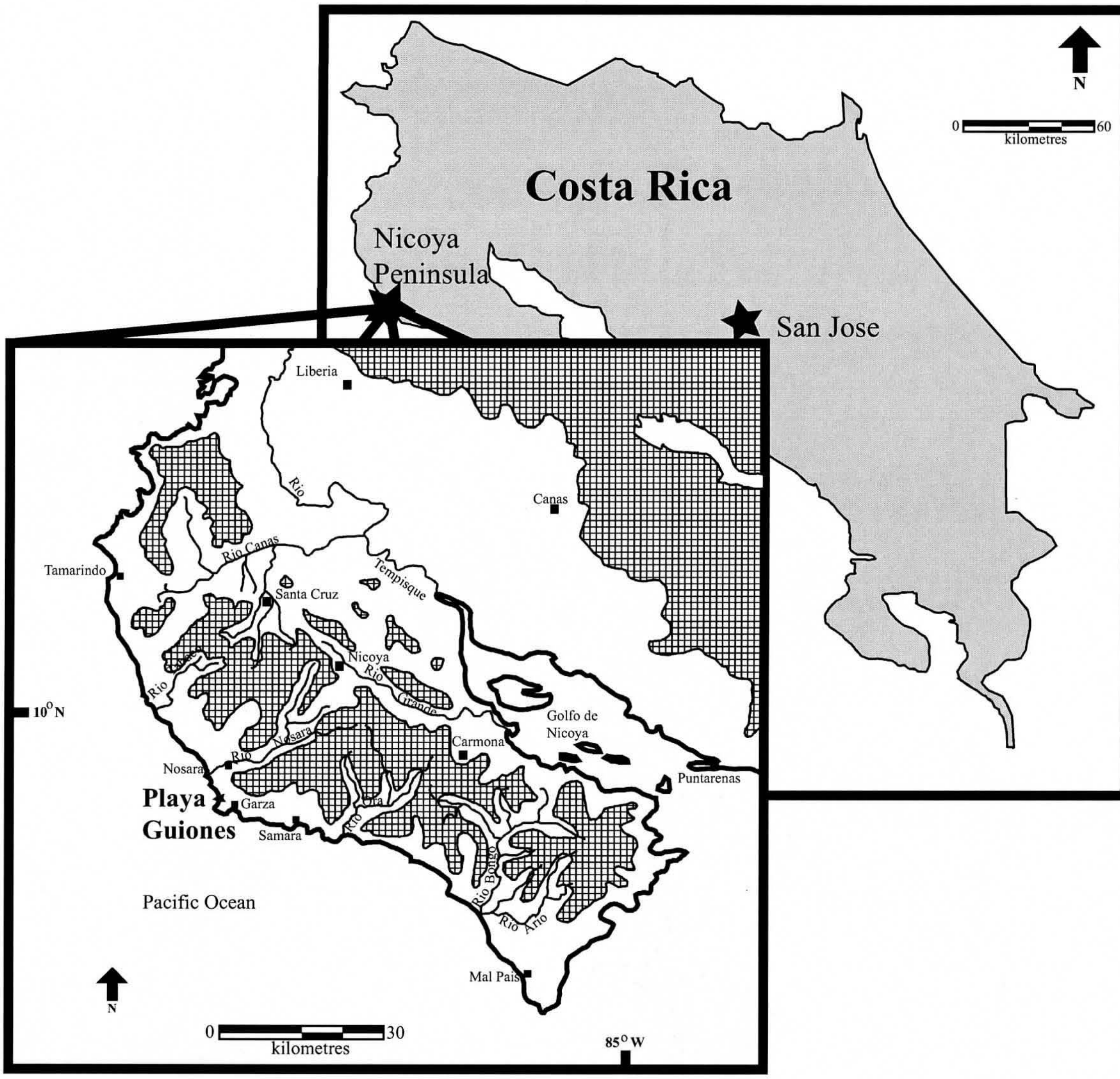


Figure 1.1: Map illustrating the position of the Nicoya Peninsula within Costa Rica. The inset map shows the location of the study area, Playa Guiones, on the western coast of the Nicoya Peninsula. The inset map is modified from: Marshall and Anderson, 1995

data and detailed examination of current topograpic information through the creation of a digital elevation model, from real time kinematic global positioning system (RTK GPS) data. The analysis for the secondary aim of the thesis involved a qualitative time series analysis of remotely sensed imagery including aerial photographs and a Quickbird satellite image.

1.3 Relevance

Monitoring shoreline change along the Costa Rican coastline is important for two main reasons. First, tourism within Costa Rica has exploded in the past fifteen years. Tourist arrivals have increased from 435 000 visits in 1990 to 1 032 000 visits in 2000 (United Nations, 2006). Many of these tourists are attracted to coastal regions that boast miles of sandy beaches, coral reefs and waves for surfing. Understanding the nature of the shoreline is important for making effective decisions regarding land use practices in this region.

Secondly, Fernandez et al., 2000 demonstrate that 43% of large earthquakes ($M_s \geq 7$) along the Pacific coast of Central America and 100% along the Caribbean coast generate tsunamis. During the period 1850-1996, 49 tsunamis have impacted Central America with 37 along the Pacific coast and 12 along the Caribbean coast. These tsunamis have resulted in 455 deaths (Fernandez et al., 2000). Goes et al., 1993 have identified a large seismic gap along the Nicoya Peninsula which last fully ruptured in 1950 with a $M_s = 7.7$ event. Given the seismic risk, the increasing number of Costa Ricans living along the Pacific coastline and the large number of tourists who visit this region, who likely have minimal understanding of earthquake and tsunami risk, it is important for effective risk mitigation to more fully understand the current coastline dynamics.

1.3 Organization of Thesis

Chapter One provides an overview of the thesis and describes the aims of the study. Chapter Two discusses the regional geology and tectonics of Costa Rica. It provides background information on the study area and an introduction to coastal geomorphology including a discussion of geo-indicators. Chapter Three describes the different methodologies employed in this research project (field, analysis and laboratory methods) and their respective limitations to this study. Chapter Four presents and discusses the results of this project, highlighting the relevance of the results. Chapter Five concludes and summarizes the main points of the study as well as providing insight into direction for further work in this area.

CHAPTER 2: BACKGROUND AND PREVIOUS WORK

2.1 Introduction

This chapter commences with a discussion of the regional geology and tectonic setting of Costa Rica, and the Nicoya Peninsula. This is followed by an introduction to the field site Playa Guiones. Background coastal geomorphology and the use of geoindicators to monitor shoreline change will also be described.

2.2 Regional Setting

2.2.1 Costa Rica

Costa Rica with a population of 4 million people borders the Caribbean Sea and Pacific Ocean between Nicaragua and Panama (CIA, 2006). It comprises an area of 51,000 km^2, but, is no wider than 280 km at its widest point (CIA, 2006). The Caribbean coastline extends for 210 km, whereas, the Pacific coastline extends for more than 1000 km and consists of four major peninsulas: Santa Elena, Nicoya, Osa and Burica (Instituto Geográfico Nacional Costa Rica, 1981).

Regional Geology

Costa Rica centered at 10°N 84°W forms a portion of the southern province of Central America and lies within the Caribbean Plate, adjacent to the subducting Cocos Plate at the Middle American Trench (Escalante, 1990). Southern Nicaragua, Costa Rica and Panama comprise the southern province which was termed by Schuchert, (1935) as the Isthmian Link and later termed the South Central American Orogen by Dengo, 1962, Lloyd, 1963 (Escalante, 1990). This region is influenced by four tectonic plates: Cocos Plate, Nazca Plate, Caribbean Plate and the South American Plate (Figure 2.1). The movement of these plates provides Costa Rica with attributes such as: volcanism, earthquakes, karst and an overall tectonic instability (Gardner et al, 1987).

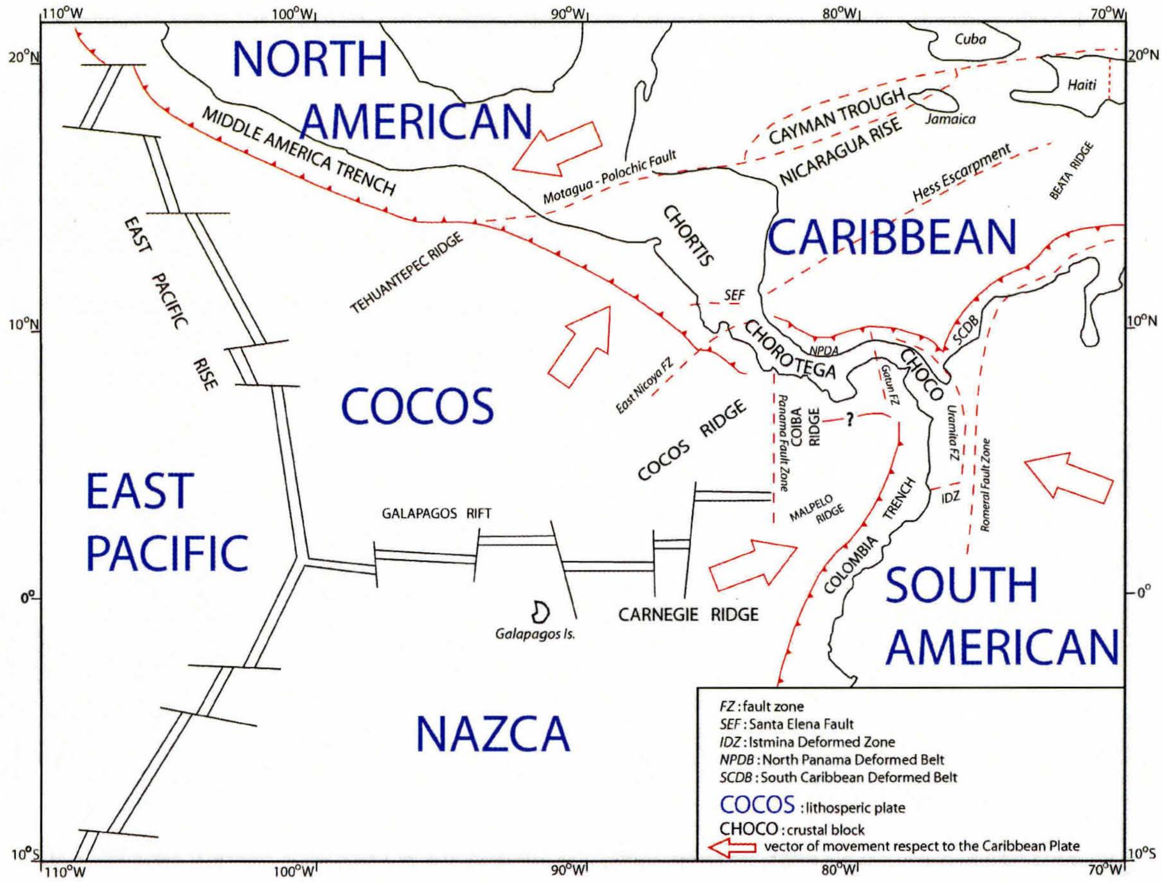


Figure 2.1: Lithospheric plates (names are in bold) in Central America. The arrows indicate the vector of plate movement relevant to the Caribbean Plate (modified from: Gardner et al., 1987).

The interaction and influence from the tectonic plates have been the major factors to produce Costa Rica's major physiographic features (Gardner et al, 1987). Currently the primary tectonic influence in Central America is from the subduction of the Cocos Plate at the Middle American Trench under the western edge of the Caribbean Plate which has resulted in the volcanic activity evident in Central America. The Cocos Plate, which is defined by the East Pacific Rise on the west portion of the plate, the Galapagos Rift Zone along the southern portion and the Panama Fault Zone along the eastern portion, is moving northeastward relative to the Caribbean Plate resulting in an estimated convergence along the Pacific coast of Costa Rica of 100mm/yr which has resulted in rapid uplift of 1.0 – 4.00 mm/yr (Gardner et al, 1987). The effect from the active tectonics has produced a very complex geology for Central America.

The South Central American Orogen is composed of Cretaceous oceanic crust and ophiolites (i.e. Nicoya Complex) that are overlain by Cretaceous, Tertiary, and Quaternary marine and volcanic rocks (Gardner et al, 1987). During the late Tertiary and Quaternary the sequence underwent complex deformation and was subsequently intruded by late Tertiary (Neogene) granodiorites (Gardner et al., 1987). The next layer in the sequence is a series of Tertiary and Quaternary volcanics of the Middle America Volcanic Province. These tectonic interactions have created four distinct structural subdivisions within Costa Rica (Figure 2.2). These include: the accreationary zone, the fore arc ridge, the magmatic fore arc and the back arc basin (Limon-Bocas Del Torro Basin) (Escalante, 1990). The accretionary zone and the fore arc ridge provide the tectonic framework for the Nicoya Peninsula.

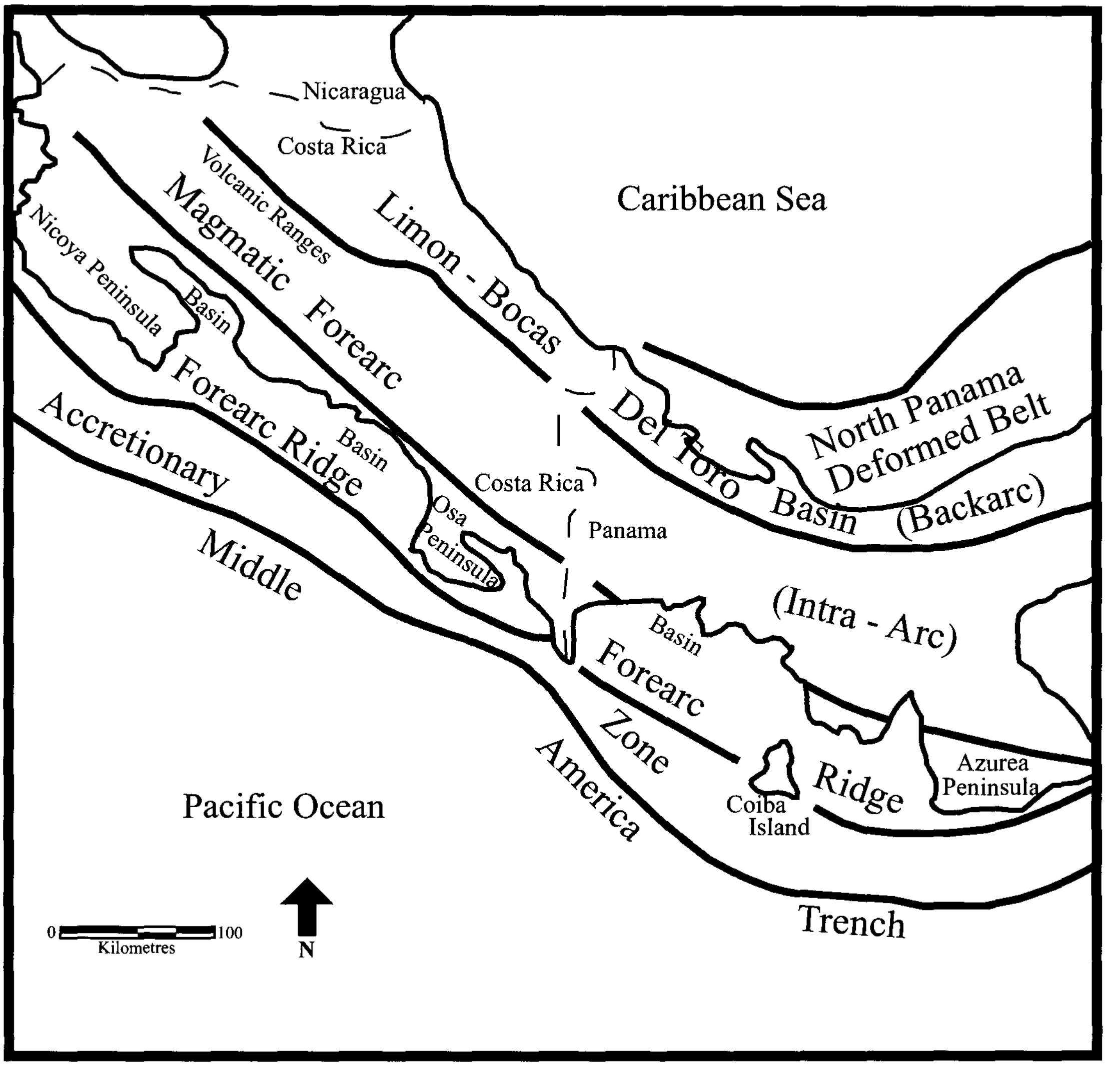


Figure 2.2: Structural subdivisions of Costa Rica (modified from Escalante, 1990)

In the accretionary zone, sediments are scrapped off the Cocos Plate as it subducts beneath the Caribbean Plate along the Middle American Trench and subsequently form the accreationary wedge and its associated formations. These sediments are a potential sediment source for beaches along the Pacific coast of Costa Rica.

The Costa Rican fore arc is divided into two portions: a northern and southern fore arc. Studies conducted by Astorga et al. (1991) on regional geology; Güendel and Pacheco (1992), Goes et al. (1993) and Fan et al. (1993) on seismicity; and by Marshall et al. (1993) and Fisher et al. (1994) on fault kinematics have lead to the hypothesis that the Caribbean-Panama boundary (is shown by the East Nicoya Fault Zone on Figure 2.1) transects central Costa Rica and intersects the Pacific coast southeast of the Nicoya Peninsula (Marshall and Anderson, 1995). As seen in figures 2.1 and 2.2 this hypothesis requires two fore arc regions: the northern fore arc associated with the Caribbean Plate and the southern fore arc belonging to the Panama microplate (Marshall and Anderson, 1995). Even though the Caribbean-Panama boundary has a large effect on landward tectonism, the characteristics of the seafloor being subducted offshore is the principal controlling factor within the deformation of the fore arc (Marshall and Anderson, 1995). This has resulted in variations among the segmented fore arcs along the Pacific coast as the different portions of the Cocos Plate are subducted. The northern fore arc, which subducts beneath the Nicoya Peninsula, is comprised of relatively dense and smooth oceanic crust that was created during the late Oligocene at the East Pacific Rise (Marshall and Anderson, 1995; Hey, 1977; Klitgord and Mammerickx, 1982). The southern Costa Rican fore arc undergoes subduction of buoyant seamounts that originated from the

Cocos-Nazca boundary during the early Miocene (Marshall and Anderson, 1995; Hey, 1977; Lonsdale and Klitgord, 1978). Further southward the southern Costa Rican fore arc is further subducted by the buoyant Cocos Ridge under the Osa Peninsula, which was created in the middle Miocene at the Cocos-Nazca boundary (Marshall and Anderson, 1995; Hey, 1977; Lonsdale and Klitgord, 1978). These distinct differences within the subducting Cocos Plate create significant variations in Wadati-Benioff zone geometry, seismic potential, arc volcanism, trench morphology and fore arc deformation (Marshall and Anderson, 1995).

Tectonic History

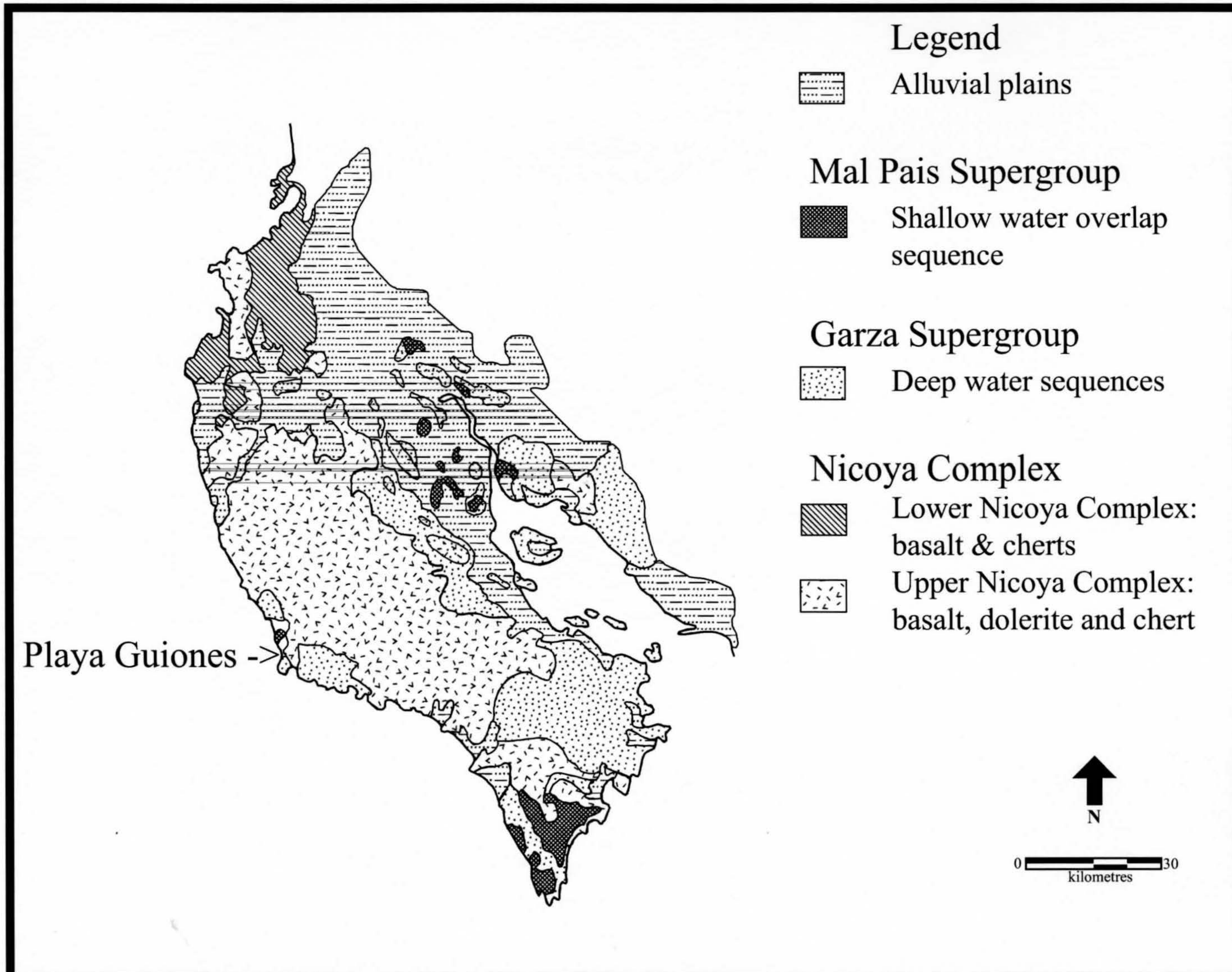
During the late Miocene, approximately 8 Ma, the Panama Fracture Zone grew northward to intersect the Middle American Trench in the vicinity of the Nicoya Peninsula (Gardner et al., 1987). At this time, the Panama Triple Junction was created and subduction east of the Panama Triple Junction beneath Costa Rica became much more oblique with a decrease in relative velocity (Gardner et al., 1987). Within the vicinity of the Nicoya Peninsula, along the west side of the Panama Triple Junction, a relatively high convergence rate continued with subduction (Gardner et al., 1987). Subduction continued as the Panama Triple Junction slowly moved southeasterly but volcanic activity decreased drastically due to the slow down in convergence on the eastern side of the Junction. Starting approximately 1 Ma the Cocos Ridge began interacting with the Middle America Trench and subducting beneath Peninsula de Osa in southern Costa Rica. This interaction with the buoyant Cocos Ridge resulted in localized fore arc deformation and up lift which differs from the subduction occurring along the Nicoya Peninsula that is considered to occur under normal parameters, unaffected by the Cocos Ridge interaction (Gardner et al., 1987; Gardner et al, 1992).

2.2.2 Nicoya Peninsula

The Nicoya Peninsula is located on the Pacific coast of northwestern Costa Rica and comprises approximately 2400 Km^2 of the northern Costa Rican fore arc (Marshall and Anderson, 1995). The Middle American Trench runs parallel with the peninsula as well as the Cordillera de Guanacaste; the northern Costa Rican volcanic arc. The bedrock geology of the Nicoya Peninsula is largely comprised of the Nicoya Complex, a Triassic to Cretaceous ophiolites sequence containing pillow basalts, mafic intrusions and pelagic sediments that have been intensely deformed (Marshall and Anderson, 1995). The Nicoya Complex is then unconformably overlain by a late Cretaceous and Cenozoic sedimentary rock sequence, the Garza and Mal Pais Supergroups (Vannucchi et al, 2001; Marshall and Anderson, 1995; Gardner et al., 1987). This sequence begins with the Garza Supergroup which is subdivided into two different groups: Sabana Grande Group and Samara group (Figure 2.3).

A large seismic gap exists along the Nicoya Peninsula. The last full rupture along this gap occurred in 1950 with a M_s= 7.7 major earthquake (Goes et al., 1993). A second seismic concern for this region was identified on April 22, 1991 when a M_w= 7.7 occurred along the east coast of Costa Rica near the Panama border killing 75 people and leaving 10,000 homeless as well as generating a 2 m tsunami (Geos et al., 1993).

Figure 2.3: Summary geological map of the Nicoya Peninsula (modified from: Vannucchi et al., 2001).



The Sabana Grande group represents a pelagic sedimentary deposit, while the Samara group represents a shallower water deposit that is characterized by proximal turbidity flows (Vannucchi et al, 2001; Baumgartner et al, 1984). The Mal Pais Supergroup then unconformable overlies the Garza Supergroup or in some cases lies directly on the Nicoya Complex. This neritic to non-marine depositional sequence is further subdivided into three units that represent three time frames of vertical movement of adjacent crustal blocks (Vannucchi et al., 2001, Baumgartner et al., 1984). The peninsula consists of a rugged, linear mountain chain (altitudes > 900m) and a narrow coastal piedmont (Marshall and Anderson, 1995). The elongate fore arc basin contains the Rio Tempisque and Golf of Nicoya separating the peninsula and volcanic arc (Marshall and Anderson, 1995). The peninsula's overall structural geology is a large anticlinal dome that peaks along the peninsula's central mountain chain and flattens towards the northwest and southeast coastlines (Marshall and Anderson, 1995). Faults that are parallel with the Middle America Trench are believed to be Miocene or younger in age and represent extension from arching along the Nicoya dome axis (Marshall and Anderson, 1995). This is further supported by geomorphic analyses by Hare and Gardner (1985), on drainage basins and old erosional surfaces located in the central mountains which illustrate doming of the peninsula in the Quaternary.

2.2.3 Playa Guiones

Playa Guiones is a small tourist town based around a 6 km sandy beach located on the Pacific coast of Costa Rica approximately midway between the coastal fishing community of Garza and small farming town of Nosara on the Nicoya Peninsula (Figure 1.1).

Tourism in the region has increased dramatically in the past ten years as Europeans and North American's are drawn to the coastal town. Figure 2.4 illustrates the tropical wet/dry climate that characterizes the region. The wet season occurs during the period May – November and the dry season during December – April (U.S. National Climatic Data Centre, 2006).

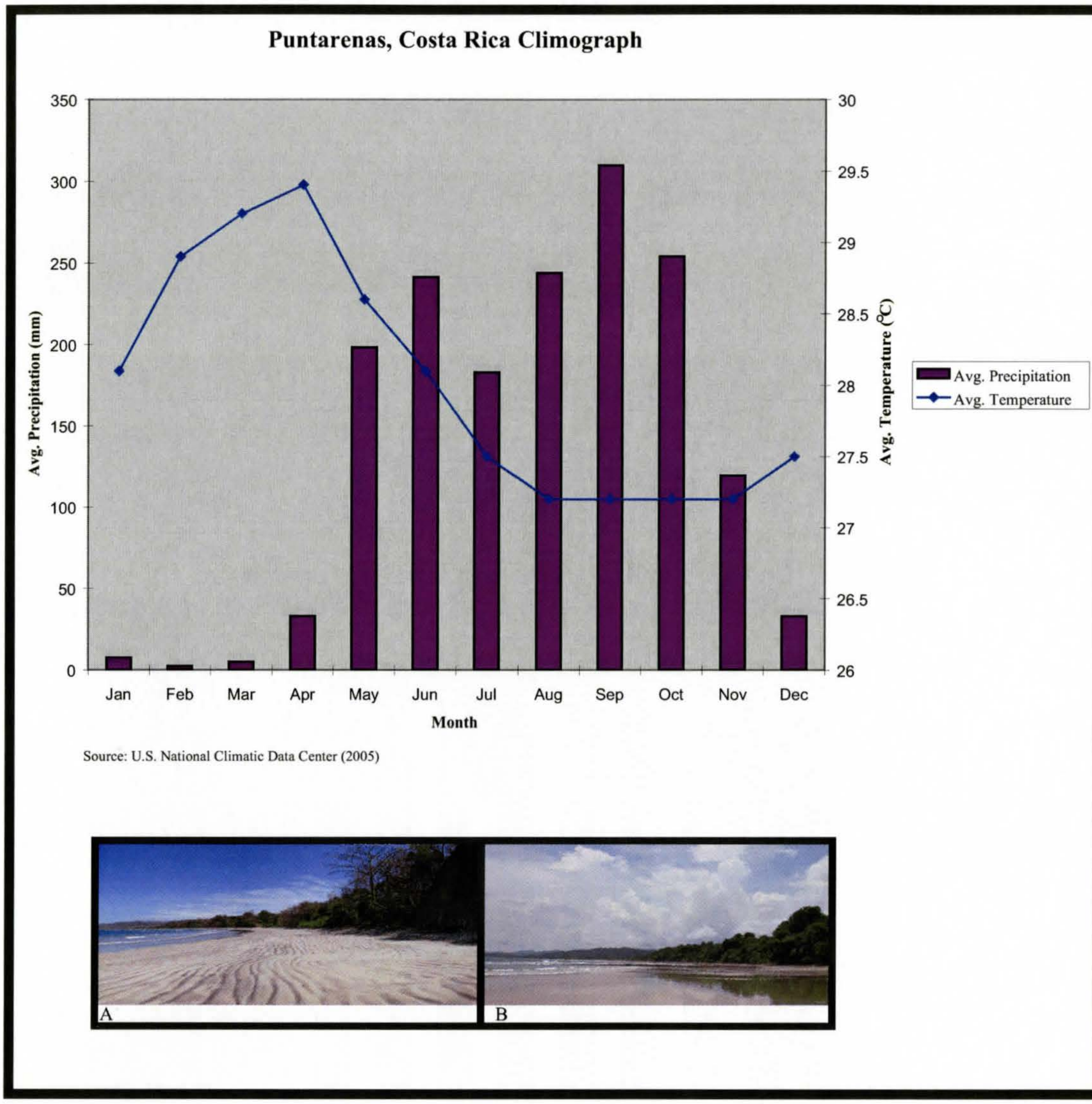


Figure 2.4: Climograph illustrating the distinct dry and wet season observed at Puntaneras (the nearest climatic station to Playa Guiones). Image A shows the vegetation and cloud cover on a typical day during the dry season (February 2005) and Image B shows the vegetation and cloud cover on a typical day during the wet season (June 2005) at Playa Guiones.

The distinct seasonality occurs because of the movement of the Inter Tropical Convergence Zone (ITCZ). This extensive low pressure region impacts the climate in the summer months resulting in overcast skies, lower temperatures and large amounts of precipitation. During the dry season the ITCZ has moved south of the equator and this region experiences high pressure and very little precipitation.

Playa Guiones experiences a semi-diurnal tide. Although there is no tidal gauge at Playa Guiones there is a gauge at Puntarenas which has a mean tidal range of 2.2 m, spring tidal range of 3.2 m and neap tidal range of 1.3 m (Costa Rica, 2006).

Marshall and Anderson, (1995) acquired anecdotal evidence from farmers and fisherman about the 1950 Nicoya Peninsula earthquake from 25 coastal residents from Nosara in the north to Puerto Carrillo in the south (Playa Guiones lies between these two communities along the Pacific coast). The residents described a co-seismic uplift of 1-2 m and subsequent subsidence of 0.5 m.

2.3 Coastal Geomorphology

2.3.1 What is Coastal Geomorphology?

Geomorphology originates from Ancient Greek as ge – earth, morphe – form, and logos – a discourse. It refers to the scientific study of morphology of the Earth surface and the processes that create and act upon them (Trenhaile, 2004). Coastal geomorphology is narrowing that definition down to a selected type of environment: coastal regions. In essence, coastal geomorphology studies landforms and processes that encompass a transitional region where terrestrial environments are influenced by marine processes and vice versa (Woodroffe, 2003). The coast is extremely dynamic, allowing for landform changes over a large time span, ranging from nearly instantaneous (e.g. waves, tides) to geological (e.g. reef structure, sea level change) and is involved in both positive and negative feedback cycles (i.e. a perpetual cycle), maintaining itself with erosion, transport and deposition of sediment. This cycle is most commonly measured as the sediment budget which identifies inputs and outputs to the coastal compartment (Figure 2.5).

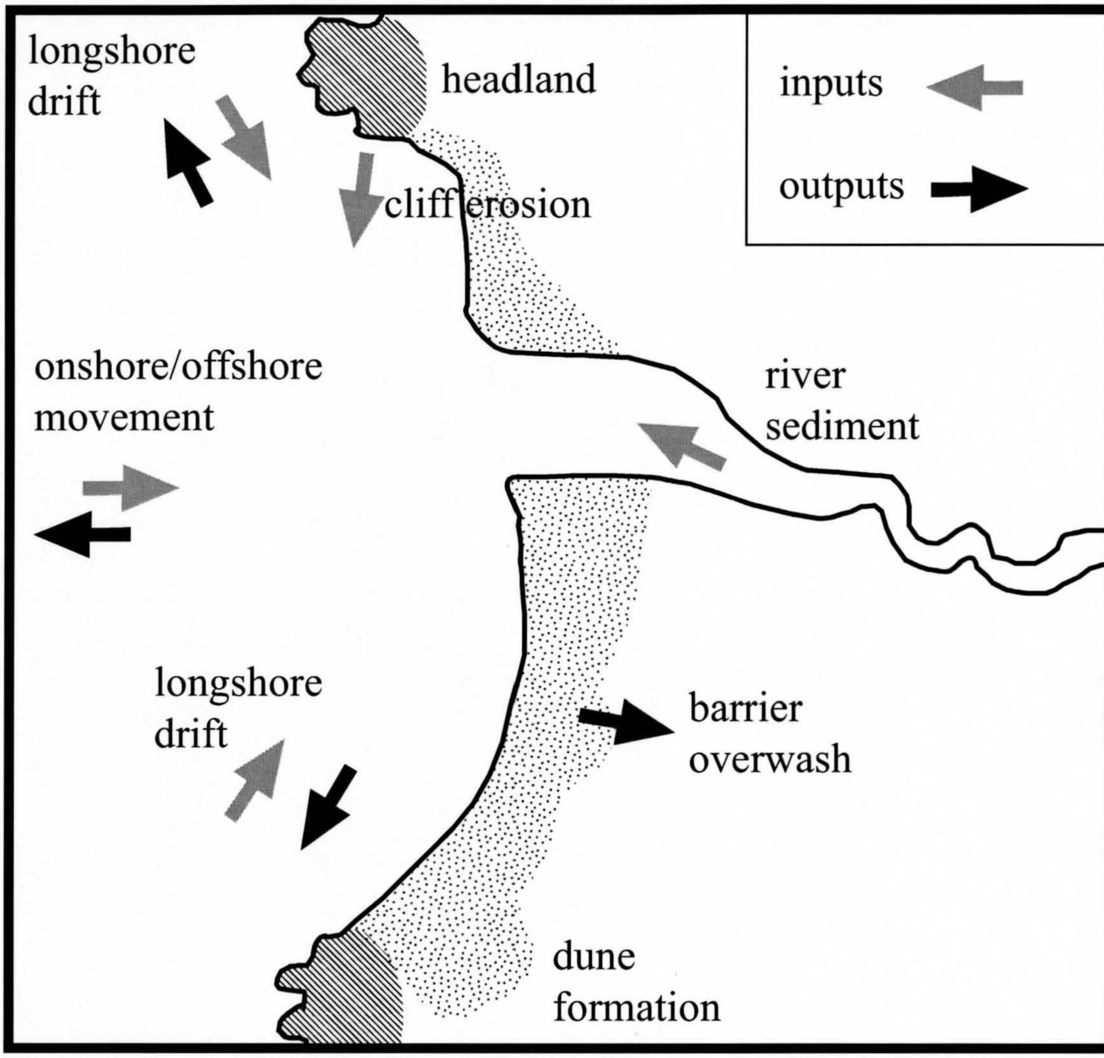


Figure 2.5: A schematic sediment budget illustrating inputs and outputs to the dynamic coastal system. (Modified from: Woodroffe, 2003)

Understanding a beach's sediment budget is crucial because approximately 50% of the world's population lives within 60km of a coast and human actions have interrupted the sediment budget, which disrupts the ultimate goal of the coastline to achieve equilibrium (Woodroffe, 2003).

2.3.2 Shaping the Coast

Short (1999, pg3) defines the beach as "a wave deposited accumulation of sediment lying between modal wave base and upper swash limit, where [modal] wave base is the maximum depth at which waves can transport beach material shoreward and the swash limit, the landward limit of sub-aerial wave action and sediment transport." According to Short's beach definition any sedimentary shoreline that is exposed to wave action will have a beach. Beaches form mainly independent of most other surface processes, thus, can be located in all climates, latitudes, tidal ranges and on all manner of coasts (Short, 1999). The remainder of this section will describe the five main controls on beaches:

geology (influenced by cross-shore gradient, accommodation space, pre-existing coastal topography);
climate (influenced by latitude);
sediment (influenced by latitude, grain size and mineralogy);
global wave climate; and,
tides.

(i) Geological Boundary Conditions

The geological substrate upon which the beach is situated on will influence the nature and size of the beach in three major ways:

cross-shore gradient;
accommodation space; and,

pre-existing coastal topography.

(a) Cross-shore Gradient

Cross-shore gradient is a measure of the steepness of the beach slope and is largely controlled by global tectonics (Masselink and Hughes, 2003). A model developed in 1994 that suggested beaches exist only on a narrow range of cross-shore gradients between 0.1° and 0.8° and that any beaches with gradients below 0.1° are exposed to excessive wave shoaling and sub-aqueous sand ridges and flats will be created (Short, 1999). Beaches with gradients over 0.8° result in high amounts of offshore sedimentation resulting in shoreline erosion, thus, creating bedrock coasts (Short, 1999).

(b) Accommodation Space

The accommodation space is the volume of sediment that can be stored between the substrate and the beach surface for a given sea level and wave climate given the overall three-dimensional morphology of the substrate (Cowell et al., 2003). Combining knowledge about available accommodation space with sediment supply characteristics is useful for long term and large scale beach system monitoring (Short, 1999). Cowell et al., (2003) demonstrate that the primary reasons for change in the amount of accommodation space are changes in sea level and changes in sediment availability.

(c) Pre-existing Coastal Topography

Also known as geological inheritance, pre-existing coastal topography, produces a chain reaction that begins with controlling the nearshore zone morphology which directly influences the wave shoaling process (Carter and Woodroffe, 1994). This sequentially causes wave height and direction at the shore to change which then ultimately controls the beaches shape and type (Short, 1999). Rocky coasts are more strongly influenced by inheritance. Tectonic activity along coasts has a major influence on the pre-existing coastal topography. In the early 1970's, two scientists, Douglas Inman and Carl Nordstrom, created a classification of coastlines based upon the application of the plate tectonic theory to coastal geology, therefore, allowing for a first order classification of the morphology and tectonic processes along large scale sections of the coast (Davis and Fitzgerald, 2004). Of course these are general observations and coastlines will have secondary factors creating subclasses for these coasts (Davis and Fitzgerald, 2004). The Inman and Nordstrom coastal classification is as follows:

Collision coasts
- A Continental collision coasts
- B Island arcs collision coasts

Trailing edge coasts
- A Neo-trailing edge coasts
- B Afro-trailing edge coasts
- C Amero-trailing edge coasts

Marginal sea coasts

As described in table 2.1 coasts are commonly defined by the type of tectonic margin (i.e. convergent vs passive).

Table 2.1: A summary table illustrating the difference between convergent margin coasts (i.e. collision coasts) and passive margin coasts (i.e. trailing edge and marginal sea coasts) (modified from: Short, 1999).

Characteristic	**Convergent Margin**	**Passive Margin**
Age	1 to 10s million years	Old (100s million years)
Relief	Steep, mountainous	Low gradient plains
Landforms	High mountains & volcanoes	Coastal aggradation plains
	Narrow continental shelf	Wide, low continental shelf
	Deep sea trough	Continental slope
Tectonics	Active earthquakes	Quiescent, stable
Weathering	Physical mass movements	Chemical, fluvial
Drainage	Short steep streams	Long, meandering rivers
Sediments		
Quantity	Low	High
Size	Fine to coarse	Fine
Sorting	Poor	Well
Colour	Dark	Light
Composition	Unstable minerals	Stable minerals
Coastal Landforms	Rocky, few beaches	Extensive barriers and deltas
Wave Attenuation	Low	Moderate to high
Tide Range	Minimal amplification	Enhanced
Examples	West coast Americas New Zealand Iceland Japan	East coast Americas Southern Africa Southern Australia North Alaska India

(ii) Climate

Solar energy is the key energy source for many primary coastal processes including: ocean wind, currents, waves, and biological and chemical weathering (Short, 1999). It is also responsible for secondary processes like the erosion of the sediment sources (coastal hinterland) through a combination of precipitation and temperature influences on the coast (Short, 1999). The largest and most evident influence climate has on the coastline is through latitudinal temperature variation. The resulting variation allows the development of three temperature controlled zones: high, mid and low latitudes (Davies, 1980). Temperature impacts beach morphology by influencing: size and nature of sediment, level of zonal wave energy and specialized physical impacts (Short, 1999).

(a) High Latitude Beaches

Polar beaches are dominated by physical weathering processes, a limited time of open ocean (sea), sea ice interaction throughout a large portion of the year and a strong Coriolis effect (Short, 1999). Polar beaches have a distinct morphology because the majority of the year is spent in sub-zero temperatures. The coastal environment in these regions experiences a yearly shut down of the coastal evolution cycle because the frozen beaches and nearshore sea ice ceases wave action, therefore, stopping one of the two beach shaping factors (Short, 1999). The ice then becomes a shaping factor as a result of its ability to move with tides creating a shore linear ice foot against the shoreface ice (Short, 1999). In the nearshore region sea ice may run aground on offshore bars and shoals which can create ice pressure ridges (Short, 1999). In general, retardation of coastal evolution is the main characteristic of high latitude beaches due to the limited amount of time 'normal' coastal processes can actually occur (Short, 1999).

(b) Mid-Latitude Beaches

Mid-latitude beaches are geographically the most limited but experience greater variation than any other coastal environment because of the highly variable waves and wind speed. This region experiences massive storms ranging from hurricanes (typhoons) which develop in the low-latitudes and travel into the mid latitudes and intense winter storms in the North Pacific, North Sea and Southern Pacific.

(c) Low Latitude Beaches

Tropical beaches tend to be low energy environments due to: lower energy waves from mild local winds, the protection provided from coral reefs, and/or a sheltered orientation from mid-latitude wave sources (Short, 1999). Some low latitude beaches that are exposed poleward, eg. Hawaii, South Pacific Islands (Tonga, Fuji), South Africa and Southern Indonesia, will usually experience large waves during winter swells from the mid-latitudes, as a result they are very popular surfing destinations during these times (Short, 1999). Most low latitude beaches are comprised of well-weathered quartz sand that is diluted by carbonate sand from the natural erosion of offshore coral reefs (Short, 1999). The higher ocean temperatures in this region cause quicker cementing of intertidal beach sands, which leads to increased beach erosion (Short, 1999). When the erosion takes place the beachrock remains as natural breakwaters modifying wave energy thus, retarding the retreating shoreline (Short, 1999).

(iii) Coastal Sediments

(a) Latitudinal Variation

Coastal sediments can be divided into the same latitudinal divisions as climate. Generally, beaches in the low to mid-latitudes are composed of fine to medium sand while beaches in high latitudes are composed of gravel to cobble (Short, 1999). Coastal sediment supply is a function of the hinterland climate,

> "particularly precipitation and temperature which control the rate of denudation; the geology which will determine the nature of sediments; the structure and topography which will influence the drainage pattern and locations coastal sediment sources including streams, rivers and glaciers; and the nature and extent of rocky coast exposed to wave erosion" (Short, 1999 pg.25).

(b) Grain Size

The size of sediment contributed to a beach is very important to beach dynamics and is directly proportional to energy of the processes responsible for sediment deposition (Davis and Fitzgerald, 2004). Sediment size (excluding clays and silts due to their low fall velocities which would cause them to remain in a suspend state through and beyond the surf zone) can be used as an indicator of a potential source or origin of the sediments, (Short, 1999). River systems and reworking of continental shelf deposits during sea level transgressions are usually the source for sand supply for beaches (Short, 1999). Sand has the ability to travel large distances but has a quick enough fall velocity so that it remains in the beach environment; whereas, coarser grained beaches, such as cobble and boulder beaches tend to have local sources due to their inability to travel large distances because of their high fall velocities (Short, 1999). An adjacent bluff or a coarse river supply sediment for cobble beaches while boulder beaches need an immediate local sediment source to form such as an eroding headland, glacier or eroding bluff (Short, 1999).

Grain size is related to beach gradient, beach width and mobility of sediment. Beaches composed of fine sand produce a lower gradient swash zone, a wider surf zone and the possibility to be very mobile (Short, 1999). As the grain size coarsens the gradient increases, the surf zone narrows and sediment mobility decreases, thus, beaches composed of varying sediment size impacted by identical waves would react differently to the wave (Short, 1999).

(c) Mineralogy

Sediment mineralogy is also influenced by latitudinal variation and source (Short, 1999). Low to mid-latitudes beaches are dominated by quartz sand (silica) with rock fragments increasing in the higher latitudes (Short, 1999). Input of carbonate sediments increases in low latitude areas with significant regional inputs on some arid temperate coasts (Short, 1999). Heavy minerals are a direct result of a suitable source rock and transport mechanism (Short, 1999).

(iv) Global Wave Climate

It is estimated that half of the world's coast energy budget results from waves (Short, 1999). Wave characteristics throughout the world, along with sediment characteristics are the prime determinants of the beach system character (Short, 1999). The shape and size of the ocean basins and seas the waves form in are a major factor in determining the nature of the waves, also the region and zonal wind regimes contribute a great deal to their nature (Short, 1999). Wind waves are generated by wind blowing over a water surface located in the area of formation, they are also called sea (Short, 1999). Short (1999 pg. 27) identifies five factors that determine the size of wind waves:

> "*wind velocity* - wave height will increase exponentially as velocity increases;
> *wind duration* – longer the wind blows with a constant velocity and direction the larger the waves will become until a fully arisen sea is reached (maximum size sea for a given velocity and duration);
> *wind direction* – determine (with Coriolis effect) the direction of wave travel;
> *fetch* – the stretch of water the wind can blow over, the larger the sea; and,
> *water depth* – shallow seas will cause wave friction and possibly breaking (not important in deep ocean)"

When wind waves leave the area of generation, by traveling out of the region or the wind ceases, a swell is created which allows the wave to travel large distances with minimal energy loss (Short, 1999). This transformation decreases wave height and increases wave length, causing wave velocity to increase since wave velocity is proportional to the wave length (Short, 1999). Swells travel in wave groups with waves of higher and lower sets (Short, 1999). These sets are important to the surf zone because of their contribution to infragravity energy in surf zone processes (Short, 1999). Wave climate is the average monthly and annual wave conditions at a location including height, period, direction and the source. Wave climate is determined by their major generating source, and the zonal wind systems (Short, 1999). Globally these are divided into three major regimes: trade winds of the lower latitudes, westerlies of the mid-latitudes and the polar easterlies in the high latitudes (Short, 1999).

(v) Tides

Tides generally only have a small role in beach dynamics except when large tidal ranges are combined with storm wave conditions then their contribution is significant (Short, 1999). Tides contribute to shoreline dynamics in three ways by;

(a) shifting the shoreline horizontally both raising and lowering due to high and low tide and vertically shifting the extent of the shoreline distance dependent upon tidal range and intertidal gradient ;

(b) shifting the swash, surf and wave shoaling zones by 'smearing' the potential impact of each; and,

(c) generating tidal currents regional that can be and local which transport sediment and influence beach and barrier morphology (Short, 1999).

This discussion has demonstrated that there are two major components that shape the coast and beach systems; waves and sediments. These two components are influenced by geological substrate, tectonic imprint and latitude of the beach. Predictable regional variations in beach type and character are produced by these major components and influences. Beaches can be placed on a continuum from reflective through intermediate to dissipative. A reflective beach is characterized by steep relief, narrow in extent and composed of coarser grained material and dominated by lower wave heights, whereas, a dissipative beach tends to be gentle slopes, horizontally extensive, composed of finer grained material, with larger wave heights and typically two or more shore parallel bars (Finkl, 2004). Finkl (2004) argues that the primary controlling factor is grain size. This is contrasted by Davis & Fitzgerald (2004) who propose that the primary control is wave energy and further that a beach may change from reflective to dissipative from high to low tide.

2.3.3 Surf Zone & Nearshore Zone

The shallow waters that extend from the low tide line to the breaker zone are called the surf zone and extending this limit to the inner continental shelf is the nearshore zone (Figure 2.6) The nearshore profile will be influenced by similar controls and processes to those which act upon the beach profile (see section 2.3.2).

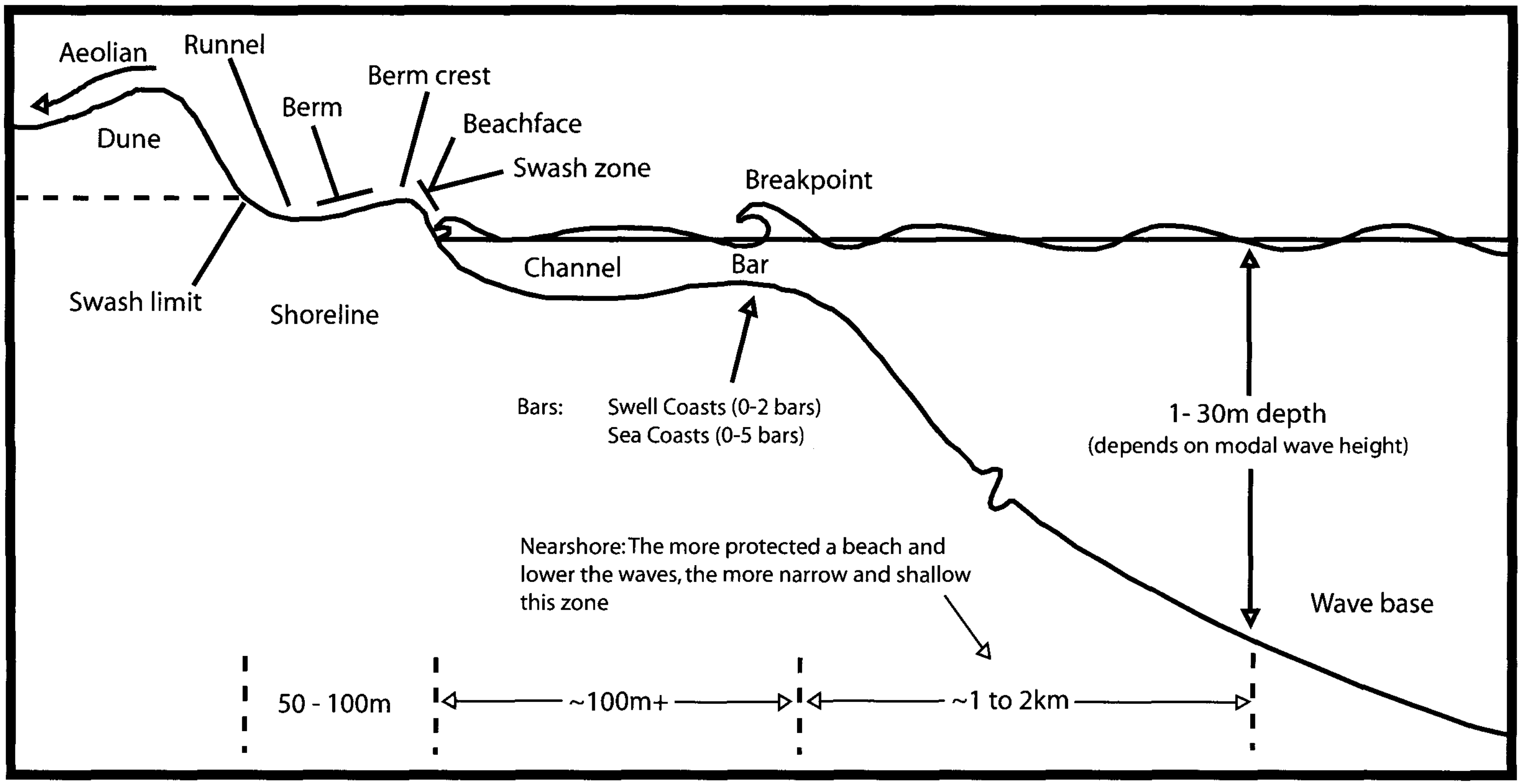


Figure 2.6: Schematic diagram of a typical high energy beach system. In a low enery beach system the 100m+ surf zone between the bar and the beachface is small to non-existent (modified from: Short, 1999).

According to Davis and Fitzgerald (2004) the most common morphologic feature in the nearshore is the presence of a shore parallel bar system, in which the first bar occurs approximately 30 to 50 meters and the other roughly double the distance seaward. The crest of the first bar, also known as the longshore bar, has mild variations in height. Where lows occur in this bar, rip channels are usually present (Davis and Fitzgerald, 2004).

In a typical sand dominated beach system they are three, possible four features present: the ridge and runnel (if present); the foreshore; the backshore; and, the storm ridge (Davis and Fitzgerald, 2004). The farthest feature seaward would be the ridge and runnel, if present on that beach system, that is similar to a bar and trough on a much smaller scale (Davis and Fitzgerald, 2004). The feature is located in the lower portion of the intertidal part of the beach, where the ridge begins symmetrical and becomes asymmetrical as the tides rise creating wave generated currents that transport sediment landward (Davis and Fitzgerald, 2004). This produces a gentle slope on the stoss side and a steep lee side. The runnel tends to be broad and nearly flat lying ranging in size from several metres to 10 m (Short, 1999). As the ridge migrates landward it over tops the runnel and eventually becomes part of the beachface where swash activity removes all evidence of its presence (Davis and Fitzgerald, 2004). Davis and Fitzgerald (2004) state that migration rate is inversely related to tidal range. Due to the dynamic nature of beaches the presence of ridge and runnel features are usually only on the order of weeks (Davis and Fitzgerald, 2004).

The next feature landward is the foreshore portion of the beach that is typically flat or gently sloping seaward (Davis and Fitzgerald, 2004). This section includes the swash zone and under more intense wave climates (eg. winter storms) can be modified in profile. The lower part of the foreshore is marked by the plunge step, a small topographical break that is usually marked by a coarsening of sediments either very coarse sand to gravel or a large concentration of shell fragments (of a large size fraction) (Davis and Fitzgerald, 2004). The foreshore is bounded landward by a berm, which is defined as the inter to supra-tidal shore parallel ridge (Short, 1999). Beyond the berm is the backshore portion of the beach that is either horizontal or landward dipping (Davis and Fitzgerald, 2004). This portion of the beach is supra-tidal and is only exposed to waves during storm condition. Due to this fact it is possible to create a multi berm system where the width of the backshore is controlled by sediment supply and wave climate energy (Davis and Fitzgerald, 2004). The backshore region may support opportunistic vegetation that helps minimize erosion and provides structural support (Davis and Fitzgerald, 2004). If vegetation is absent the backshore will most likely have ripples and a surface layer of shell fragments that provide some stabilization (Davis and Fitzgerald, 2004). High latitude beaches experience a retardation of sediment transport in the backshore due to frozen conditions for a large part of the year (Short, 1999). When the backshore is inundated a range of morphological features can be created: washover fans and sheets, washover terraces, barrier and backbarrier flats, hummocky dunes, dissected foredunes, and foredune remnants (Short, 1999). The last feature which is located beyond the backshore is storm ridges. These swash-deposited features are caused from high energy waves that rush up past the normal berm carrying a coarser size fraction of sediment that is deposited farther landward (Short, 1999; Davis and Fitzgerald, 2004). Due to the lack of backwash from these waves through percolation of the water, the sediment accumulates creating a larger and more stable ridge (Davis and Fitzgerald, 2004). These ridges are usually present where large storms play an important role in the beach system, typically mid-latitude beaches (e.g. extreme winter storms or hurricanes).

2.3.4 Embayed Beaches

All beaches have a terminal boundary, which can be a sandy foreland, an inlet or a rocky headland. Rocky headlands are the backbone for the creation of embayed beaches due to the fact that they are independent of the formative beach process, thus, ensuring a major influence on beach planform, sediment transport and morphodynamics (Short, 1999). These types of beaches tend to form along rocky shorelines which are usually associated with hilly and mountainous coastal terrain which according to Inman and Nordstrom (1971) occurs along 51% of the world's coast line implying a large occurrence of embayed beaches. The length and form of these beaches is totally controlled by the pre-existing bedrock topography and there is typically a strong relationship between the beach plan form and the refraction pattern resulting from the prevailing swell waves (Figure 2.7; Short, 1999; Woodroffe, 2003).

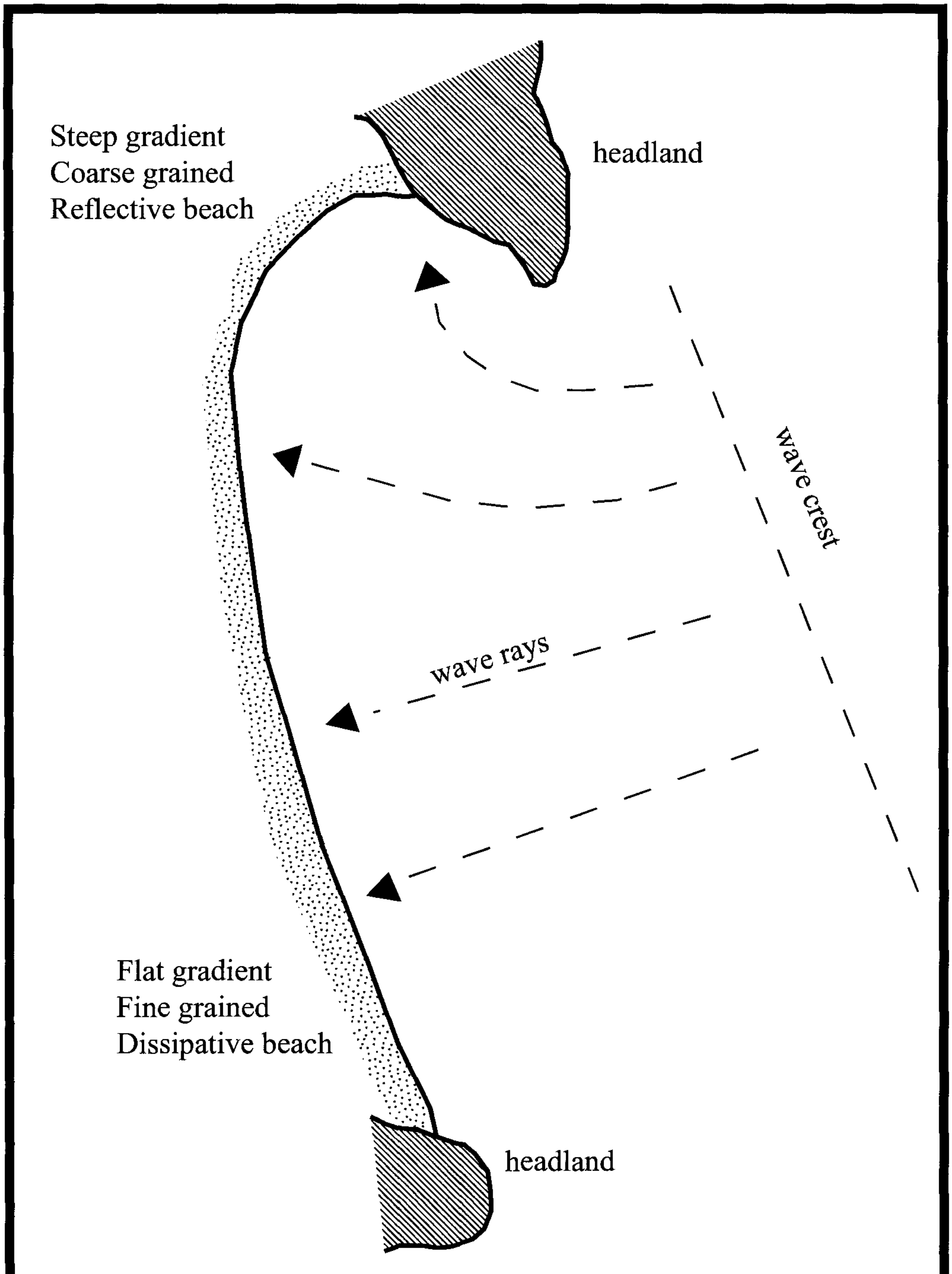


Figure 2.7: A typical embayed beach showing the relationship between planform, grain size, beach gradient and energy level (modified from: Woodroffe, 2003)

Embayed beaches have gained attention in recent years due to the realization that they are morphologically distinct from open coastlines (Stephenson and Brander, 2003). Davies (1958) concluded that the orientation and planform of embayed beaches are determined by wave refraction of the prevailing swell waves (Short, 1999). Furthermore, if the embayed beach is in hydrodynamic equilibrium the refraction that occurs poses no net longshore transport due to the obliquity of the waves, which have all breaking waves arriving at normal angles to the beach (Short, 1999). However, a minor longshore current may be present from alongshore gradient in wave height, creating a current which flows from regions of maximum wave energy to minimum wave energy (Short, 1999). Embayed beaches typically have an asymmetric planform that consists of a strongly curved shadow zone that is steep, coarse and characterized as a reflective beach, a mildly curved centre zone and a relatively straight down coast end that is relatively flat, fine grained and characterized as a dissipative beach (Short, 1999; Woodroffe, 2003). Model tests and field observations have identified certain equilibrium characteristics of the planform of embayed beaches, as a result comparison of observed bay geometry and predicted geometry can reveal the stability of these embayed beaches (Short, 1999). Another characteristic of embayed beaches is the effect that headlands have on the circulation pattern (Short, 1999). As wave height increases and/or shoreline length decreases the end members (headlands) have an increasing modification effect on the circulation type (Short, 1999). A transitional circulation is created when the size and shape of the embayment start to influence the surf zone circulation causing the longshore currents to turn and flow seaward at the headlands, while keeping some normal circulation away from the headlands (Short, 1999). When topography dominates the circulation pattern a cellular circulation is created. Within the embayment longshore currents dictate strong seaward-flowing megarips at either one or both of the headlands and in large embayments also away from the headland (Short, 1999). These megarips have been observed to flow seaward for up to a kilometre from the breaker zone, therefore, becoming a very important factor for seaward sediment transport and beach erosion (Short, 1999).

2.3.5 Beach Hazards

Beaches and coasts yield many activities which draw millions of people to them every year but they pose dangers that are sometimes hidden from the average beach visitor. Being situated at the transition zone between the terrestrial and aquatic environment provides a multitude of potential risks but there are three risks associated with every type of beach: water depth, breaking waves and surf zone currents (Short, 1999).

(i) Water Depth

Water depth can be considered in three divisions when considering hazards in the surf zone: too shallow, too deep and spatially variable (Short, 1999). Impact injuries with the bottom are common with a shallow surf zone. These can result in drowning if the victim becomes unconscious or in broken bones and spinal injuries from being driven into the bottom by the breaking wave. These injuries are more common with surfers and/or body boarders trying to surf shallow breaks. Deep water, usually defined as chest height, in the surf zone may result in panicked swimmers and drowning (Short, 1999). This risk is particularly prevalent with non-swimmers and inexperienced swimmers (Short, 1999). Variations in water depth are a result of bars, troughs, channels, steps and sloping swash zones which pose hazards by providing unstable footing on steep slopes (Short, 1999). While the combination of shallow bars and deep channels can result in a person being unexpectedly moved from a reasonable safe shallow water bar to a deep water channel where they may be exposed to strong currents, thus, variations in water depth result in a combination of the risks associated with shallow and deep water (Short, 1999).

(ii) Breaking Waves

The breaker zone is where the wave expends the energy that was created and modified from the area of generation. This region produces strong shoreward turbulence, wave bore and currents that can knock and hold a person under water (Short, 1999). Also, the height and type of breaking wave is important due to the fact that wave energy increases with the square of the wave height and the type of breaking wave will determine the distance over which the wave energy is dispersed (Short, 1999). The waves that pose the most danger are high waves that break over a short distance, usually characteristic of plunging or collapsing waves (Short, 1999).

(iii) Surf Zone Currents

This hazard poses the greatest threat to swimmers, mainly because this is the least obvious risk and can be difficult to observe even if the swimmer(s) are aware that they exist in the area (Short, 1999). Rip currents are especially dangerous because of their fast flowing seaward velocity that can carry a person up to a couple hundred metres off shore. A very common mistake made by people is to try and swim against the rip causing them to become fatigued and drown.

Conclusion

As the world's population continues to grow and the desire to live in regions of that provide intrinsic value, aesthetical pleasing views and the opportunity to participate in fitness orientated activities grows along with the population coastal regions are becoming increasingly popular areas to reside. Since the coastal region is one of a few areas that meet all of these desires and already approximately 50% of the world's population lives within 60km of a coast a better knowledge of coastal landforms and the process that shape the coast must be obtained (Woodroffe, 2003). The coasts perpetual cycle to reach equilibrium through landform alteration is a dynamic process that humans will have to minimize their influence upon and/or adapt to the changes that this environment presents.

2.4 Geoindicators

Geoindicators are biological and physical measures of rapid geologic change that is happening at or near the earth's surface (IUGS, 2006). The use of geoindicators developed in response to a desire to link geological sciences and environmental planning. Ideally, geoindicators provide a mechanism to monitor environmental change, thus, making it feasible to balance anthropogenic exploitation of the environment with conservation of the environment. A key piece to using geoindicators is the establishment of initial or baseline conditions from which to measure change.

In coastal environments the most reliable and most frequently measured geoindicator is shoreline position (Morton, 2002). Shoreline position may be measured on site, through the use of historical maps or with remotely sensed imagery. Although on-site measurements may be very accurate they can be time consuming to collect and only represent a 'snap shot' in time. Historical maps provide longer time scales of information but may contain cartographer bias and measurement error. Remotely sensed imagery is fairly fast and inexpensive to analyze but may contain error from the original collection of data from the plane or satellite (Morton, 2002; 1996).

Shoreline position as a geoindicator may involve measuring beach width. This is a very simple measurement to make but there are a number of weaknesses with this method including the long time span of data required (>10 years) and the lack of information about local variation in sea level and sediment storage (Morton, 1996). The use of shore normal profiles (beach profiles or transects) provides more detailed information about changing beach morphology but are site specific, and are more expensive (capitol and labour). Sediment budgets are often used as an accounting method to explain changes in the volume of material on a beach but are restricted to areas where there is a detailed understanding of bathymetry in the nearshore region. Changes in beach morphology or the position of the vegetation line (which usually mimics the movement of the actual beach) may be used as geoindicators. Changes in beach morphology may be relatively easy to observe but can be challenging to interpret (Morton, 2002). The vegetation line tends to be a good long term indicator of shoreline change but often changes at a slower rate than the shoreline position. As well the vegetation line is subject to anthropogenic traffic and may change as a result of a change in human traffic quite independently to movement of the shoreline position.

CHAPTER THREE: METHODOLOGY

This chapter consists of three sections. The first section commences with a discussion of the criteria that were used to select a field site. The second section describes the field methods employed during this study including the methods used for the detailed survey, aerial photography geo-rectifying, and sediment, rock and vegetation collection. The final portion of the chapter will describe the methods used for data and laboratory analysis including the methods used for the creation of the Digital Elevation Model (DEM), geo-rectifying of the aerial photography, qualitative comparisons of remotely sensed data (aerial photographs and satellite imagery), analysis of grain sizes, and identification of mineral, rock and vegetation material..

3.1 Site Selection

A number of criteria were identified a potential field site had to meet. The potential field site had to be accessible by motor vehicle, ideally at several locations along the beach, because there was a lot of equipment to be transferred to the site daily. The potential field site had to be greater than two kilometers in length. The beach at the potential field site had to be composed of soft sediment and have a sand grain size (0.063 – 2mm). Ideally, the petrological characteristics at the potential field site would display spatial variability. A time series of remotely sensed data needed to be accessible for the potential field site. The potential field site had to be located in a tectonic active region. Ideally, the potential field site would be experiencing relatively significant land use changes. Finally, the provincial and national government of Costa Rica had to be willing to provide permission to conduct field work, including the collection of samples at the potential field site.

Using topographic and geologic maps of Costa Rica available from the Lloyd Reeds Map Collection at Mills Library at McMaster University a number of potential sites in Costa Rica were identified. A reconnaissance trip to Costa Rica in February 2005 resulted in a number of the potential field sites being eliminated because they did not meet all the selection criteria. Playa Guiones, Guanacaste province met all the criteria and was selected as a suitable field site.

3.2 Field Methods

Field work comprised three separate excursions to Playa Guiones, Costa Rica. The first took place between February 16-26, 2005, the second took place between June 8–July 7, 2005 and the third between February 18-21, 2006. The objectives of the first excursion were primarily reconnaissance in nature and included: identification of an ideal field site based on the selection criteria described above, creation of detailed site sketch maps of the beach, acquiring historic aerial photogaphs, acquiring detailed topographic maps and making contacts for logistically considerations for the longer summer excursion.

The second excursion consisted of the bulk of field data collection. The objectives of this excursion were to conduct a detailed survey of Playa Guoines, creation of detailed sketch maps, collection of sand and rock grab samples and beach vegetation identification. It is important to note that the reconnaissance field excursion occurred in the dry season and the second, main field excursion occurred during the wet season

This following section will describe the methods that were used in the field for the collection of sediment, rock and vegetation samples. As well it will describe the collection of data for the detailed survey and geo-referencing the remotely sensed imagery.

3.2.1 Sediment and Rock Samples

Representative rock samples (5 samples) and sediment grab samples (4 samples) were collected during the second field season. The objective of collecting these samples was to obtain a basic understanding of the sediment grain size, its distribution and mineral composition along Playa Guiones. The rock samples were collected to obtain a basic understanding of the local outcrop exposures.

3.2.2 Vegetation

Beach vegetation was observed, detailed notes were recorded and digital photographs were collected. The objective was to identify the beach vegetation, observe spatial variability in the vegetation and make qualitative comparisons while minimizing the anthropogenic impacts from collecting hand samples.

3.2.3 Detailed Survey

A detailed survey, with the prime objective to collect topographic information about the current beach morphology, was conducted during the summer field season. A real-time kinematic global positioning system (RTK – GPS) detailed survey was used to collect data. The system used was the Trimble 4600LS Surveyer and the Trimble Handheld Computer TSC1. When operating effectively this system has an associated sub-centimetre error. If the error associated with a single data point was greater than 5 cm the point became a null point. This system consists of a base system GPS which is located centrally along the section being studied and a roving GPS system mounted on a back pack. The data is recorded automatically every one second to the hand-held computer (Figure 3.1). This system was selected rather than using traditional surveying because the On-The-Fly technology employed by RTK-GPS is superior to traditional surveying (Berg, 1996).

Figure 3.1: An image illustrating the set up of the real-time kinematic GPS unit at Hotel Nosara, Costa Rica. Note the presence of the base station (tripod with the extended pole) and the roving GPS unit (attached to the backpack on the ground).

To collect the topographic data a series of survey lines were walked shore normal at an approximate spacing of two to five metres along the entire length of Playa Guoines A tie line was collected at the start and end of each measurement period if possible. This tie line was useful for quality control when the data was being analysed because it provided multiple points that should have the same x,y and z coordinate. This data was collected over a five week period. Each time the RTK-GPS was initialized, either on a new day or following some failure of the equipment (discussed more fully below), a new line path was created. Successive line paths were required to overlap for data processing (Figure 3.2). The RTK – GPS was programmed to only accept data points that had sub-centimetre precision. When using this system it is imperative to record who was wearing the back pack so that variations in the data that result from the height of the individual can be corrected.

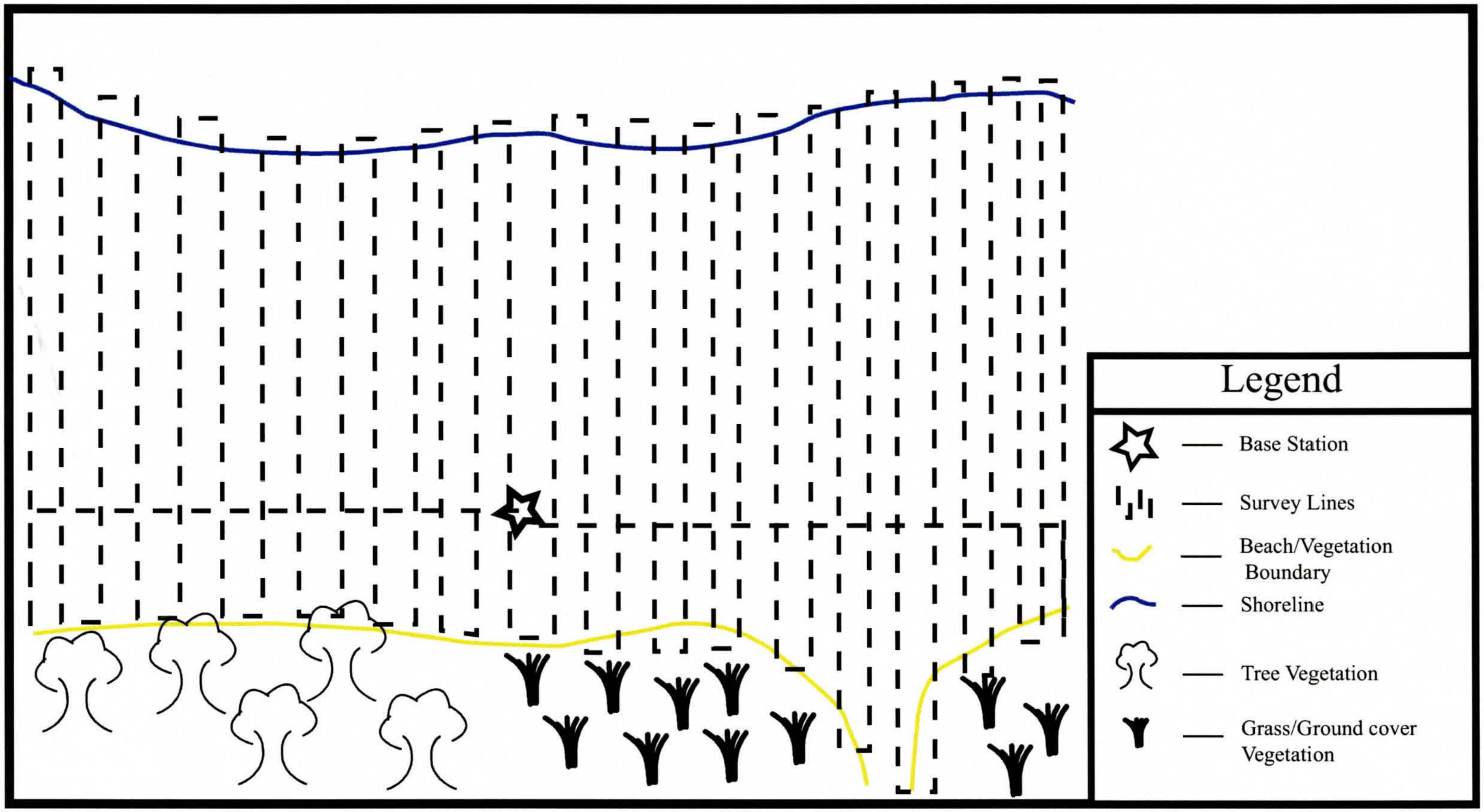


Figure 3.2: A schematic diagram that illustrates a typical section of beach and the grid pattern that would normally be walked to collect data (the star represents the location of the base station, the dotted lines represent the path that the person collecting data would walk and the lines running parallel to the shore are the tie lines).

Using the RTK – GPS system in this environment provided some challenges. Vegetation was quite dense at the landward side of the beach and cloud cover was extensive because the field season occurred at the height of the rainy season. Vegetation and cloud cover interfered with the radio linkage signal between the roving and base GPS and with the satellite signal reception. The base GPS station consisted of a tripod with a 4 metre metal antennae, thus, it had to be immediately dismantled for safety reasons if a thunderstorm occurred in the vicinity. Thunderstorms are frequent during the rainy season along this coastline. On certain days the RTK-GPS equipment would lose signal for no apparent reason. This resulted in a number of days when no meaningful data could be collected.

3.2.4 Remotely Sensed Imagery

A series of aerial photographs and a Quickbird satellite image were used in this study. The satellite image was geo-rectified when purchased. The aerial photographs were not. The objective for the aerial photography field work was to identify and collect latititude and longitude coordinate information for a series of ground control points for use when geo-rectifing the aerial photographs. For each aerial photograph a minimum of three ground control points were identified and data gathered. Four series of aerial photographs were used representing the years between 1944 and 1997. This region is densely vegetated and has only recently been cleared for limited agriculture and tourism. As a result to determine the coordinates of the ground control points the RTK – GPS system had to be set up primarily in roadway intersections, and sometimes on topographic highs as these were the only locations with windows in the vegetation canopy that permitted the satellite signal to penetrate.

3.3 Data Processing and Laboratory Analysis

3.3.1 Mineral Analysis

(a) Grain Size Analysis

Grain size analysis was conducted on the grab samples that were collected from the field using the standard method outlined by Kunze and Dixon (1986). The samples were dried for 24 hours at 105° C in the drying oven. Then approximately 100g of sample was sieved in a nested sieve stack for 30 minutes. The nested sieve stack contained the following sieves (mesh size in mm): 15.9, 8.0, 6.35, 4.0, 2.83, 2.00, 1.41, 1.0, 0.5, 0.355, 0.212, 0.125, 0.063, and catch pan. Once sieving was completed the percentage caught in each sieve was calculated by weighing the material caught in each sieve. The samples were then placed in a muffle furnace at 550° C for four hours to remove organic content. The samples were re-sieved and weighed using the same nested sieve stack and the percentage caught was again calculated. To determine the carbonate content of the samples, the samples were immersed in a 0.5M hydrogen chloride wash. Once all carbonate material was dissolved the samples were re-seived and weighed using the same nested sieve stack and the percentage caught was calculated.

(b) Mineral Identification

To determine the mineral composition of the samples the acid wash samples were examined under a Nikon SMZ1000 microscope and then a digital photo was taken using a Nikon digital camera DXM1200F. The captured images were enhanced using Nikon ACT-1 image capturing software. The images were collected in a TIFF file format and were taken at a resolution of 1280x1024. The digital images were used for identification of the mineral matter.

3.3.2 Rock Analysis

The five representative rock samples were identified by hand specimen in the field. Once back in the lab the carbonate content of the samples was confirmed through the use of HCL.

3.3.3 Vegetation Identification

The digital photographs taken in the field were examined and the vegetation was identified and classified. The prime tools used for vegetation identification were a book titled A Guide to Tropical Plants of Costa Rica (Zuchowski, 2005), and the knowledge of a local expert, Mario Garcia Quesada. A generalized map showing the vegetation distribution along Playa Guiones was created to highlight the relationship between current beach morphology and dominant vegetation. As well a visual index of beach vegetation was created.

3.3.4 Digital Elevation Model

To visualize the data collected from the RTK – GPS system and create a Digital Elevation Model (DEM) of Playa Guiones a modeling software was required. Oasis Montaj, produced by GEOSOFT was selected for the creation of the DEM. The following section will describe the systematic procedure that was followed to create the DEM. Digital elevation and topographic data were converted from DC files on the handheld computer to ACSI files and downloaded daily to the computer while still in the field. All remaining data processing occurred after completion of field work. The steps followed for data processing are outlined below.

1. The ACSII data was converted to a .CSV file format that was imported into Oasis Montaj.
2. Once all data was inputted, the data was separated based on date of collection to create lines. Further splitting occurred in each line based on every time the RTK – GPS needed to reinitialized.
3. The antenna height was corrected by identifying who carried the receiver back pack and subtracting the height of each individual from the data points.
4. To determine and help in identifying errors in the data, the difference between the elevation of one data point and the previous data point was calculated to identify any major slope changes (eg. lifting the receiver backpack to the individual).
5. A low pass filter was then applied to the data which smoothed out the high frequency noise (disturbance) associated from walking on unconsolidated material.

6. The data was then manually cleaned by reviewing all data points and removing those which were erroneous. The reason for excluding some data points included: repetitive points (caused by the individual collecting data standing still), single point lows and/or highs, locations where the signal faded and points adjacent to the base station (since they often represented the lifting or placing down of the receiver backpack).
7. Due to different satellites signals being received from day to day and the concept behind GPS and the datum upon which it uses, a data height shift needed to be applied.
8. Each time the RTK-GPS system initializes a different base height is identified. To combine all the lines from step 2 above a single line on a single date was identified and all other data was corrected to this base. The criteria used to determine the base was the line with: the cleanest data, the most extensive data set and the largest portion of exposed beach (i.e. lowest tide). The line J23B (June 23, Line B) was selected because it fulfilled all the necessary criteria.
9. All cleaned lines were shifted to June 23B using Boolean operation logic to mask the grids together where they overlapped (Figure 3.3). The grids were then subtracted and the overlap statistics were used to correct to the line. This process was repeated for all cleaned lines.

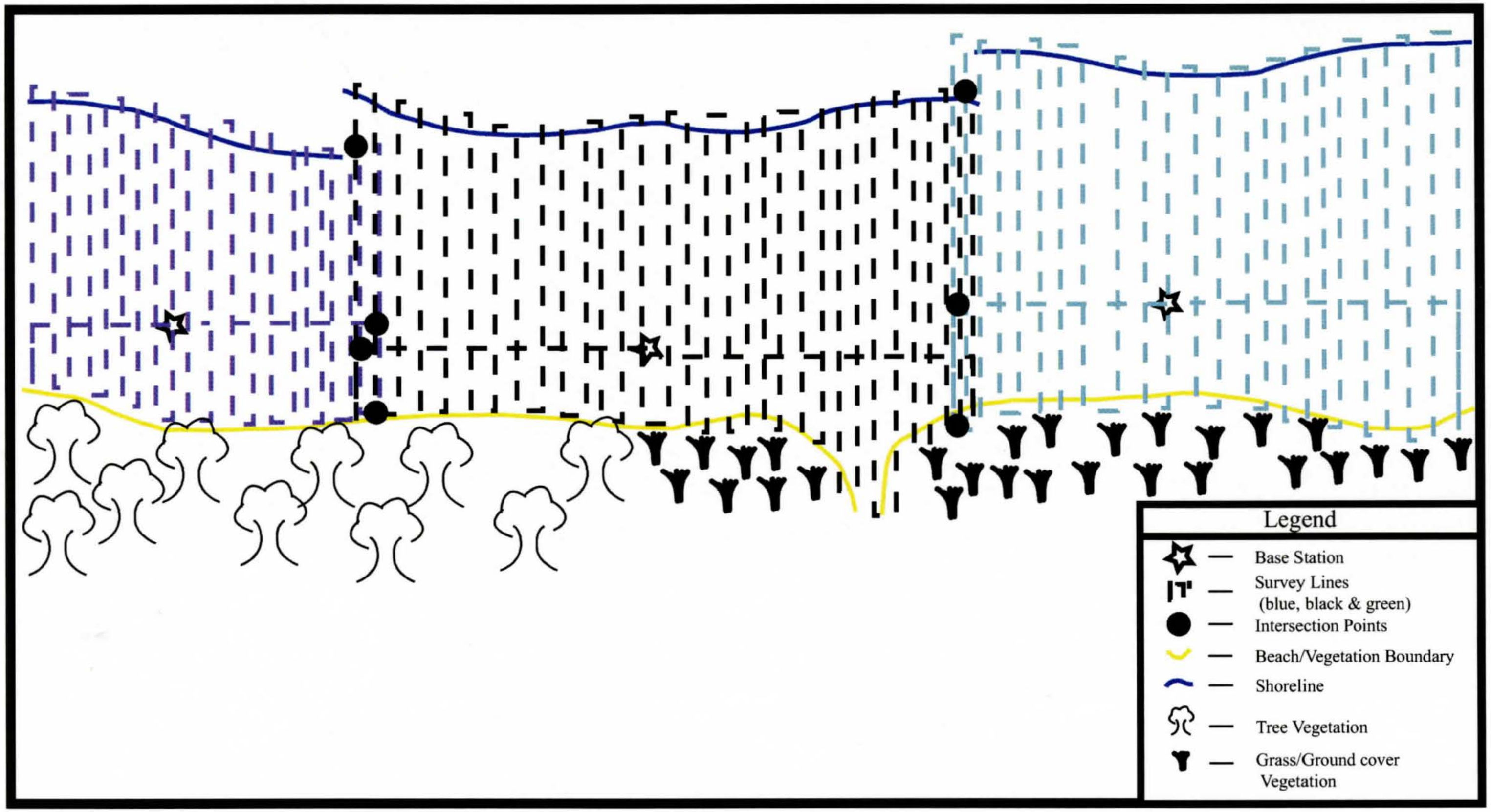


Figure 3.3: A schematic diagram to illustrate the line overlap required for data collection. The different coloured survey lines correspond to different base station locations. The intersection points highlight the overlap that must occur when the base station is moved.

10. Once completed, artificial sun shading was applied at the angle that would illuminate any other remaining errors in the data. These errors were identified and then manually removed from the data.
11. Once the data was cleaned a DEM of the beach was created.
12. From the DEM representative regions were identified and profiles were created along these lines. These profiles were used to identify the elevation of mean sea level and its location was added to the DEM.

3.3.5 Remotely Sensed Imagery

The digital aerial photographs were geo-rectified in ArcGIS. To complete the geo-rectification the ground control points gathered in the field using the RTK – GPS system were loaded into an Excel table and imported into ArcGIS to analyse with the geo-reference tool. The coordinates of the ground control points were combined with a world map using a WGS84 datum upon which the geo-reference tool in ArcGIS used to geo-rectify the aerial photographs.

3.3.6 Earth Resources (ER) Mapper

To create an image that combined the February 2004 satellite data and the DEM data collected during June 2005 ER Mapper was used. The geo-rectified satellite image was imported into ER Mapper as a geo-tiff. The image was altered to remove background noise. The DEM was then merged as an intensity layer (i.e. grey scale) with the satellite imagery.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Beach Texture and Composition

A total of four representative grab samples were collected that illustrate the texture variation in sand at Playa Guiones (Figure 4.1). The southern rocky headland had an extensive carbonate rock shore platform with sporadic gravel deposits. Sample G1 was collected north of the southern headland area at the point where the beach becomes continuous sand as opposed to exposed rocky shore platform and gravel. Sample G2 was collected in the area where the coastal hinterland changed from a moderately steep cliff to a gently undulating vegetated seasonal stream valley. Sample G3 was collected near the mouth of a seasonal river. Sample G4, was collected towards the northern headland and represents the sand texture for the greatest geographical area.

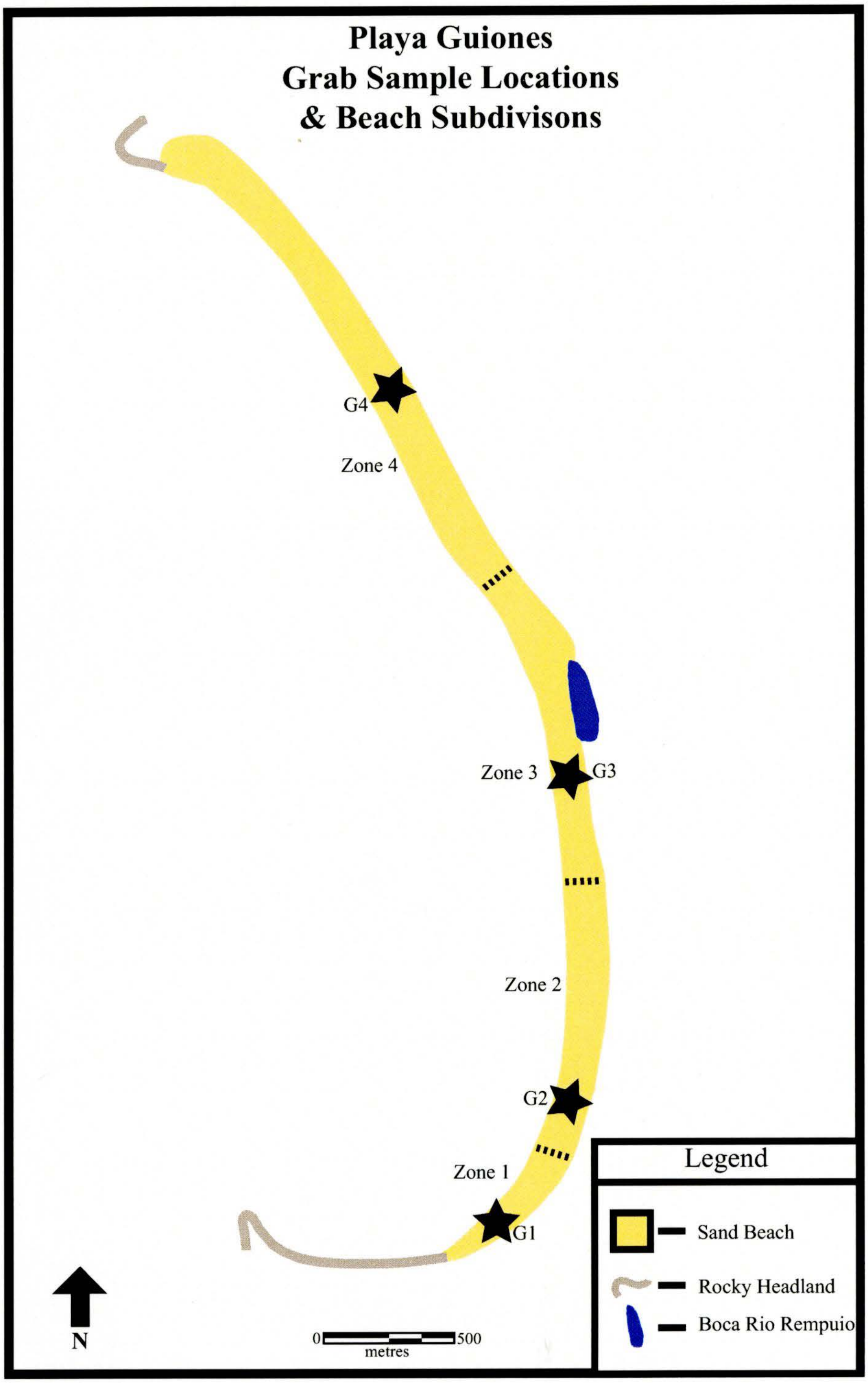


Figure 4.1: A map showing the location of the grab samples. The dotted line shows the division along the beach from one sample dominating to the next sample dominating

4.1.1 Results

Five minerals dominated the sediment samples quartz, olivine, obsidian, K-feldspar, and garnet (Figure 4.2). The minerals were predominately angular to sub-angular with occasional sub rounded material evident. Sample G3 contained coarser grained material than the other samples.

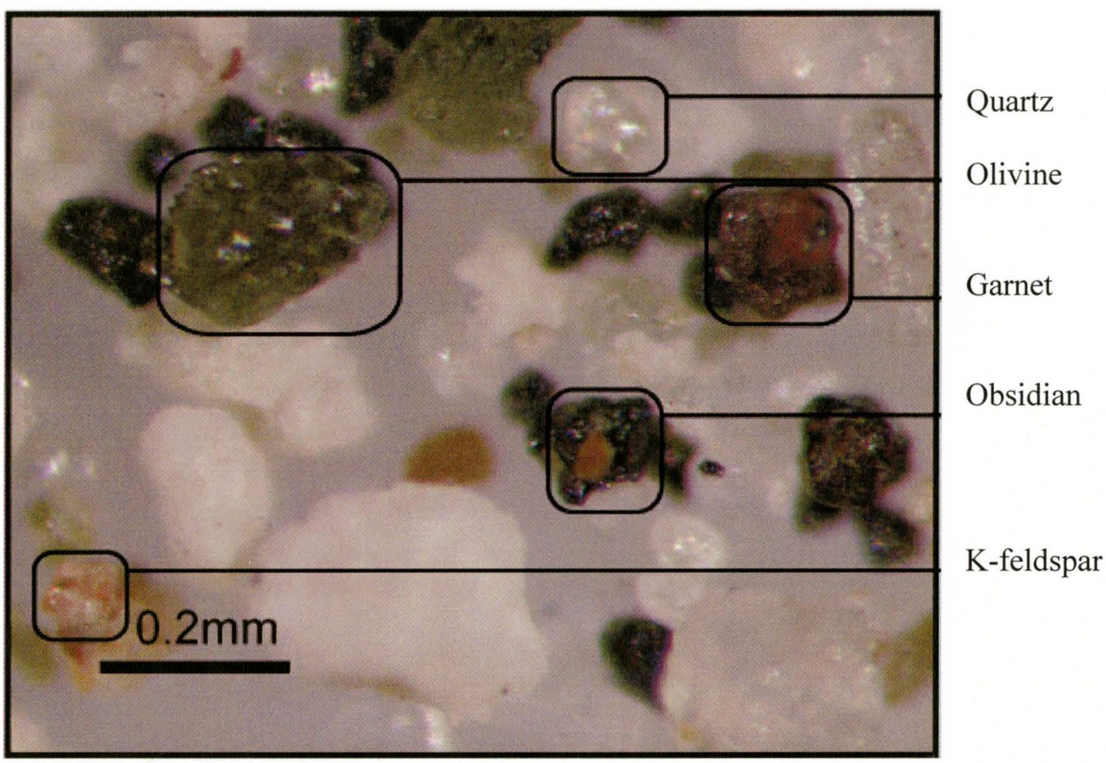


Figure 4.2: An image showing the dominant minerals identified on Playa Guiones (140x zoom) A complete set of images is available in Appendix Two.

The mineral composition along the beach remained relatively similar throughout, with quartz being the dominant mineral in all of the samples. In samples G2 and G4 obsidian was the second most dominant mineral, whereas, in samples G1 K-feldpsar was the second most dominant mineral and in G3 olivine was the second most dominant. Garnet was always the least frequent in all of the samples. (Table 4.1; Figure 4.3)

Table 4.1: Percentage composition of dominant minerals in the sediment grab samples collected at Playa Guiones

Sample	Quartz	Olivine	Obsidian	K-feldspar	Garnet
G1	70	7	7	15	1
G2	38	15	38	6	3
G3	50	31	1	18	0
G4	44	18	28	6	4

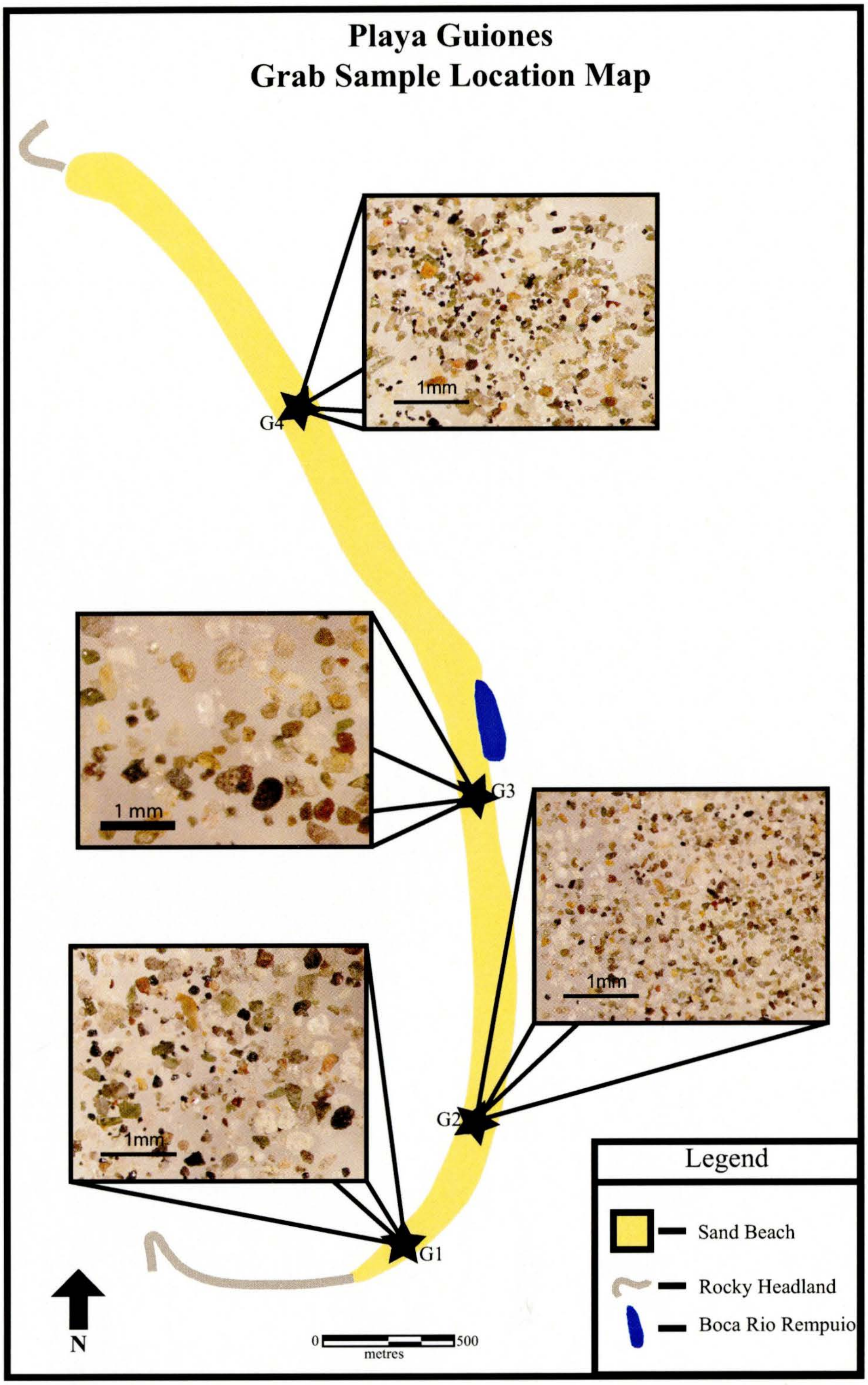


Figure 4.3: A map illustrating the collection location of the grab samples and representative images that illustrate the mineral composition in each sample (40x zoom)

The texture of the four representative samples was measured following three different preparations: 24 hours of oven drying, four hours of furnace burning (loss of ignition) and acid washing (Appendix 1). The samples contained a large shell fragment and contained very little other organic material (Table 4.2). The carbonate shell component was greatest in samples G1 and G2 and it was lowest in sample G3.

Table 4.2: The percentage of organic content and carbonate shell fragment in the representative grab samples at Playa Guiones

Representative Grab Sample	Organic Content (%)	Carbonate Shell Fragment (%)
G1	3	64
G2	2	60
G3	2	32
G4	1	46

Figure 4.4 illustrates the differences in the cumulative percentage passing grain size analysis for the different treatment methods (oven dried, furnace dried and acid washed). In graph A samples G1 and G4 which are collected towards the southern and northern headland respectively are nearly mirror images. It appears that the mineral matter signal in this data is being overwhelmed by the carbonate shell material signal. In graph B samples G1 and G4 are very similar in shape and samples G2 and G3 are very similar in shape. Samples G1 and G4 have a strong negative signal in Graph B because they contained a large coarser grained carbonate shell component which has been removed by the acid wash.

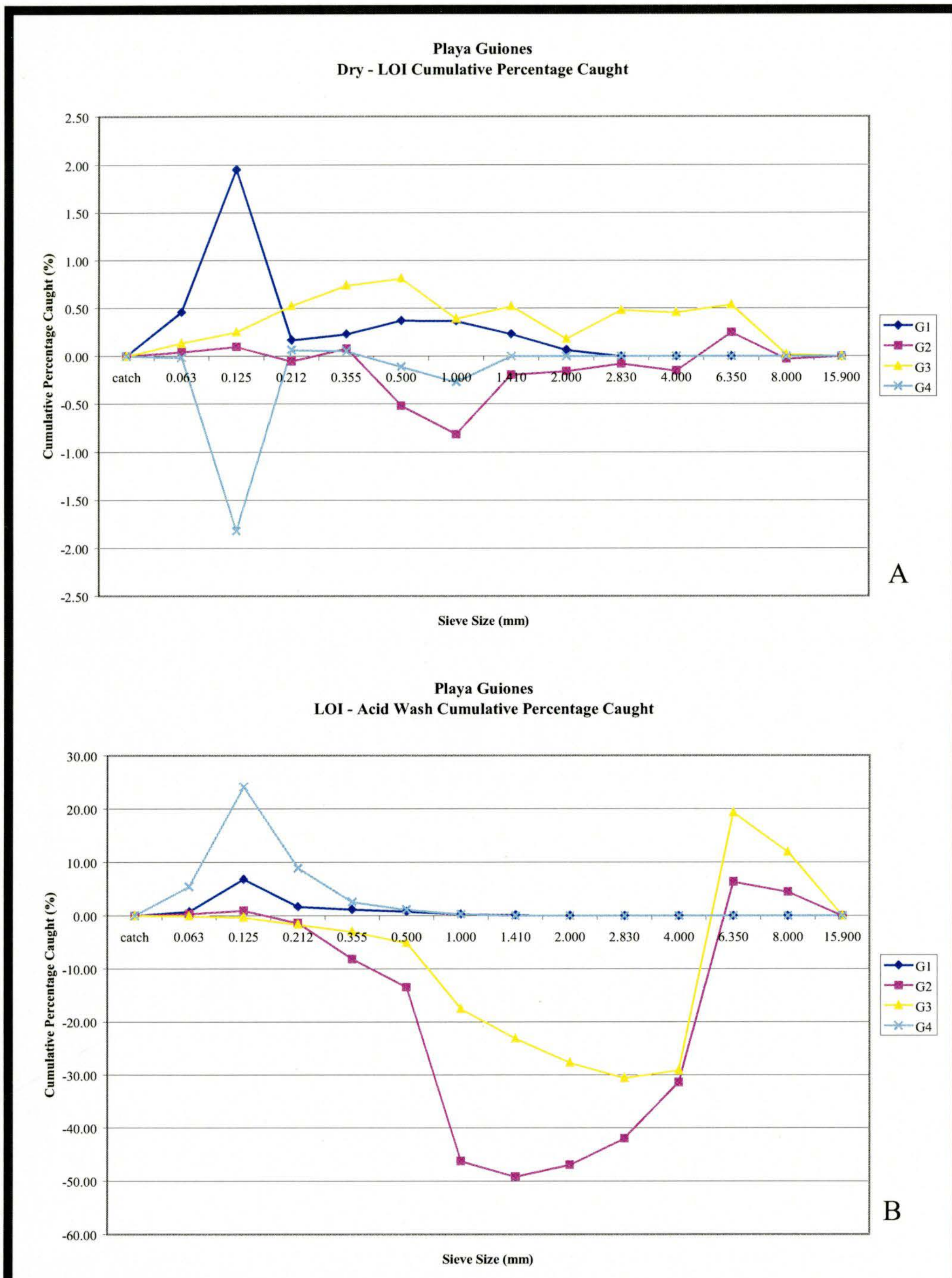


Figure 4.4: Graphs illustrating the cumulative percentage passing grain size analysis of the four grab samples from Playa Guiones. Graph A illustrates the difference between the oven dried sample and the furnace dried (i.e. Loss On Ignition – LOI) sample. Graph B illustrates the difference between the furnace dried and acid washed sample

4.1.2 Discussion

Sample G3, collected near a seasonal river outlet, contained the coarsest grained material with the least amount of calcareous shell material and was located towards the centre of the beach in an area of high wave energy. On an earlier visit to this portion of the beach in February 2005 the grain size was much finer and contained more shell material. It appears that finer grained material containing more shell material is deposited at this site during the dry season and is subsequently eroded during the wet season. During the wet season coarser grained material, with substantial less calcareous shell material, is being reworked in this area.

The beach texture and composition varied temporally. During February 2005 and February 2006 (winter, dry season) the beach was characterized with finer grained sands. The southern portion of the beach contained a large amount of gravel and cobble material which was arranged in semi-regular pods, towards the high tide mark. During February 2005 there was extensive broken and whole shell material on the beach. There was substantially less shell material during February 2006. During the wet summer season (June 2005) the beach contained more pebble material and less shell material. The semi-regular pods were not evident on the southern portion. The gravel and cobble material that composed the pods appeared to be deposited at the base of the cliff.

The three main sources of sediment at Playa Guiones are onshore/offshore movement, longshore drift and river sediment. Headland and cliff erosion which is identified by Woodroffe, 2003 as a typical input to a dynamic coastal system is less important on this beach. The relative importance of the three sources of sediment varies between the wet and dry season. During the wet season a large amount of sediment is contributed to the beach by river sediment. During the dry season longshore drift appears to be of much greater importance and most of the rivers do not bring any sediment to the beach. It is anticipated with the increased development occurring in the region of Playa Guiones that the amount of sediment being contributed during the wet season will increase as vegetation is removed for buildings making the sediment more mobile. It is also anticipated that as relative sea level continues to rise at Playa Guiones (due to subsidence) that the contributions by the various sediment sources may vary. It is likely that onshore/offshore movement of sediments will increase in importance (Short, 1999).

4.1.3 Limitations

Only four samples were collected, thus, limiting the credibility of the conclusions that can be drawn from these observations. The number of samples collected was limited because Playa Guiones is part of a wildlife nature refugee and exporting of sand/shell samples is limited in Costa Rica. Permission was received to collect only limited number of samples. Even though there were a limited number of samples collected, the laboratory work (grain size analysis) provided excellent sample recovery (>98% recovery on all samples) ensuring a high level of accuracy in the results. As well on visual inspection of the beach sediment there did not appear to be a huge degree of variability beyond the four types of samples that were collected.

4.2 Rock

Five samples representing the exposed rock at Playa Guiones were collected (Figure 4.5). Samples GR-1 to GR-4 were collected in the southern portion of the beach. Sample GR-5 was collected near the northern headland in the region where rock is again exposed along the beach (Figure 4.5). The collection locations were selected based upon observed changes in the type of rock material exposed along the beach. No samples were collected in an extensive portion of the beach simply because there were no exposed rock outcrops.

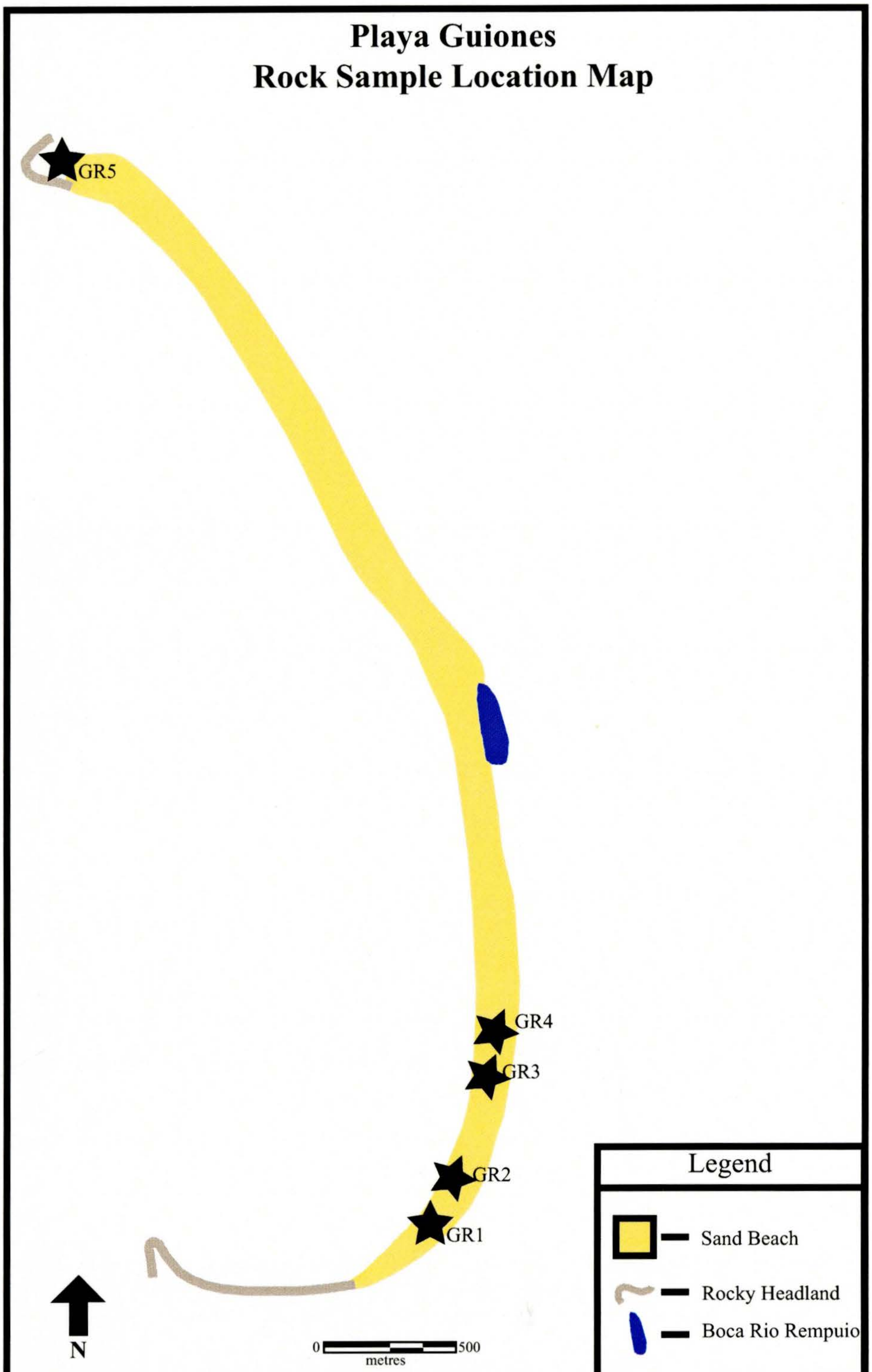


Figure 4.5: A map showing the location of the rock collection points. Note: that rock was only exposed at the beach on the southern and northern end

4.2.1 Results

The southern samples are all fine to medium grained and light grey in colour (GR-1 to GR-4). Samples GR-1 and GR-2 display white, crystalline material within veins. Sample GR-2 has a 2.5 cm smooth, dark grey nodule evident. Samples GR-3 and GR-4 are a uniform darker grey colour with no veining present. Sample GR-5 exhibits a coarser grained matrix then the other samples and is white and rust/tan colour. When a 0.5 M HCl solution is dropped on the samples, GR-1 reacted; whereas, GR-2 to GR-5 did not react.

4.2.2 Discussion

These samples are likely an extremely small outcropping of upper Cretaceous to early Paleocene rocks of the uppermost Samara Group which is a part of the Garza Supergroup and is known to exist along the Pacific coast of the Nicoya Peninsula as illustrated in Figure 2.3 (Vannucchi et al., 2001). Sample GR-1 and GR-2 are limestone with deformation structures (i.e. glide planes) and white crystalline calcite veins. The dark grey nodule in Sample GR-2 is chert. Samples GR-3 and GR-4 are fine-grained siltstone to fine-grained sandstone. These two samples likely represent the interbedded material that is described by Vannucchi et al., (2001) in the Samara Group of the Garza Supergroup. Sample GR-5 consists of sandstone. It likely represents the top of the Punta Pelada Formation which is part of the Mal Pais Supergroup (a shallow water overlap sequence). The top portion of the Punta Pelada Formation consists of approximately 30 m alternating sandstone and siltstone (Vannucchi et al., 2001).

4.2.3 Limitations

There were a limited number of samples collected that represented a relatively small geographic area. In the future it would be helpful to collect a greater number of samples that were more widely dispersed; particularly at the northern headland which represents an important geologic contact in the area. The number of samples collected was limited because Playa Guiones is part of a wildlife nature refugee and exporting of samples is limited in Costa Rica. Permission was received to collect only limited number of samples.

4.3 Vegetation

The objectives of the vegetation portion of the study were to identify the dominant types of vegetation present and to make qualitative statements about the health of the vegetation at Playa Guiones.

4.3.1 Results

The vegetation observed on Playa Guiones ranged from fully mature trees, through deciduous shrubs to incipient grasses and ground cover. Appendix 3 contains a series of plates of the vegetation identified at Playa Guiones. The southern portion of the beach was dominated by mature trees; whereas, the northern portion was dominated by ground cover and grasses except at the headland which is again dominated by trees. The central portion of the beach was transitional in nature and contained a mixture of trees and shrubs with a declining dominance of trees when moving northwards (Figure 4.6).

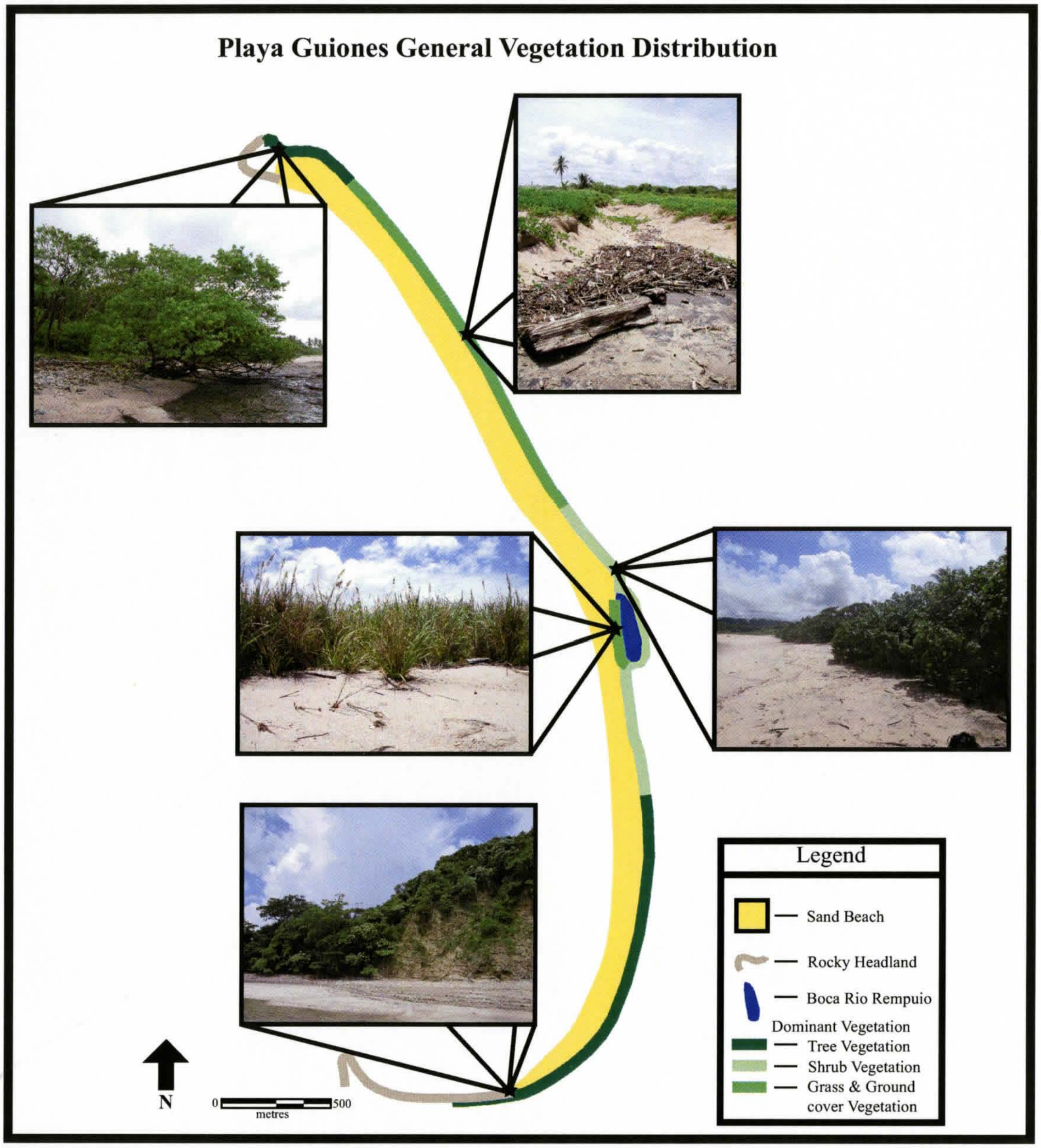


Figure 4.6: A map identifying dominant vegetation zones at Playa Guiones. The insets provide illustrations of the dominant vegetation in each zone. Appendix Two contains a series of plates of the vegetation identified at Playa Guiones

The primary trees in the southern region and northern headland area are: *Hibiscus pernambucensis, Conocarpus erectus*, *Hippomanne mancinella, Anacardium exelsum* and *Cocos nucifera*. When moving northwards there was a transition with the dominant trees becoming more sporadic and an increase in the amount of grasses present. The dominant grass was *Digitaria bicornis.* In this region there was also the introduction of shrub vegetation dominated by *Indigofera suffruticosa, Coccoloba caracassana, Stachytarpheta jamaicensis,* and *Sesuvium portulacastrum.* The headlands had one type of Yucca plant present, *Bromelia penguin* and one cacti, *Acanthocereus tetragonus*.

The vegetation observations were made during the height of the wet season, thus, the height of vegetative growth. The vegetation appeared to be in good health along the entire beach. Some of the trees near the edge of the beach had exposed roots (Figure 4.7). The grass and shrub areas were periodically inundated at high tide (spring tide)

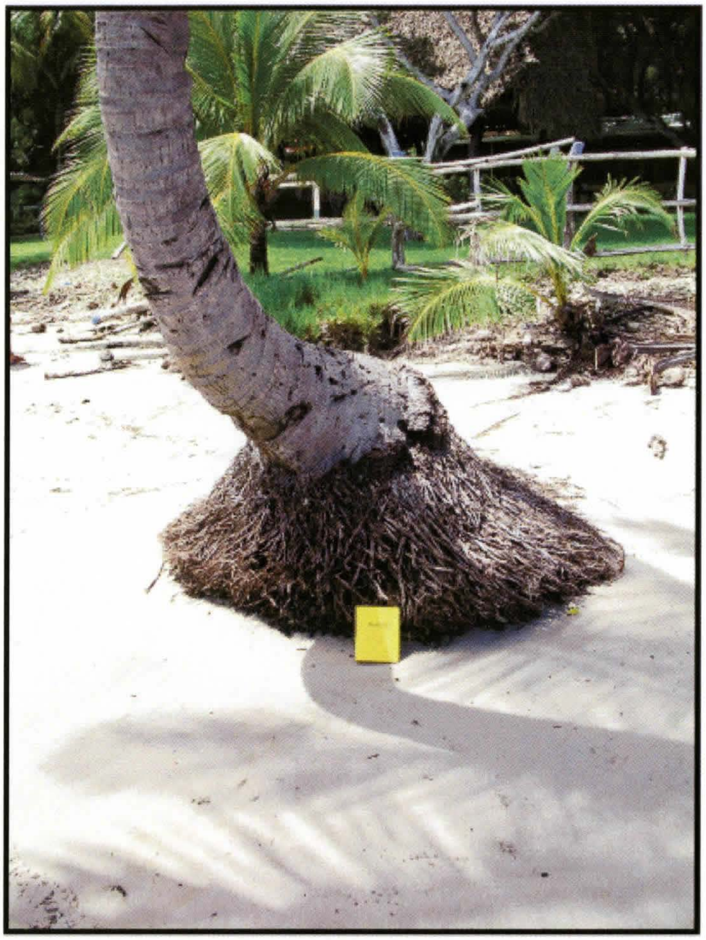


Figure 4.7: A plate showing the exposed roots of *Cocos nucifera*

4.3.2 Discussion

Both rocky headlands were characterized by vegetation (i.e. trees) which indicated the area was relatively stable and that vegetation had developed over a longer time period. Northward from the southern rocky headland, trees continued to dominate adjacent to the sand beach. Further north the shrubs, ground cover and grasses were encountered. The distribution and type of vegetation evident at various locations along Playa Guiones is structurally controlled. In the region of the headlands the lack of accommodation space results in a beach that is not very laterally extensive, thus, there is little room for grasses, ground covers and shrubs and the dominant vegetation in the area is trees. In the lower energy region of the beach there is more sediment available and more seasonal sediment movement occurring, thus, it lacks the stability necessary for mature trees to develop and is dominated by grasses, ground covers and shrubs.

Due to the large variation in moisture availability at Playa Guiones between the wet and dry season a variety of plants exist at the edge of their ranges of tolerance. For example, *Conocarpus erectus* which is associated with mangrove or near-mangrove conditions (i.e. roots inundated with water) co-exists on the same beach that plants like *Acanthocereus tetragonus* and *Bromelia pinguin* which are adapted to living in dry conditions exist (Zuchowski, 2005).

4.3.3 Limitations

Ideally vegetation would be assessed during the dry season to observe the entire growing period. Very few guidebooks exist to describe coastal vegetation in Costa Rica. Locating additional guidebooks on tropical vegetation along wet/dry coastlines would be helpful. The emphasis in most Costa Rican guidebooks is rainforest vegetation. Further study about plant health (e.g. plant density) could occur. For this research only vegetation directly in contact with the beach was considered. In future studies that are considering the land use pressures in the region it would be beneficial to establish baseline indices of vegetation health normal to the shoreline. It is anticipated that vegetation will be impacted by the increased density of human, including vehicular traffic in the future.

4.4 Digital Elevation Model

A major component of this study was the creation of a detailed Digital Elevation Model (DEM). The complete data set is available in Appendix Four.

4.4.1 Results

Figure 4.8 is the June 2005 DEM for Playa Guiones. This DEM was created using a gridding distance of 3 m, a blanking distance of 7.5 m, edge clipping of zero and a 3 m extension of cells beyond data. A gridding distance of 3 m was selected because it represented the minimum distance that could be used based on the spacing of the survey lines. The blanking distance was selected as 2.5x the gridding distance. The extension of cells was set to 3 m to match the gridding distance. There was 4.5 m of relief between the high and low topography measured at Playa Guiones. The DEM illustrates that the gradient between the northern and southern portions of the beach is different, as well it illustrates that the beach is not uniform in its extent. At the southern end of the beach there are a number of regions that appear to be lacking topographic data (labeled A on Figure 4.8). These regions are rock outcrops and were not surveyed in this research. An outline of their shape was taken. The rock outcrops had quite uneven surfaces that varied in elevation by 10s of cm over a distance of less than 1 m, thus, even with the resolution that is contained within this DEM these outcrops could not be precisely mapped.

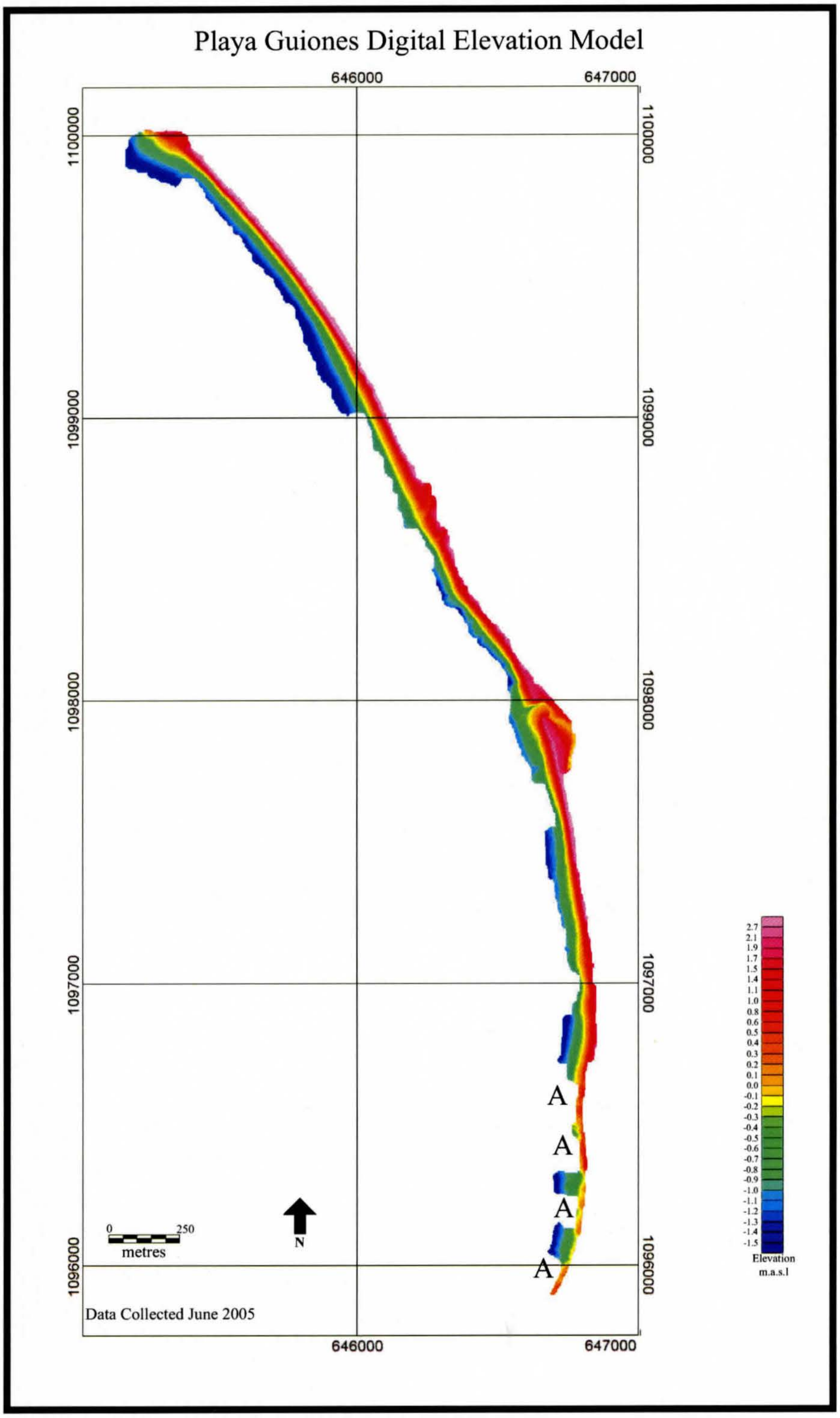


Figure 4.8: The corrected digital elevation model (DEM) prepared from data collected during June 2005 at Playa Guiones

A DEM must be referenced to a baseline. The baseline that is often selected is a government identified benchmark. At Playa Guiones 3 benchmarks at 4 m are identified on a road running parallel to the beach on the 1981 topographic map. None of these bench marks could be located during the field season. Rather than tie to an existing benchmark the decision was made to use mean sea level as a base level of zero. The elevation of the government identified bench marks appeared to fit well with benchmark of mean sea level. Identification of the elevation of mean sea level was accomplished by visual observation of the gradient change observed on a series of shore-normal profiles (i.e. the position of the inflection point was taken to represent mean sea level). Once the elevation of mean sea level was identified a bulk shift of the data occurred. A subset of the series of profiles that were used to identify mean sea level are illustrated in Figure 4.9. It is important to note that elevation used on the y axis of these profiles is the corrected elevation. Profile 2000, 2001, 2002 and 2003 from Figure 4.9 all display an inflection point at the corrected elevation of 0 m.

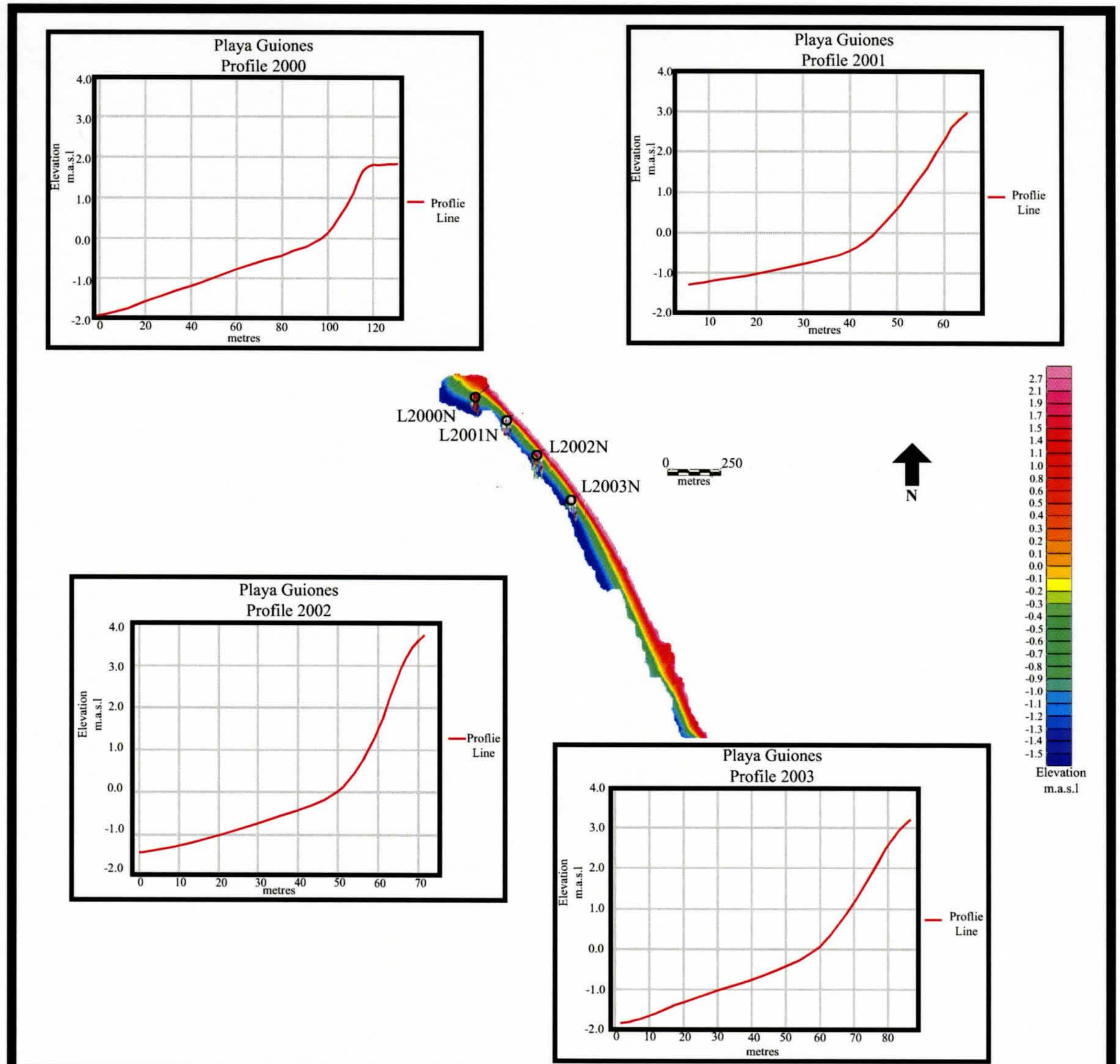


Figure 4.9: A portion of the DEM from the northern end of Playa Guiones and four of the profiles that were used to identify mean sea level

The DEM with mean high tide (Figure 4.10) illustrates that Playa Guiones contains a more extensive sand beach at the northern end than at the southern end largely due to the control exerted by the rocky outcrops that exist at the southern end of the beach. The beach at Playa Guiones has the greatest lateral extent in central portions of the beach; particularly in the vicinity of Point D on Figure 4.10. The northern end of the beach shows greater change in relief than is evident at the southern end of the beach. There is a well developed dune system at the northern end of the beach; whereas, there is no dune system at the southern end of beach.

During data collection a more extensive set of data was collected below the mean tide level at the northern end of the beach than at the southern end of the beach. This area had a fairly gentle gradient and had greater exposure during the period of data collection.

Four outlets to the ocean are visible. All four outlets are seasonal in nature. Outlets A, B and D on Figure 4.10 are identified on the topographic map as Queb Pelada, Quebrada Corea and Boca Rio Rempuio respectively (Instituto Geográfico Nacional Costa Rica, 1981). Outlet C does not appear to be named.

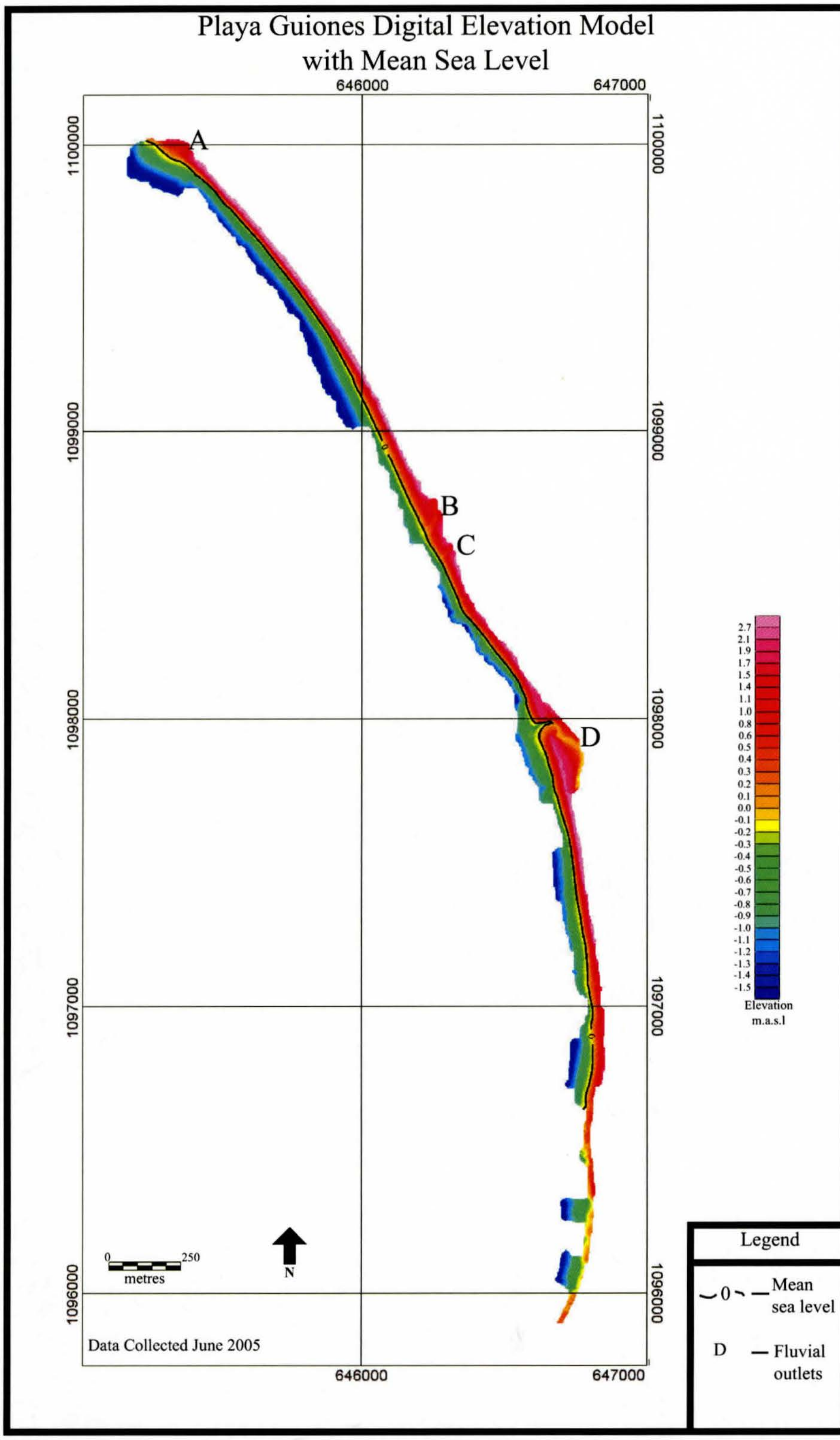


Figure 4.10: Playa Guiones DEM with mean sea level and fluvial outlets identified

Figure 4.11 contains four representative profiles of Playa Guiones (note that the x axis is not the same on all four profiles). Profile 2002 illustrates the steeper gradient that was observed at the northern end of Playa Guiones and Profile 2005 illustrates the gentler gradient that was observed at the southern end of Playa Guiones. Profile 2004 illustrates the conditions at Bocca Rio Rempuio. This profile is not illustrating a dune system but the relief evident in the profile is showing the relief from the ocean through the beach system and back to the river level of Rio Rempuio.

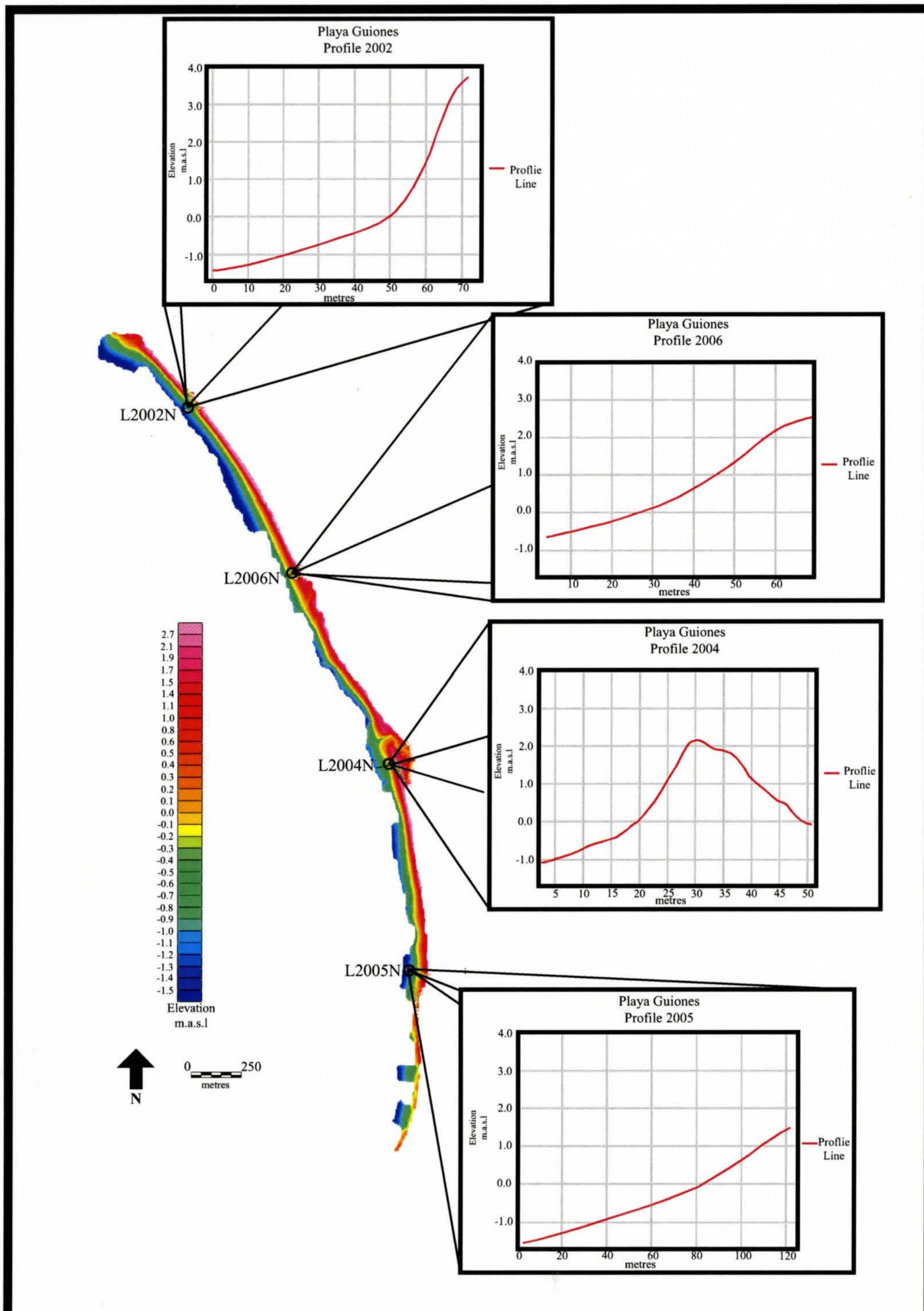


Figure 4.11: Playa Guiones DEM with four profiles and their location identified. The profiles represent the range of profiles observed at Playa Guiones

4.4.2 Discussion

The topographic map for this region identifies Outlets D as being perennial but it was a seasonal outlet in 2005 (Instituto Geográfico Nacional Costa Rica, 1981). The same map identifies the location of Outlet B approximately 75 m north of its current location (Instituto Geográfico Nacional Costa Rica, 1981). One additional outlet is evident on the topographic map (labeled as points E) but was not flowing with water during the period of observation and a channel is not identifiable in the DEM (Instituto Geográfico Nacional Costa Rica, 1981). There was a channel south of the mapping area that appears on the topographic map and was visible during data collection; but, is in the region where technical difficulties prevented the collection of data (Instituto Geográfico Nacional Costa Rica, 1981).

4.4.3 Limitations

The quality of the data was less at the southern end of the beach because of the greater density and size of the vegetation and the greater amount of exposed rock both of which hindered signal reception. Data collection was limited by high tide and the primary period of data collection was three hours prior to and three hours post low tide. The tidal limitation on data collection limits the number of observation points that exist near the low tide mark, thus, the DEM illustrates the general shape of the beach but omits an area adjacent to low tide on most days. Equipment malfunctions created numerous technical difficulties in obtaining satellite signal and maintaining the radio link between the two GPS units. Many of these malfunctions appeared to be random with no explained cause. The objective while collecting the data was to collect points along a uniform pacing distance and line separation. Three individuals were involved in pacing, the topography was uneven and the sediment was loose introducing an element of inconsistency in the pacing interval and the line spacing. The data for this project were collected during the wet season when numerous thunderstorms occur at Playa Guiones. The expense of the equipment combined with the method of data collection (i.e. tall metal rod) prevented data collection whenever a storm was in the region. These storms occurred at some point on most days.

4.5 Remotely Sensed Imagery

A series of aerial photographs (1944, 1977, 1991, and 1997), a satellite image (2004) and the DEM (2005) have been qualitatively compared to assess change which as occurred at Playa Guiones over the past 65 years.

4.5.1 Results

The time series of photographs highlights the dramatic increase in human influence at Playa Guiones and Nosara (Table 4.3). The 1944 image shows little to no anthropogenic influence (no access points to the beach or buildings are evident). By 1977 nine buildings and seven beach access points had been developed. Between 1977 and 1991 a dramatic increase in the number of buildings (39 buildings; >300 % increase) was observed but there is no increase in the number of beach access points (7 beach access points). During the period 1991 to 1997 there was a 57% increase in the number of beach access points and a 9% increase in the number of buildings adjacent to the beach. During the six year time span from December 1997 to February 2004 there was a 35% increase in the number of beach access points and a 69% growth in the number of buildings adjacent to the beach. Based on observations by the researcher between the 2005 to 2006 field seasons the acceleration in growth is continuing. During the period July 2005 to February 2006 a plaza, art store, major hotel extension, and car rental facility were erected. During this time period it was also observed that a large number of foreigners had purchased property and were in the process of developing substantially residences (e.g. a gated community).

Table 4.3: A comparison of human influence (number of beach access points and buildings) on Playa Guiones during the period 1944 – 2005 using remotely sensed imagery and ground observations ([1] Instituto Geográfico Nacional Costa Rica, 1994; [2]Instituto Geográfico Nacional Costa Rica, 1977; [3]Instituto Geográfico Nacional Costa Rica, 1991; [4]Instituto Geográfico Nacional Costa Rica, 1997; Digital Globe Incorporated, 2004)

	1944[1]	**1977[2]**	**June 9, 1991[3]**	**Dec. 04, 1997[4]**	**Feb. 03, 2004[5]**	**June 2005**
Type of Image	Aerial Photo	Aerial Photo	Aerial Photo	Aerial Photo	Quick Bird Satellite Image	DEM
Scale	1:20,000	1:10,000	1:10,000	1:40,000		
Season	End of wet season	Dry	Wet	End of wet season	Dry	Wet
# Beach Access Points (roads & paths)	0	7	7	11	17	17
# buildings within 1.25 km normal of the beach	0	9	39	43	140	Not measured

Figure 4.12 illustrates the increase in agriculture and settlement patterns adjacent to Rio Nosara during the time period 1944 to 1997. During this time period there has been a tremendous amount of growth in this region. The growth has been controlled by the location of Rio Nosara and the local topography. There is has been little to no development in the first major meander bend upriver of Boca Rio Nosara as this area is frequently inundated with water during the wet season. In this first meander loop there has been substantial movement of the stream channel during this 30+ year time period.

Figure 4.12: A visual comparison of the anthropogenic influences on a region adjacent to Rio Nosara 1944 -1997. A. is a section of an aerial photograph from 1944 and B. is a section of an aerial photograph from 1997. Note: Rio Nosara and the town of Nosara are located approximately 5 km north of Playa Guiones. (Instituto Geográfico Nacional, 1944;1997)

4.5.2 Discussion

Rapid growth is occurring in the region. This is substantiated by visual observations by the researcher, communication with locals and the literature (United Nations, 2006; Inman, 2002; Windevoxhel et al., 1999). This rapid growth has resulted in clearing of native vegetation, and has had implications for water quality and quantity. The Nicoya Peninsula experiences a tropical wet/dry climate. During the dry season there are regular fresh water shortages and during the wet season there is heavy reliance on septic beds resulting in water quality issues. These issues are being exacerbated by the rapid development.

4.5.3 Limitations

The 1977 series of aerial photographs showed a large amount of edge distortion to the point that this set of photographs could not be geo-rectified. This problem was exacerbated by the minimal amount of overlap between successive images. For valid photo merger and geo-rectification a minimal overlap of 60% is required. On this series of photographs there was often less than 10% overlap.

The 1999 series of aerial photographs were limited by the cloud cover and over exposure of the film.

The aerial photographs were acquired through the Instituto Geográfico Nacional Costa Rica. A number of key pieces of information regarding the exact date and time of collection, the details of the flight (pitch, yaw, and roll), camera details (camera used, and focal length) and scanning resolution of the original image were not available. The lack of this information greatly reduced the usefulness of this imagery. It was originally intended to do a much more detailed analysis of the remotely sensed imagery than what has been accomplished given these limitations.

The collection of useable ground control points was limited by a number of factors: dense vegetation limited penetration of satellite signal to the GPS unit preventing accurate readings; thus, limiting where ground control points could be collected. The lack of anthropogenic features combined with the dense vegetation cover made it nearly impossible to identify useable points on the 1940s image. More recent images contained more anthropogenic features (e.g. roads) which could be identified on the photographs and provided windows in the dense vegetation.

4.6 Beach Morphology

4.6.1 Seasonality

The researcher completed detailed mapping and field observations of this beach on three occasions (February 2005, June 2005 and February 2006). The beach texture and composition varied temporally. During the winter dry season the beach was characterized with finer grained sands in most regions but, the southern portion of the beach contained a large amount of gravel and cobble material which was arranged in semi-regular pods, towards the high tide mark. During February 2005 there was extensive broken and whole shell material on the beach, whereas, this type of material was not evident in February 2006. The deposits in February 2005 may have represented a single storm event. During the wet summer season (June 2005) the beach contained more pebble material and less shell material. The semi-regular pods were not present and the gravel/cobble material that the pods had previously consisted of appeared to be deposited at the base of the cliff.

The change in texture of the material on the beach between the wet and dry season was likely indicative of the wave energy on the beach. In general the low pressure systems associated with the presence of the ITCZ in the winter (February field seasons) generated higher energy waves causing coarser grained material to be deposited on the beach, particularly at the southern end of the beach. The higher pressure systems that dominated the region during the summer months (June field season) were associated with lower energy waves causing finer grained material to be deposited.

Although vegetation data collection was formally conducted only during June 2005 visual observations and photographs highlight the seasonality that was observed in this region (Figure 2.5). During the wet season the vegetation appeared to be very healthy and growing robustly. During the dry season a number of the plants adapt by losing their leaves or by reducing moisture loss by curling their leaves. During the dry season the vegetation appears less healthy and is likely less effective at stabilizing the sediment.

During the wet season there were at least six river/stream outlets that flowed across the beach. During the dry season none of these rivers/streams actually flowed to the ocean. These rivers/streams are important sources of sediment during the wet season but do not contribute at all during the dry season. In the future these seasonal rivers/streams may be of increasing significance to the beach as they may contribute substantial levels of pollutants from growing anthropogenic demands in the region.

4.6.2 Plate Margin

Playa Guiones lies along a convergent plate boundary but does not display all the typical characteristics of a beach along a convergent margin (Table 4.2). These discrepancies occur because the mountains do not directly contact the coastal zone rather there is a buffer zone with the presence of the narrow coastal plain. A second reason for the discrepancies between a typical convergent coastal margin and Playa Guiones is the large influence of the wet and dry season in this region. The wet and dry season influences the size, type, magnitude and sorting of sediment that occurs at Playa Guiones.

Table 4.4: Comparison of Playa Guiones to a typical convergent and passive margin beach using the classification scheme produced by [1]Short, 1999. ([2] Vannucchi, 2001 [3]Marshall and Anderson, 1995 [4] Instituto Geográfico Nacional Costa Rica, 1981) The yellow colour indicates characteristics of a convergent margin, blue indicates characteristics of a passive margin and green indicates characteristics of both a convergent and a passive margin.

Characteristic	**Convergent Margin**[1]	**Playa Guiones**	**Passive Margin**[1]
Age	1 to 10s million years	Upper Eocene (54.8 to 33.7 million years)[2]	Old (100s million years)
Relief	Steep, mountainous	Rugged linear mountain chain with narrow coastal piedmont[3]	Low gradient plains
Landforms	High mountains & volcanoes	Interior mountains & volcanoes with a narrow coastal plain	Coastal aggradation plains
	Narrow continental shelf	Narrow continental shelf (< 10 km)	Wide, low continental shelf
	Deep sea trough	Middle American Trench	Continental slope
Tectonics	Active earthquakes	Active earthquakes	Quiescent, stable
Weathering	Physical mass movements	Physical mass movements, chemical weathering, fluvial	Chemical, fluvial
Drainage	Short steep streams	Initially short steep streams that meander on the alluvial plain[4]	Long, meandering rivers
Sediments			
Quantity	Low	High	High
Size	Fine to coarse	Fine sand to pebbles	Fine
Sorting	Poor	Moderate to well sorted	Well
Colour	Dark	Light tan	Light
Composition	Unstable minerals	Stable minerals	Stable minerals
Coastal Landforms	Rocky, few beaches	Extensive sand beaches anchored by rocky headlands (i.e. embayed beaches)	Extensive barriers and deltas
Wave Attenuation	Low	Low	Moderate to high
Tide Range	Minimal amplification	Minimal	Enhanced
Examples	West coast Americas New Zealand Iceland Japan		East coast Americas Southern Africa Southern Australia North Alaska India

4.6.3 Embayed Beach

A typical embayed beach is anchored by a major headland with the adjacent sandy beach consisting of coarse grained sediment, a steep gradient and reflective. At the opposite end of the beach there is typically a minor headland with the adjacent sandy beach being composed of fine grained sediment, relatively flat gradient and dissipative. Figure 4.13 illustrates the typical embayed beach and the DEM of Playa Guiones.

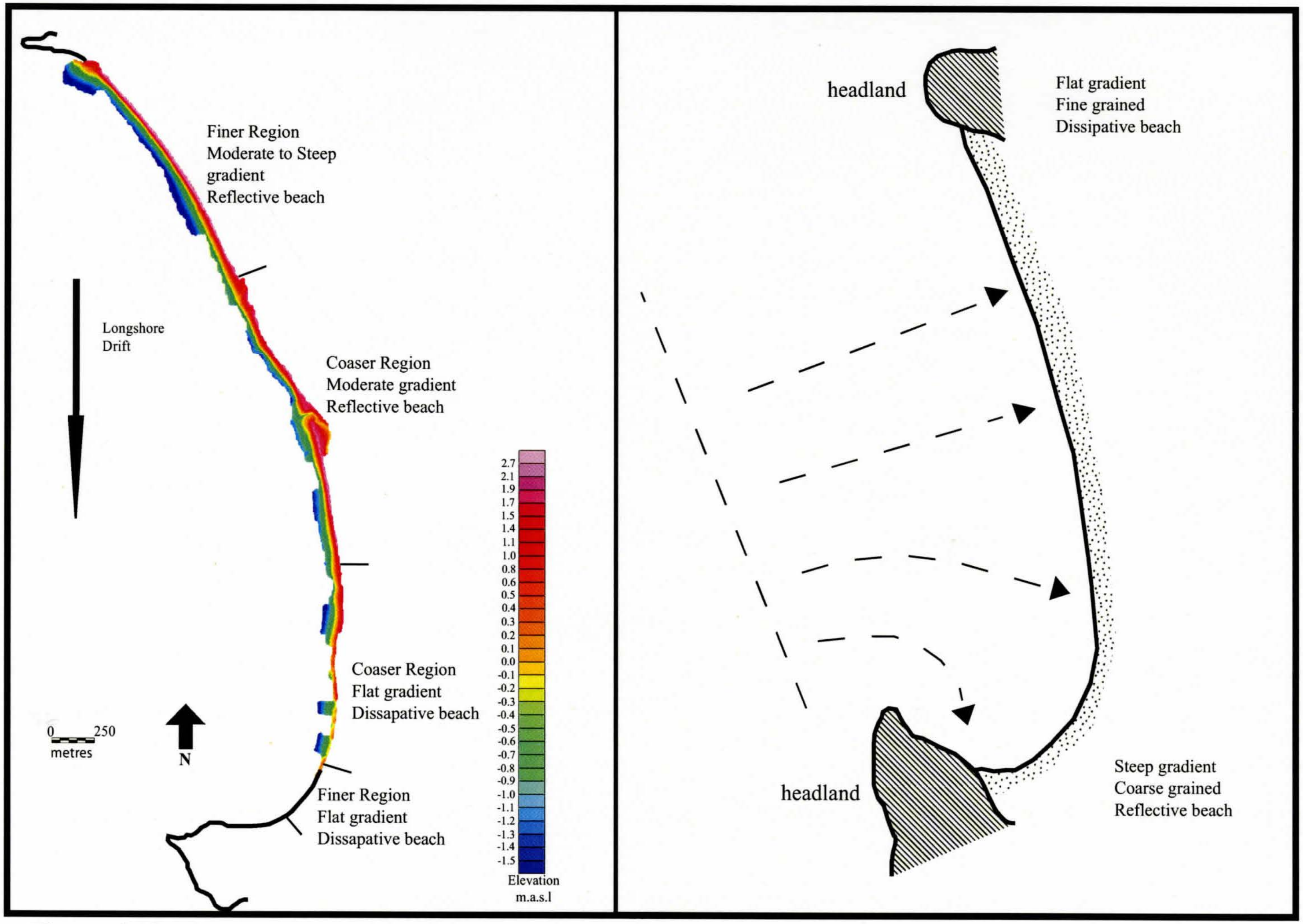


Figure 4.13: A comparison of the DEM from Playa Guiones with sediment grain size, beach type and longshore drift direction identified (right diagram modified from: Woodroffe, 2002)

It is evident from Figure 4.13 that Playa Guiones has a major headland at the southern end of the beach and that the adjacent sandy beach has a gentle gradient, is composed of finely grained material and is a reflective beach type. The grain size and reflective nature of the beach is not supported by the typical embayed beach described by Woodroffe, 2004. The gentle gradient at the southern end of this beach occurs because there is a lack of accommodation space due to the shallow depth to rock surface, thus, the rock surface and not the sediment is controlling the beach gradient. The minor headland that is typical of an embayed beach occurs at the northern end of Playa Guiones. In a typical embayed beach the area adjacent to the minor headland is relatively flat lying, fine grained and dissipative in nature. At Playa Guiones the area adjacent to the northern headland (i.e. minor headland) is composed of relatively fine grained sediment (which supports the characteristics of an embayed beach) but has a moderate to steep gradient and is reflective (which does not support the characteristics of an embayed beach). Overall, based on the presence of rocky headlands it would be assumed that Playa Guiones is an embayed beach but it displays few characteristics of an embayed beach.

4.6.4 Tectonics

There is substantial evidence to indicate that Playa Guiones is actively subsiding. Gregorio Escalante, a noted Costa Rican geologist who owns property along the beach, informed the researcher that a significant portion of the beach had been lost since the 1950 earthquake as the land had subsided raising relative sea level 1.5 m. Marshall and Anderson, (1995) confirm that a 7.7 M earthquake occurred in the Nicoya Peninsula and these researchers acquired anecdotal evidence from 25 coastal residents from Nosara to Puerto Carrillo (both farmers and fisherman) that confirm a co-seismic uplift of 1-2 m and subsequent subsidence of 0.5 m.

A second local resident, Mario Quiros, informed the researcher that in the early 1950s his great-grandfather had flown over the region and landed his plane on the southern end of Playa Guiones which at that time was an extensive sandy beach. The current size of the beach would prohibit landing a small plane in the region. He also reports his great-grandfather building a home on the beach and it being subsequently washed away during his grandfather's life. His grandfather built a second home which is currently experiencing significant erosion problems. He also reports substantial loss of sand in the southern region. This anecdotal evidence supports the evidence of a subsiding coastline in an environment with a sandy beach underlain by a rock surface and a decreasing amount of accommodation space.

Approximately 150 m north of Playa Guiones on Playa Pelada there is evidence of the subsidence in a cement stairway which is being eroded at its base (Figure 4.14)

Figure 4.14: Evidence of relative sea level rise is evident by the erosion of this staircase found at Playa Pelada 150 m north of Playa Guiones.

This rise in sea level has resulted in the loss of shrub and grass vegetation in the southern region and the encroachment of the ocean to the trees. This is supported by the observation that tree roots were exposed (figure 4.7).

4.6.5 Satellite Imagery and Digital Elevation Model Merged

ER Mapper was used to combine the satellite image (February 2004) and the DEM (June 2005) to assess the quality of the DEM image and to see the relationships between the two images (Figure 4.15).

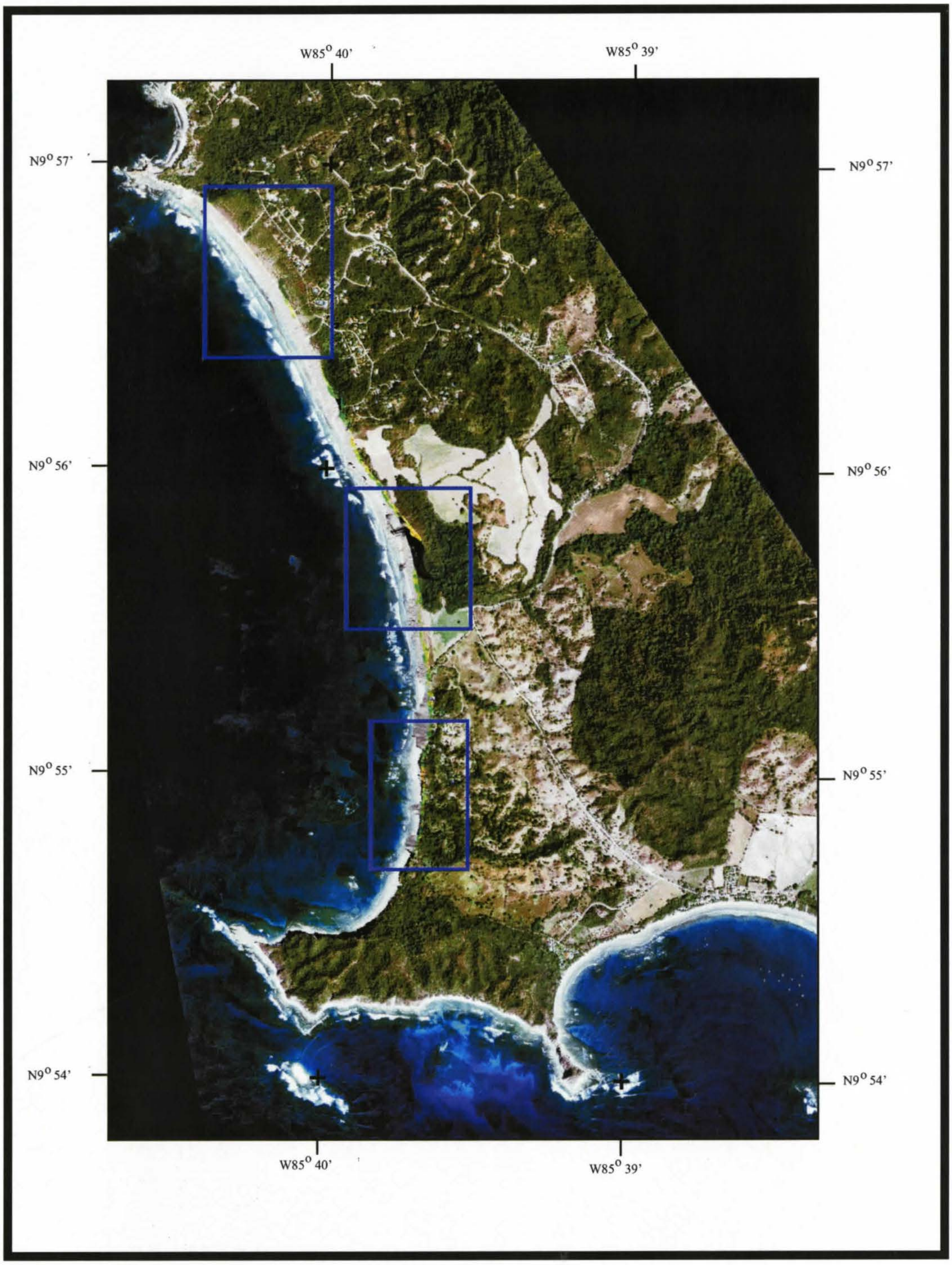


Figure 4.15: Geo-referenced Quickbird satellite image of Playa Guiones (February 2004) with the DEM overlain. The blue boxes identify sections that will be visible in more detail in Figure 4.16 (Source: Digital Globe Incorporated, 2005).

The Quickbird satellite image represents a section of a 16.5 km wide swath at nadir. It has been pre-processed with radiometric, sensor and geometric corrections and has been geo-rectified. It is a multi-spectral image with blue (450-520 μm), green (520-600 μm), red (630-690 μm) and infared (760-900 μm) bands.

Figure 4.16 has three expanded images that show the relationship between the DEM and the satellite imagery data. The most northern image illustrates relatively good agreement between the two sources of data. The central image shows excellent agreement between the two data sets and illustrates the Bocca Rio Rempuio. The southern most image shows the least agreement between the two sources of data. The DEM data appears to extend into the vegetation at this end of the beach. It is relevant to note that at this end of the beach there is more vegetation that overhangs the beach than in the other regions of the beach. Data for the DEM was collected first from the southern end of the beach. This data has been more problematic to work with than data over the rest of the beach. The lack of agreement between the two sources of data could be indicative of a large amount of erosion occurring between 2004 and 2005. This is unlikely to be the explanation because none of the anecdotal accounts that were obtained reported a recent period of intense erosion. A final explanation for this observed discrepancy may lie in the quality of the satellite data. The satellite data may represent data that was collected on ascent and the overlap of the DEM into the vegetation may represent clipping of the trees onto the beach in the satellite image due to the image angle.

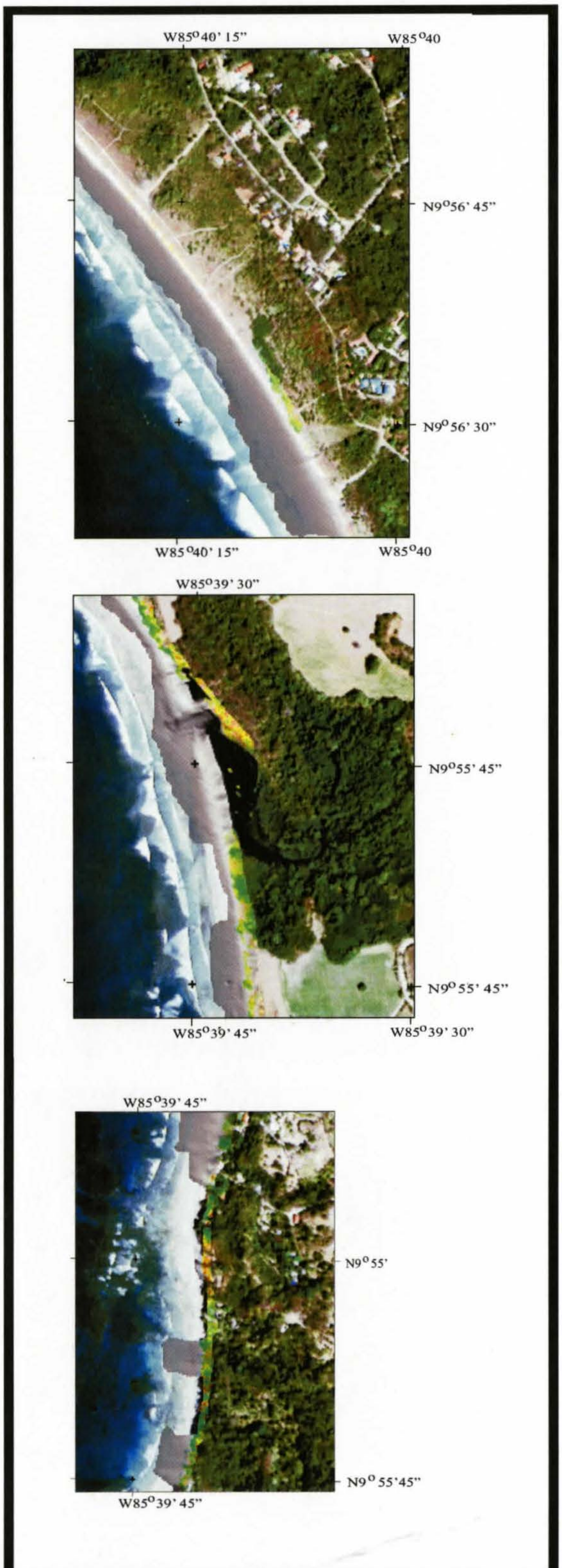


Figure 4.16: Three portions of the Quickbird satellite image with the DEM overlay (Source: Digital Globe Incorporated, 2005)

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDY

5.1 Summary

This research provided the first detailed study of the coastal geomorphology of Playa Guiones, Costa Rica. It was also the first study conducted by the student researcher and supervisor in this region; thus, it provides important baseline information for future work.

The sediment at Playa Guiones consisted largely of fine grained carbonate shell material. The sediment samples collected near the central portion of the beach were composed of slightly coarser material than the samples collected in other areas of the beach. The dominant minerals in the sediment were quartz, obsidian, olivine, K-feldspar and garnet (in declining order of dominance).

Playa Guiones lies at an important geologic contact between the Garza Supergroup and Mal Pais Supergroup. Rock samples collected at the south end of the beach were part of the uppermost Samara Group (part of the Garza Supergroup) and consisted of limestone and interbedded sandstone and siltstone. The rock collected at the north end of the beach were part of the Punta Pelada Formation (part of the Mal Pais Supergroup) and consisted of sandstone.

The coastal vegetation at Playa Guiones exhibited relatively distinct zonation from fully mature trees at both headlands to dune grasses in the higher energy portion of the beach. The distribution and type of vegetation observed along Playa Guiones was structurally controlled in large part by the lack of available accommodation space.

On initial observation Playa Guiones appears to be a classic example of an embayed beach but through detailed examination of grain size, beach gradient, beach type and wave energy dispersal it has been illustrated that structural controls at Playa Guiones supersede the general text book characteristics of an embayed beach. Furthermore, Playa Guiones exists along a convergent margin but again does not show all the typical characteristics that are associated with beaches present along a convergent margin coastline.

By conducting a detailed survey of Playa Guoines a data set has been established that provides a baseline for future geo-indicator studies. This is particularly important at Playa Guiones because of the increasing land use demands and the large seismic gap that occurs on the Nicoya Peninsula.

Playa Guiones has undergone rapid land use change which is evident in the qualitative comparison of remotely sensed imagery. In 1944 there were no buildings or beach access points. There was a gradual increase in anthropogenic influences until 1997. Between 1997 and 2004 the change has occurred at a much faster rate. By 2004 there were 140 buildings within 1.25 km of the beach and 17 beach access points.

This study provides a much higher resolution DEM than is typical collected in geo-indicator studies.

5.1 Recommendations for Further Study

To more fully understand the coastal morphology and dynamics at Playa Guiones more sediment and rock samples should be collected. These samples would allow for increased understanding of lateral variation at Playa Guiones and a better ability to infer wave energy and sediment budget dynamics.

Assessing temporal variability was greatly hindered by the quality of information that could be extracted from the aerial photographs. An increased number of and distribution of ground control points (GCP's) should be gathered. These points would permit more quantitative analysis of the beach morphology and surrounding land use characteristics.

Due to the drastic weather variability at Playa Guiones between the wet and dry season a second digital elevation model composed of data collected during the dry season would establish a excellent baseline data series upon which further studies may expand this current work. Furthermore, acquiring better climate data (including wind data) and buoy data would greatly improve future studies and allow for enhanced understanding of process dynamics on this beach.

Vannuchi et al. (2001) illustrate on a gross scale the geologic significance of the Playa Guiones and Playa Pelada region as a geologic contact region. An interesting future project would combine the coastal geomorphic study with detailed geological mapping of the headland regions between Playa Pelada and Playa Guiones and determine the degree of geologic control on the geomorphology of these two beaches.

A greater quantitative assessment of vegetation could be conducted. This could include density counts, traverses of the vegetation normal to shore and conducting a survey to determine stabilizing characteristics of the vegetation during the wet season versus the dry season.

Risk assessment and hazard mapping of this coastal region would be beneficial because of the large seismic gap which last fully ruptured in 1950 on the Nicoya Peninsula, the potential tsunami risk along the western coast of the Americas and the current development pressures.

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APPENDIX ONE

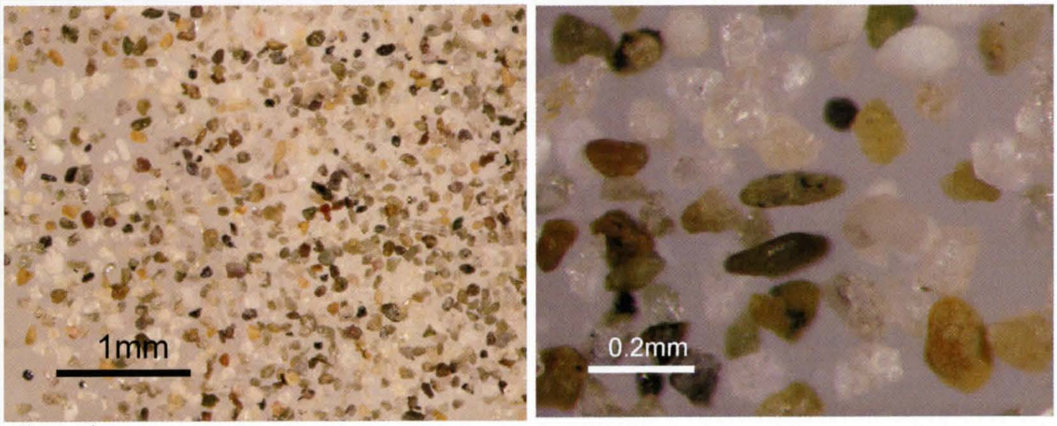
Playa Guiones Field Samples								
						LOI		
Sample	Weight [dry] (g)		Size Fraction	Percentage	Cum. Perc.	Size Fraction	Percentage	Cum. Perc.
			Weight (g)	Caught (%)	Caught (%)	Weight (g)	Caught (%)	Caught (%)
G1A		catch	4.72	4.42	100.00	5.06	4.88	100.00
	106.97	0.063	81.25	76.16	95.58	80.51	77.64	95.12
		0.125	18.33	17.18	19.42	15.97	15.40	17.48
LOI - 550		0.212	0.87	0.82	2.24	0.91	0.88	2.07
in/out		0.355	0.23	0.22	1.42	0.37	0.36	1.20
		0.500	0.55	0.52	1.21	0.53	0.51	0.84
in - 106.69		1.000	0.32	0.30	0.69	0.17	0.16	0.33
out - 103.94		1.410	0.31	0.29	0.39	0.13	0.13	0.16
		2.000	0.11	0.10	0.10	0.04	0.04	0.04
		2.830	N/A	0	0.00	N/A	0	0.00
		4.000	N/A	0	0.00	N/A	0	0.00
		6.350	N/A	0	0.00	N/A	0	0.00
		8.000	N/A	0	0.00	N/A	0	0.00
		15.900	N/A	0	0.00	N/A	0	0.00
		TOTAL	**106.69**			**103.69**		
						DRY-LOI Cumm% Caught		**LOI-ACID Cumm % Caught**
G1 - acid wash		catch	1.82	5.62	100.00	0.00		0.00
	Pre acid wash	0.063	27.11	83.72	94.38	0.46		0.74
	91.61	0.125	3.33	10.28	10.65	1.95		6.82
		0.212	0.12	0.37	0.37	0.17		1.70
	Post acid wash	0.355	N/A	0	0.00	0.23		1.20
	32.85	0.500	N/A	0	0.00	0.37		0.84
		1.000	N/A	0	0.00	0.37		0.33
		1.410	N/A	0	0.00	0.23		0.16
		2.000	N/A	0	0.00	0.06		0.04
		2.830	N/A	0	0.00	0.00		0.00
		4.000	N/A	0	0.00	0.00		0.00
		6.350	N/A	0	0.00	0.00		0.00
		8.000	N/A	0	0.00	0.00		0.00
		15.900	N/A	0	0.00	0.00		0.00
		TOTAL	**32.38**					

Playa Guiones Field Samples								
						LOI		
Sample	Weight [dry] (g)		Size Fraction	Percentage	Cum. Perc.	Size Fraction	Percentage	Cum. Perc.
			Weight (g)	Caught (%)	Caught (%)	Weight (g)	Caught (%)	Caught (%)
G2B		catch	0.14	0.13	100.00	0.18	0.17	100.00
	106.73	0.063	0.28	0.26	99.87	0.33	0.32	99.83
		0.125	5.77	5.44	99.60	5.48	5.29	99.51
in - 106.15		0.212	11.25	10.60	94.17	11.12	10.73	94.22
out - 103.95		0.355	9.92	9.35	83.57	9.07	8.75	83.49
		0.500	45.56	42.92	74.23	44.18	42.62	74.74
		1.000	6.39	6.02	31.30	6.88	6.64	32.12
		1.410	4.69	4.42	25.28	4.62	4.46	25.48
		2.000	5.1	4.80	20.87	5.06	4.88	21.02
		2.830	4.79	4.51	16.06	4.6	4.44	16.14
		4.000	5.25	4.95	11.55	5.54	5.34	11.70
		6.350	2.28	2.15	6.60	1.94	1.87	6.36
		8.000	4.73	4.46	4.46	4.65	4.49	4.49
		15.900	N/A	0	0	N/A	0	0
		TOTAL	**106.15**			**103.65**		
						DRY-LOI Cumm% Caught		**LOI-ACID Cumm % Caught**
G2 - acid wash		catch	0.18	0.53	100.00	0.00		0.00
	Pre acid wash	0.063	0.32	0.95	99.47	0.04		0.36
	84.74	0.125	1	2.96	98.52	0.10		0.99
		0.212	1.34	3.96	95.57	-0.05		-1.35
	Post acid wash	0.355	1.17	3.46	91.61	0.08		-8.11
	34.1	0.500	3.33	9.84	88.15	-0.52		-13.40
		1.000	1.25	3.69	78.30	-0.81		-46.19
		1.410	2.27	6.71	74.61	-0.20		-49.13
		2.000	3.33	9.84	67.90	-0.16		-46.88
		2.830	5.09	15.05	58.05	-0.08		-41.91
		4.000	14.55	43.01	43.01	-0.15		-31.31
		6.350	N/A	0.00	0.00	0.25		6.36
		8.000	N/A	0.00	0.00	-0.03		4.49
		15.900	N/A	0.00	0	0.00		0.00
		TOTAL	**33.83**					

Playa Guiones Field Samples										
						LOI				
Sample	Weight [dry] (g)		Size Fraction	Percentage	Cum. Perc.	Size Fraction	Percentage	Cum. Perc.		
			Weight (g)	Caught (%)	Caught (%)	Weight (g)	Caught (%)	Caught (%)		
G3A		catch	0.11	0.10	100.00	0.25	0.24	100.00		
	107	0.063	0.71	0.67	99.90	0.81	0.78	99.76		
in - 106.56		0.125	1.58	1.48	99.23	1.82	1.76	98.98		
out - 103.84		0.212	1.56	1.46	97.75	1.74	1.68	97.22		
		0.355	2.79	2.62	96.28	2.79	2.69	95.54		
		0.500	18.76	17.61	93.67	17.81	17.18	92.85		
		1.000	10.34	9.70	76.06	10.19	9.83	75.67		
		1.410	11.94	11.20	66.36	11.26	10.86	65.83		
		2.000	12.04	11.30	55.15	12.02	11.60	54.97		
		2.830	12.63	11.85	43.85	12.26	11.83	43.37		
		4.000	12.91	12.12	32.00	12.64	12.20	31.54		
		6.350	8.46	7.94	19.89	7.69	7.42	19.35		
		8.000	12.73	11.95	11.95	12.36	11.93	11.93		
		15.900	N/A	0	0	N/A	0	0		
		TOTAL	**106.56**			**103.64**				
						DRY-LOI Cumm% Caught		**LOI-ACID Cumm % Caught**		
G3 - acid wash		catch	0.1	0.17	100.00	0.00		0.00		
	Pre acid wash	0.063	0.32	0.53	99.83	0.14		-0.08		
	88.94	0.125	0.27	0.45	99.30	0.25		-0.33		
		0.212	0.22	0.36	98.86	0.53		-1.64		
	Post acid wash	0.355	0.34	0.56	98.49	0.74		-2.95		
	60.13	0.500	2.86	4.74	97.93	0.82		-5.08		
		1.000	2.57	4.25	93.20	0.39		-17.53		
		1.410	3.8	6.29	88.94	0.52		-23.11		
		2.000	5.26	8.71	82.65	0.18		-27.68		
		2.830	8.05	13.33	73.94	0.48		-30.57		
		4.000	36.61	60.61	60.61	0.46		-29.07		
		6.350	N/A	0	0.00	0.54		19.35		
		8.000	N/A	0	0.00	0.02		11.93		
		15.900	N/A	0	0	0.00		0.00		
		TOTAL	**60.4**							

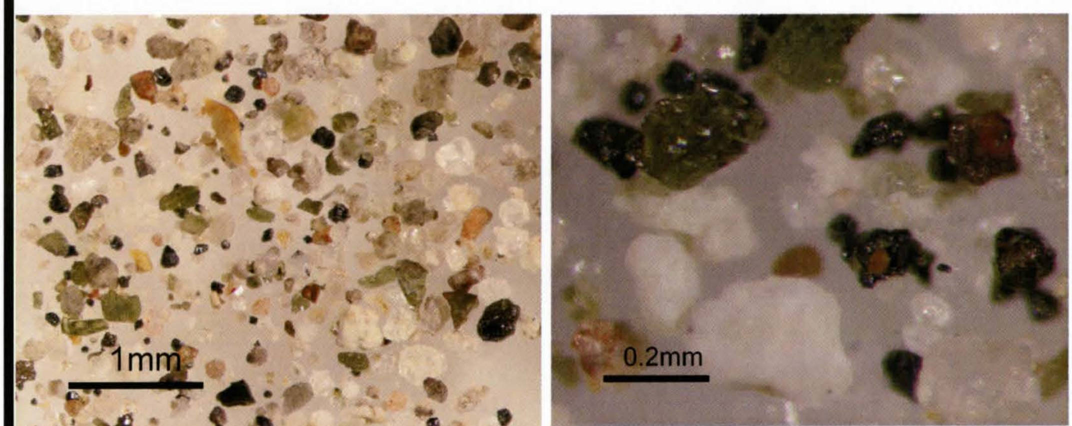
Playa Guiones Field Samples										
						LOI				
Sample	Weight [dry] (g)		Size Fraction Weight (g)	Percentage Caught (%)	Cum. Perc. Caught (%)	Size Fraction Weight (g)	Percentage Caught (%)	Cum. Perc. Caught (%)		
G4B		catch	5.22	5.16	100	5.15	5.14	100		
	101.57	0.063	34.75	34.35	94.84	32.59	32.54	94.86		
in - 101.17		0.125	47.87	47.32	60.49	49.27	49.20	62.31		
out - 100.39		0.212	10.45	10.33	13.18	10.33	10.32	13.11		
		0.355	1.83	1.81	2.85	1.65	1.65	2.80		
		0.500	1.01	1.00	1.04	0.84	0.84	1.15		
		1.000	0.04	0.04	0.04	0.31	0.31	0.31		
		1.410	N/A	0	0	N/A	0	0		
		2.000	N/A	0	0	N/A	0	0		
		2.830	N/A	0	0	N/A	0	0		
		4.000	N/A	0	0	N/A	0	0		
		6.350	N/A	0	0	N/A	0	0		
		8.000	N/A	0	0	N/A	0	0		
		15.900	N/A	0	0	N/A	0	0		
		TOTAL	**101.17**			**100.14**				
						DRY-LOI Cumm% Caught		**LOI-ACID Cumm % Caught**		
G4 - acid wash		catch	4.94	10.56	100	0.00		0.00		
	Pre acid wash	0.063	23.96	51.21	89.44	-0.02		5.42		
	87.35	0.125	15.91	34.00	38.23	-1.82		24.08		
		0.212	1.89	4.04	4.23	0.06		8.88		
	Post acid wash	0.355	0.09	0.19	0.19	0.05		2.60		
	47.06	0.500	N/A	0	0	-0.11		1.15		
		1.000	N/A	0	0	-0.27		0.31		
		1.410	N/A	0	0	0.00		0.00		
		2.000	N/A	0	0	0.00		0.00		
		2.830	N/A	0	0	0.00		0.00		
		4.000	N/A	0	0	0.00		0.00		
		6.350	N/A	0	0	0.00		0.00		
		8.000	N/A	0	0	0.00		0.00		
		15.900	N/A	0	0	0.00		0.00		
		TOTAL	**46.79**							

APPENDIX TWO



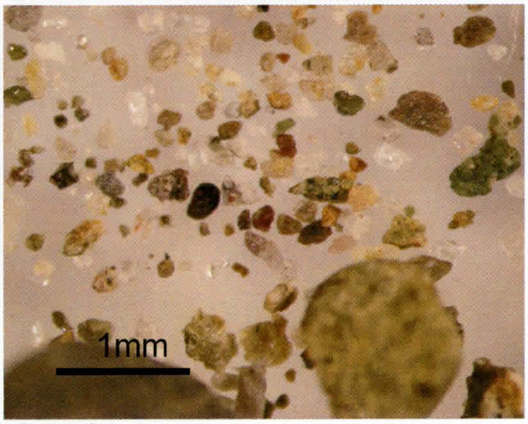
Sample

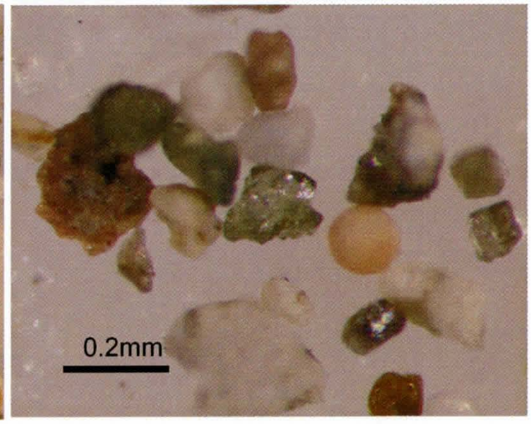
G-1



Sample

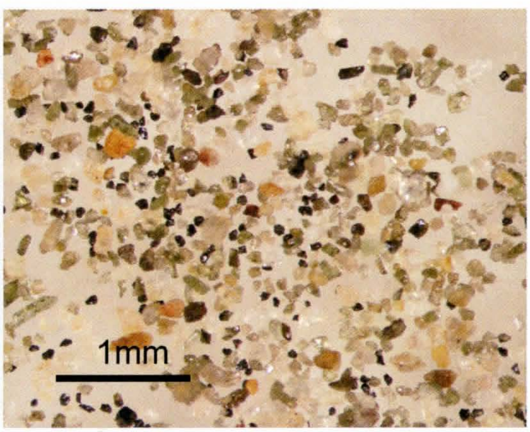
G-2

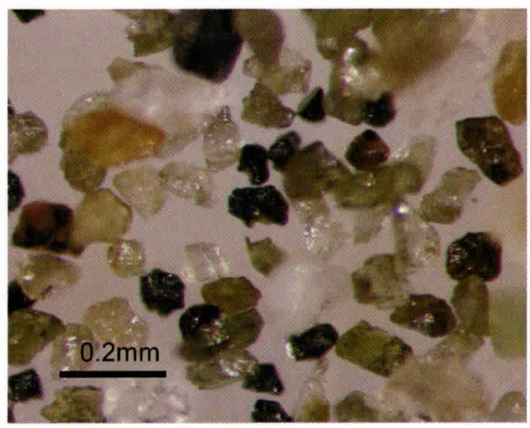




Sample

G-3





Sample

G-4

APPENDIX THREE

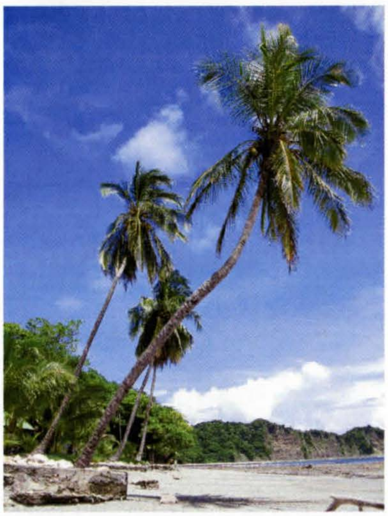
Latin Name	Common Name
Acanthocereus tetragonus	Triangle Cactus

Latin Name	Common Name
Anacardium exelsum	Espave, Wild Cashew

Latin Name	Common Name
Bromelia pinguin	Yucca, Wild Pineapple

Latin Name	Common Name
Canavalia rosea	Beach bean

Latin Name	Common Name
Coccoloba caracasana	



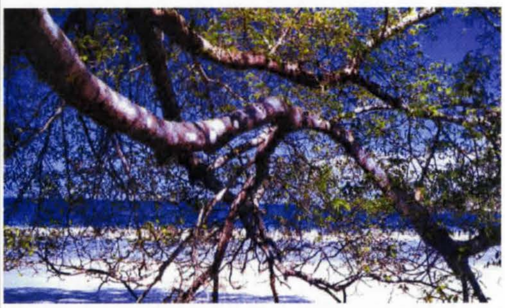
Latin Name	Common Name
Cocos nucifera	Coconut Tree

Latin Name	Common Name
Conocarpus erectus	Bottonwood

Latin Name	Common Name
Digitaria bicornis	Asian Crabgrass

Latin Name	Common Name
Gynereun sagittatum	Gaint Cane

Latin Name	Common Name
Hibiscus pernambucensis	Mahoe, Beach hibiscus



Latin Name	Common Name
Hippomanne mancinella	Manchineel

Image from Zuchowski, 2005

Latin Name	Common Name
Indigofera suffruticosa	Anil

Latin Name	Common Name
Sesuvium portulacastrum	Portulaca

Latin Name	Common Name
Stachytarpheta jamaicensis	Blue Snakeweed

APPENDIX FOUR