

**SEDIMENT DISTRIBUTION AND DEPOSITIONAL PROCESSES ON
THE CARNEGIE RIDGE**

A Thesis

by

NELSON A. PAZMIÑO MANRIQUE

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2005

Major Subject: Oceanography

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ABSTRACT

Sediment Distribution and Depositional Processes on the Carnegie Ridge. (May 2005)

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Sediment sampling, bathymetric data, and seismic reflection profiling were used to classify sediment deposition patterns on the Carnegie Ridge. Core sampling was used to relate compositional characteristics between equivalent areas, and seismic profiling to establish vertical variations. Three study areas were selected based on core distribution along the ridge. Grids of the following parameters were obtained: slope, elevation, percentage of carbonate, SiO_2 , and organic carbon contents. The general CaCO_3 content distribution is highest on the ridge except in the areas affected by terrigenous deposition from the mainland, and volcanic debris from Galapagos Volcanic Platform. The general SiO_2 content distribution is highest south of the Equator, bordering the west ridge. The organic carbon content is high in the equatorial upwelling area and close to the mainland. The relationship between organic carbon and carbonate was determined through correlation analysis. Based on those analyses, and considering the mixture of sedimentary sources and tectonic processes, the carbonate sediment is more important to this area. Sediments on the Carnegie Ridge above the lysocline are affected by three different types of processes controlling the sediment deposition. The first is the location of the high productivity zone in which pelagic settling is the source of sediment. The second is the difference in sea water properties between the Panama and Peru Basins surrounding the ridge, which creates different depositional environments. These properties create horizontal and vertical variations within water masses. Intermediate depths are affected by northward Pacific Central Water and bottom waters by northward Pacific Deep Water. The deflection of the bottom water flow by the existence of the Carnegie Ridge as a natural barrier produces scouring effects on the south flank. The third process controlling deposition is underwater dissolution on the saddle and east ridge by organic carbon degradation, which is enhanced by bottom water flow. Significant differences in sedimentation types were found in areas with hilltops, contrasted slopes, and slope bases, primarily related to changing depths and water flows, and lateral transport along the steepest north scarp.

DEDICATION

To my family for their endless patience and support through all the days that I was absent, both at home and away working to get my degree and complete my goal. To God for his sight through my world.

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My sincere thanks to Dr. William Bryant for his vision, supervision and guidance during all processes of the thesis preparation. I am also deeply grateful to CPNV-EM Fernando Zurita for his confidence and the opportunity that he provided me to find new challenges in my career.

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TABLE OF CONTENTS

	Page
ABSTRACT	iii
DEDICATION	iv
ACKNOWLEDGEMENTS	v
TABLE OF CONTENTS	vi
LIST OF FIGURES	viii
LIST OF TABLES	xi
CHAPTER	
I INTRODUCTION.....	1
Problem.....	2
Objectives	2
Hypotheses.....	3
II GENERAL DESCRIPTION OF THE STUDY AREA	5
Geographic location.....	5
Oceanographic settings.....	6
Geological settings:	10
Bathymetric summary.....	14
III LITERATURE REVIEW	18
Sediment characterizations	20
Sediment thickness	20
Seafloor composition	20
Deep currents.....	21
IV DATA AND METHODS.....	22
Data.....	22
Methods	22
Seafloor morphology description.....	29
Core to core correlation	31
Bottom currents	32
V SEDIMENT CHARACTERIZATION.....	34
Physiography of deposition environments.....	34
Sediment composition	42
Sediment properties	49
Sediment structure and stratigraphy	51

TABLE OF CONTENTS (CONTINUED)

CHAPTER	Page
VI SEDIMENT THICKNESS.....	53
Determination of sediment thickness.....	54
Distribution of sediment thickness	57
Sediment thickness and gravity anomalies association	59
VII FACTORS CONTROLLING DEPOSITION.....	64
General conditions	64
Bathymetry	67
Bottom currents	69
Deposition types	74
VIII SEDIMENT DISTRIBUTION	78
Western area	81
Saddle central area.....	82
Eastern area.....	84
Depositional sedimentary environment.....	86
IX DISCUSSION	89
Thickness and compositional distribution	90
Process and environmental control on sedimentation history.....	91
Dominant processes controlling sediment deposition.....	94
Environmental factors affecting deposition.....	95
X CONCLUSION	100
Summary and conclusions.....	100
REFERENCES	104
APPENDIX 1	113
APPENDIX 2	116
APPENDIX 3	119
VITA	125

LIST OF FIGURES

FIGURE	Page
1 Location of the Carnegie Ridge.....	5
2 Primary surface and subsurface water currents around the Carnegie Ridge	7
3 Plot of different tracers at the saddle area	9
4 Age prediction for the Carnegie Ridge.....	11
5 North-south transect in the saddle area of the Carnegie Ridge.	12
6 Acoustic reflection profiles of a North-South transect.	14
7 Ship tracks (1970 – 2004) in the study area.	15
8 Digital elevation model of the east ridge.....	16
9 Multibeam bathymetry plotted in the study area.	17
10 Core distribution.....	19
11 Depositional processes flow chart.....	25
12 Grid analysis flow chart.....	27
13 Methodology to identify areas susceptible to sediment transport.....	28
14 Acoustic profile from north to south in the central saddle	34
15 Seismic profile of the east ridge	35
16 Seamount morphology on the east ridge	36
17 Multibeam sonar bathymetry at the central saddle area	37
18 Bathymetry model showing the east-west trend of ridge formation.....	38
19 Bathymetry plots in the eastern Carnegie Ridge.	39
20 Circular depressions in the south flank.....	41
21 CaCO ₃ content distribution in bottom deposits along the Carnegie Ridge.....	43
22 Content of opal in surface sediments (as a percent of the sample).....	44
23 Distribution of organic carbon in surface sediments on the Carnegie Ridge.	46
24 Cores in surfaces at sites 1238 and 1239.....	47
25 Lithology based on core description from NGDC.....	50
26 Stratigraphic sequences on the southeast ridge.	52
27 Sediment thickness distribution.....	53
28 Sediment thickness along the Carnegie Ridge.....	54

LIST OF FIGURES (CONTINUED)

FIGURE	Page
29 Distribution and thickness of sediments from the saddle area using the single channel reflection profiles to update the general area.	55
30 Distribution of sediment thickness in the saddle area	56
31 Seismic examples of a post depositional seamount at the west ridge.....	57
32 Histogram of sediment thickness distribution represents the average sedimentation thickness in the ridge up to 500 meters.....	58
33 Western ridge sediment thickness distribution and gravity anomalies.....	61
34 Non-deposition areas.....	62
35 Eastern ridge and adjacent saddle sediment thickness distribution and gravity anomalies.	63
36 Generalized areas below carbonate compensation depth and lysocline depth of the Panama Basin and Peru Basin.....	64
37 Quartz content in the Carnegie Ridge area	66
38 Seafloor bathymetry map.....	68
39 Major bottom channels diverging from the Carnegie Ridge	69
40 South-north profile of the Ecuadorian Trench.	70
41 Meridional velocity variations	72
42 Erosionally exposed rocks on the central saddle area	73
43 North-south directions of the valleys in the southern flank of the Carnegie Ridge.....	74
44 Carbonate content (%) vs. depth for the Panama Basin, Peru Basin, and Carnegie Ridge .	75
45 Scatter diagram showing an inverse correlation between carbonate and organic carbon values in the west ridge.	75
46 Distribution of sedimentation rate in the Carnegie Ridge using the upper core values.....	76
47 Trend curves for the relationship between sedimentation rate and carbonate content.	77
48 Distribution of bulk MAR	80
49 Seismic profile west ridge	82
50 Central saddle area bathymetry	83
51 Migrated sections on the southeastern flank on the east ridge.....	85
52 Sources distribution on Carnegie Ridge	86
53 Erosional areas of the east ridge.....	97

LIST OF FIGURES (CONTINUED)

FIGURE	Page
54 Erosional zones in the saddle area	98
55 Erosional areas of the west ridge	99

LIST OF TABLES

TABLE	Page
1 ODP core lithology.....	13
2 Average total organic carbon in the upper part of the ODP cores (Leg 202).....	47
3 Brief definitions of the depositional processes in the Carnegie Ridge area, and estimation of general physical properties such as velocity and sedimentation rate.....	88

CHAPTER I

INTRODUCTION

The Carnegie Ridge is an underwater aseismic volcanic chain in the Eastern Pacific, located at the north-western corner of the Nazca plate, and southeast of the Galapagos hot spot. This ridge developed off the west coast of South America, with a length of 540 miles extending from the Galapagos Volcanic Province (GVP) to about 30 to 40 miles off the coast of mainland Ecuador. Depths of the ridge vary between 900 to 2900 meters from hills to the surrounding abyssal plain. The ridge surface is relatively shallow and geologically different than the adjacent sea floor, and works as a natural barrier separating the Panama Basin to the north from the Peru Basin to the south

The distribution of sediments on the Carnegie Ridge is a product of complex biological interactions throughout the water column, particularly important nutrient inputs from upwelling, and advection of nutrients by surface currents. Unique conditions create a high productivity zone resulting from complex interactions between coastal upwelling from the cold Peru Current, the South Equatorial Current (SEC) rich in nutrients, and the proximity to the divergence equatorial zone. The location within a high productivity zone and the dynamics of accretion and denudation of the relief are some of the most important characteristics affecting sediment distribution. The sediment distribution can be very important in establishing correlations between seafloor topography and variability in oceanic surface productivity.

The nature of the sediments on the ridge based on geographic location, water depth, and age is important to define patterns of sedimentation. Sediment deposition on the ridge occurs above the lysocline and the carbonate compensation depth, defined as equilibrium between carbonate production and dissolution. It is necessary to identify and characterize the composition of sediment in order to identify recent sediment inputs, sediment thickness, and depositional processes on the Carnegie Ridge. This study focuses on the distribution of sediments in areas where sufficient data are currently available for characterization, and aims to recognize the primary processes responsible for sediment accumulation in those areas.

The method used to characterize sediments is based on the analysis of the geologic, morphologic and oceanographic processes that contribute to the production, accumulation,

This thesis follows the style and format of *Journal of Geophysical Research*.

deposition, and thickness of the resulting deposits. The use of different geological oceanographic datasets and geographic information systems (spatial analysis) in classifying and mapping sediment distribution can increase the accuracy and objectivity of mapping and analysis, as well as monitoring sediment distribution and sediment thickness over the Carnegie Ridge.

Problem

The analysis of sediment depositional processes and their distribution is a very important instrument for understanding the geological conditions within a high productivity zone. The lack of accurate and reliable information about sediment distribution has contributed to general assumptions of latitudinal oceanic transport of terrigenous sediment within the areas surrounding mainland and Galapagos Islands, and pelagic sediment distribution related to productivity. This hypothesis needs to be re-evaluated in order to identify the processes that control transport and deposition.

The purpose of this study is to identify depositional episodes in time and space in order to discuss the processes that affect sediment thickness, composition, and location over the Carnegie Ridge. This thesis also intends to discuss how the original sediment patterns may have been altered, and to identify environmental processes that can modify the initial deposits. Moreover, it is important to relate sediment packages to major chronological events in order to identify other factors that may have affected sediment distribution, such as slope stability, water depth, and the physical properties of the sediment. However, in the study area the availability of seismic profiles are insufficient to identify discontinuities and sediment offsets in detail.

Objectives

In this study the principal aspect is to examine the processes that control accretion, erosion, and distribution of marine sediments over the study region and their geological and morphological characteristics along the Carnegie Ridge.

The relationship between sediment composition and sediment thickness is fundamental in determining depositional processes. Sediment distribution and their morphologic variation can provide important clues to establish the processes that have affected sedimentation on the ridge. The spatial variation of sediments along the ridge and the relationships between biogenic, volcanic, and terrigenous inputs are fundamental to better understanding the origin and movement of different types of sediments.

In summary, the major goals of this study are:

1. to determine the distribution and thickness of sediments;
2. to characterize major factors that affect sediment thickness and composition;
3. to determine how sediment thickness along the Carnegie Ridge was influenced by the location of the high productivity zone; and
4. to identify transport processes affecting the redistribution of sediments.

Hypotheses

The analysis of sediment in the Carnegie Ridge can be used to relate variations in sediment distribution to water depth, geographic location, and sediment composition. It was hypothesized by *Lyle* [1992]; *Lonsdale* [1977a]; *Lonsdale and Klitgord* [1978]; *Malfait* [1974]; and *Van Andel et al.* [1971] that sediment distribution in the study area varies as a function of:

1. the existence of a high productivity zone due to upwelling, and cool waters coming from the divergent equatorial zone;
2. pyroplastic input from volcanoes in South Colombia and North Ecuador;
3. terrigenous sediment input from the mainland and Galapagos Islands;
4. climatic changes over geological time that have affected the input and nature of sediments;
5. water depth;
6. relative location of deposition area to the mainland, and Galapagos Islands; and
7. influence of physiographic units such as hilltops, base of escarpments, and canyons.

As a result of data restrictions, the major factors effecting sedimentation will be evaluated based on the following assumptions:

1. organic carbon and carbonate are diluted by siliciclastics in areas affected by terrigenous sediments from land;
2. the accumulation of siliciclastics is highest in areas close to land and river discharge, and biogenic sediments is higher, where siliceous productivity is high due to upwelling processes;
3. core site data can be used as the base for sediment classification under particular composition and physical properties important when I determine depositional processes;
4. the south-north bottom currents that cross the ridge cause asymmetries in sediment

composition between the northern and the southern sites;

5. sediment accumulation is higher at the base of slope and is scarcer at the top of hills in the ridge due to downslope transport.

CHAPTER II

GENERAL DESCRIPTION OF THE STUDY AREA

Geographic location

The Carnegie Ridge is located in the Galapagos volcanic province between latitudes $0^{\circ}00'$ and $2^{\circ}30'$ S, and longitudes $91^{\circ} 00'$ and $80^{\circ} 30'$ W. It occupies an area of approximately of 325,000 square kilometers (282 km from north to south, and 1045 km from east to west).

The ridge has an elongate shape in the east-west direction, and is separated by a saddle area diving it into eastern and western segments (Figure 1).

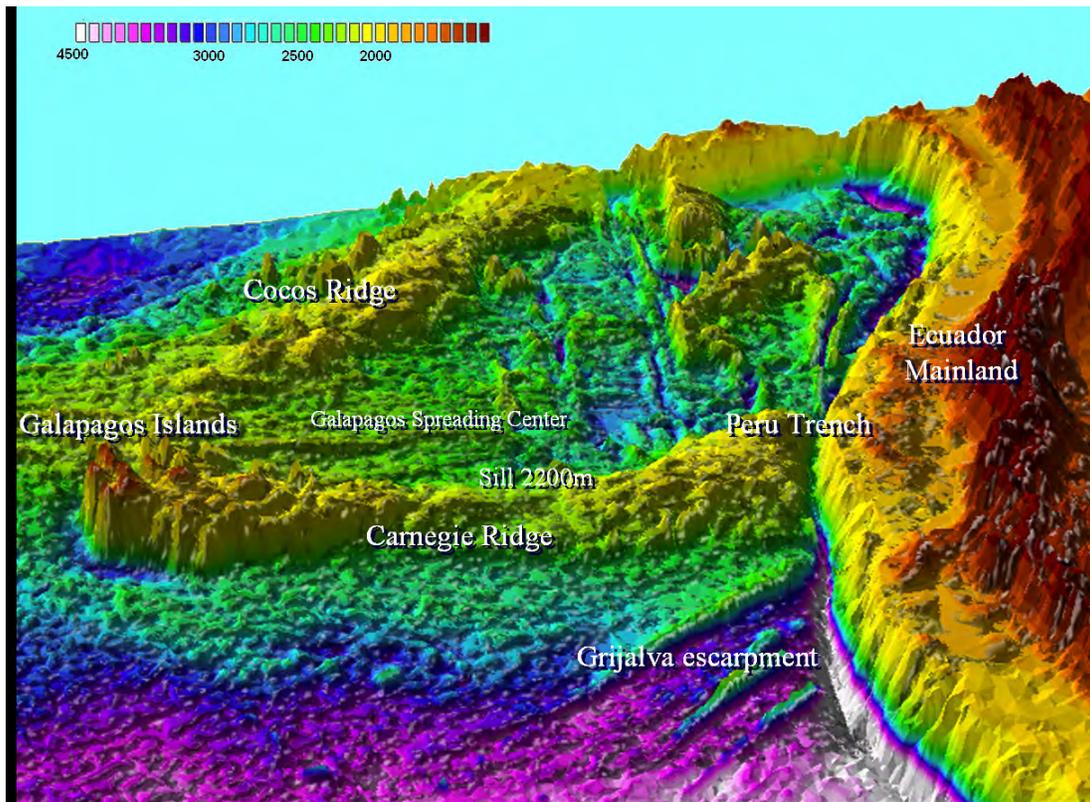


Figure 1. Location of the Carnegie Ridge. Digital bathymetry and major geological features on the study area.

The geographic location, core distribution and general morphology were used to subdivide

the study area into three major regions: the west ridge, the central saddle, and the east ridge. The west ridge is part of the Galapagos Volcanic Platform. In this area, the ridge flanks form a broad terrace with an east-west orientation [Van Andel, 1973b], with the steepest slope to the south. This area is characterized by recent volcanic activity and presents little influence of hydrothermal venting [Backer *et al.*, 2000]

The saddle of the Carnegie Ridge shows reduction of volcanic material emplaced on the Nazca Plate. This could be related to the ridge jumps between 14.5 to 7.5 Ma and the northward migration of the Cocos-Nazca spreading centre (CNSC) away from the Galapagos Hot Spot (GHS) [Hey *et al.*, 1977; Hey 1977; Barckhausen *et al.*, 2001]. This process produces the sill formation, which allows the inflow of water from the Peru Basin into the Panama Basin [Lonsdale, 1976]. These special conditions lead to discontinuities in sediment distribution, size and sedimentary components from south to north, with a major role played by re-deposition [Moore *et al.*, 1973; Lonsdale and Malfait, 1974].

Previous studies of sediment from the Carnegie Ridge to the Panama Basin through the sill [Lonsdale, 1976], and detailed bathymetry from studies of GEOMAR [Flüh *et al.*, 2001; Hauff *et al.*, 2001] and regional studies [Malfait, 1974] confirmed the importance of re-deposition in the saddle area.

The east ridge, a hill region with depths ranging from 960 m to 2300 m, is an important area of crust accretion identified through bathymetry. In this area there is an interaction between sediments formed in shallow and deep waters and the specific depositional processes related to the presence of a subduction zone. Subduction is produced by the eastward movement of the oceanic Nazca Plate, which collides and moves beneath the westward-moving South America Plate. Associated with subduction are variations in the structural and sedimentary character of bottom layers, from deformed rocks to the accretion of sediments at the trench [Gutscher *et al.*, 1999; Collyot *et al.*, 2002]. This section of the ridge presents shallow depths, and it is there that the oldest crust in the ridge can be found [Meschede and Barckhausen, 2000, 2001].

Oceanographic settings

The waters above the Carnegie Ridge are affected by the strength of the South Equatorial Current (SEC), and they are conditioned by the seasonal displacement of the Intertropical Convergence Zone (ITCZ). This convergence zone is an area where the trade winds from southern and northern hemispheres meet, and the seasonal strength of the trade-wind systems

create seasonal changes in the equatorial current system [Mayer *et al.*, 1992]. From August to December, the ITCZ is in a most northerly position, moving south for the rest of the year. Upper ocean circulation dominated by the westerlies that directly affect the high productivity associated with the Peru Current.

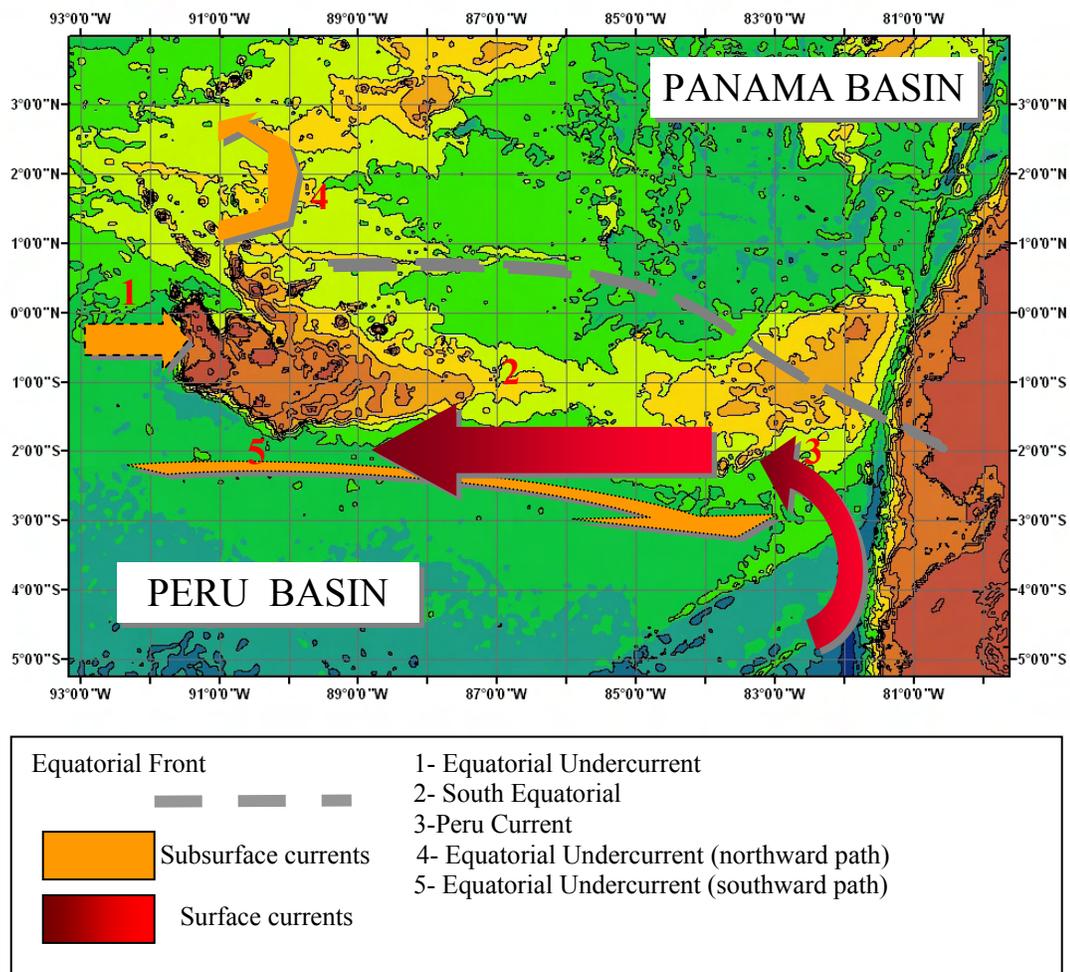


Figure 2. Primary surface and subsurface water currents around the Carnegie Ridge. Red arrows represent surface currents, gray shaded line the equatorial front location. Based on [Lonsdale 1977, Lyle, 2002]

Over the year, the position of the equatorial divergence varies, and can be determined by the

location of the equatorial front, which is the gradient that differentiates upper water masses, and by the Southern Oscillation Index [Martinez and Bedoya, 2001]. This index is based on the cyclic warming and cooling of the Eastern Equatorial Pacific.

High primary production in the Carnegie Ridge region of the Equatorial Pacific is associated with deep-water upwelling from an equatorial divergence zone and the SEC. This current, flowing west along the equator is the main shallow circulation feature over the ridge and is controlled by the south east trade winds. The coastal upwelling of the cold waters of the Peru Current feed the SEC with high concentrations of nutrients.

Surface water in the Panama Basin is characterized by warm temperatures (28°C on average) and low salinity (approximately 34 ppt) [Tsuchiya and Talley, 1998]. Farther south, at the equator, the water temperature is slightly lower (27°C) and the salinity presents a local maximum of 34.6 ppt [Tsuchiya and Talley, 1998]. The coastal upwelling from the Peru Current maintains a cool flow that is advected westward following the south equatorial current. These cool waters are maintained at the surface by the equatorial upwelling along the ridge, forming the Equatorial Cold Tongue [Pisias *et al.*, 1995, 2000].

Subsurface currents moving eastward are also very important to understand the movement of water masses, especially the Equatorial Undercurrent that is related with an upwelling in the western region of the Galapagos Islands (Figure 2). The productivity of waters on the west side of the Galapagos Islands is altered by this nutrient rich equatorial undercurrent, which is pushed to the surface by differences in bathymetry producing upwelling in Urbina Bay (Isabela Island) [Steger *et al.*, 1998].

Two water masses meet south of the equator – the Antarctic Intermediate Water [AIW], moving from south to north and having high oxygen and low phosphate content, and the North Pacific Intermediate Water, moving southeast from the Northwest Pacific and having low oxygen content [Mix *et al.*, 2003]. These currents control the distribution of phosphate and nitrate in the water column between 500 to 1000 meters.

Subsurface circulation was observed from a leg of the Joint Oceanographic Institutions for Deep Earth Sampling [JOIDES], and it showed a northward flow in the upper 400m related with the Peru Current, and a westward flow that it is related to the trade winds that affect the area closer to the equator.

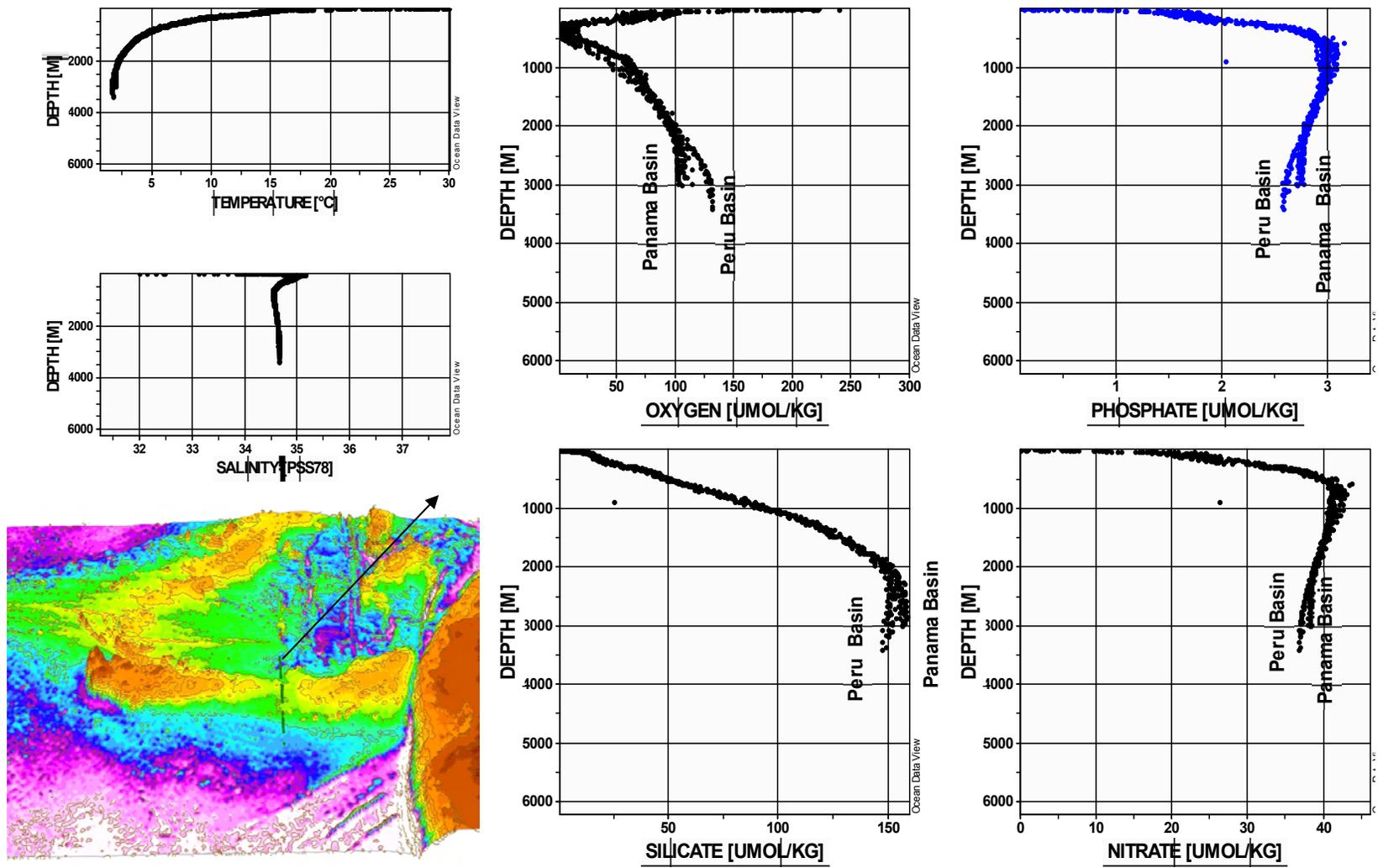


Figure 3. Plot of different tracers at the saddle area. Ocean data views from transect P19 of WOCE, global data source version 3.0 August 2002, show major differences in the composition of the water in the Panama and Peru two basins.

Bottom waters moving northward through the saddle in the central and the trench in the eastern parts of the ridge produce an inflow of water into the Panama Basin. The velocity of this inflow has been determined to be 33cm/s [Lonsdale and Malfait, 1974].

Major water parameters such as phosphates, oxygen, nitrates, and silicates are different from the Panama Basin to the Peru Basin. These differences are more significant below water depths of 2000 meters, where waters from the Panama Basin consistently show lower levels of oxygen and higher levels of phosphates, nitrates and silicates than the Peru Basin waters (Figure 3).

Geological settings

The formation of the Carnegie Ridge occurred as a result of the break up of the Farrallon Plate 23 million years ago. [Hey *et al.*, 1977; Lonsdale and Klitgord, 1978; Meschede and Barckhausen, 2000], creating two new plates, the Cocos Plate, under the Panama Basin, to the north, and the Nazca Plate, under the Peru Basin, to the south.

Divergent stresses pulled apart the Nazca and Cocos Plates and led to the creation of the Galapagos spreading center (GSC) [Hey, 1977; Lonsdale and Kligton, 1978]. The position of the Galapagos hotspot (GHS) in regard to the Nazca and Cocos Plate has been a source of new magma, responsible for two tracks of material accreted to the seafloor. This interaction formed two long aseismic ridges [Johnson and Lowrie, 1972]:

- the Cocos Ridge, moving north east, is being subducted under the Costa Rica convergent margin; and
- the Carnegie Ridge, which is part of the Nazca Plate, moving east under the South American Plate.

The Carnegie Ridge moves along with the Nazca Plate in relative to the GHS [Pennington, 1981]. Support for the GHS as a source of material is the excessive volcanism in the Galapagos Platform [Christie *et al.*, 1992; Sinton *et al.*, 1996]. South of Carnegie Ridge is the Grijalva Escarpment, an old N60E fracture zone in the Farrallon Plate [Flüh *et al.*, 2001]. It is considered part of a scarp of the oldest Nazca Plate and remains as a trace of plate turn off [Flüh *et al.*, 2001]. Relative to the escarpment, the Carnegie Ridge should be considered as a hot spot tracer on younger crust (Figure 4).

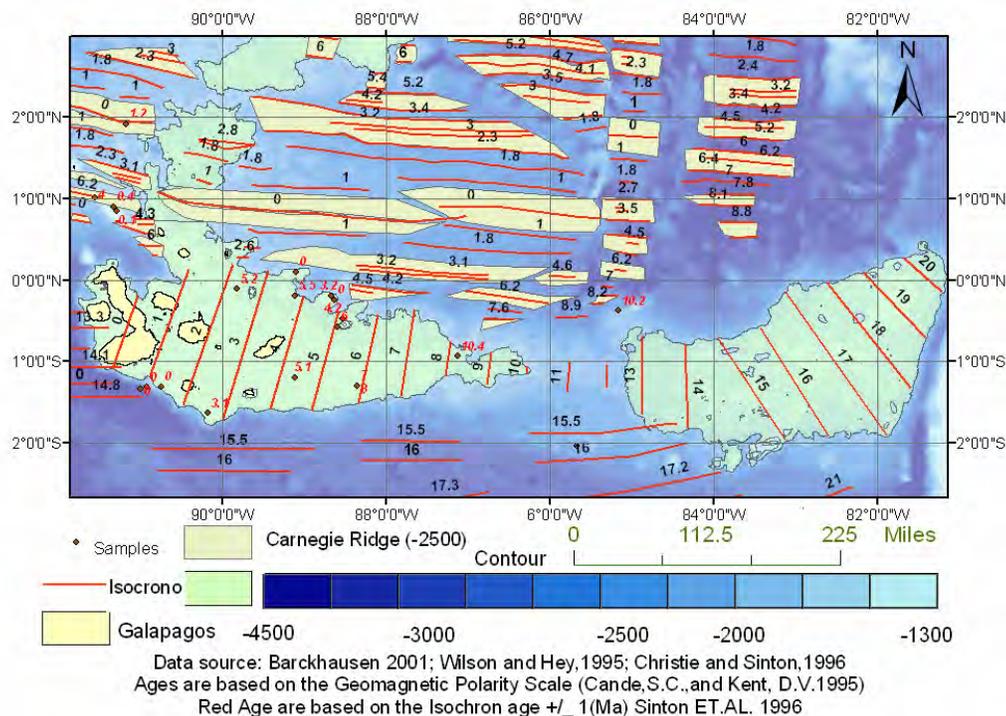


Figure 4. Age prediction for the Carnegie Ridge. Compiled according to magnetic reversal time scale and reconstruction based on aging samples and magnetic anomalies in the Carnegie Ridge. [Integrated and modified [Meschede and Barckhausen, 2001], [Wilson and Hey, 1995], and [Barckhausen et al, 2001]].

The age of the formation of this aseismic ridge, based on magnetic anomalies, age of samples, and reconstruction [Meschede and Barckhausen, 2001] is older moving from west to east. This increase in the age of the ridge is related to reconstruction and to anomalies in the ridge–trench junction area close to 20 Ma [Hey, 1977; Lonsdale, 1978; Wilson and Hey, 1995; and Barckhausen et al., 2001]. In the eastern area of the section that includes the Galapagos Islands, the youngest crust is associated with active volcanism. The age pattern obtained from volcanic samples suggests that the origin of the Carnegie Ridge was a hotspot [Christie et al., 1992; Meschede and Barckhausen, 2001].

The 2000 meter isobaths outline an area with a triangular shape to the east of the west ridge, where the narrowest part is located at longitude 86° 00' W, and the maximum width is at the

Galapagos Islands (Figure 4). The east part of Carnegie Ridge does not present large variations in width, with the maximum close to the eastern end where most of the hotspot products were formed. The difference in shape and the reduction of volcanic material emplaced on Nazca Plate in the central saddle were the result of the relative location of the hot spot in relation to the Galapagos spreading axis at 14.7 Ma [Meschede and Barckhausen, 2001].

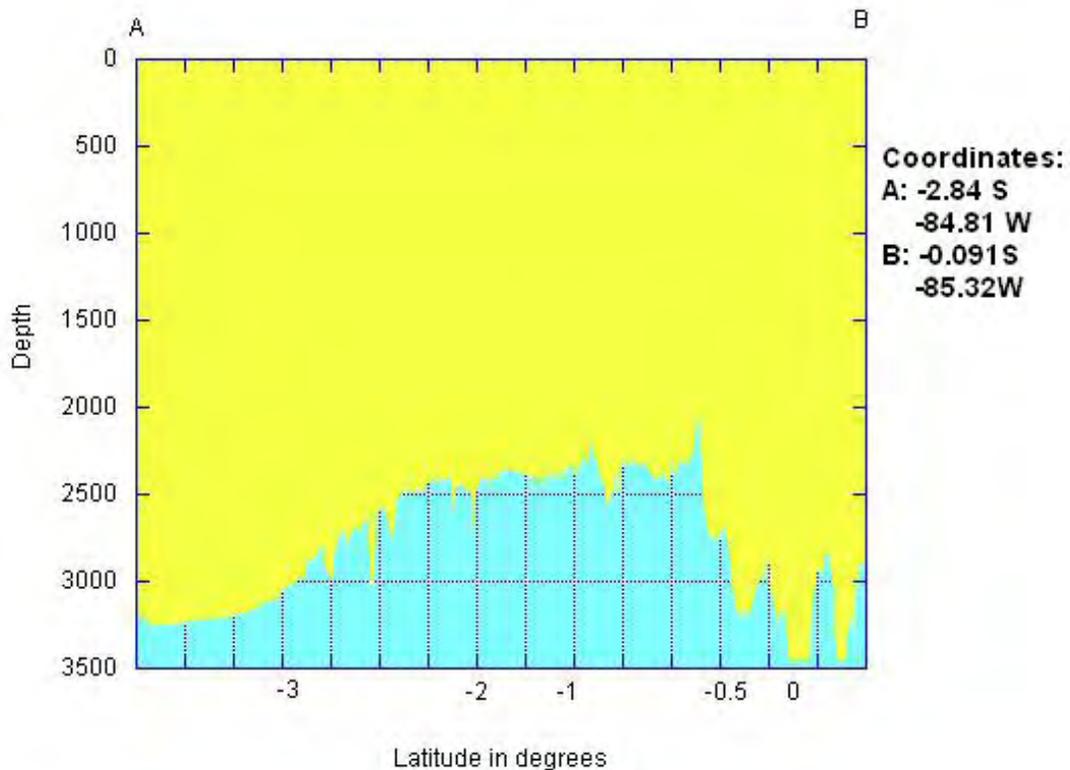


Figure 5. North-south transect in the saddle area of the Carnegie Ridge. The steepest escarpment, which is typical of aseismic ridges, is observed to the north side [in agreement with Detrick and Watts, 1979].

Bathymetric data show that the northern flank of the ridge is steeper than the southern flank. The longitudinal profile of the ridge at 83° W (Figure 5) provides a good illustration. The steeper scarp and block fault morphology on the northern side is correlated with the local isostatic adjustments by vertical movements of the crustal blocks [Detrick and Watts, 1979]. The faults are related to lineations of the volcanic basement.

Influxes of continental debris and ash from volcanoes of the Ecuador mainland and southern

Colombia were detected by *Ninkovich and Shackleton* [1975] near the eastern side of the ridge. Re-deposition due to deep water currents was observed in the form of dunes by *Lonsdale* [1976], who also detected sediment input from hydrothermal vents at the GSC.

The major geological formations in the surface of the study area, identified from the stratigraphic sequence of ODP and DSDP, are summarized and characterized in table 1:

Table 1. ODP core lithology. It was based on description of lithology from ODP AND DSDP sites.

<i>Site</i>	<i>Age</i>	<i>Lithologic Units</i>
1238 Leg 202	Pleistocene (0-98mcd)	Nannofossil and diatom ooze; clay and foraminifers
1238 Leg 202	Pliocene (98-322mcd)	Nannofossil and diatomsooze, organic carbon
1238 leg 202	Miocene (322-480 mcd)	Lithified diatom and nannofossil oozes with chalk and chert horizons
1239 leg 202	Pleistocene (0-97 mcd)	Calcareous nannofossils, planktonic foraminifera, less diatom ooze than site 1238
1239 leg 202	Pliocene (97-410 mcd)	Chalk ooze-calcareous ooze.
1239 leg 202	Miocene (410-560 mcd)	Lithified diatom and nannofossil oozes with chalk and chert horizons
157 Leg 16	Pleistocene (0-85 m)	Diatomaceous foraminiferal nannofossil chalk ooze
157 Leg 16	Pliocene (85-330 mcd)	Chalk ooze
157 Leg 16	Miocene (330-440 mcd)	Nannofossil chalk limestone and lesser chalk

mcd = A meters composite depth

The Carnegie Ridge is exposed to productivity changes that affect mainly pelagic settling. The pelagic sediment contains more biogenic carbon and silica and more organic matter than neighboring sediments [*Einsele*, 1992]. The sediments are re-distributed producing abyssal dunes consisting of foraminifera sand [*Lonsdale and Malfait*, 1974].

The geological structure of Panama Basin in the northeast part of the Carnegie Ridge has been affected by faults trending along meridian 91° W. The spreading center changes its axis due to several transform faults crossing it, the most important transform fault systems belonging to the Inca, Ecuador, and Panama Fracture zones. This active seafloor tectonism in the basin has played an important role in ridge jumps, and influences the amount of mantle plume that is

created. The Carnegie Ridge has been suffering local isostatic adjustments along a series of east-west trending normal faults resulting in the formation of terraces on each flank (Figure 6). These terraced areas have the thickest sediments in the profile, and are obstructed by downfaulted structure and draped sediment [Van Andel *et al.*, 1973].

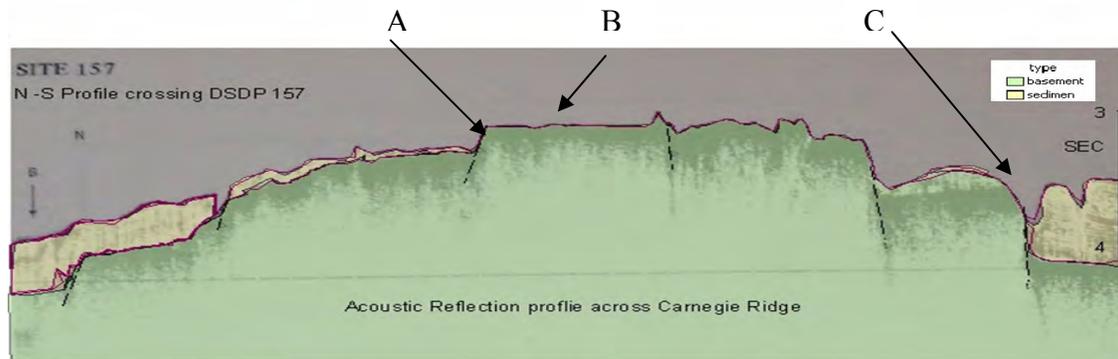


Figure 6. Acoustic reflection profiles of a North-South transect. A: fault blocks, B: flat terraces, and C: erosional canyons [Modified from Van Andel *et al.*, 1973]

Volcanic lineaments are observed in the northeast section of the Galapagos Volcanic Platform, and seamount lineaments are observed as a ridge track in the southeast ridge.

Bathymetric summary

Multibeam bathymetric analyses were based on data sets from GEOMAR, Salieri cruise s159 [Flüh *et al.*, 2001], and NGDC multibeam datasets, and interpolated using ARCGIS (Figure7).

Bathymetric data represents the study area as mostly jagged, showing steep slopes on the north and southwest ridge. A saddle area is observed as a second sill with depth of slightly shallower than 2300 m. The deepest part of the ridge is located in this saddle. The saddle area is divided into two passes by a seamount [Malfait, 1974]. The eastern side has formed channels that are a source of the redistribution of fine particles in the Panama Basin.

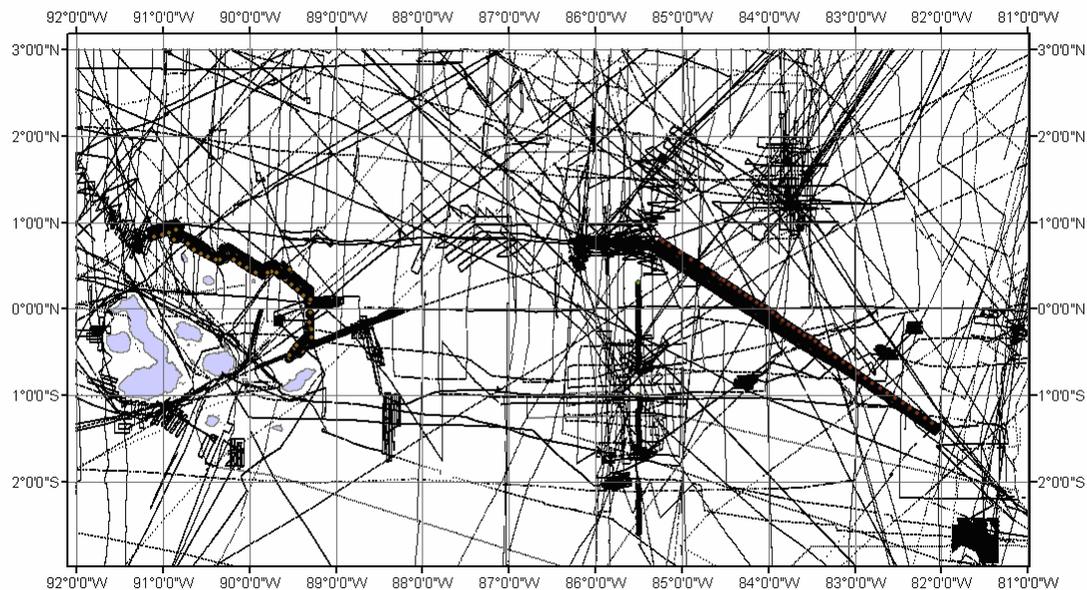


Figure 7. Ship tracks (1970 – 2004) in the study area. Different coverage explains the uneven distribution of bathymetry data available over the ridge.

The saddle in the study area is narrower on the eastern side, where erosional canyons are the primary component that results in the redistribution of sediments. The plateau is at 2400 m, and the bases of the slopes are bordering 3200 m in the north, and 3000 m in the south. Flat terraces and seamounts are part of the morphology in the central saddle and in the southeast ridge (Figure 8).

The western portion of the study area is part of the Galapagos volcanic platform. It is shallower than the eastern, and has its steepest slope on the southwest ridge. An alignment of seamounts following hotspot tracks, extending between depths of 2500 m in the north and 2800 m in the south, are the most important features.

The east ridge in the study area is generally asymmetric, with a gentle southward slope and a steeper northern slope. The general triangular shape of the east ridge is wider close to the ridge-trench junction. The level of surrounding oceanic crust in the southern flank is found at 3100 m, and at 3000 m in the northern flank [Flüh *et al.*, 2001]. On the southern flank there is a chain of seamounts and rough basement.

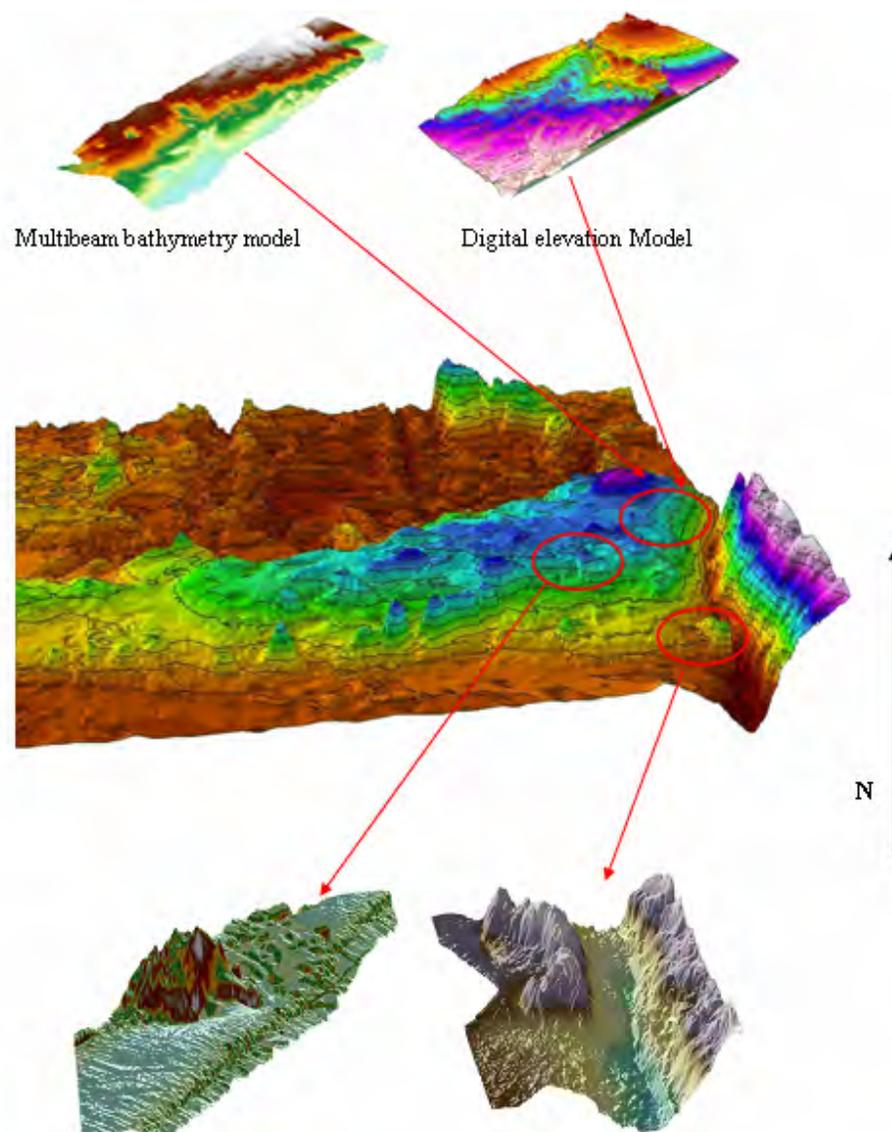


Figure 8. Digital elevation model of the east ridge. The bathymetric models are showing features of swath bathymetry from data acquired during SO-159, GEOMAR

The multibeam bathymetry data utilized in this thesis is compiled in Figure 9.

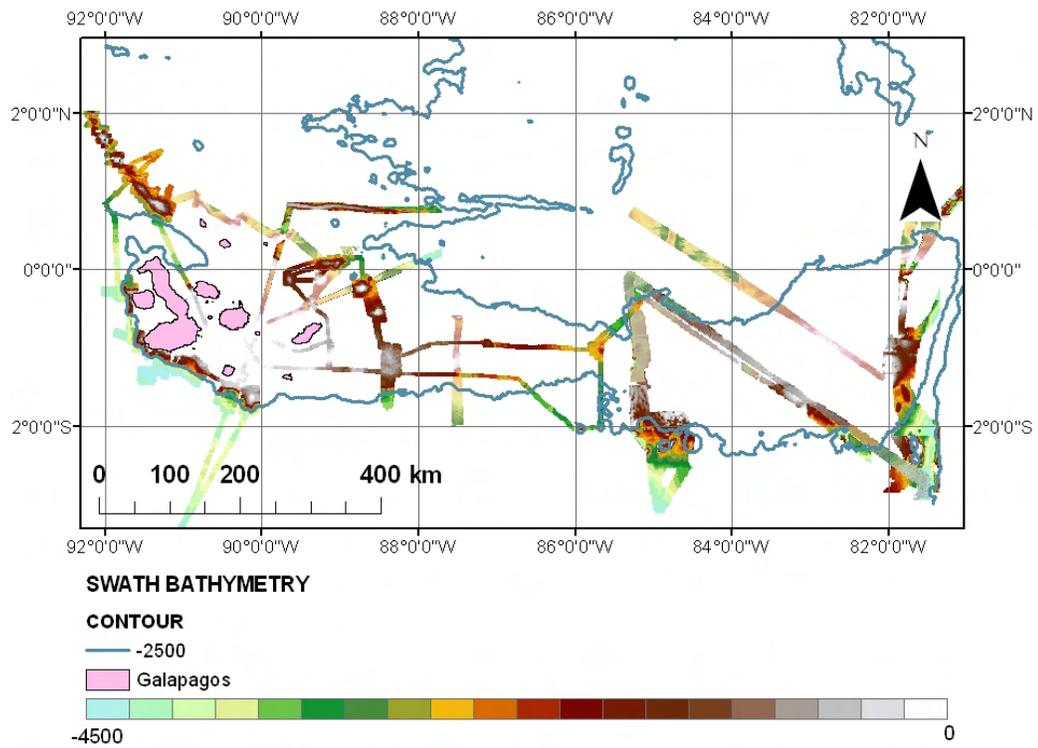


Figure 9. Multibeam bathymetry plotted in the study area. Data source GEOMAR SO159, GEOMAR SO158, NGDC, Plume2. Lamont- Doherty Earth Observatory [Columbia University]. Compiled in ARCGis.

CHAPTER III

LITERATURE REVIEW

Several expeditions have studied the seabed around the Galapagos Islands and the Carnegie Ridge. These cruises were planned in order to understand the processes operating at the GHS, the GSC, and the ridge-plume interactions between the GCS and the GHS. In addition, climatic changes have been extensively studied using carbonate and silica distribution in the Eastern Equatorial Pacific because these cycles are the consequence of glacial to interglacial oceanographic changes. Local studies have focused on the structure, morphology and tectonics of the Panama and Peru Basins. They are important for understanding the sediment processes operating in the Carnegie Ridge. Two theories are discussed by several scientists in relation to the carbonate cycle, which is a basic component of the sedimentation. The proponents of cyclic sediment sequences of biogenic component produced by the variations in productivity are the main process affecting carbonate sediments [Lyle *et al.*, 1988; Pedersen *et al.*, 1988; and Archer, 1991]. The proponents of carbonate content changes in dissolution from changes in bottom water chemistry [Pisias and Rea, 1988].

Deep Sea Drilling Project (DSDP) and Ocean Drilling Program [ODP] legs have drilled on the Carnegie Ridge and in the Panama basin since 1970. The drilling sites were Leg 16, Site 157; Leg 111, Site 677, 678 and 504B; Leg 138 Site 846; Leg 148 Sites 501, 504, 505 and 896, and Leg 202 Site 1238, 1239, 1240 and 1241 (Figure10). More specifically, the purpose of the various legs was verifying a hypothesis of ridge formation, examining the ages of volcanic basement, and the depositional histories of the general region. As well as, paleoceanographic legs were evaluating climatic and oceanographic changes to understand the evolution of the South Pacific Ocean. Regional changes in biota, chemistry of water, in time scales of centuries to millions of years were reviewed to assess carbonate cycles and their accumulation by Lyle *et al.* [1988, 1995, and 2002] in the area.

Likewise, several scientific institutions, such as Scripps Institution of Oceanography and University of Washington, have been working in the area to identify and characterize past events such as the closure of the Isthmus of Panama, which produce a reorganization of Pacific Waters, and the environmental changes in glacial and interglacial periods. Oxygen and carbon isotope variations in sediments were used to determine changes in the SST, and counting assemblage of benthic foraminifera to establish paleoproductivity [Loubere *et al.*, 1999]. The Christian

Albrechts University & GEOMAR from Kiel, Germany, in conjunction with Geosciences AZUR, from France, have worked on the project “Panama Basin and Galapagos Plume” (SONNE 144-3). Data on magnetism, gravity, bathymetry, and seismic from different cruises are available in digital file such as Sisteur (IFREMER), Salieri SO159 (GEOMAR), and Megaprint SO158 (GEOMAR). From them the seafloor features in the ridge have interesting features such as flat-topped seamounts, peaks, and crests. Circular depressions were identified by the Geomar campaign, data from Salieri SO158 Paganini SO144 and Megaprint SO159. The geographical distribution of the major drilling sites is represented in Figure 10:

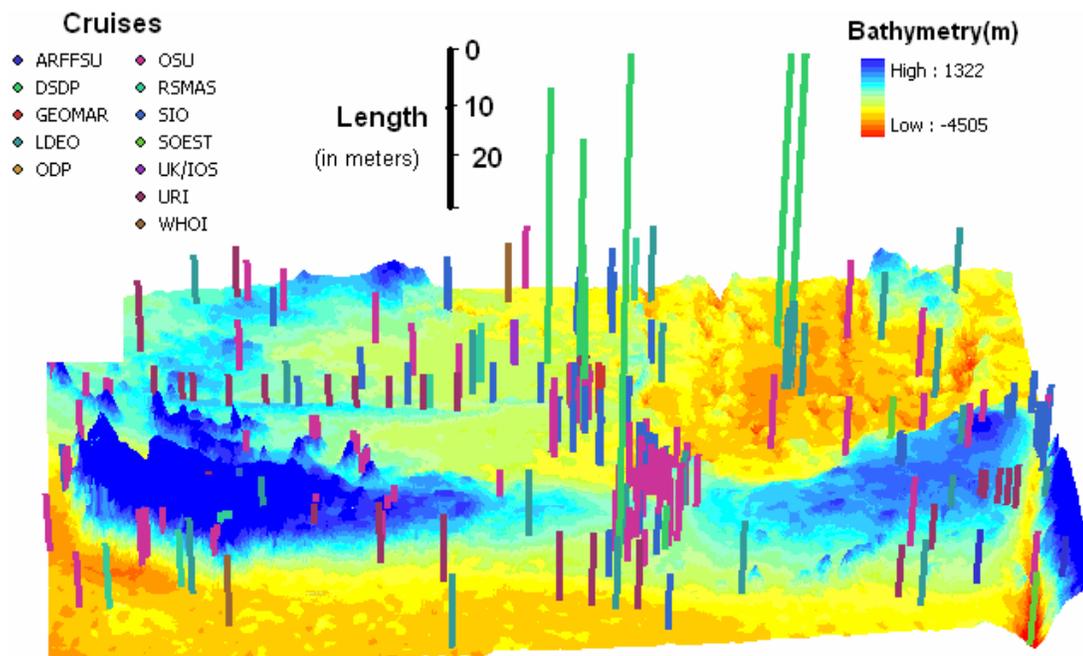


Figure 10. Core distribution. Location of gravity, piston, DSDP and ODP cores in the study area

The list of the all the cores, including those collected from NGDC and GEOROC, is presented in Table 1 of Appendix A. Multibeam bathymetry data from Geomar [Flüh *et al.*, 2001; Hauff *et al.*, 2001] were analyzed, and seismic reflection profiling from Cruise NEMO 3 [Lyle *et al.*, 2000a, 2000b] and Ventura Cruise (Scripps) come from the public domain. They were used to extract the morphologic and stratigraphic profile of this area.

Sediment characterizations

Malfait [1974] examined the effects of erosion and transport processes using subsea photography on the north flank of the central saddle area; he found dunes restricted to areas where the currents were above the threshold for bed-load transport. By studying grain size variations in erosional environments *Malfait* [1974] confirmed the hypothesis that transport of sediments was primarily performed by bottom currents. Sediment composition and distribution of sediments were analyzed by *Van Andel* [1973b] and *Kowsman* [1973a, 1973b]. They suggested that the winnowing and lateral transport is an important factor controlling the distribution of opal and carbonate. *Kowsman* [1973a] also advanced the general hypothesis that the distribution of biogenic sediments is mainly controlled by lateral transport, dissolution, and dilution rather than productivity patterns. The major patterns of sediment distribution are mainly explained by bottom topography. Carbonate fractions have been found on the flanks of the ridge, where the bottom currents produce flow that removes the smaller sediments and carry them downslope. Concentrations of coarser sediments were left in areas dominated by current action [*Moore et al.*, 1973]. *Lyle* [1992] examined the composition of surface sediments to improve the understanding of the relationships between production and burial of biogenic sediment, giving us a possible mechanism that define the sediment composition the seasonality variation for primary production, and the upwelling strengths.

Sediment thickness

One of the first studies to characterize sediment thickness and the relative distribution of sedimentary particles in the central saddle area on the Carnegie Ridge was performed by *Malfait* [1974]. He centered his research on the effects of erosion and transport processes on the morphology of the saddle area in order to identify which transport processes are recorded in physical bed forms such as dunes, ripples and scours in the superficial sediments most affected.

Seafloor composition

Surface sediments are directly related to environmental factors of deposition. The Carnegie Ridge has high primary productivity gradients associated with the upwelling from coastal margins and equatorial divergence, and advection of nutrients by currents [*Lyle*, 1992]. Empirical data has shown latitudinal patterns of productivity produced by the zonal position of currents [*Lyle*, 1992]. Terrigenous sediments occur within 500 km of the mainland and in the Galapagos

volcanic platform; calcite has the lowest distribution in areas controlled by terrigenous deposition [Lyle, 1992]. In the Panama Basin side of the Carnegie Ridge, the lysocline is located at 2869 m [Thunell *et al.*, 1982] and the carbonate compensation depth (CCD) is located at 3200 m [Lyle, 1992]. In the Peru Basin side the CCD is located at 4100 m [Lyle, 1992], and the lysocline is located at 2900 m [Lyle *et al.*, 1988]. Differences in the organic carbon content of sediments produce variations in their color. These variations in the color of sediments were related to the flux of organic carbon explained by the latitudinal pattern of high productivity [Lyle, 1983]. Colors could change from brown to green when organic carbon increases due to sedimentary oxygen reduction intensity from Fe (III) to Fe (II). Malfait [1974] also examined the relationships between erosional and transport processes and textural variations of grain sizes. The sand content exceeds the average of surface sediments in the Panama basin from 15% to 50% on the crest of the ridge [Van Andel, 1973a]. This concentration was related to winnowing and downslope transport [Malfait, 1974].

Deep currents

The Carnegie Ridge forms a submarine structure that blocks latitudinal flows of water. However, there are areas in the trench with a sill depth of approximately 3000 meters that allow an inflow of water from northward to the Panama Basin. Another inflow was identified in the saddle area of the Carnegie at a depth of about 2400 meters [Malfait, 1974, Lonsdale, 1976]. Bottom circulation was inferred by Van Andel [1973] and Kowsman [1973a] based on sediment distribution and sea floor topography. The distribution of suspended matter in the near bottom water was analyzed by Plank *et al.*, [1973]. Bottom water flow is predominantly from south to north both through the saddle of the Carnegie, and from the Peru Basin to the Panama Basin through the Ecuador Trench [Malfait and Lonsdale, 1974; Lonsdale, 1977a; Malfait, 1974; Lonsdale, 1976]. Abyssal dunes seen on side scan sonar and bottom photographs were mapped across the seafloor, and inferred sand transport paths from the orientation of ripples.

CHAPTER IV

DATA AND METHODS

Data

Bathymetric data for this thesis come from ship tracks, satellite altimetry data [*Sandwell & Smith, 1997*], and swath bathymetry from GEOMAR (Salieri 2001, Megaprint 2000) and NGDC (Plume 2). From core, dredges, and grabs general composition values were extracted from published records and publicly available data from NGDC, ODP, PANGEA, and Columbia University. Seismic data used in this study came from SCRIPPS Institute of Oceanography (Nemo 03, Venture). Single channel profiles from LDEO at Columbia University, and published seismic profiles reviewed from published literature [*Van Andel et al., 1971; Malfait, 1974; Jhonson et al., 1976; Lonsdale, 1976, 1977a, and 1978; Rogan and Langseth., 1985; Feighner, 1994; Piasias et al., 2000; Collyot et al., 2000; Flüh, 2001*] and public domain database (NGDC, Ldeo Columbia University, Scripps, Georoc (Germany)). The distribution of sediments in the area was obtained by the global sediment thickness dataset of NGDC, and regional studies [*Malfait and Van Andel, 1980*].

The following parameters were reviewed for the cores [*Dinkelman, 1974; Swift, 1976; Molina-Cruz, 1975, 1977; Lyle, 1992; Lyle et al., 1995; Lyle et al., 2002; Mekik et al., 2002; Lyle 2003*] in the Carnegie Ridge area: location, water depth, and weight percentage of calcium carbonate, silica, and organic carbon. These parameters were chosen in order to assess variations in sediment distribution (Appendix 2). In this thesis, dilution and concentration were considered important to the depositional process because the lysocline borders the ridge and the carbonate concentration increases with higher sedimentation rate. They were analyzed in terms of carbonate, non-carbonate, and organic carbon content distribution. These elements are directly related to dilution and concentration processes [*Riken, 1993*]

Methods

Processes controlling sedimentation analysis

The processes controlling accretion, erosion, and distribution of marine sediments over the Carnegie Ridge were determined through the following stages:

- a) Boundaries between different concentrations of carbonate sediment of biologic origin

and silica concentrations were identified; in locations where data was lacking, the type of sediment was chosen based on the nearest data and surrounding depositional processes.

- b) A basement model of the geological structure was analyzed using the bathymetry map and the sediment thickness distribution from NGDC data. Some basic characterizations of geological structure were identified from the general basement map.
- c) Bathymetry was used to infer water pathways where downslope flows were more probable.
- d) The lysocline and carbonate compensation depth were used to determine the most likely sediment composition below 2,896 meters in the Panama Basin, and 2700 meters in the Peru Basin. Cores were used to confirm the dissolution of carbonate and the influence of depth on the sediment distribution.
- e) Stratigraphic sequences within the study area were identified based on seismic profiles, in order to determine drapes or basin fill deposits.
- f) Relative variations in the carbonate content of sediments in ODP and DSDP cores were used to verify the origin of reflectors in seismic profiles.

Task description

Since the availability of information is irregular, collected from different sources and by different methods, I must consider a characterization of sediments with limited control points. Nevertheless, bathymetry models and slope distribution are necessary to improve the knowledge of the general area. The distribution helps to understand the sediment sequences deposited on the seafloor in specific areas, and their association with other information layers is important for identifying primary changes in deposition.

The GIS techniques helped to lay down basic conditions of sediment deposition, manage different datasets, and relate different variables such as sediment composition thickness and rate to the seafloor morphology. These associations are employed with a goal of identifying factors controlling the distribution of sediments. As a result, it was possible to infer environmental factors controlling sediment deposition in some areas of Carnegie Ridge.

These grids and layers are:

- a) bathymetry maps related to sedimentation rate, areas with high productivity related to high slope, to identify major areas of deposition;
- b) sediment thickness map compiled from datasets from NGDC, regional studies and

layers of seismic profiles. These results were added to the NGDC global sediment thickness dataset and the grid was updated;

- c) a basement grid created from the difference between bathymetry and sediment thickness and related to negative gravity anomalies, to identify depressions;
- d) slope degree and slope direction to determine areas susceptible to sediment transport;
- e) distribution of faults to identify terrace formation

Sediment coring and sampling only provide information on sediments at the core position. Lateral variation is obtained from different cruises by seismic multi channel or single channel profiles. Both can be analyzed in order to model variations over large distances. Model results are usually based on extrapolations from similar areas containing spatial information for comparable attributes. Core comparisons are possible when sediments are deposited in similar conditions and affected by similar depositional processes. The incorporation of new information to previous studies can provide major support to the predictions made in the study area. Hence, the general methodology is based on determining sediment distribution from core composition, seafloor morphology and structural features, and analysis of seismic profiles to identify old depositional processes.

The information dataflow in Figure 11 synthesizes the methodology used in this study. The analysis was subdivided into three major components. The first focused on sediment thickness and its spatial distribution (based on existing datasets). Information was updated using regional works, seismic profiles, and single channel profiles. The sediment thickness of sediments imaged by single channel seismic profiles was compared to negative gravity anomalies in order to identify the thickest sediment areas. The second component focused on sediment characterization, employing composition maps for different types of sediments, such as those showing the relative content of carbonate, siliciclastic, and organic carbon. Additionally, the sedimentation rate was analyzed from core extrapolation in the upper layer to find a correlation with the specific environment in which the sediments were deposited. Sediment properties were briefly described to evaluate the general environment of deposition. Variations in mass accumulation rate were observed via changes in the thickness between reflectors. The distribution was determined by changes in sedimentation sequences. Finally, the analysis of seismic and sub-bottom data using Seismic Micro-Technology's 2d/3dPAK Seismic Interpretation Software was employed for fault/horizon interpretation, to find the general ridge structure.

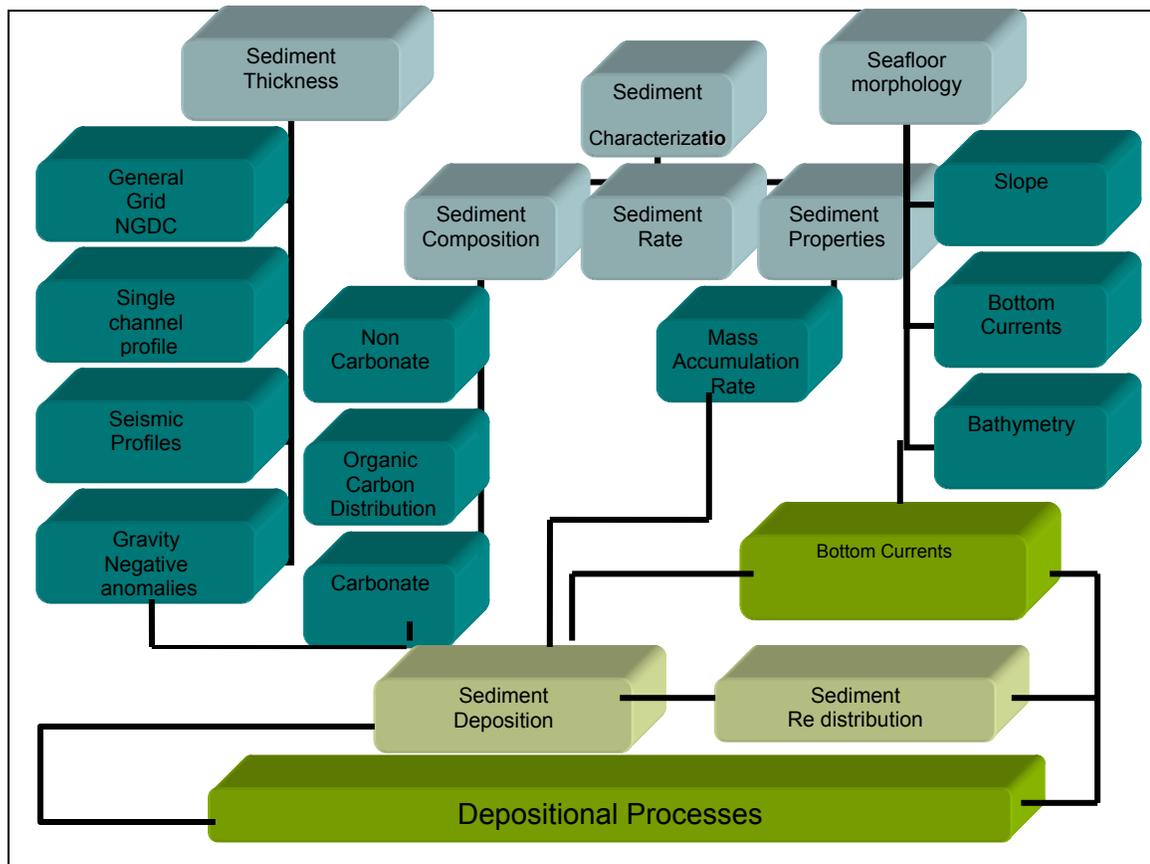


Figure 11. Depositional processes flow chart. Blue blocks represent data generated through the analysis; green blocks represent external factors that also affect deposition.

The third component relates to seafloor morphology. Grids of slope and bathymetry were associated with bottom currents, and geologic structures were identified in specific physiographic units. Depressions, scouring features, seamounts, chaotic zones in areas of instability, and flat summit terraces were plotted to analyze depositional environments. These environments are associated with the general distribution of faults, carbonate compensation depth, and land influence by terrigenous sediments.

Factors that can affect sediment accumulation and properties were integrated into the analyses of sediment distribution. Bulk density variations were related to the general composition of sediments, allowing the identification of specific factors that affected sedimentation. The bulk mass accumulation rate was also analyzed, in order to determine areas of sediment deficiency. Finally, oceanographic variables such as water temperature and salinity were analyzed to

determine spatial variations in water masses and associate them with CaCO₃ dissolution.

An attempt to summarize the steps in the analysis of sediment distribution is shown in Figure 12.

The methodology can be summarized as follows:

A) Create different input data sets:

1) characteristics of bottom sediment, based on:

Composition of three major components

- Carbonate content percentage. The carbonate fraction is composed primarily of pelagic ooze; a grid was created by extrapolating the value of the upper 30cm using the nearest neighbor interpolation method.
- Opal content; a grid composed primarily of the siliceous biogenic sediments was determined by extrapolating the upper core Opal calcite free content values using a tensile spline interpolation method due to the spatial distribution of Opal core values is fewer than the Carbonate core composition values .
- Organic carbon composed of matter primarily produced in the upper waters and from different sources [Ricken, 1993] was extracted from previous studies values and a general grid determined using the nearest neighbor interpolation method.
- The supply of terrigenous sediments was created by extrapolating upper core values of quartz using nearest neighbor interpolation methodology.

2) slope on the flanks of the ridge, expressed in degrees [which may also help in identifying erosional areas and the redistribution of deposited material] was computed using an ArcGIS algorithm based on the general bathymetric model.

B) Sediment distribution was analyzed as follows:

- 1) slope, which contributed to explain sediment location and the areas of possible redistribution of sediments through slumping, was reclassified to identify higher values (greater than 5 degrees). They location contributes to predict areas of sediment transport.
- 2) isostasy, especially modifying depocenters, could explain subsidence in the basement due to pressure increase associated to maintain large loads of volcanic material during the aseismic ridge formation ; as a result, flexure rigidity of the lithosphere can be produced by either an excess of volcanic material in the basin or isostatic adjustments of vertical movement of crustal blocks. These were reviewed via a comparison

between sediment thickness profiles and the negative gravity anomalies grid compiled in this study to confirm downslope transport is an important process in the sediment distribution on the flanks.

- 3) relative sedimentation rates using upper core values and applying a nearest neighbor interpolation.

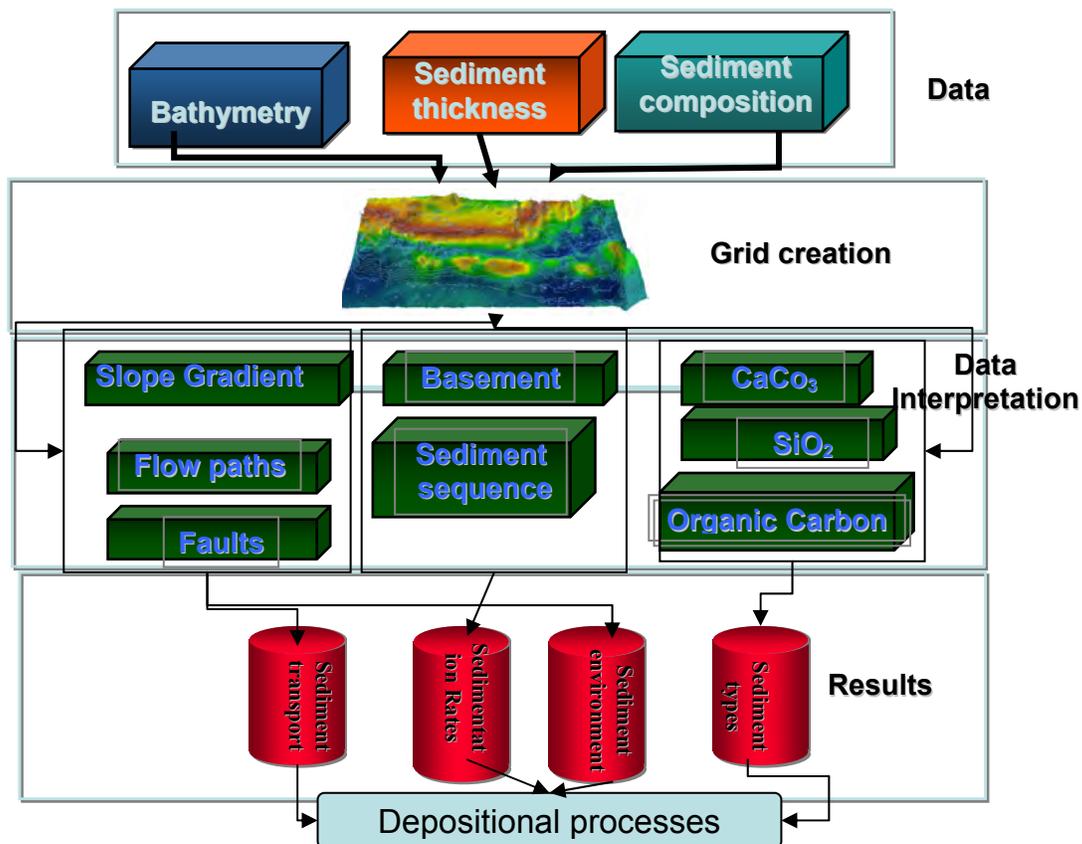


Figure 12. Grid analysis flow chart. Different levels of data integration and processes to evaluate the depositional processes. Red cylinders refer to outputs of different association between grids, layers in the study area.

C) Sediment thickness was analyzed as follows:

- 1) sediment thickness data sets were associated to the sediment thickness measured from single channel reflection records to add data on sediment thickness general grid. The sediment thicknesses information was determined digitizing the top of crustal and the seafloor. The distance was calculated converting the two way travel

- time to depth using a velocity value 1530 m/s [Van Andel *et al.*, 1973].
- 2) the sediment thickness regional studies were obtained digitizing the contours; these digital vectors were extrapolated in the area and added to the general grid.
 - 3) published sediment thickness profiles values were associated spatially to the negative gravity anomalies. The digital sediment thickness grid was created in areas relating the thickness to the negative gravity anomalies. Digital sediment thickness contours for those areas were created from overlying the thickness to the negative gravity contours and interpolated using the depths from seismic profiles and following isolines of similar negative gravity anomalies.
 - 4) these results were added to the NGDC general dataset and the grid was updated.

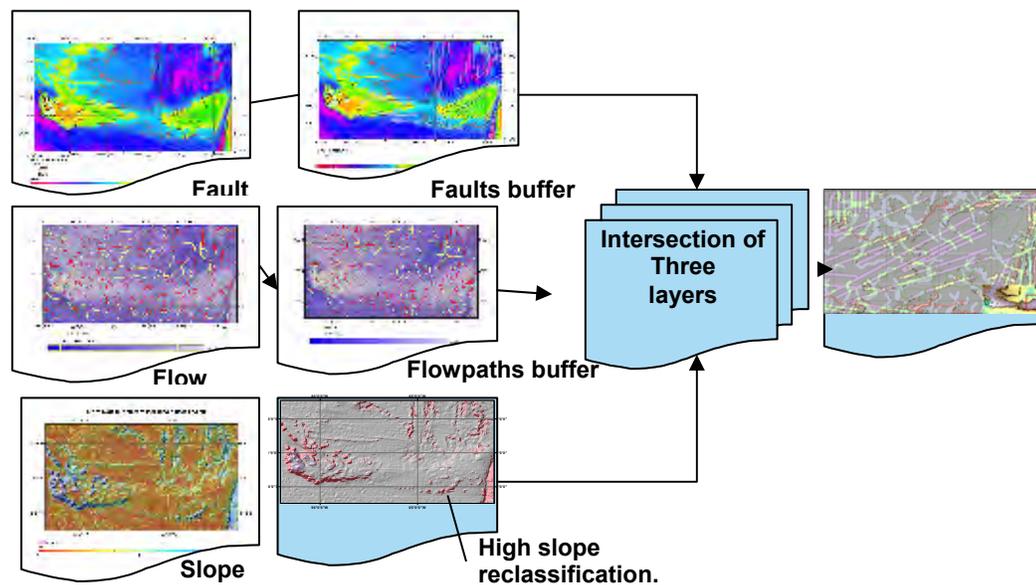


Figure 13. Methodology to identify areas susceptible to sediment transport

In general, seafloor cores are very helpful in determining sediment composition. In this study, detailed data from bathymetry was integrated to create a seafloor model, and sediment thickness was used to assess sediment sequences. Once sediment patterns were identified, it was

possible to extract the environmental conditions of deposition.

The areas susceptible to sediment transport (Figure 13) were identified from the intersection of faults, high slope gradient and flowpaths. Carnegie Ridge presents a remarkable variety of tectonic settings, including east-west fault blocks [Van Andel *et al.*, 1971] and tensional faults in an active convergent margin at the Ecuador trench, all resulting in important variations of bathymetry.

Depth and the fault location are important factors in the re-deposition of sediments. Fault influence area was determined using a buffer, expansion of influence based on multibeam distance of an area affected by the separation of sediment beds. Flowpath buffer, area influenced based on the majority of these V-shaped relieves.

Finally, high slope was reclassified based on angle greater than 5 degrees. High slope gradients are related to the fault distribution and the channels produced by bathymetric variations, which are potential pathways into areas of re-deposition. In the end, I was able to classify sediments deposited in areas susceptible to sediment transport.

Seafloor morphology description

Rapid changes in seafloor bathymetry may indicate changes in the structure of the underlying basement, which in this case is of volcanic origin. Indeed, the importance of seafloor description for understanding sediment distribution can be observed in areas of variable topography and multiple sediment sources, which creates different sediment types. These bathymetric changes and the physical and biological processes create a variety of depositional settings [Levin and Nittrouer, 1987].

A multibeam bathymetric map of the areas around Carnegie Ridge was necessary in order to identify regions where submarine landslides and marine slope failures are more likely to occur, or have already occurred. A general bathymetric map was created from public domain datasets (GEODAS, NGDC, and DOD data center Germany), and complemented by several cruises from GEOMAR and Columbia University. A general grid was built using kriging interpolation, which analyzes the statistical properties of the data, guaranteeing high degree of accuracy and representation. Potential error maps were also created to identify areas with potentially higher error due to large distances between interpolation points. The error maps were reclassified using values of “No data” or “1”, the former for areas with higher error potential, and the latter for areas with reliable values. Map algebra (operations between grids) was used to reclassify the

values in the bathymetric map and the general grid. As a result, bathymetric data interpolated from points distant up to 0.0025° were plotted, and the remainder was eliminated.

A new bathymetry map was created, and areas without information or a high potential error were replaced by satellite altimetry datasets [Smith and Sandwell, 1997], whose scale is 30 seconds. This procedure may modify bathymetric values by up to 30 meters. The results were compiled in ArcGIS, and map algebra used to consolidate the two grids into one. In the final map, bathymetric changes were enhanced by illuminating the contours [Kennelly and Kimerling, 2001](Appendix 1).

Plume 2, Salieri SO158, and Megaprint SO159, cruise containing high-resolution multibeam bathymetry [Flüh *et al.*, 2001], were used to recreate detailed seafloor morphology. A digital elevation model of multibeam point data from the Salieri SO158 cruise (DOD data center) was created using ArcGIS geostatistical analysis module. Geostatistical techniques were applied to these multibeam datasets to create a continuous and detailed surface of the areas with multibeam bathymetry at the Carnegie Ridge. The model of bathymetry over space created by multibeam bathymetry originally showed depth distribution influenced by the central beam. A small-scale grid was used to improve resolution and soften bathymetric variability. The pixel size in the model was based on an average minimum containing five depth values (soundings) because this provided an appropriate balance of detail to represent major physiographic units.

The geostatistic analysis extension of ArcGIS performs diagnostics in order to understand how well a model predicts unknown values. With the bathymetry grid, it was used to find the best predictions of unknown values [Setijadji, 2003]. The multibeam bathymetry datasets were separated into two subsets using ArcGIS geostatistic modules, which use exploratory analysis to identify the distribution of the data and allow modification of its geodatabase. The first resulting dataset contained 90% of the data, chosen randomly, and the second [a test set] the remaining 10%. Then, a semi-variogram model was fit to the data. These subsets allowed a better prediction of the bathymetry grid. In our case, I chose the nearest neighbor relationship among data and selected the median to represent the pixel size. The same methodology was used to produce both a prediction bathymetry surface and an error surface. Kriging interpolation is used for both models, based on the quantification of the spatial structure of the data.

3D virtualization of the area was created using the ArcMap grids and displayed in the ArcScene module for better analysis and representation. The artificial hill-shading and slope gradient algorithms from ArcGIS were used to illuminate regions of steep slope [McAdoo, 1999].

A map of predicted run-off pathways was created for the Carnegie Ridge by deriving run-off direction from terrain surface parameters (attributes) such as height, slope and aspect, curvature, etc. These parameters were also used to extract topographic features in drainage basins and channels from the convergence of flow across the bathymetry model in ArcGIS, using hydrologic analysis modules. These channel distributions are used to illustrate where potential areas of re-deposition have greater interactions with water bottom flow. These areas can be found and reorganization of sediments identified where fine sediments could be re-deposited and coarse sediments stay in the original deposition. Thus, general models were used to identify and characterize areas of erosion or deposition, evaluating the dynamics and history of the seabed.

Contours, at intervals of 100 meters, were obtained by interpolation. A triangulated irregular network (TIN), reflects the variable density of data points and the roughness of terrain [Booth and Bratt, 2000], was created using the contours and the irregularly spaced multibeam points. The TIN models and digital elevation models were related to identify similarities between physiographic units in the area of study, based on details of multibeam bathymetry with more points in areas of rough terrain and fewer in smooth terrain. Depressions, Scouring effects, and seamounts were well defined. The grid and TIN creation processes were accomplished using ArcGIS's Spatial Analyst extension.

Core to core correlation

Sediment cores were interpreted from previous studies [Dinkelman, 1974; Swift, 1976, Molina-Cruz, 1977; Lyle, 1992; Lyle et al., 1995; Lyle et al., 2002; Mekik et al., 2002; Lyle, 2003] to provide information about the physical, chemical and geological nature of the sediments at the seafloor. Available samples came from the upper 30 cm below the seafloor. This restriction is based on analysis of recent deposition, and physical properties of water column are well defined during the late Pleistocene. Core distribution used to create sediment composition contour maps has been affected by sediment disturbance in the upper part of the core, by uneven distribution, and by being spaced, which forced additional restraints on the degree of grid resolution and the prediction of contours. Time-spatial variations of depositional processes would be desirable to understanding the sources and evolution of the different types of sediment [Einsele, 1992]; however, the lack of the seismic information and radiometric age of the cores restricted our study to recent deposition.

The sediment compositions of the upper surface layer were analyzed with grids of

representing the content of carbonate, SiO₂, and organic carbon were created. These grids were based on published data of calcium carbonate weight, siliciclastics, and organic carbon [Dinkelman, 1974; Swift, 1976; Molina-Cruz, 1977; Lyle, 1992; Lyle et al., 1995; Lyle et al., 2002; Mekik et al., 2002; Lyle, 2003]. Opal distribution was extrapolated to give us an idea of distribution of silica in the water by which its distribution in the seafloor sediments resembles the high productivity influences [Molina Cruz, 1975]. Carbonate and silicate accumulation was used to show depositional environments, which were then used to identify processes and factors that control sedimentation. Distributions were used to identify sediments accumulated below similar environmental conditions in the study area that can be spatially related with other processes controlling deposition. Along with the sediment composition, additional datasets on water temperature, salinity, and depth were collected and associated with carbonate and non-carbonate distributions to provide extra information of how physical and biological sediments may redistribute sediments. This association will improve interpolation results.

Sedimentation rate values from cores was used to adjust some sedimentation rates [Dinkelman, 1974; Swift, 1976; Molina-Cruz, 1977; Lyle, 1992; Lyle et al., 1995; Lyle et al., 2002; Mekik et al., 2002; Lyle, 2003]. The grid of sedimentation rate was extrapolated and their values related to the general composition to determine depositional processes. Physical properties of sediments were revised from previously published papers to give a better knowledge of the velocity of propagation. These values were used to convert the two way travel time from seismic and single channel profiles to depth, in order to distinguish the sediment thickness.

Bottom currents

Understanding ocean dynamics in the bottom boundary layer is essential to determine the movement of water masses through sills, passages and trenches. In the study area there is an inflow of dense water over variable bathymetry [Lonsdale, 1977a], which needs to be analyzed on the basis of observed features of seafloor structures such as dunes and hard grounds, using new multibeam data. Despite the features on the seafloor as evidence of bottom water flow are small-scale natures. They are relevant to sediment distribution at the flanks of the ridge.

Bottom currents can also be affected by thermohaline circulation [Beckman, 2002], whose variability is identified using grids from global circulation models of latitudinal velocity flow [Giese, 2002]. A set of temperature and salinity datasets (NAVOCEANO) combined from different months was used to determine seasonal variation of water circulation over the Carnegie

Ridge. Strong near-bottom velocities and/or density gradients, in particular over sloping and highly variable topography in Carnegie Ridge, were analyzed by *Malfait and Lonsdale* [1974]; *Lonsdale* [1977a] with bottom cameras in order to identify dunes high. This study intent to show variability in the direction of bottom water flow using global models; likewise, general analysis of physiographic units with new bathymetry data to identify depositional environments based on pre-existing morphology, bottom water flow, and dissolution.

CHAPTER V

SEDIMENT CHARACTERIZATION

Physiography of deposition environment

The study area contains several physiographic units belonging to the Nazca Plate. The most important of them are the Galapagos Islands, Galapagos Volcanic platform (GVP), Carnegie Ridge, Panama Basin and Peru Basin.

The Carnegie Ridge is formed from volcanic material emplaced on the Nazca Plate. The ridge during this process is unable to distribute laterally the loading stress product of volcanism by bending. As a result, local isostatic adjustments by vertical movement of crustal blocks produce a series of east-west trending normal faults separated by horizontal terraces. The west ridge has east-west terrace surfaces on both sides, bordered by step scarps that are the base for the next faults, downward to the basin. The horizontal terraces have the thickest sedimentary blanket according to the acoustic reflection profile cruise C111 Lamont Columbia University (Figure 14). For general location of the seismic profile refer to Appendix 2.2. Similar structures are observed in the saddle area, the west and east ridge.

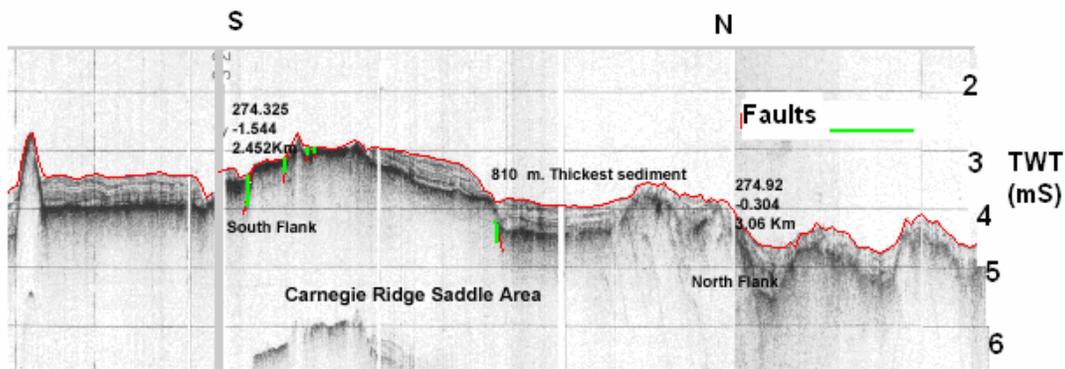


Figure 14. Acoustic profile from north to south in the central saddle area. Faulted blocks and steepest north flank are identified (Based on LDEO data Cruise Yaloc 69).

In the study region, six different physiographic deposition environment units can be individualized: abyssal plain, hilltops, slopes, saddle area, faults, and depressions.

Abyssal plain

The northern and southern sides of the ridge are surrounded by the abyssal plains of the Panama and Peru Basins. The southern abyssal plain is 200 m deeper than the northern abyssal plain because the Peru Basin is older crust and minor tectonics than Panama Basin. In the Peru Basin the abyssal plain is gentle, with slope ranging between 0.2 and 2°, and depth variations from 3000 to 3300 m. The relief in the Panama Basin is marked by transform faults surrounding the east ridge and the Galapagos spreading center at the west ridge.

Hilltops

On the northeast Ridge there is a prominent crest at 900 m depth. Volcanic gravel, sand and silt form the general lithology of the surrounding hill area [Hallbouty *et al.*, 1985]. The sediments on the hill is scarce.

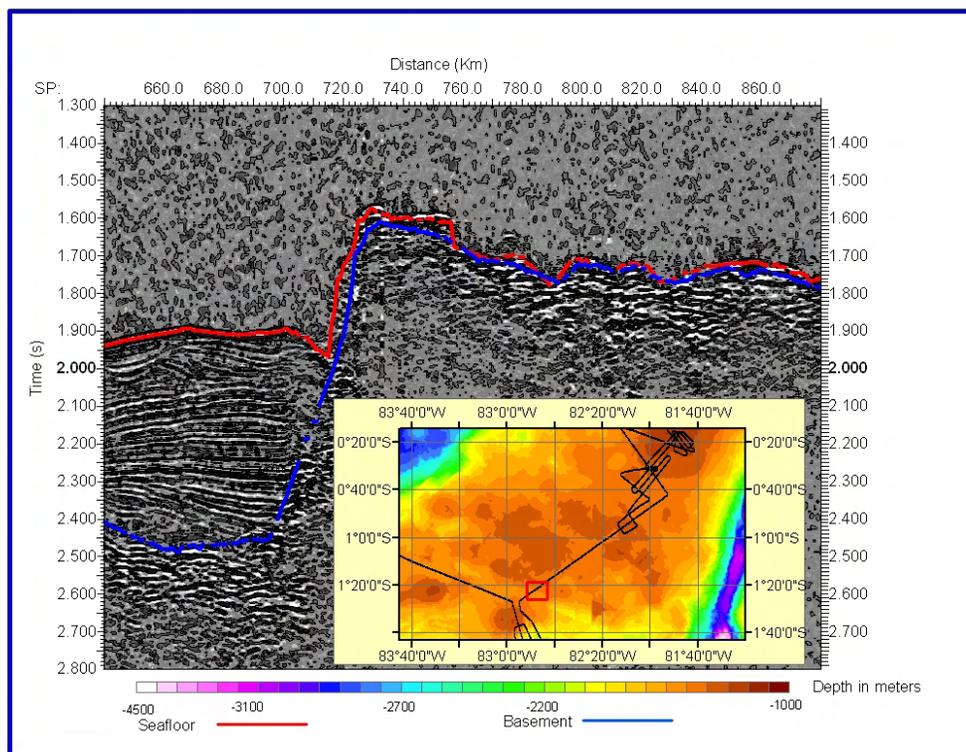


Figure 15. Seismic profile from Scripps Institution of Oceanography cruise Nemo 03 showing a steep slope on the east ridge of the Carnegie Ridge. This is located at the shallowest depth, showing areas of volcanic basalt exposed to the water/sediment layer interface.

Evidence of a thin sediment layer is shown by seismic profiles from the area (Figure 15). The exposed basaltic basement is altered due to water interaction.

Slopes

The western end of the Carnegie Ridge forming the GVP at the western and southern sides has the steepest flanks supported by elastic flexure of lithosphere [Feighner and Richard, 1995]. At the saddle and East Ridge, the steepest slope is observed in the northeast ridge extending northeastern from of the GVP to the eastern end flank. Interruptions are due to the margin parallel, fault controlled escarpments and margin- normal valleys affected by erosion [Christie and Fox, 1990]. Slopes range from 3 to 58°, and depth varies between 750 to 3250 m.

On the north side of the east ridge, slopes range between 2 to 11°, and bathymetry variation from 2000 to 2750 m. Over the southeast ridge the relief is gentler, covering approximately 10,800 square miles; which is delimited by the area between the Carnegie Ridge and the trench.

Seamounts

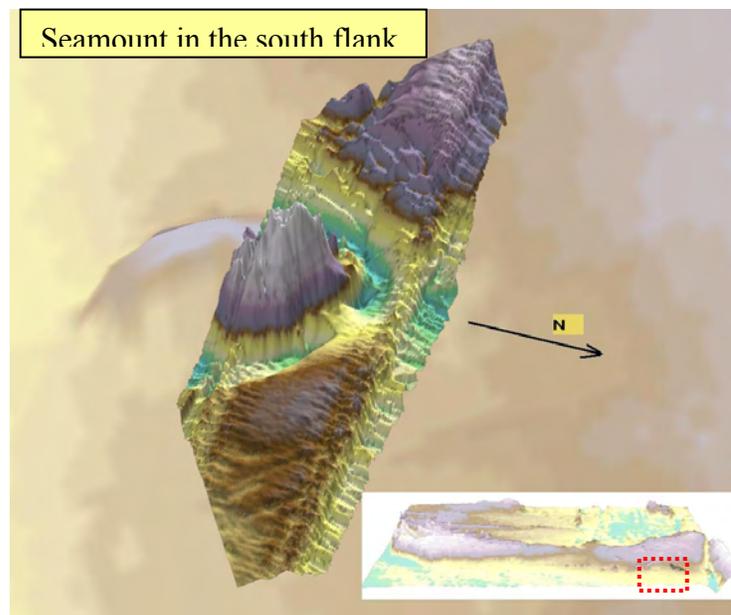


Figure 16. Seamount morphology on the east ridge. Model showing moat produced by bottom water flow and little flexure bulge formed by topographic variations linked to regional isostasy (Dataset from GEOMAR, Salieri SO158).

A series of flat-topped seamounts follow the southwest-northeast trend observed in the southern flank. They were interpreted as drowned islands [Christie *et al.*, 1992]. The seamounts isolated from the ridge are subject to erosion, as bottom water flow interacts with the seafloor and produces erosional canyons along their edges. This effect was clearly identified in the seamount on the east ridge (Figure16). The formation of seamounts produces an excess of mass that is bent by topographic loading, and the water dynamics produces a deficit of sediment fill around the seafloor. A small peripheral flexural bulge is observed due to a young lithosphere, creating local isostatic equilibrium.

Saddle area

Topographic variations displayed by the multibeam bathymetry along the boundaries between the saddle area and the east ridge are dramatic in the region of the north edge, while the southern edge has a gentler slope. At the south side of the saddle, multibeam bathymetry shows numerous peaks and seamounts, which are the most significant difference between the east ridge and the central saddle area.

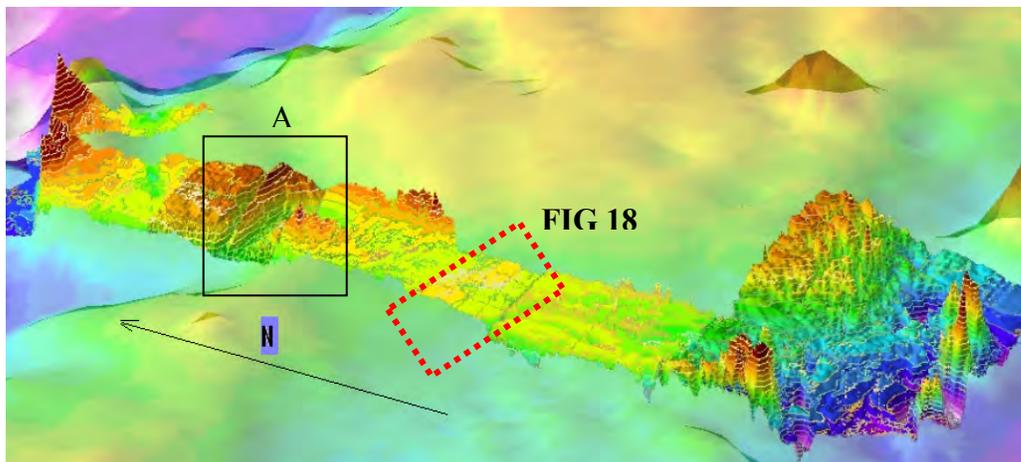


Figure 17. Multibeam sonar bathymetry at the central saddle area. The south side is rougher with depressions, and the north side is steeper. [Dataset from Salieri, SO158, GEOMAR]. A: It is showing normal faults on the saddle area. For details refers to appendix 2.

The separation between blocks by faults has obvious effects on the bathymetry such as disconnection of sediment beds, scarps associated with basement offsets, and drag on both sides

of the fault. These physiographic units exist as a product of a weak lithosphere that is unable to maintain loads of new magma from volcanism over long periods. Local adjustments are observed due to the inexistence of lateral stress bending the Carnegie Ridge; isostatic adjustments produce the vertical movement along the Ridge [Detrick and Watts, 1979]. This reorganization produces large scarps and fault blocks morphology with thin and offset sediment covers over an uneven surface. The fault scarps are easily identified on the ridge by the change of slope, by chaotic sediment covering the fault influence area, and by erosional features. On the east ridge there is a tensional fault (Figure19) at the intersection of the trench with pre-existing normal faults [Lonsdale, 1978], their deflection follows the strike-slip motion of the fault.

In the northwestern area of the saddle, eroded sediments are transported downward through channels and re-deposited at deeper depths [Malfait, 1974]. Sediments at the break of the slope are made of fine materials removed from the ridge [Kowsman, 1973a]. The adjacent Panama basin is covered with fine carbonate sediments particles (high content of planktonic foraminifera fractionated is the main composition). The area is dominated by lateral transport at the flanks [Malfait, 1974]. Slope ranges are from 10 to 58°, and depth ranges between 2000 to 2750 m.

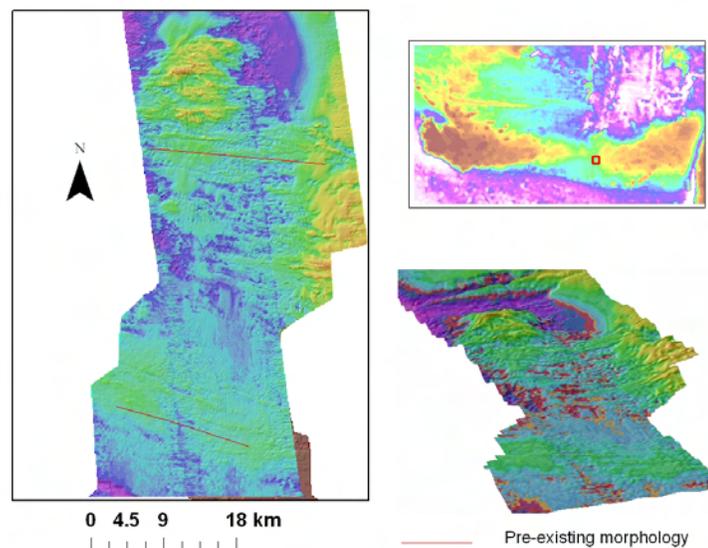


Figure 18. Bathymetry model showing the east-west trend of ridge formation. The spreading fabrics are located in the central section of the saddle area [data set from GEOMAR cruise SO159, Salieri].

Faults

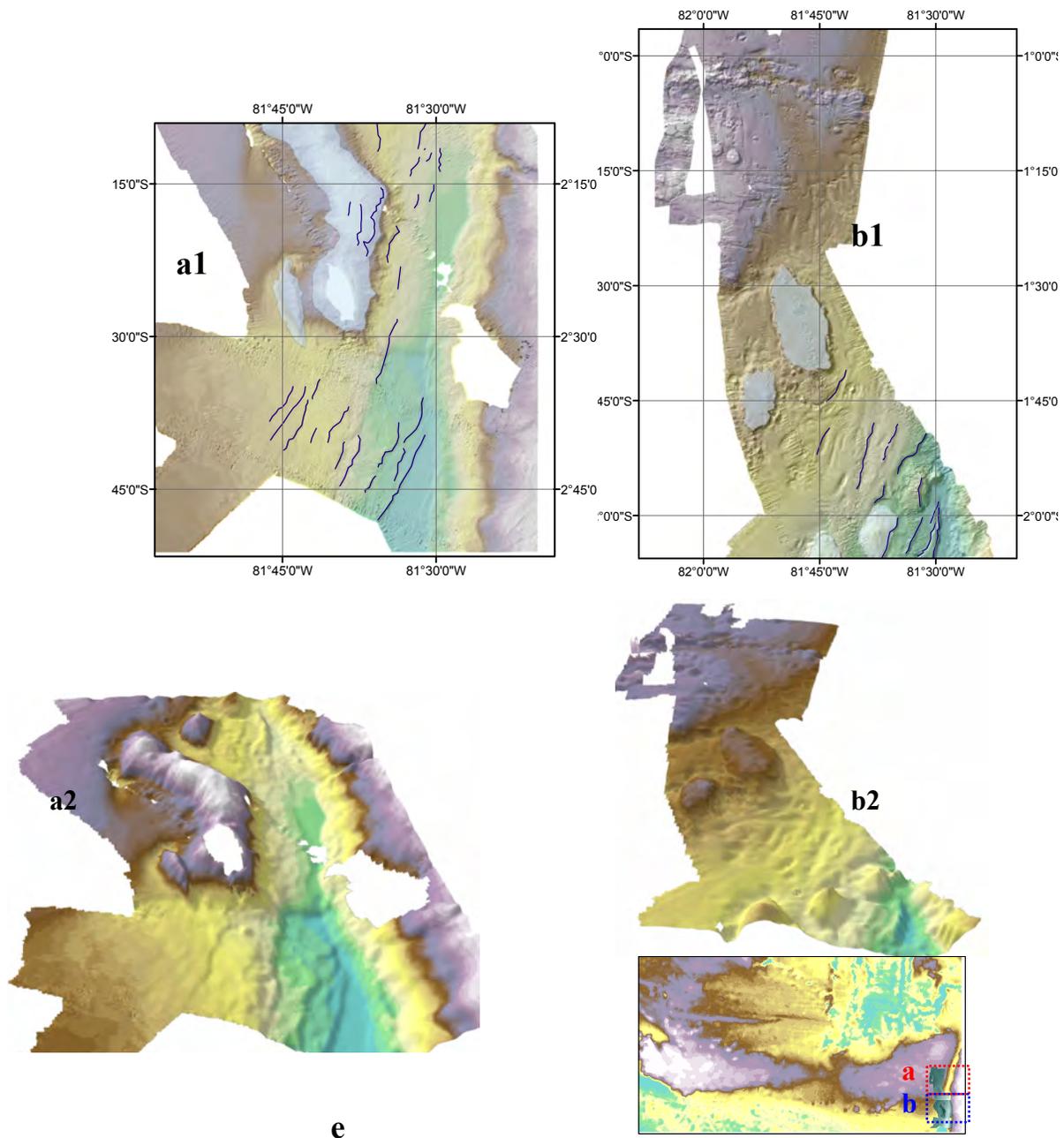


Figure 19. Bathymetry plots in the eastern Carnegie Ridge. a1. Offset blue lines are explained by tensional failure defined as tensional faults, of the ridge crust deformed into a convex curve (Lonsdale, 1978); b1. Flat seamonts along tensional fractures; a2. Tri-dimensional model roughly describing a seamont 5 km wide, and 45 km long, b2 2-D oblique view with east-west rift zone [Flüh *et al.*, 2001]. e. Geographical location of the area is shown in green.

The separation between blocks by faults has obvious effects on the bathymetry such as disconnection of sediment beds, scarps associated with basement offsets, and drag on both sides of the fault. These physiographic units exist as a product of a weak lithosphere that is unable to maintain loads of new magma from volcanism over long periods. Local adjustments are observed due to the inexistence of lateral stress bending the Carnegie Ridge; isostatic adjustments produce the vertical movement along the Ridge [Detrick and Watts, 1979]. This reorganization produces large scarps and fault blocks morphology with thin and offset sediment covers over an uneven surface. The fault scarps are easily identified on the ridge by the change of slope, by chaotic sediment covering the fault influence area, and by erosional features. On the east ridge there is a tensional fault (Figure 19) at the intersection of the trench with pre-existing normal faults [Lonsdale, 1978], their deflection follows the strike-slip motion of the fault.

Depressions

Enclosed depressions were identified along the Carnegie Ridge [Flüh *et al.*, 2001; Michaud *et al.*, 2003 and 2004], especially on the volcanic basement of the mid-slope of the ridge (Figure 20). This type of depression was also observed on the north flank in much fewer frequencies. Underwater dissolution of carbonate-rich sediments is considered the origin of these features [Flüh *et al.*, 2001; Michaud *et al.*, 2004].

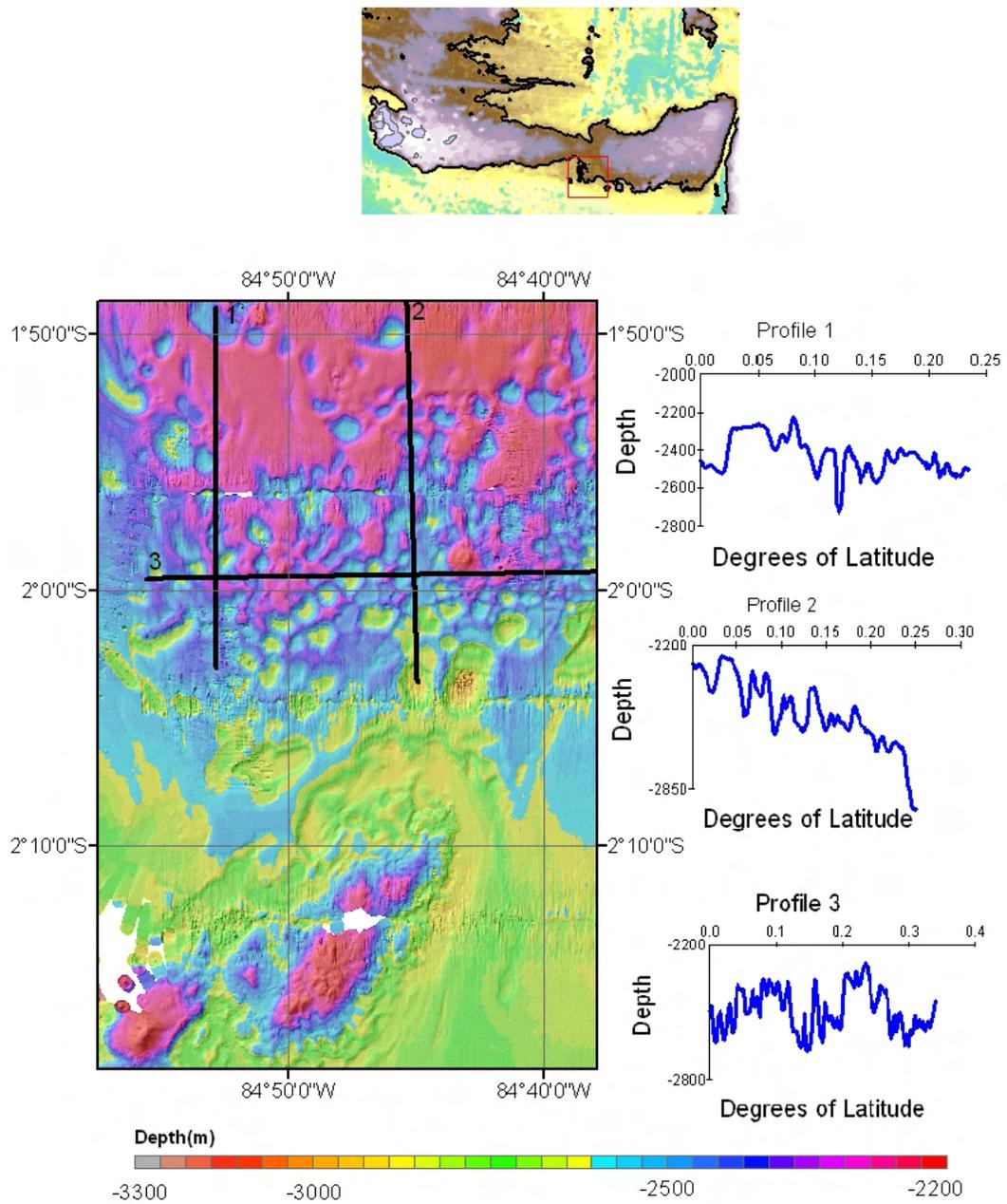


Figure 20. Circular depressions in the south flank. Closed depressions of 1-3 km in width and up to 400 m deep are observed in the middle position of the southern slope of Carnegie Ridge.

Sediment composition

The composition of sediments along the elongated shape of Carnegie Ridge and the surrounding basin areas is affected by the surface productivity, crustal age, carbonate compensation depth, distance from the mainland (source of terrigenous sediment), dissolution, and bottom water flow. Dilution by terrigenous material near the mainland, and eroded volcanic debris around the Galapagos Volcanic Platform [Kowsman, 1973b] are locally important to the sediment composition. Likewise, re-distribution of biogenic sediment, mainly carbonate, is produced by erosion produced by bottom water flow. All sediments in the study area are classified in a three component system of CaCO_3 , siliciclastics, and organic material; below this consideration, other minor constituents such as hydrothermal and volcanic sediments, salts, etc., were not taken into account.

Initially, 165 cores were selected for the area (Annex 1) with known values of carbonate weight percent, normal opal weight percent, organic carbon weight percent, sedimentation rate, etc. A brief summary of sediment composition at the Carnegie Ridge area is given in the following.

Biogenic deposits

1. Carbonate deposition

The CaCO_3 in this study has been analyzed in terms of dissolution, productivity; and dilution, because the interactions between carbonate and non-carbonate sediments in the environment and their accumulation with depth are extremely important in determining the amount of CaCO_3 deposited on the sea floor. The sediment composition based on the weight percent of CaCO_3 in the upper part of the existing cores was assembled and mapped in general CaCO_3 percentage grids (Figure 21). The patterns in the CaCO_3 distribution are marked by the terrigenous dilution, siliceous zones, and the differences between the climatic zones produced by the geographical position of the equatorial front [Lisitzin, 1996]. The dominant carbonate is found in the ridge, not in the east ridge where siliceous sediment accumulation is important. In slope, the percentage has minimum variations. In the hills, this is observed in the Leg 202 Sites 1238 and 1239 with moderate accumulation of 58% and 72% respectively. An important factor to consider when dealing with CaCO_3 is the state of preservation, which is the fractional percentage of organism

shells; they give us an idea of the environmental condition of deposition. The shells are preserved in an initial state and begin a destruction process due to chemical dissolution. On the seafloor the thickest shells tend to be preserved. The analysis of the preservation and the temporal and spatial changes in sediment composition and accumulation should give us an idea of the depositional environments formed by the deposition of sediments. Their preservation distribution on the ridge is affected by chemical and mechanical processes such as effects of solution, winnowing, and lateral transport to the surrounding basin [Dikelman, 1974]. The carbonate is saturated at the surface and begins the dissolution process with increases of pressure and decrease in temperature, leading to an increase in CO_2 content.

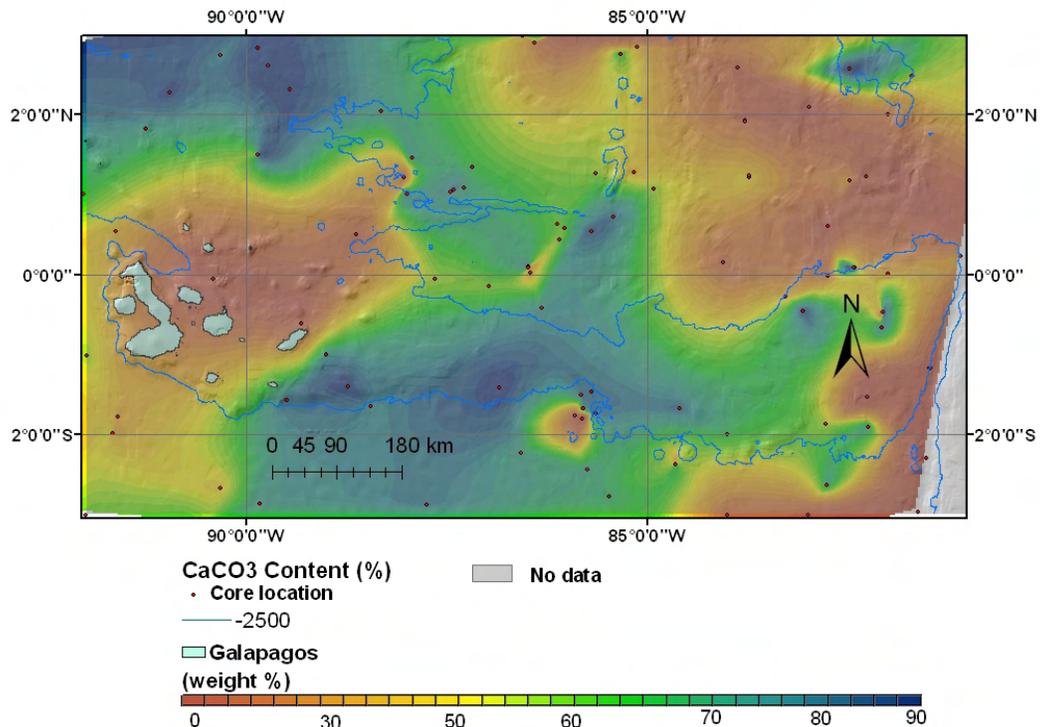


Figure 21. CaCO_3 content distribution in bottom deposits along the Carnegie Ridge. It was compiled by using the percent of CaCO_3 in the upper 30 cm of each core (data from Lyle *et al.*, 1995, Lyle, 1992; Swit, 1976; Mekik, *et al.*, 2002; Molina Cruz, 1975).

Dilution via mixing with other elements is important in determining preservation. In the Panama Basin, the dissolution was observed in cores below the sedimentary lysocline, which is

either located at 2800 m [Thunell *et al.*, 1982], or at 2700 m [Lyle, 1992]. As expected, dissolution was not evident in the upper 1770 m of the Panama basin. The state of preservation differs from one species to another because they are different in their compositions. Some species such as Foraminifera *G. Theyere* and *G. Ruber* have thin dissolved -walls, whereas others with thick-walls are preserved, such as *G. Dutertrie* [Allen, 1984].

2. Opal deposition

Amorphous silica is produced by diatoms, silicoflagellates, and radiolarians in the upper ocean. Equatorial waters, where radiolarians are in the most abundant concentration, has high production of amorphous silica [Archer *et al.*, 1993]. Sediments are rich in siliceous remains in the study area. Opal silica located on the seafloor is composed of remains of biogenic siliceous sediments formed of the residues of diatom and radiolarian.

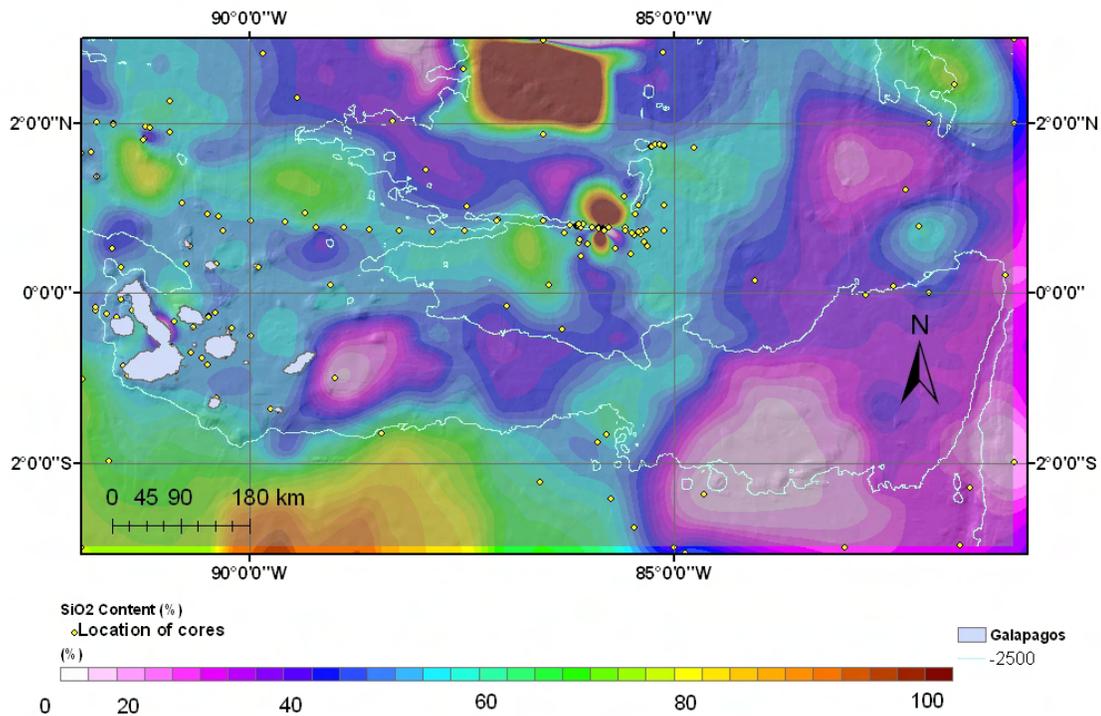


Figure 22. Content of opal in surface sediments (as a percent of the sample). Dots show sample locations. Dataset [Leinen, 1986; Lyle *et al.*, 1995]

The assembled distribution of radiolarians reflects an area of high productivity [Molina Cruz, 1977]. Preservation of radiolarian in the west ridge is greater than in the east ridge. The content of opal in recent sediments (Figure 22) in the Carnegie Ridge ranges from 13 to 80 weight percent. Three essential zones of recent silica deposition are identified: (1) the east ridge, which has the lowest values; (2) the west ridge area shows moderate values (3) Silicious rich deposits are found in Peru Basin , where CaCO₃ undergoes dissolution. Opal distribution, which is well correlated with the surface productivity maps, is affected by calcite artifact [Archer *et al.*, 1993]. This is because the grid was compiled using the values of percent Opal calcite free. The sediment Opal burial represents these values, and they are a fraction of the total opal production, which is affected by dissolution.

Siliciclastic deposits

The east ridge receives a moderate supply of terrigenous sediment from the mainland. The concentration produces a dilution of the other components of the sediment system. They distribution on the east ridge is influenced by bottom water currents. The clay concentration in the northeastern part is mainly of continental origin [Van Andel, 1973b].

Organic carbon deposits

The smallest fraction in sediments is composed of organic matter produced in the upper waters and imported from the mainland; higher Organic carbon percents are present in the east ridge (Figure23).

Variations in organic carbon reflect different degrees of decomposition related to water mass oxygenation, and changing primary productivity in surface waters [Ricken, 1993]. In the Eastern Equatorial Pacific, grazing is inefficient, and as a result more carbon is exported to the seafloor under in these conditions [Pedersen and Calvert, 1990]. The bottom waters are almost devoid of dissolved oxygen because it is consumed by the high carbon flux creating anoxic conditions. Anoxic conditions and high productivity water controls organic-rich carbon in sediments [Pederson and Calvert, 1991].

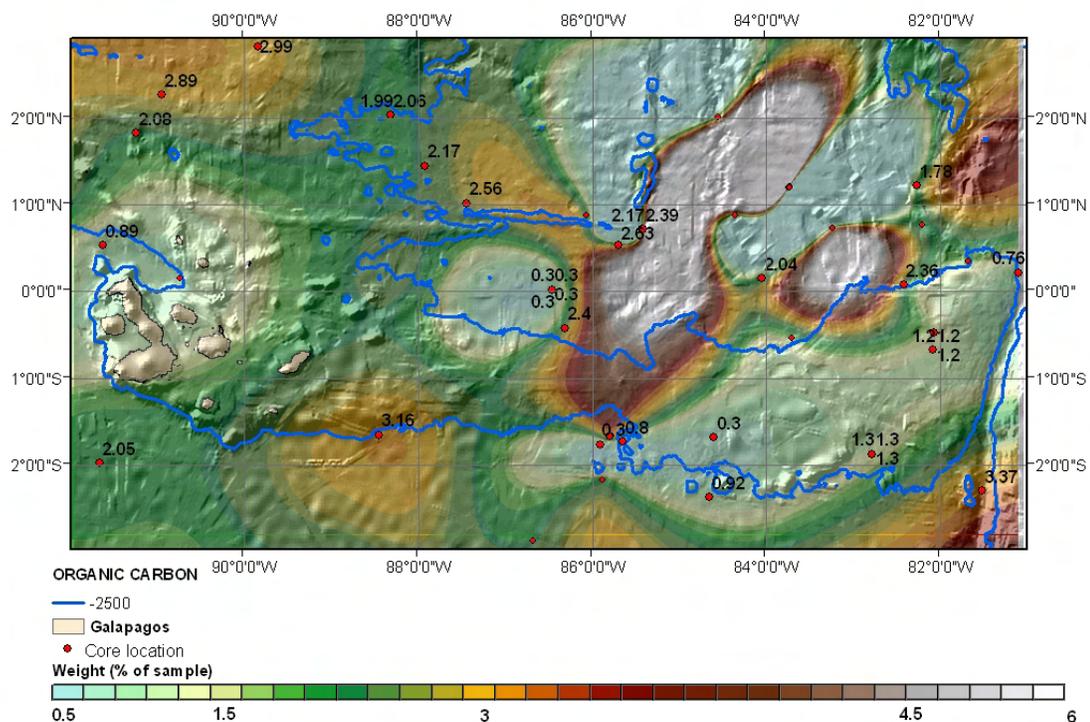


Figure 23. Distribution of organic carbon in surface sediments on the Carnegie Ridge. Positions of sites listed in anex1 are indicated. Dataset [Lyle,1992; Lyle et al., 1995; Mekik et al , 2002]

Dark colored organic matter was identified in ODP at site 1239 (Figure24) since the hilltop in the eastern flank has a sediment-water interface closer to the oxygen minimum zone. This area lies in high input flux of organic matter (Table 2) due to the formation of oxygen depleted water masses.

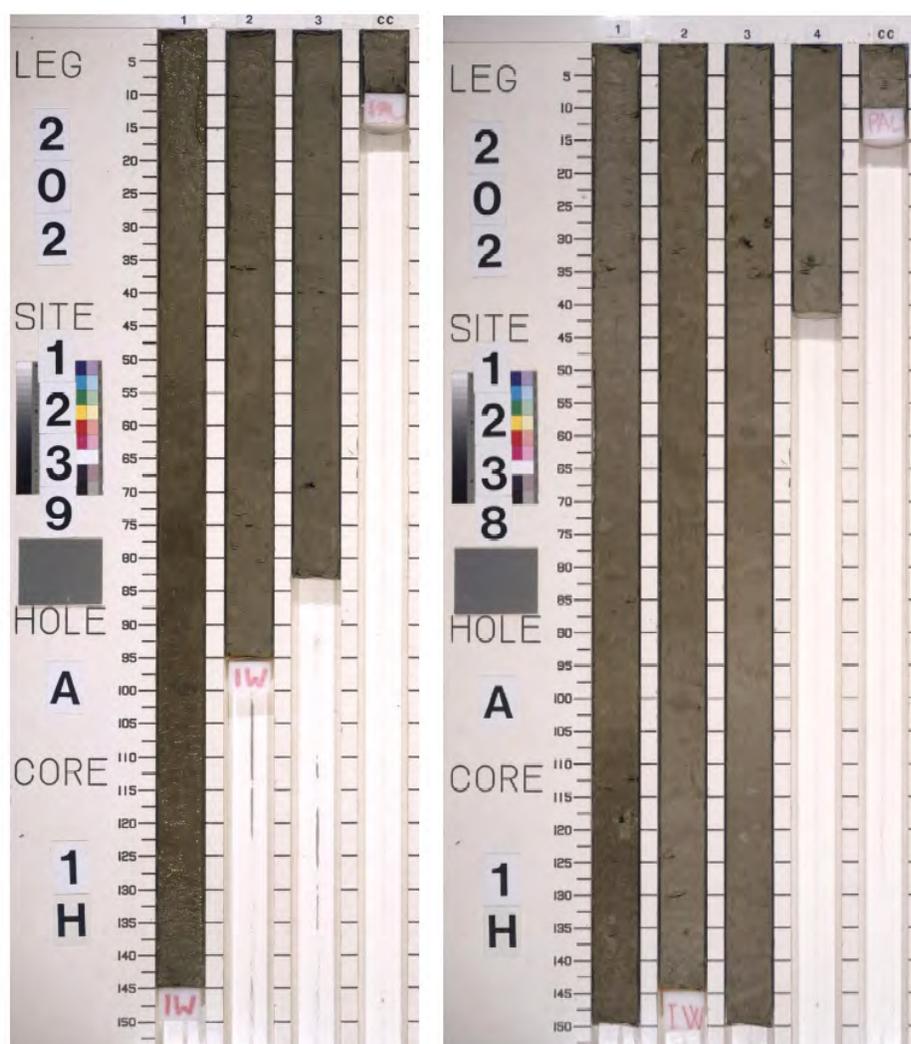


Figure 24. Cores in surfaces at sites 1238 and 1239 (depth values in cm). Darker bed of oxide-rich and bioturbated nannofossil ooze site 1239; bioturbated sediments with abundance of clay at site 1238. Data source: ODP Janus database.

Table 2. Average total organic carbon in the upper part of the ODP cores (Leg 202). The highest concentration was founded in core 1238 and 1239, characterized by the lower depths and location closer to the mainland (for core location refer to Appendix 2 number 2).

Core number	Total organic carbon TOC%	DEPTH(meters)
1238	3.4-11.8	2203
1239	3.7	1414
1240	1.5	2921

High productivity produces large amounts of decaying organic matter during organic matter decomposition, and high consumption of dissolved oxygen [Pedersen and Calvert 1991].

On the north flank of the saddle, the sedimentation rate is greater than the east ridge (where the sedimentation rate is moderate). The organic carbon in the sediments in areas of high sedimentation is buried faster and receives protection from oxic respiration and benthic digestion [Schulz, 2000], and in the east ridge the organic carbon content is higher near the coastal areas and decreases offshore [Lyle *et al.*, 1988]. Coastal areas and the northeast ridge, in conjunction with the west area from Galapagos where the coastal upwelling is high, determine where the highest values of organic carbon are present.

Summarizing, the proportion of carbonate in sediment varies between 1 and 97.76 weight percent, while opal content varies from 20 to 70 weight percent, and organic carbon content varies from 0 to 3.5 weight percent. In general, the rate of deposition of carbonate sediment is high, due to the sediments are deposited above CCD.

Bottom deposits

Granulometric studies from *Malfait* (1974) and *Van Andel* (1973a) show that the distribution of material is coarser on topographic hills, and fine material is deposited in the abyssal plain surrounding the ridge, and flat summit terraces. In depressions and channels running from the saddle area, the sediment is swept away [Dinkelman, 1974] by bottom water flow, and erosion is evident where ripple marks are evident [Malfait, 1974] and abyssal dunes are the result of mechanical processes [Lonsdale, 1976]. These local topographic conditions are important in determining how the material is formed and re-deposited. However, the high zonality of biogenic material formed, the dissolution of calcareous material with depth, and the disturbance by bottom currents are important processes that have defined the sediment deposition in the area.

The concentrations of sand and silt on the ridge are mainly foraminifera material, the abundance is between 10 and 30%. The clay fraction is less than 10% and between 50 and 70% in the abyssal plain surrounding the ridge. Major input of clay is observed in the ridge-trench junction, between 70 and 90% [Lisitzin, 1996]. Surface sediments containing concentrations of metals were limited to manganese nodules in the Carnegie Ridge [Rosato *et al.*, 1975]. The northeast ridge and surrounding areas have greater concentration of clay minerals [Heath *et al.*, 1974] than the rest of the ridge. They are composed mainly by kaolinite and chlorite, which are mixing with feldspar lavas [Werner *et al.*, 2000]. Smectite, clay mineral formed in the ocean as

well supplied from continents, is distributed with high content in the Galapagos Platform [Heath *et al.*, 1974]. Oceanic debris rich in basalt is also supplied to the Galapagos Platform as a product of volcanism of the Galapagos Islands.

Sediment properties

Sediments in the study area originate from the mixing of calcareous oozes, biogenous silica, and pelagic clay, creating a grain density lower than calcareous sediment [Hamilton and Bachman, 1982]. Sediment properties (physical and chemical) were revised from previous published works. In this study, grain size distribution is determined according to Lonsdale and Malfait [1974] for the saddle area, and based upon core information in the east and west ridges. Reworking of older sediment occurring on the ridge, was observed via the existence of sediment layers containing extinct species from tertiary and late quaternary periods, resulting from sediment disturbances of bottom water, slumping, and benthic activity [Dinkelman, 1974]. Considering homogeneous areas, the flat terraces and the adjacent abyssal basins, the sediment properties are the same for determined sediment types and environments if porosity is the same [Hamilton and Bachman, 1982]. The general lithologies on the ridge are (Figure 25):

- Terrigenous sediments in the area surrounding the Eastern Galapagos Islands, and the boundaries of the ridge-trench junctions at the north and south, which are mainly composed of clay from the mainland and glass volcanic from Galapagos Volcanic Platform.
- The abyssal hills to the east and west ridge, mainly formed from calcareous ooze.
- Abyssal Plain properties at the Peru Basins and surrounding areas the ridge at the south side, whose average depths are 3200 meters to the south, are mainly composed by calcareous ooze.
- Abyssal Plain properties at the Panama Basin and surrounding areas the ridge at the north side, whose average depths are 3000 meters to the north are mainly composed by clay and calcareous ooze.
- Calcareous sediment properties in the saddle area and in the flanks of the ridge are based on the general environment.

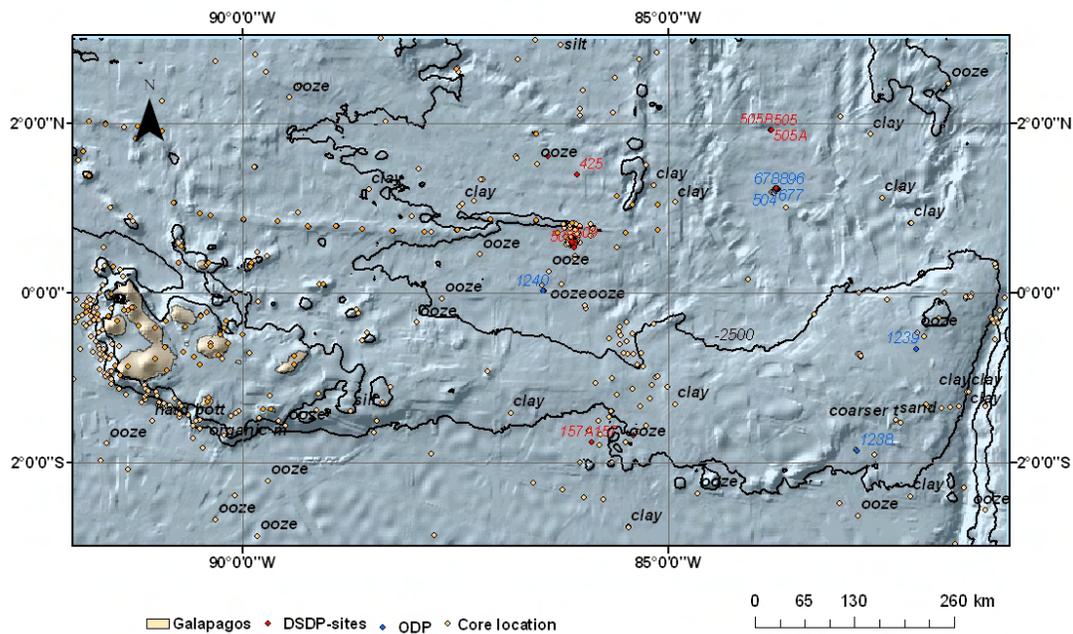


Figure 25. Lithology based on core description from NGDC. The red circles relate the seafloor surficial sediment descriptions in the early 1970's [Deck41 data set, NGDC].

The Carnegie Ridge has a high level of carbonate and biogenic silica, as observed on the upper part of ODP cores 1238 and 1239 from Leg 202, and Site 846 from Leg 138. The Sites 1238 (Mass accumulation rate (MAR) carbonate 2 g/cm²/ky and MAR noncarbonated 1.4 g/cm²/ky) and 1239 (MAR carbonate 1.8 g/cm²/ky and MAR noncarbonated 1.4 g/cm²/ky) carbonate accumulation is greater than non-carbonate accumulation. The cores 138 (MAR carbonate 1.2 g/cm²/ky and MAR noncarbonated 0.8 g/cm²/ky) has a higher carbonate accumulation rate [Mix *et al.*, 2002]. The environmental conditions at Carnegie Ridge are carbonate sediments where these sites are located are affected by processes such as changes in vertical pelagic settling and slow lateral advection through the water column. These conditions vary a result of land influence producing areas of hemipelagic sediments, where black shale hemipelagics have 10 cm/ky sedimentation rates in a high productivity zone [Stow *et al.*, 2001]. The intermediate water affecting the sites 1238 and 1239, and black shale deposited as a result of processes that control fine-grained sedimentation in deep water describe the depositional

environment on the shallow east ridge. This area was also considered as an area of hemipelagic distribution based on the illite content distribution [Heath *et al.*, 1974].

Sediment structure and stratigraphy

Local sediment sequence of the seafloor with a lateral resolution is observed with seismic reflection profiling obtained from Scripps Institution of Oceanography expeditions (cruises Nemo Leg III, and Venture Leg I). Those profiles show a high amplitude acoustic basalt basement. The depositional sequence is constant, except in instable areas of highly variable topography produced by a chaotic part of the escarpment, and in areas where basin fill pattern has different spacing between reflectors. This is an indication that the ridge has even sediment settling through the regional water column. Pelagic drape sediment was observed in the Panama Basin surrounding area reflectors. The traceable reflectors were related to variation in the surface productivity, which produces a decrease in sedimentary carbonate content from the dissolution produced by the increases in silicious radiolarian content [Kemp and Baldauf, 1993].

The general deposition on the hilltops at the east ridge is a pelagic basin fill, where sediments are deposited in low topographies [Lyle *et al.*, 2000a and 2000b]. The bow-tie effect is observed to the area surrounding the hill tops toward the south side showing evidence of erosion (Figure 26) The sediments in the northern part of the central saddle are concentrated as a result of reworking [Malfait, 1974; Knappenberger, 2000].

The reflectors are related to the glacial times of deposition when the combination of surface cooling produced an increase in the accumulation rates of calcite and organic carbon [Loubere, 2001]. This is observed in seismic waves because it produces different impedance, which is the product of bulk density and sound velocity [Mayer, 1980]. Carbonate has a higher density than opal. Mayer [1980] established density for carbonate at 2.7 g/cm^3 and opal at 2.3 gm/cm^3 . Since density is based on porosity, the carbonate sediments have greater porosity than the opal rich sediments. Variations in the composition of sediments cause seismic reflections [Knappenberger, 2000]. Overlying the sediment strata is a flat blanket with a slightly uneven distribution in the east ridge, which suggests that the sediments were either located in an area of major sedimentation or influenced by coastal upwelling with higher sedimentation rate than the local areas with moderate sedimentation rates. Younger sediments are mostly formed by nanofossil carbonate from pelagic sediments. On a regional scale, the east ridge hills display basement exposed to the water column. The oldest sediments observed in the seismic reflection profiling

seem to indicate a transition from sediments deposited below more pelagic conditions to hemipelagic conditions.

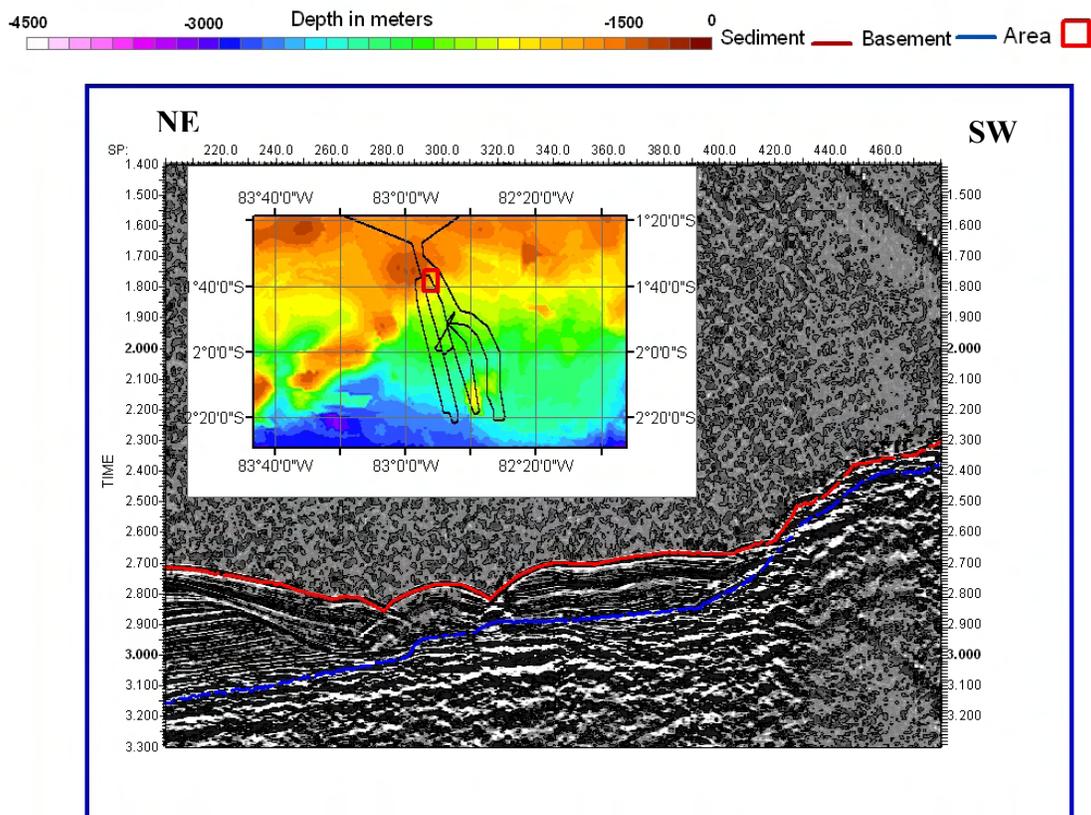


Figure 26. Stratigraphic sequence on the southeast ridge. The bow-tie effects are observed along the profile: the horizontal trend helps to predict continuous reflectors in sediment stratigraphy at the left side, and the bare sediment from the hill top at the right. A basin fill deposition domains the sediment sequence. Seismic datasets from cruise Nemo 03 (Scripps Institution of Oceanography).

This association is made by matching the negative gravity anomalies with the thickest sediments in the general area. Sediment thickness data are available on line at the following address <http://www.ngdc.noaa.gov/mgg/sedthick/sedthick.html>. The sediment thickness has irregular sediment coverage produced by roughness of the volcanic basement and extensive erosion on the sill areas at Carnegie Ridge. The stratified complex is observed in profiles which show a normal sediment sequence. Areas of nonconformities are restricted to the lower part of the sedimentary sequence, with an offset produced by transform faults at the east-west trend [Van Andel *et al.*, 1971]. The chaotic parts draped by sediment are restricted to the edge of flanks related to down faulted. [Lyle *et al.*, 2000; Michaud *et al.*, 2003; and 2004]. Sediment creeping downhill [Pisias *et al.*, 2000, Lyle *et al.*, 2000a, 2000b] is the main factors modifying the sediment stratigraphy due to the structural control in the down faulting areas.

Determination of sediment thickness

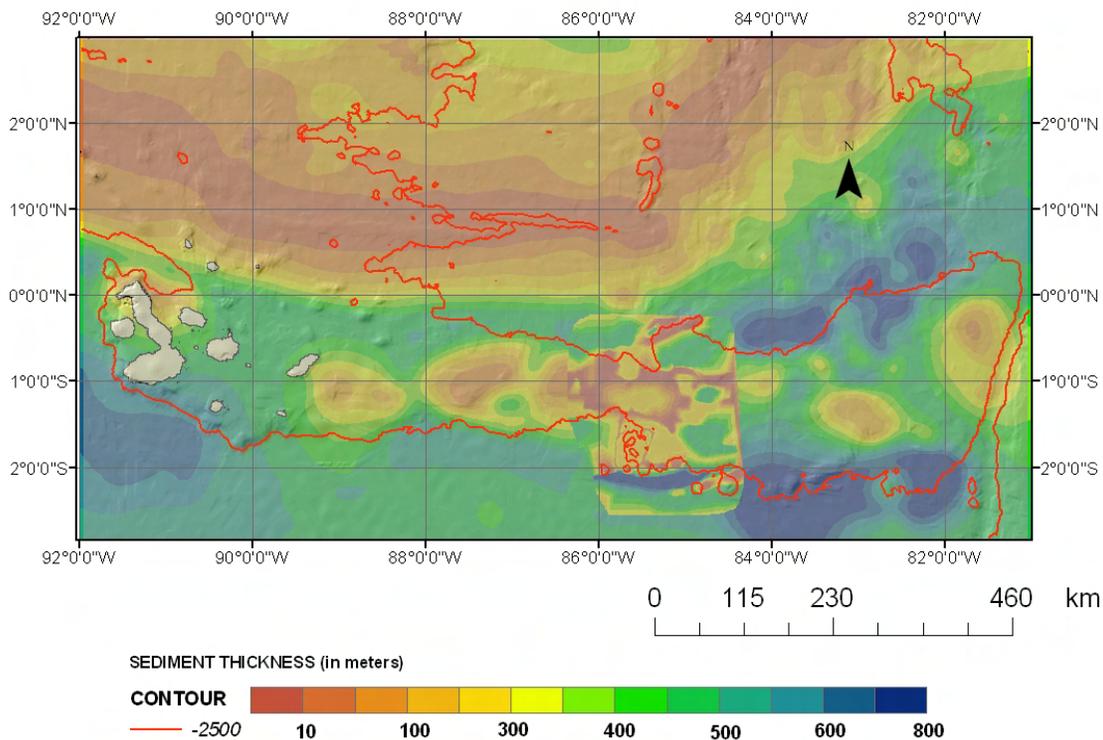


Figure 28. Sediment thickness along the Carnegie Ridge. The saddle area and hills are characterized by the absence of significant sediments.

According to the National Geophysical Data Center (NGDC), the general grid of sediment thickness is compiled mainly based on: seismic reflection profiles archived at NGDC, the age of the underlying crust, the type and nature of sediment source, and by nature of the sedimentary processes. Based on this initial dataset, a grid was created containing the NGDC general dataset and added regional studies in the area (Figure 28).

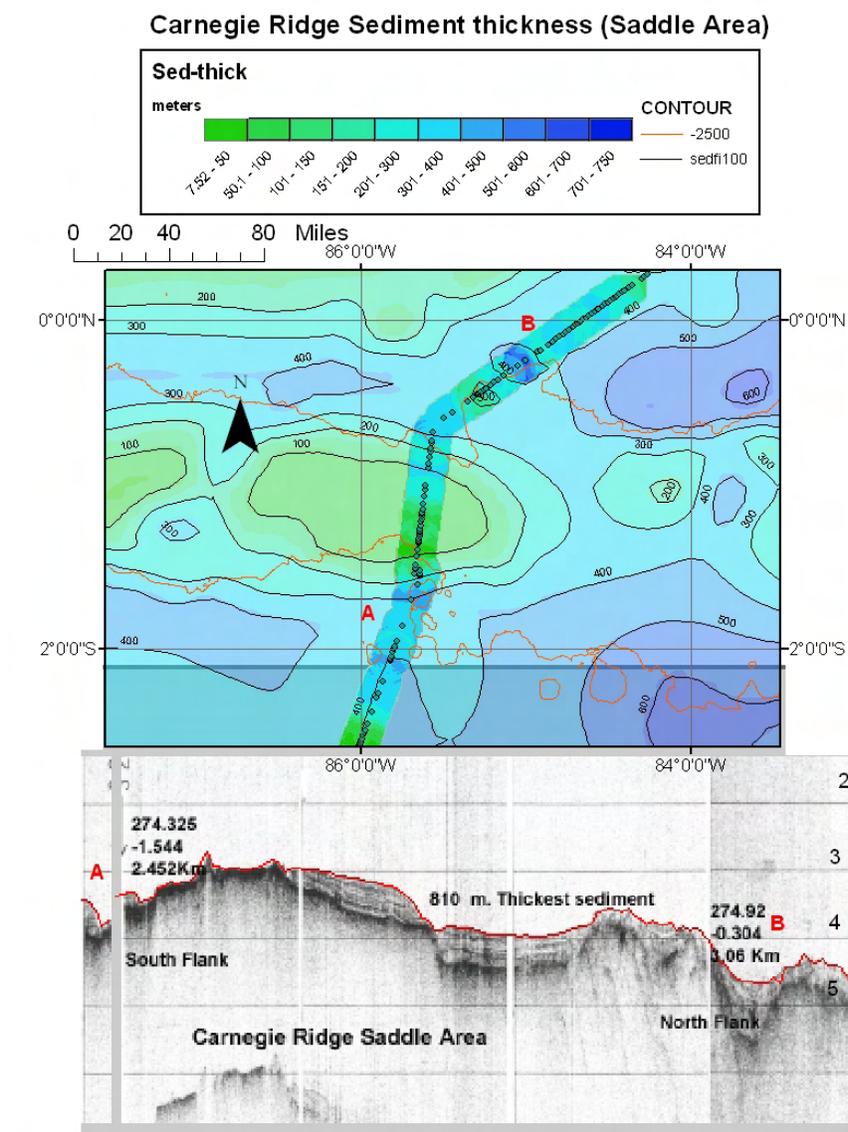


Figure 29. Distribution and thickness of sediments from the saddle area using the single channel reflection profiles to update the general area.

The amount of data incorporated is limited to seismic profiles from Nemo 3 [Lyle *et al.*, 2000], single channel profile Cruise C111 Lamont observatory (Figure 29), and regional study Malfait [1974] (Figure 30).

These profiles are in two way travel time scale (TWTT). Time conversion to depth on the seismic profiles was assumed that the sonic velocity is 1530 m/sec in the upper 330 m of sediment of the DSDP Leg 16 Site 157. This value is representative of the central saddle and west areas. The regional studies grid was created from the previous sediment thickness studies. Using their contours a grid was created with better resolution (Figure 30). These results were added to the NGDC general dataset and the grid was updated.

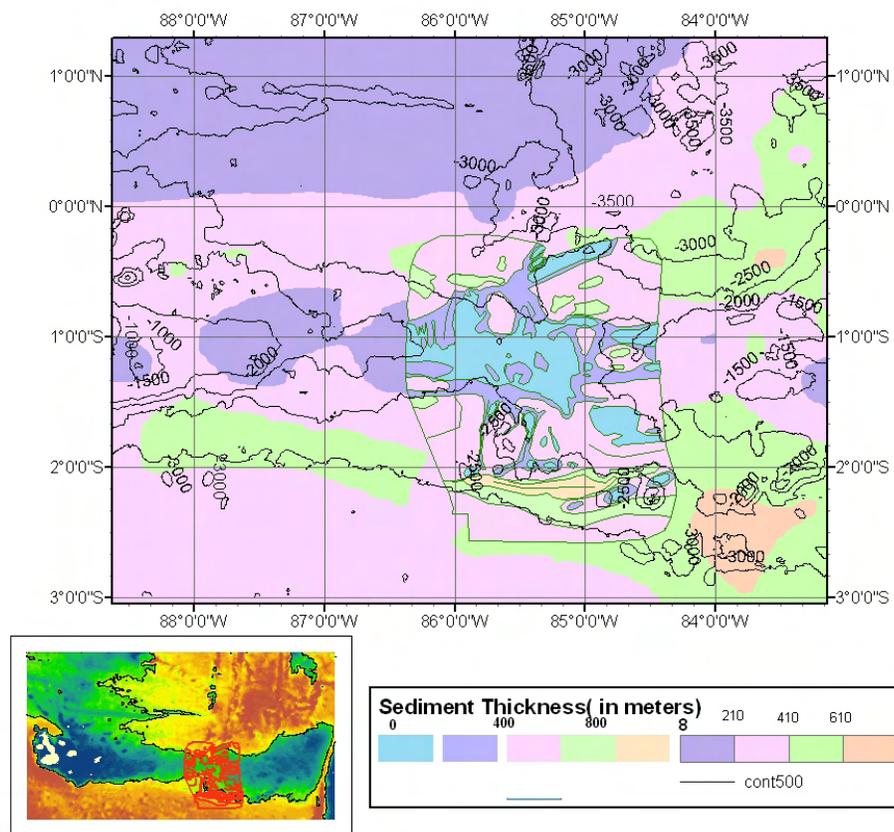


Figure 30. Distribution of sediment thickness in the saddle area. It was made using the global grid as a background, and adding local studies [Malfait, 1974].

Distribution of sediment thickness

The general distribution of the sediment thickness in the study area is as follows:

South-west of the Galapagos Islands and in the area of Galapagos Volcanic Platform, where the slope is more pronounced, sediment thickness is between 400 and 500 meters (Figure 28). The major deposition is controlled by downslope gravity transport on the steep escarpment, and the general area doesn't show evidence of slide deposits on the adjacent abyssal plain [Christie and Fox, 1990]. The southwest ridge is faulting controlled escarpment and shows no change over time due to infilling. This evidence reflects erosional activity, which was analyzed by Johnson *et al.*, 1976; Feighner and Richards, 1994; Christie and Fox, 1990. The post-depositional volcanic events were observed on seismic profile Ventura 1989 (Figure 31) on the GVP, those post depositional events were also identified [figure8, Erlandson *et al.*, 1981] on the saddle area.

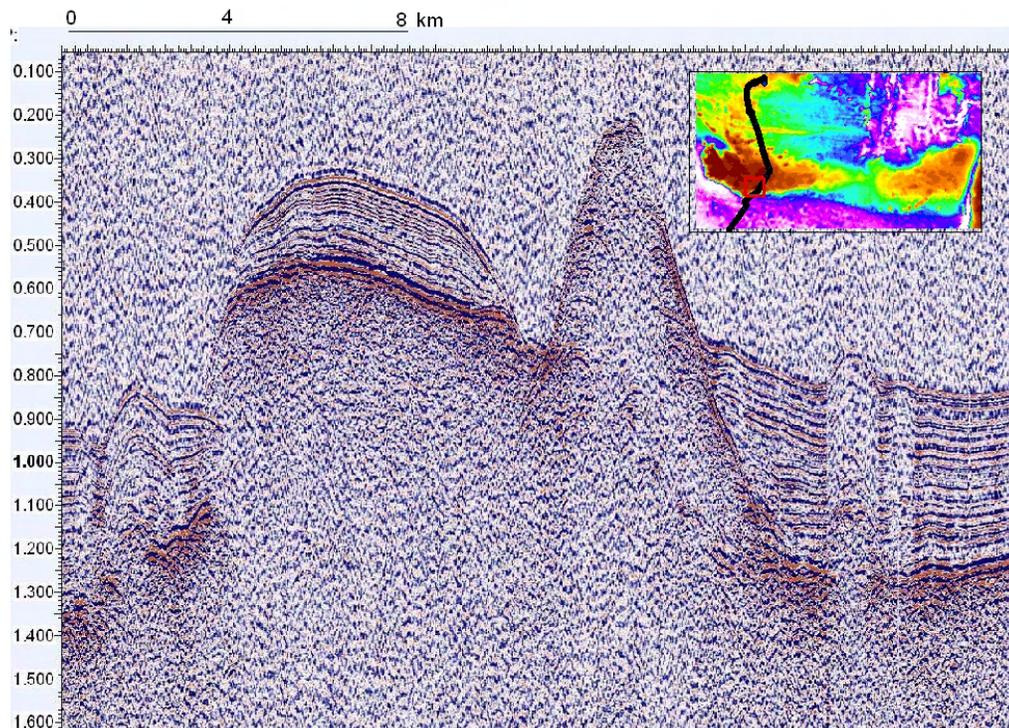


Figure 31. Seismic examples of a post depositional seamount at the west ridge.

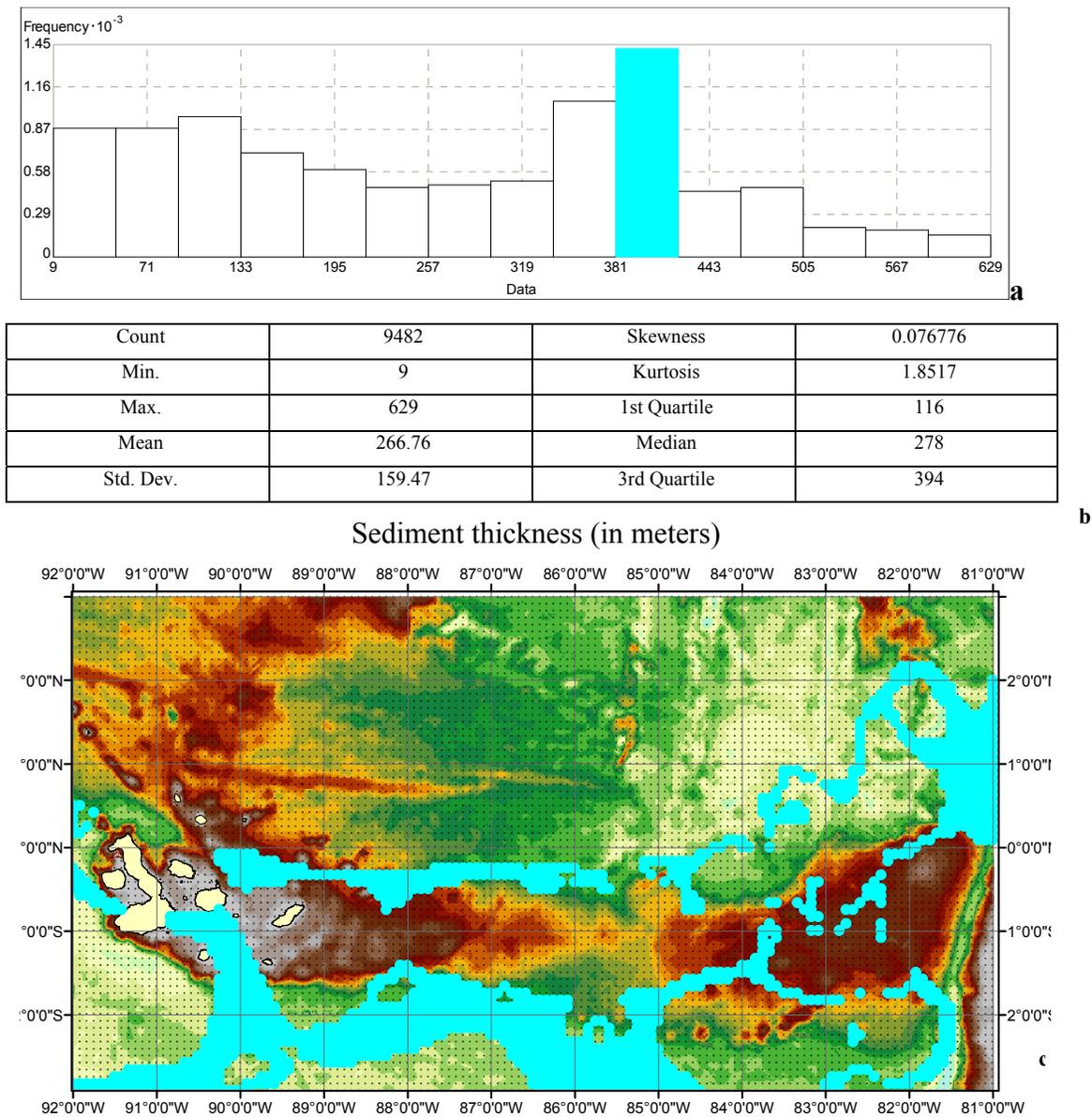


Figure 32. Histogram of sediment thickness distribution represents the average sedimentation thickness in the ridge up to 500 meters [a]. The statistics of sediment thickness distribution are represented by the average minimum and maximum values [b], and the most representative interval of sediment thickness distribution is represented in highlight blue [c].

The central saddle deposition is controlled by downslope gravity transport, and reduction in basin fill was observed due to variable velocity in the bottom boundary layer of the abyssal

current [Lonsdale and Malfait, 1974, Lonsdale, 1976]. The incised valleys cut the sediment sequence up to 500 m [Fig.9 Lonsdale, 1976]. In the area, erosion produced by active currents (Appendix 3.2) is the main factor modifying sediment thickness. The variations from thinnest to thickest sediment occur at the adjacent abyssal plain at north side. The hilltop is observed as an area draped of sediments.

The east ridge is represented by the drape sediment on the hilltops, the down slope change is restricted to adjacent abyssal plain at the northeast ridge where no presence of large slide deposits are found. Volcanism and basement morphology are responsible for the distribution and accumulation of thickest sediments along the valleys on the east ridge. Sediment thickness histogram (Figure 32 a) intends to explain its general distribution on the Carnegie Ridge region based on the frequency of sediment thickness grid values. The thickest area is around 630 meters and minimum values are 9 meters on the hilltops spatially. The high blue represents the areas containing 400 m as sediment in the general area (Figure 32).

Sediment thickness and gravity anomalies association

The loads on the oceanic crust disturb the isostatic balance, which is directly associated to gravity anomalies [Watts, 2001]. The density of rocks modifies this deviation; material with equal mass differs in weight. Thus, emphasis has been placed on depressions of the rough volcanic basement. The infill materials that fill the depressions created by the basement displacement (which are continuous on both side of the ridge) are the thickest sediment areas and lowest gravity anomalies. These areas may be located in the flanking regions along the ridge. The negative gravity anomalies are related to the elastic flexure of the lithosphere at the south of the west ridge on the adjacent abyssal plain base on the bulge topography and high negative anomalies [Feighner and Richards, 1994]. However, the sediment thickness on the deepest part of the moats of this area are lacking in sediments [Johnson *et al.*, 1976], which directly is related to the erosion due to the bottom water flow. Figure 33 shows the thickest area at the general south side due to the high slope which is represented in small space in the general map does not produce enough detail to reflect the general trend and the NGDC grid created doesn't take in count those profiles. The association of sediment thickness and gravity anomalies is marked by a general thickest sediment area at the south site which is correlated to the higher negative gravity anomalies.

On the east ridge the hilltops are drape sediment as indicate crustal exposed in seismic digital

profiles (dataset Cruise Nemo 3 2001, Scripps) red lines (Figure 34). These areas were obtained from the basement horizon and seafloor horizon processing the digital dataset. The negative gravity anomalies are observed on the flanks. The coverage of sediment thickness profiles measured from single-channel seismic reflection record [*Rogan and Lansegh, 1985*] and added to the (Figure 35b) is too sparse and too difficult to make a general characterization. The thickest areas are located at terraces on the ridge and downslope flanks and adjacent abyssal plain (Figure 34b, 35a).

The saddle area negative gravity anomalies are observed at the flanks of the ridge and surrounding abyssal plain. Those areas are represented with high sediment thickness values.

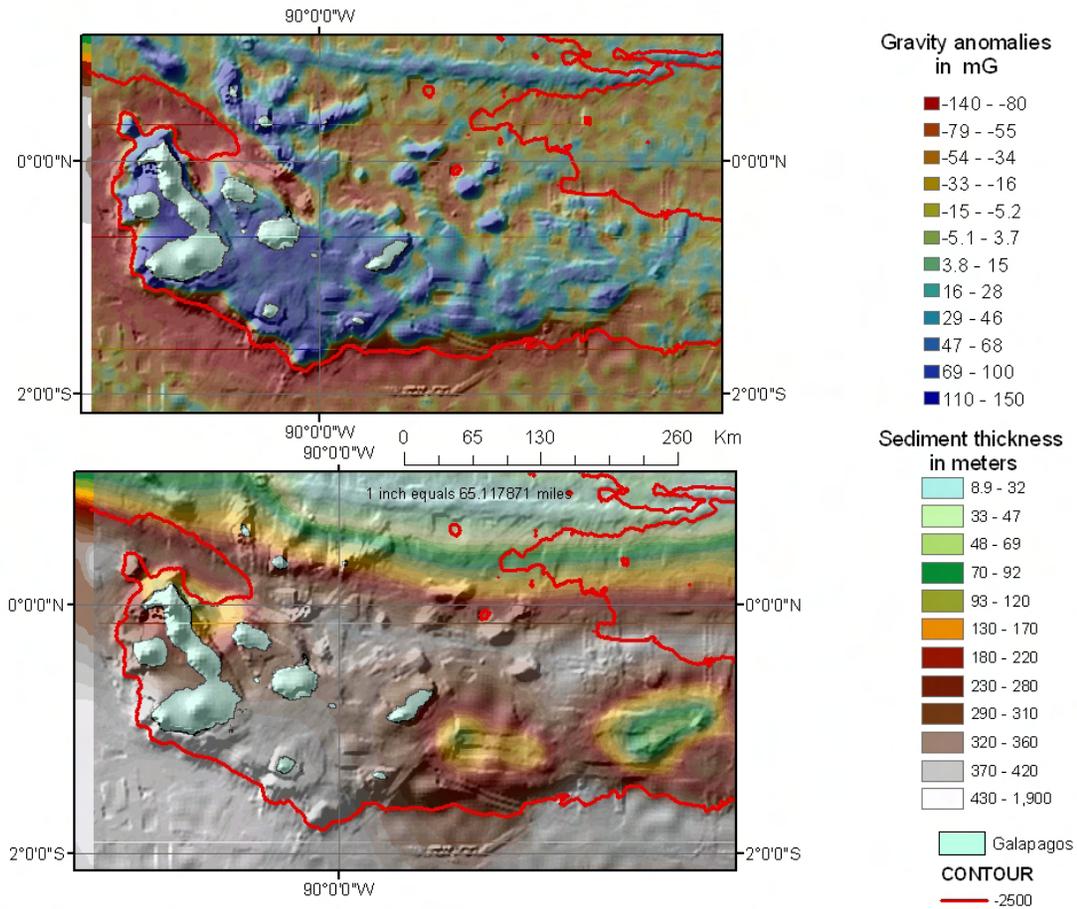


Figure 33. Western ridge sediment thickness distribution and gravity anomalies. Thickest sediments are located on the adjacent abyssal plain and thinnest sediments on the hilltops. A highly pronounced negative gravity anomaly is observed at the southwest ridge

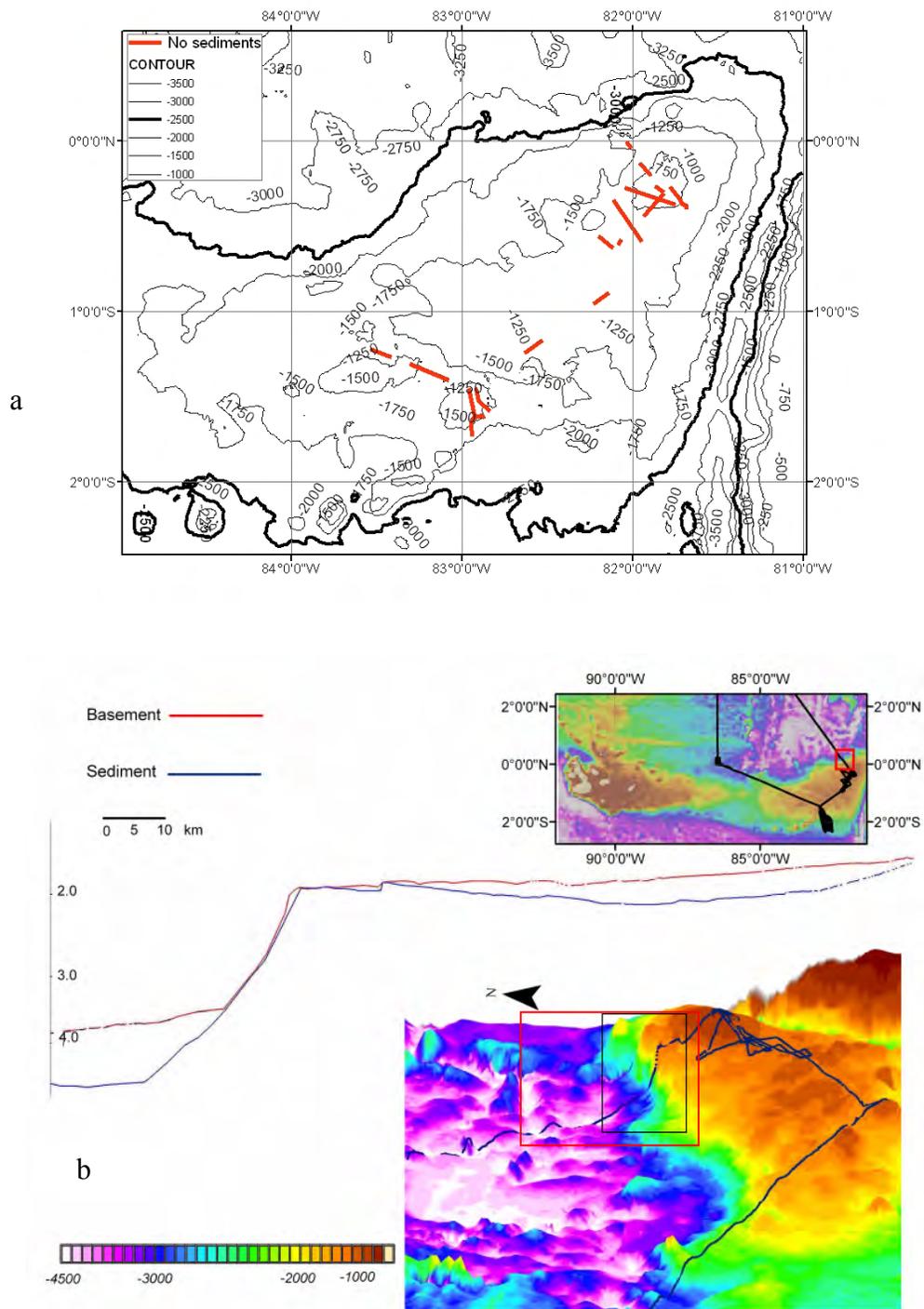


Figure 34. Non-deposition areas. **a.** Red lines represent the areas without sediment from seismic profiles [Dataset Cruise Nemo 03. Most of areas are located on the hill top. **b.** Seismic section showing the non-deposition on the middle slope at the north of the east ridge.

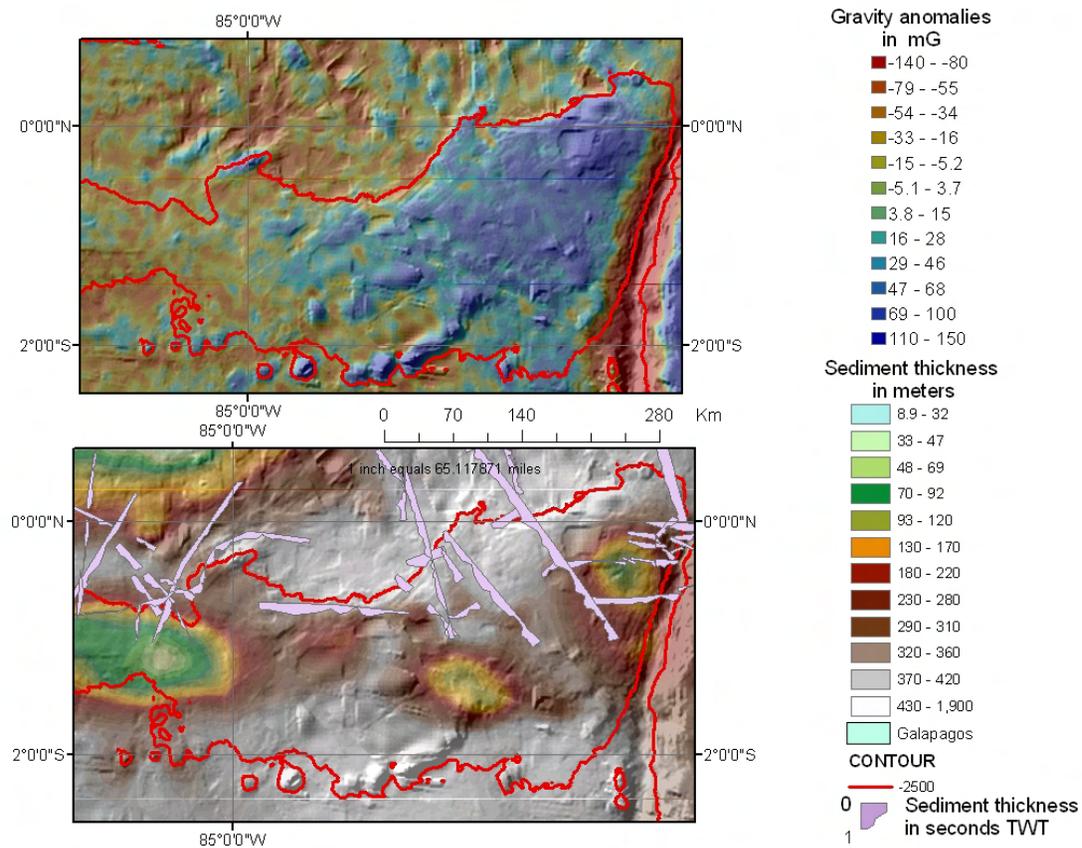


Figure 35. Eastern ridge and adjacent saddle sediment thickness distribution and gravity anomalies. Thickest sediments are located on the adjacent abyssal plain and thinnest sediments on the hilltops. Purple polygons represent sediment thickness measured from single-channel seismic reflection records [Modified Rogan and Langseth, 1986]. A pronounced negative gravity anomaly is observed at the down escarpment of the ridge.

CHAPTER VII

FACTORS CONTROLLING DEPOSITION

General conditions

The distribution of sediments is affected by physical factors such as depth, seafloor morphology, and climate. The relatively shallow depth of Carnegie Ridge (above the lysocline and carbonate compensation depth) is an important factor controlling sedimentation (Figure 36). In particular, the CaCO_3 accumulation is based on the production (pelagic deposition of calcareous tests) of the surface waters, and dissolution by organic carbon degradation within the surface sediments. Both are important in CaCO_3 to the distribution on the ridge [Pisias *et al.*, 2000].

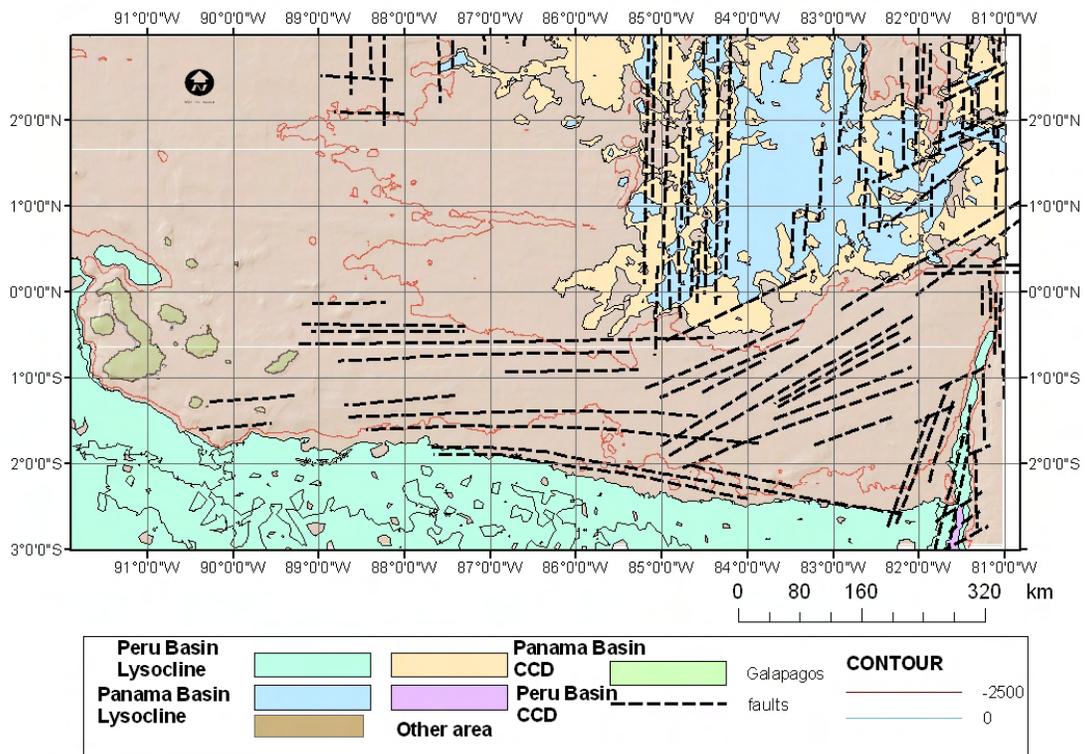


Figure 36. Generalized areas below carbonate compensation depth and lysocline depth of the Panama Basin and Peru Basin. [Fault patterns modified from Van Andel *et al.*, 1971]

The factors influencing the deposition of biogenic sediment in the general area surrounding Carnegie Ridge are:

1. Productivity in surface waters, which has a direct effect on pelagic sediment supply.
2. Dilution of biogenic sediments by terrigenous input.
3. Underwater dissolution associated with the Pacific Central Waters.
4. The circulation of corrosive waters, which are enhanced by the degradation of organic matter.

Productivity

The average concentration of organisms living in the ocean surface of the Carnegie Ridge area is around 1000 mg C/m²/d near the southeast ridge and the areas surrounding Galapagos Islands, and 500 mg C/m²/d near the north flank of the ridge and the saddle area [*Dinkelman*, 1974]. These values demonstrate where the highest productivity in the area is, based on the influence of SEC. The ridge is in the equatorial region, which coincides with the silica enrichment zone. In this area, plankton are sufficiently abundant at the surface, and their skeletons accumulate and reach the seafloor. The surface currents are directly involved in pelagic settling because of their high nutrient content. Similarly, circulation of bottom water within the restrictive Panama Basin affects local productivity on the northeast flank of the ridge.

Terrigenous input

Along the Ecuadorian Continental Margins, terrigenous sediments dilute the concentration of planktonic skeletons, which significantly reduces concentration of CaCO₃. This general variation is observed along the east ridge. Terrigenous sediment comes primarily from mainland delta systems formed around river mouths located along the continental shelf. These rivers deposit most of their sediments in the Ecuadorian Trench. Sedimentary quartz distributions are linear with respect to bottom conditions, and their source is mostly continental [*Leinen et al.*, 1986]. The general distributions match the highest concentration values of quartz closer to the continent (Figure 37), confirming a heightened input of terrigenous sediments closer to the mainland. The main patterns of non-carbonate sediments match the flux rates of terrigenous sediment. Maximum flux rates occur near the mouths of the Guayaquil, Esmeraldas, and Magdalena rivers, and at the corners of the Carnegie Ridge-Trench Junction. Sediment is distributed latitudinally, in accordance with the water masses and aeolian forces. Terrigenous sediments and basaltic ash

originating from the volcanic Galapagos Islands was found around the Galapagos Volcanic Platform, and more silicic glass shards of volcanic origin are found on the east side of the Carnegie Ridge [Roseto *et al.*, 1975].

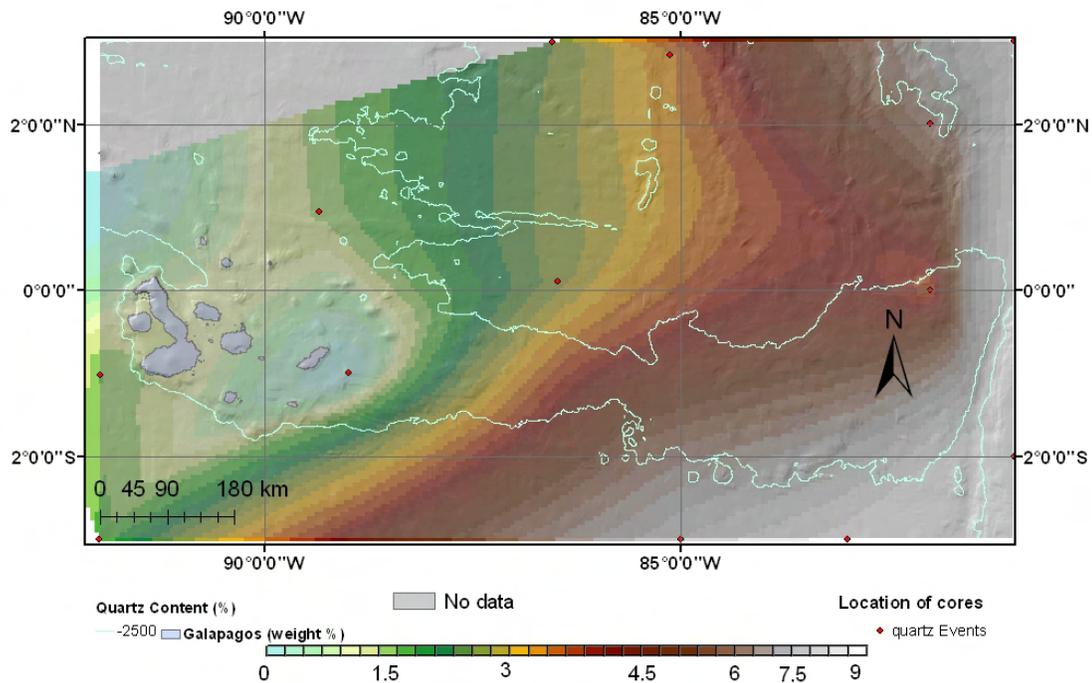


Figure 37. Quartz content in the Carnegie Ridge area. Dataset (Molina Cruz, 1975)

Underwater dissolution

Bottom water chemistry, carbonate flux from surface waters, and organic carbon flux have all been identified as variables controlling carbonate preservation [Archer, 1991]. On the Carnegie Ridge, the underwater dissolution is consistent with the migration of the ridge toward more coastal conditions, showing greater production of diatoms where the upwelling is strongest [Mekik *et al.*, 2002]. Those areas have greater organic content [Lyle, 1992] and are enhanced by

siliciclastic deposition due to land influence. The foraminifera fragmentation, which is a known index of dissolution, is confined to the middle slope of the flanks, and to the east ridge [Kowsmann, 1973a]. Thus, the east ridge is more susceptible to dissolution. Although the ridge is above the lysocline, the carbonate dissolution changes with depth, creating circular depressions on the middle slope in the saddle area [Flüh *et al.*, 2001; Michaud *et al.*, 2004]. These circular depressions tend to increase in size as the depth increases. Farrell and Prell [1989] have calculated bathymetric variations of carbonate preservation for the central equatorial Pacific shallow lysocline, and poor preservation was found during interglacial periods. Fluctuations of CCD, related to the modification of deep waters separating the Atlantic and Pacific oceans (before the closure of the Isthmus of Panama), are significant to the dissolution, and defined a carbonate crash in the late Miocene extending from 7.5 to 11 Ma [Lyle *et al.*, 1995]. These significant processes are important to the history of Carnegie Ridge sediment deposition.

Corrosive water

The circulation of old bottom water at the middle slope of the northwestern ridge and south flank of the saddle area has a dissolution effect on carbonate deposition (Appendix 3.5) due to the corrosive water properties. The organic carbon fluxes into deeper waters are higher close to the mainland. This corrosive water is an important factor affecting sediment composition. The low oxygenation of sediments helps to preserve the organic material. The circulation of corrosive water within carbonate sediments which have a heterogeneous porosity can enhance dissolution [Michaud *et al.*, 2004]. Indeed, adding CO₂ and acidity to the depositional environment makes the water very corrosive to calcite and increases the dissolution of calcite. This effect is most pronounced on the middle slope of the east ridge.

Bathymetry

The Carnegie Ridge has a clear east-west tendency with a northeasterly bend at its eastern end (Figure38). A central saddle separates the ridge into two different environments: the shallower east and west ridge, and the deeper saddle area. On the east ridge and saddle area the steepest escarpment is located on the north side. As a rule, aseismic ridges have one side steeper than the other [Detrick and Watts, 1976]. On the west flank the steepest escarpment is located on the south side. The sediments are affected by the volcanic basement morphology (Appendix 3.1).

The ridge, which is a natural barrier, deflects to the west the northward bottom water flow, producing sediment transport. Faults in the ridge are east-west normal faults, and the faults in the east ridge closer to the boundary of the ridge are southwest-northeast [Van-Andel *et al.*, 1971]. The faults in the ridge–trench junction are tensional [Lonsdale, 1977a].

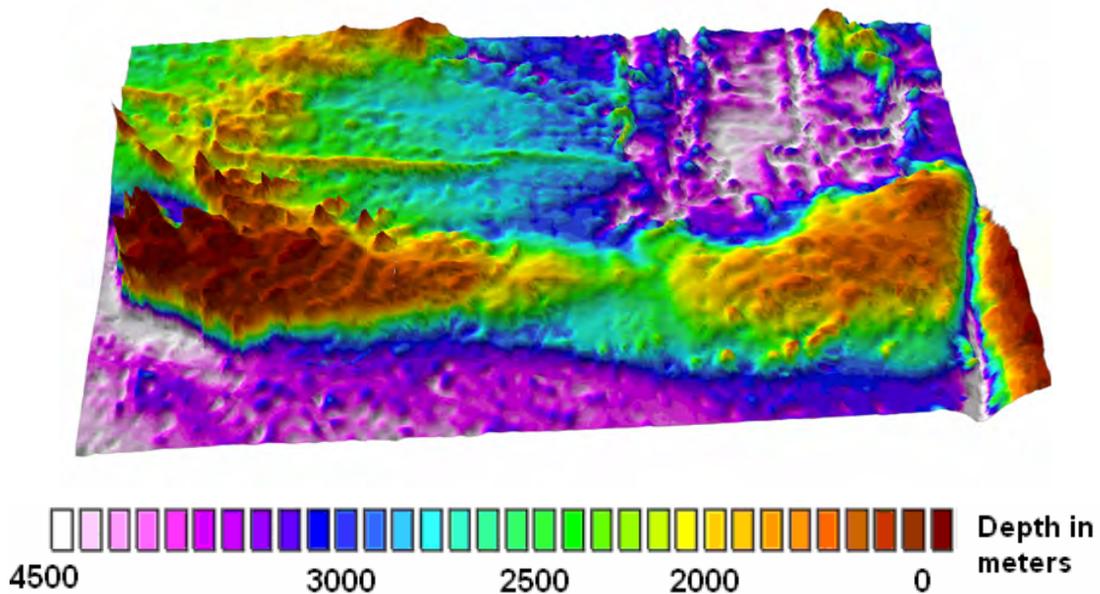


Figure 38. Seafloor bathymetry map. This image is constrained by unevenly spaced ship tracks and satellite altimetry based on Sandwell & Smith, 1997.

The rough seafloor surface affects the sediment transport, diverting it laterally and down slope. Flowpaths are important morphologies that can give an idea of bottom water flow and predict possible erosional areas (Figure 39). On the ridge, there is a channel passing seamounts at the south side which is produced by scouring effects (Appendixes 3.2 and 3.3). Channels were also identified in the area south of ODP Site 1238 [Lyle *et al.*, 2000]. The sediment is swept away from these topographic features and accumulates on the lower northern and southern slopes. The channels (classified by their topographic relationship to the general bathymetry) have been used to identify susceptible bottom flow areas. The general flowpath leads toward the Panama Basin, following the channels.

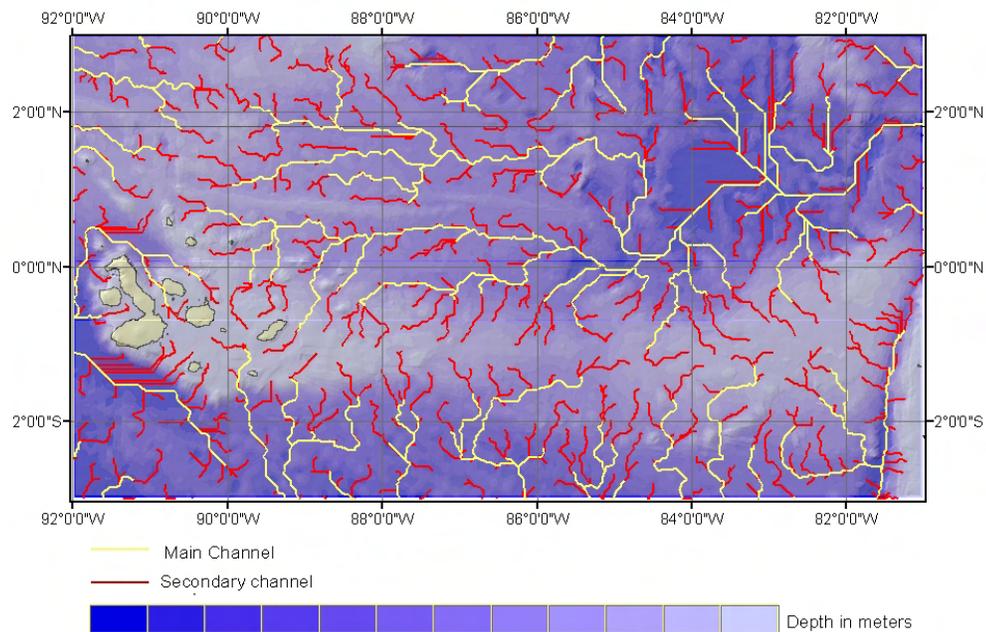


Figure 39. Major bottom channels diverging from the Carnegie Ridge. Yellow channels are considered as primary, and the red ones as tributaries. Path flow starts in faulted areas, such as the flanks. They are correlated by the greater variation in seafloor bathymetry. This calculation is based on the slope and relief of the general map and was compiled in ArcGIS.

Bottom currents

The sediment properties vary from place to place, due to re-deposition produced by abyssal currents. Their existence was determined by analyzing the distribution of temperature, salinity, and dissolved oxygen [Laird, 1972], and by analyzing the inflow of bottom water to Panama Basin [Lonsdale, 1977a]. From the deep water properties of those analyses, the water surrounding the northeast corner of Carnegie Ridge has the coldest water (1.63° C), the highest salinity (34.667 ‰), and the greatest oxygen content (2.75 ml/L) [Laird, 1972]. Likewise, a

potential temperature of 1.55°C , a salinity of 34.678‰ , and near bottom currents of 33.2 cm/s velocities [Lonsdale, 1977a] were measured in the shoaled depths of the trench (Figure 40).

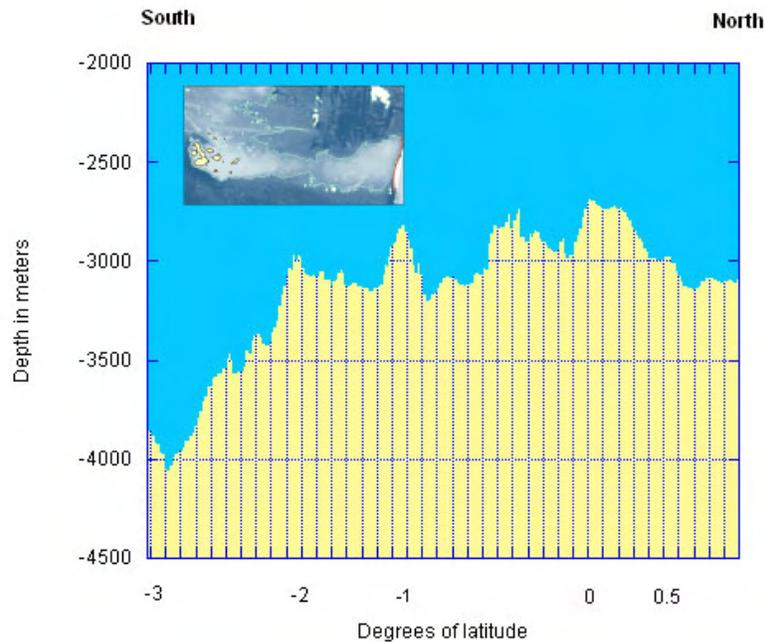


Figure 40. South-north profile of the Ecuadorian Trench.

This area is important to the change in depth at the Ecuador Trench due to the thick Carnegie Ridge being subducted. Sediment transport is produced by bottom water flow, which creates a turbulence layer over the rough seafloor [Lonsdale, 1977a]. This flow causes sedimentation to occur downslope from the shoaled point into the Panama Basin.

The dynamic of the layer adjacent to the sediments has significant control in the re-sedimentation processes. Sediment gravity flow in this area moves toward the final accumulation of sediments in the area adjacent to the northeast ridge. The seawater/sediment interface has low interchange with the adjacent fluid because it has been winnowed by bottom currents, leaving an underwater bed form. This was observed at the central saddle area [Malfait, 1974], and it provides physical evidence of lateral transport while directly affecting the sequence of

deposition.

The saddle area (as a result of erosion) has reduced the sediment cover down to hard grounds of chalk and chert [*Malfait and Van Andel, 1980*]. Such processes are the result of incipient cementation, and have been related to karst relief [*Malfait and Van Andel, 1980*]. Deep circulation has been inferred from contours and other bedforms, and the difference between Panama and Peru Basin's carbonate compensation depth. The patterns in this area are produced by dissolution at depth, and erosion, and the current velocities enhance the mechanical dissolution [*Berger, 1973*]. This condition has changed the sediment environment by becoming either erosive or non-depositional in the areas closest to the central saddle sill and trench, due to the inflow of bottom water from south to north. A proof can be seen in seismic profiles which clearly show how currents are able to produce nonconformities and redistribute sediment to the north area in Panama Basin [*Malfait, 1974*]. The little information available to describe bottom currents constrains the use of models of oceanic circulation. Those current models exist for surface currents, but have limited resolution in deep waters due to the scarce deep measurements. Global circulation model to predict ENSO variability [*Giese, 2002*], plotting meridional velocity (over time) of the high variability of bottom currents, and neither are uni-directional nor continuous (Figure 41). This leaves the physical properties observed by *Lonsdale* [1976] as the most important clues used to track currents on the seafloor (Figure 42).

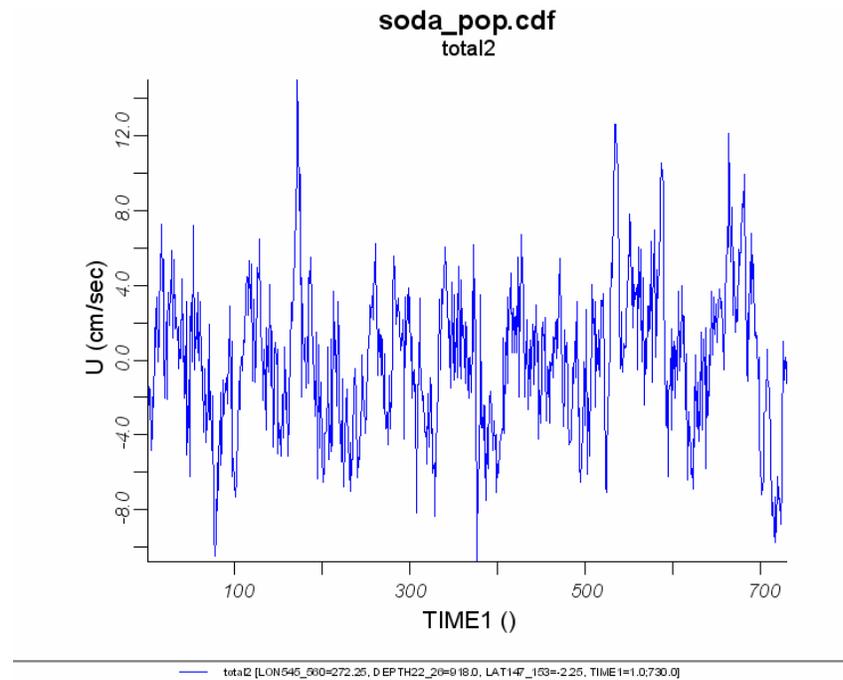


Figure 41. Meridional velocity variations. A meridional bottom velocity model for the decade 1980-1990 (Geise, 2002) shows us that currents are neither unidirectional nor continuous.

Detailed bathymetry helps to identify the current tendency, scouring effects, strip lateral valleys, and longitudinal valleys, which can be analyzed in the general area to predict bottom water flow (Figure 43). Likewise, published profiles analyzed by *Malfait* [1974] and *Lonsdale* [1977a] were used to observe how currents are able to produce nonconformities and redistribute sediments to the north area of Panama Basin. Seamounts and seamount chains on the south side of the ridge (along with the ridge itself) function as a natural barrier which interacts with the bottom-water circulation, creating specific effects in the sedimentation.

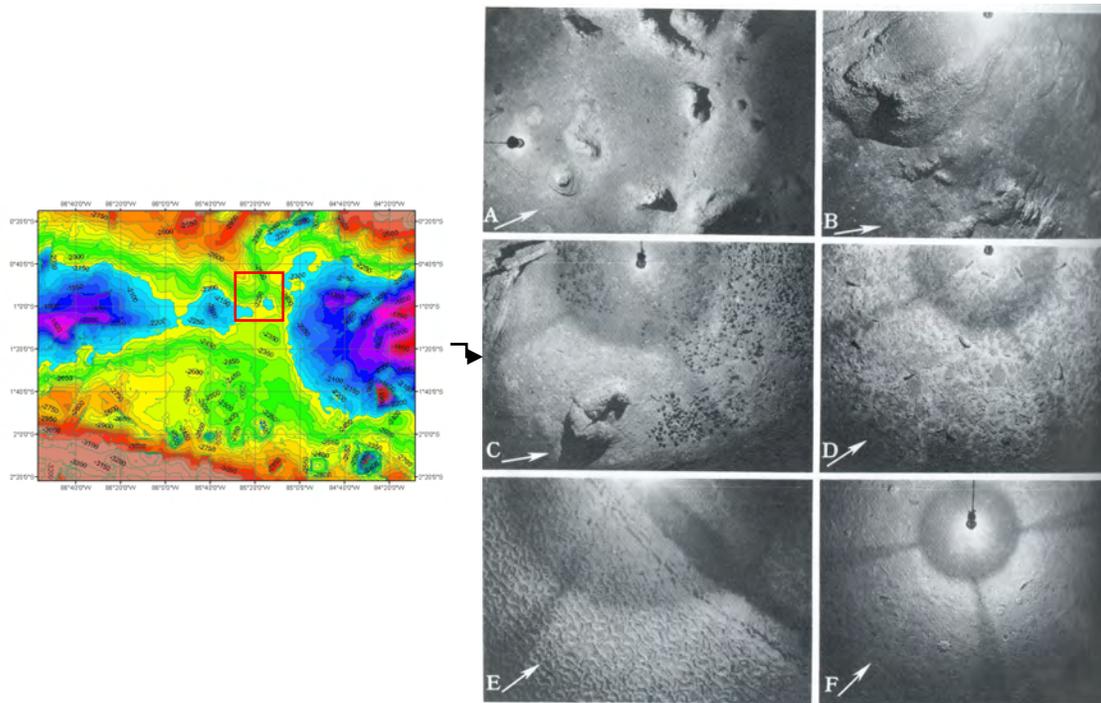


Figure 42. Erosionally exposed rocks on the central saddle area (arrows show the northern direction). Seafloor pictures courtesy of Malfait and Van Andel (1980), reprinted by permission of Blackwell Publishing Ltd.

These sediment bedforms show that bottom currents are active. Their flow can produce erosion and decelerate the rate of sediment deposition [Roden, 1987]. The erosion on top of the southern Galapagos Plateau, the lack of sediments on the slope [Johnson *et al.*, 1976], and the scoured flow channels south of the central saddle area are all physical evidence of this decelerated rate of sediment deposition.

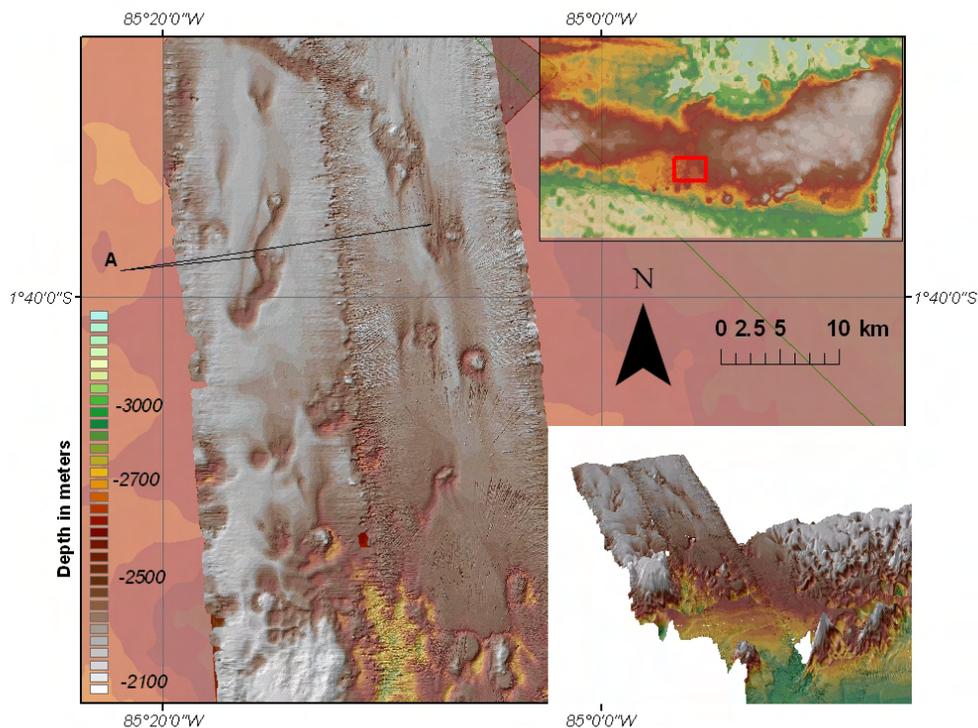


Figure 43. North-south directions of the valleys in the southern flank of the Carnegie Ridge. This area is disrupted by north-south valleys up to 1.5 km wide, 11.5 km long, and 300 m high, that in some cases have been identified (A) as a product of irregular basement, making it difficult to establish the influence of current effects as the only cause for their formation.

Deposition types

The geographic location establishes differences between deposition types. For example, on the east ridge, clastics and terrigenous sediments are the most important inputs [Lyle, 1992; Van Andel, 1973; Lonsdale, 1978]. These siliciclastic sediments, which dilute CaCO_3 concentrations (Figure 44), are influenced by the organic content [Riken, 1993]. The basic siliciclastic type of deposition is recognizable by its distinctive organic carbon and carbonate relationship (Figure 45). The linear relationship is interpolated from the CaCO_3 relationships to determine basic types of deposition. The west ridge and saddle area reflect a small supply of inorganic sediments, mostly in an area above the lysocline with high carbonate content.

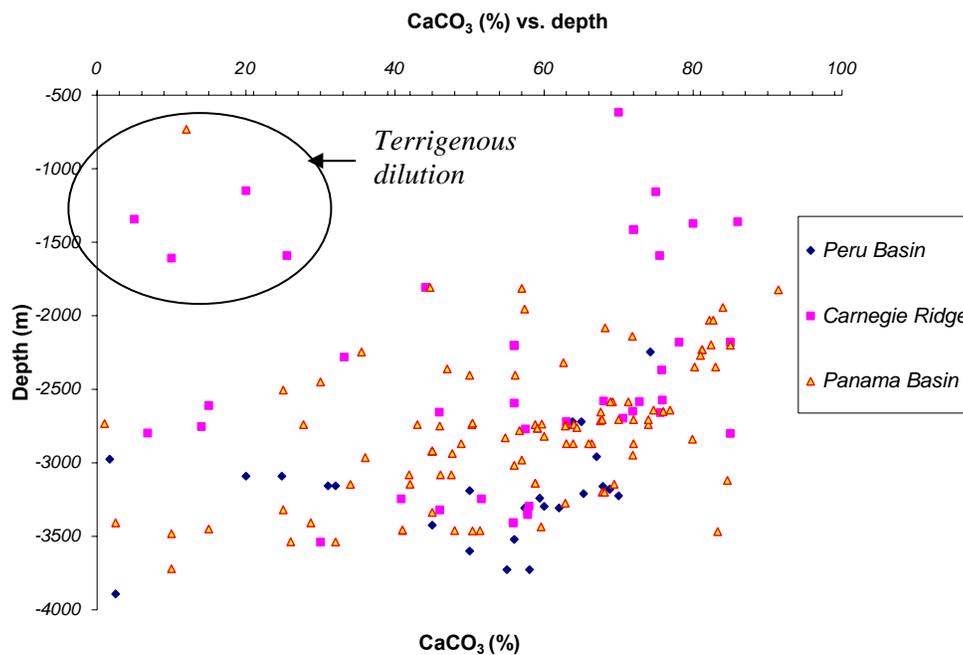


Figure 44. Carbonate content (%) vs. depth for the Panama Basin, Peru Basin, and Carnegie Ridge. The dissolution in Panama Basin is shallower than Peru Basin. The ellipse shows low carbonate content values affected by siliciclastic sediments which dilute CaCO₃.

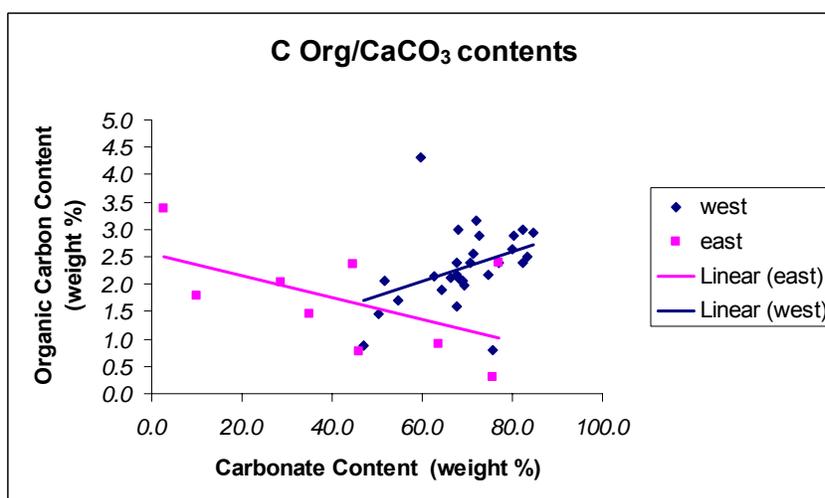


Figure 45. Scatter diagram showing an inverse correlation between carbonate and organic carbon values in the west ridge. This trend is found in carbonate deposition. The blue dots are showing a direct correlation between carbonate and organic carbon, indicating siliciclastic deposition in the east ridge.

The area surrounding the Galapagos Islands is also an important input of non-carbonate sediment. However, the decrease in organic carbon (compared to more pronounced changes in concentration of CaCO_3) has influenced the carbonate deposition environment of the west ridge. As a result, the pelagic sediments are more important to the west ridge. The general distribution of sedimentation rates in recent sedimentation is important when identifying the total area influenced by high deposition. The areas with more sediment are influenced by lateral transport, such as the north side of the central saddle area, and the southern part of the west ridge (Figure 46).

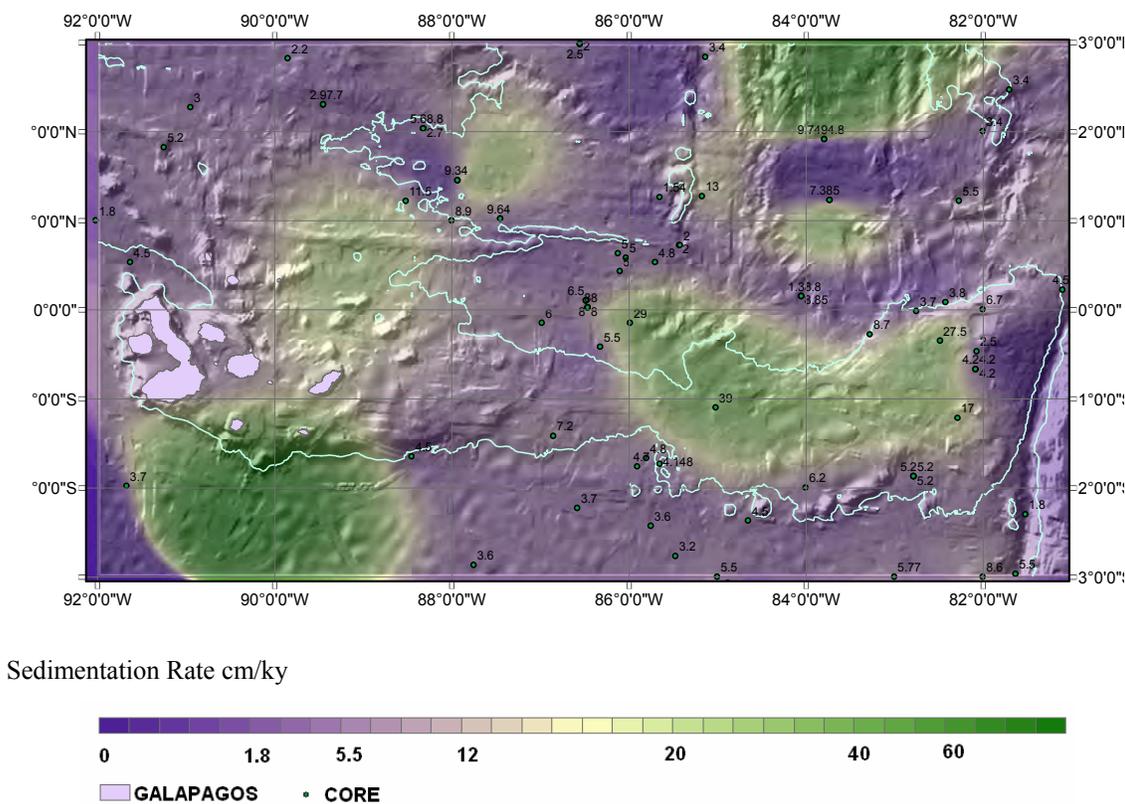


Figure 46. Distribution of sedimentation rate in the Carnegie Ridge using the upper core values.

Finally, general sedimentation rate has been evaluated in order to find any relationships which exist between the environmental areas of deposition (Figure 47). The minor correlation between cores located in the Panama Basin shows that the area is dominated by siliciclastic

deposition. The Carnegie Ridge and Peru Basin show little correlation, due to the fact that some cores are located close to the mainland. Sediment rate distribution increases in areas close to calcareous deposits, but the carbonate content decreases when the core is close to the mainland.

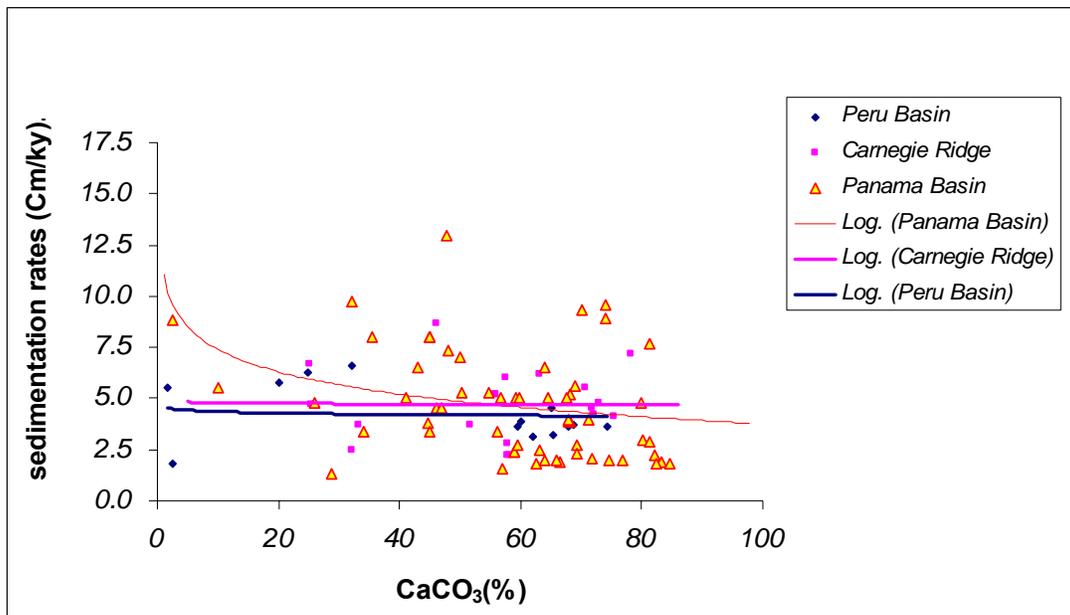


Figure 47. Trend curves for the relationship between sedimentation rate and carbonate content. High carbonate contents illustrate the trend toward a carbonate deposition at the Peru Basin. Panama Basin shows the canonical relationship for siliciclastic deposition [Ricken, 1993].

CHAPTER VIII

SEDIMENT DISTRIBUTION

Sediment distribution is classified as a function of source and formation. The source of the minerals used to create skeletons is mainly given by pelagic settling in the oceans. There is a high biogenic content in the sediments along the ridge. It is posited that all deposition is not preserved in the burial content. The diagenesis processes modify the amount of sediment which is deposited on the seafloor, and as a result, this distribution is not an accurate reflection of the high productivity at the surface. Thus, it is not appropriate to relate opal carbonate-free distribution (Figure 22) to the primary distribution of high productivity, because it is limited by the reduction of carbonate content, which modifies its general distribution [Archer, 1993]. The dilution caused by siliciclastic input from the mainland at the east ridge is more important than carbonate sediments from surface productivity, and even more important on the northeast side of the ridge [Heath *et al.*, 1974]. Carbonate deposits differ significantly in their concentration with depth. The subsidence of the ridge produced by lithospheric cooling [e.g, Parsons and Sclatter, 1977], are important to the variation of the depositional environments of the west ridge. The west ridge is still inside the influenced GHS area (350 Km [Sallares and Chavis, 2003]), and tectonic subsidence by thermal effect is affected by the GHS. Based on the interpretation of volcanic rock samples collected along Carnegie Ridge, Werner and Hoernle [2003] described drowned islands and classified the adjacent seabed as guyot-shaped seamounts, perhaps based upon paleo-beach or intertidal wave-cut platform deposits on the east and west ridge. The structure and texture of volcanic rocks implies that the ridge was changed by environmental deposition from shallower to deeper areas. This factor had modified the original deposits. Michaud *et al.*, [2004] predict an original depth of the middle saddle area of 1400-1500 m. base on crustal age and subsidence rate of 1000 m per 10 Ma [Parsons and Sclatter, 1977]. Depressions were observed on the flanks and on the east ridge (Appendix 3.5). Indeed, these structures reflect that the pattern of sedimentation in the Carnegie Ridge has not been static over geologic time.

The sediment sequences range in age from Holocene to ~3 Ma at DSDP site (157, Leg 16) [Van Andel, 1973], Miocene to ~11Ma at ODP (Site 1238, Leg 202), and Miocene to ~ 15 Ma at Site 1239 (ODP Leg 202) [Mix *et al.*, 2002]. The general distribution of sediments is modified by pre-existing morphology (bare sediments on the hilltops and drape sediments on the flat terraces). Sediment variations only appear as an offset in seafloor depth on seismic profiles [Van Andel *et*

al., 1971]. There is a fault block following an east-west trend, and as a result, the down-faulted flanks draped by sediment describe a chaotic seabed (undulations and deformations) [*Michaud et al.*, 2004; *Lyle et al.*, 2000a]. The faults have formed different structures where sediment is deposited. As a result, there are sediment creeping and depressions above faults, and flat terraces above adjacent basins that have evolved over 20 million years (which is the oldest age of the underlying east ridge crust). The sediment sequences located in the flat terraces bounded by fault blocks are continuous. During their formation, different erosions and distinct sediment distributions have occurred. Older sediment deposited at the bottom of the sequence has changed its composition due to the back track of the Nazca Plate movement, and is observed in the bottom of the ODP Site 1238 and Site 1239 east ridge sediment sequences. Data collected by *Mix et al.* (2003,144,147) allows to conclude that higher carbonate content, and lower organic carbon is found in the deepest parts of the cores, trending toward lower carbonate content and higher organic content to the upper parts of the cores. These trends can be a result of deposition in a shallower and more pelagic environment millions of years ago.

Samples from seamounts and fault scarps show an increase in basement age far away from the Galapagos Islands [*Christie et al.*, 1992], based on TiO_2 from lava composition. This rock alteration is an evidence of the GSC's decreasing influence on the Galapagos volcanism produced from GHS, and the greater length of time exposed to sedimentation in the east than the west side of the ridge is given by the basement age.

The acoustic sections in the ODP sites 1238 and 1239, and in seismic profiles from Ventura cruise, Melville Nemo3 cruise, and Sisteur Geoazur, contain closely spaced reflectors, which are related to high concentrations of calcareous deposits produced in the upper waters by an increase of production in the productivity zone [*Lyle et al.*, 2000a and 200b; *Mix et al.*, 2003].

In general, the sediments along the ridge show very stable conditions in the areas that are supported by the continuous latitudinal location of Carnegie Ridge [*Van Andel et al.*, 1973], and the general influence of the surface currents. However, the east ridge shows greater modification, caused by its proximity to the mainland and subduction systems.

The sediment distribution was also related to the grids of carbonate content, opal, and organic carbon to designate distinct regions. The assemblage of sediments from different skeletons of pre-existing organisms differs from place to place and reflects the influence of water masses flowing over the ridge.

Sediment distribution variations were inferred in the hill and slope to determine deposition

differences between different areas by using the Bulk mass accumulation rate distribution (Figure 48). Higher values were found where the non-carbonate sediment input is important and carbonate sediment deposits are influenced by high pelagic settling. This area is the southeast ridge.

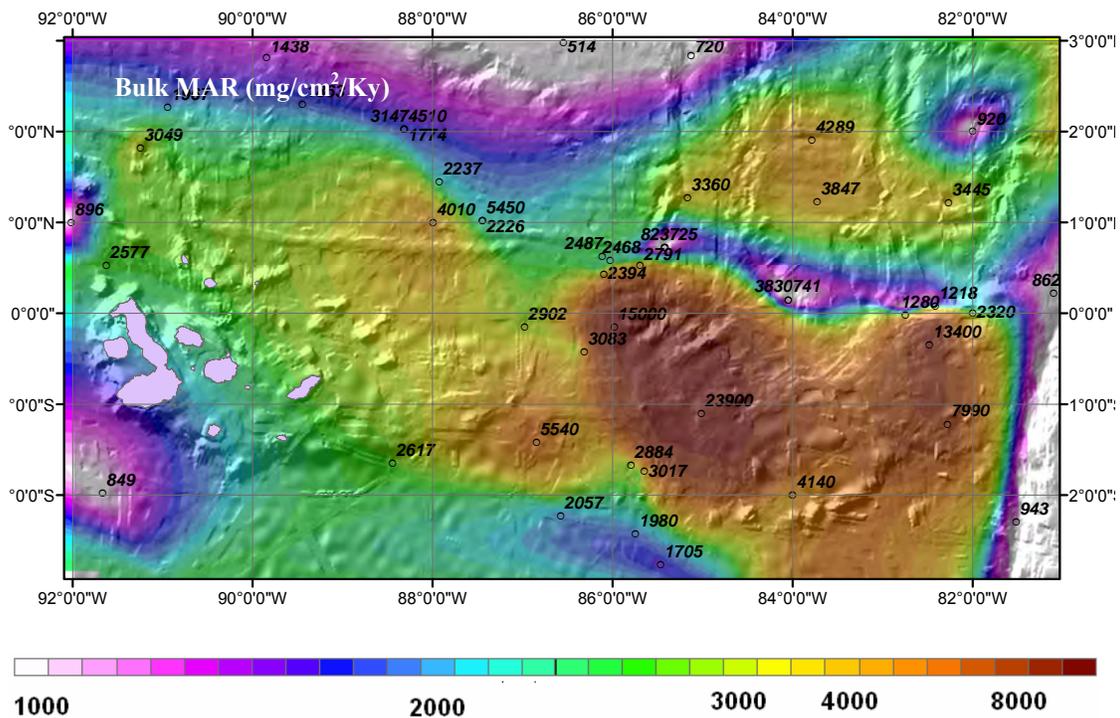


Figure 48. Distribution of bulk MAR.

More moderate values can be found along the saddle area. There is no good correlation between surface water productivity and high values of bulk mass accumulation rate (MAR) at the west ridge. The west ridge has low input from surface waters, and the east ridge and saddle area have a high input of pelagic sediments. The lack of cores around the Galapagos Islands forces the investigator to generalize the area with the trends at ODP Site 846, and hide the real values existent around the west of the Galapagos Islands. The variations on the north side of the east ridge occur by dissolution due to corrosive water that is enhanced by high organic carbon content

and multiplied by bottom water inflow. Deviations in the bulk MAR from the surface water have been identified by *Swift* [1976a] by their calcite accumulation patterns, suggesting a lateral and vertical change in dissolution. Variations in the sediment sequence are produced by post-depositional disturbances, such as local winnowing, erosion on topographic highs, the subsequent down-slope sediment transport [*Swift*, 1976b], and transport by bottom water flow. Dilution by changes in water chemistry and productivity variations are general factors which modify the original deposition. Based on these general factors, the spatial variability of sediment deposition varies by location on Carnegie Ridge.

Western area

On the west ridge, the hill sediment environment is affected by the equatorial undercurrent and the high volcanic input. This area provides the most important contribution to the sedimentary deposition of CaCO_3 .

Different depositional conditions are observed as a result of local bottom currents (the south side at the central saddle up 20 cm/sec [*Lonsdale*, 1977a; *Malfait and Van Andel*, 1980]). The pattern resulting from the flow-bathymetry interaction is important because the topography and the east-west shape form a natural barrier which produces an area of non-deposition, as evident in the strongly varying sediment thickness [*Johnson et al.*, 1976].

Different depositional conditions are observed as a result of local bottom currents (on the south side of the central saddle, speeds are measured up 20 cm/sec [*Lonsdale*, 1977a; *Malfait and Van Andel*, 1980]). The pattern resulting from the flow-bathymetry interaction is important because the topography and the east-west shape form a natural barrier which produces an area of non-deposition, as evident in the strongly varying sediment thickness [*Johnson et al.*, 1976].

The western ridge and Galapagos Volcanic Platform itself are characterized locally by eroded volcanic debris sediments, and sediments from the islands. The surrounding seafloor in the Panama Basin is composed of pelagic sediments independent of topography [*Pisias et al.*, 2000]. Pelagic drape is observed in seismic and chirp data from *Pisias et al.* [2000], and there are traces of continuous seismic horizons for the entire area.

Using a seismic section from Venture cruise [*Pisias et al.*, 2000], I identified sedimentary layer sequences varying between 0.1 seconds two way travel time (twt) and 0.3 seconds twt of thickness. The thickness of the sedimentary layer was determined along most of the line, including areas on the hill (Figure 49).

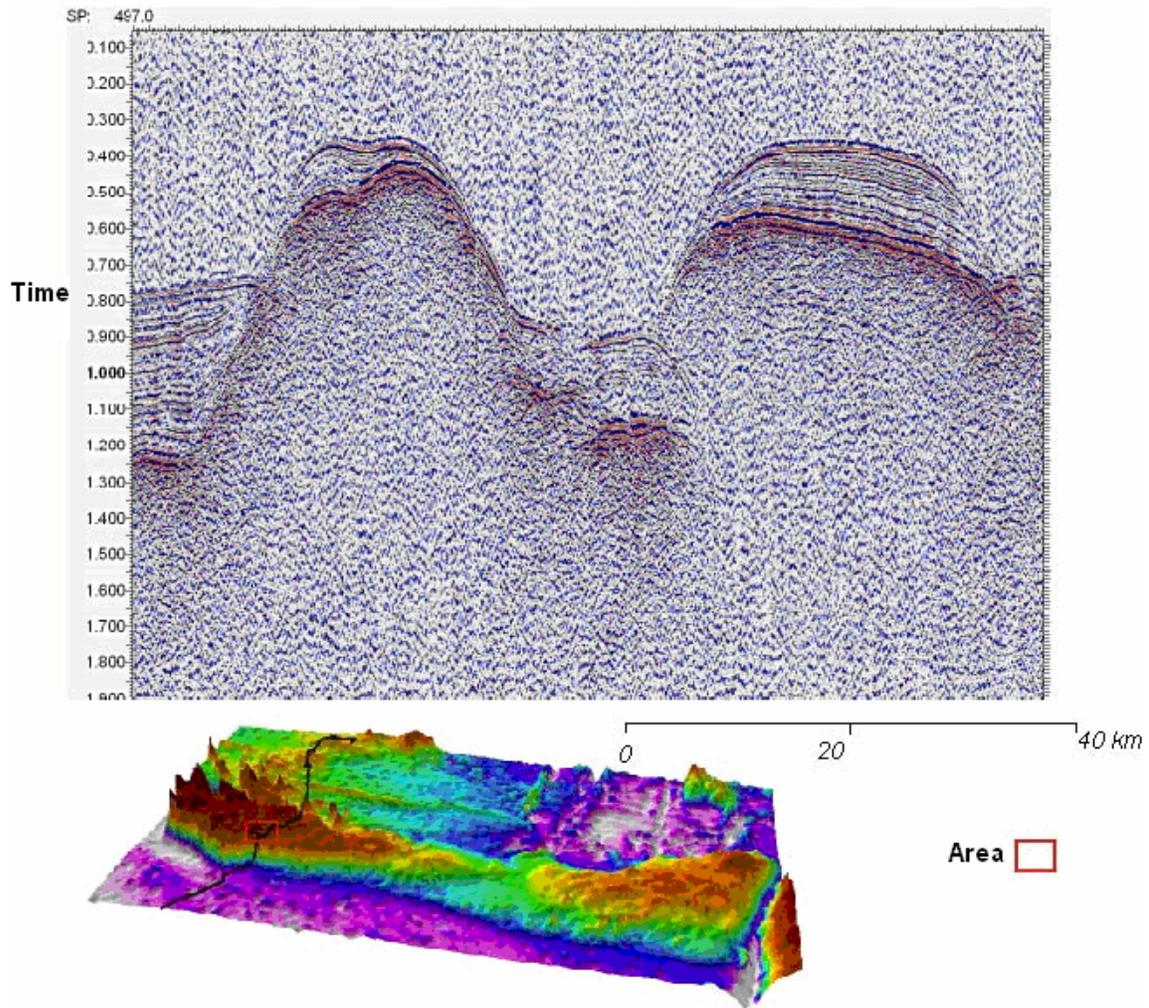


Figure 49. Seismic profile west ridge (Dataset Ventura Leg 3 Scripps Institution of Oceanography). The seafloor is identified by a blue line. The pinnacle of the Galapagos Volcanic Platform has a thin (100 m) overlay of sediment and an irregular basement.

Saddle central area

The saddle area is delimited to the north by the Panama Basin at 2700 meters, and to the south by the Peru Basin at 2800 meters (Figure 50). A seamount chain rising to 1633 meters (85.66458W, 1.0269 S) sits along the southern boundary. The slope on the west side is greater than on the east side. The sill on the west side is 30 kilometers wide, allowing an inflow of water from Peru Basin to Panama Basin. This flow pattern leads to sediment erosion in the Panama

Basin, surrounding the mouth of the sill. The area is relatively flat, with a slope of 2.5° in the east-west direction. Erosion is observed at the acoustic basement on the top of the ridge.

The crust age varies in the basement. The north side, bordering Panama Basin, is younger than the sediments deposited on the south side, bordering Peru Basin. According to the magnetic anomalies, the southern end of Panama Basin is 8.9 Ma and the Peru Basin is 15.52 Ma. The saddle's age is between 10 and 13 Ma [Meschede and Barckhausen, 2001]. In the saddle area, carbonate sediments are affected by sediment transport. This transport is characterized by different denudation processes [Malfait, 1974] observed in the multibeam bathymetry as scouring effects.

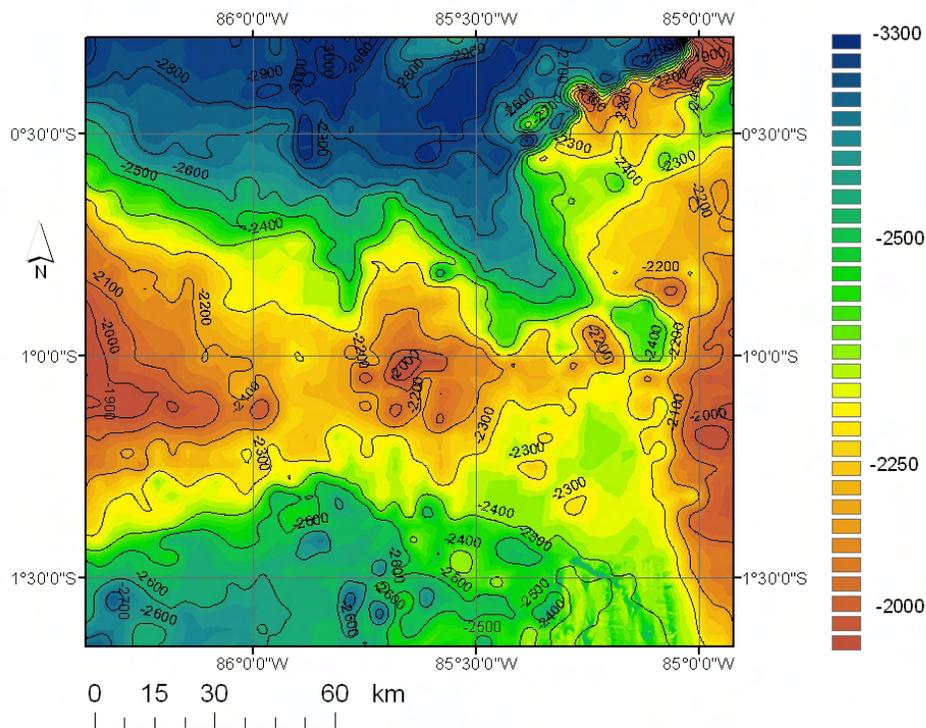


Figure 50. Central saddle area bathymetry.

Eastern area

On the east ridge, the hilltop sediment environment is affected by the Pacific Central Water Current, which causes the oxygen minimum zone to deepen to 1500-2000 m., and causes the mid-depth dissolution to become corrosive, affecting sediments [*Michaud et al.*, 2004]. The terrigenous inputs are important: the finest sediment is located in the adjacent Panama Basin, and thickest sediment on the hilltops.

On the easternmost part of the Carnegie Ridge, sediment deposition to the trench has a wide lateral variation in structural and sedimentary character. These variations can be geographically subdivided into three main groups, based on the source of sediments and tectonic activity [*Collyot et al.*, 2002]. First is the north area (located between 1N and 3N), which features abundant sediment from Esmeraldas River and Magdalena River, located on the western boundary of the mainland. These rivers bring sediments from the Andes Mountains to the Colombia Trench, characterizing the zone with a moderate to high terrigenous input of sediments. The second area (between 1N and 2.5S), where the Carnegie Ridge is located, is defined as a very critical area (where the ridge goes into subduction). It is populated with pelagic sediments formed by siliceous and carbonate oozes from the east ridge going down into the trench. These sediments are located on higher slopes which are more susceptible to failure; however, the amount of sediments is too thin (100 m) to get slumps and continuous slides. The third area (2.5S to 3.5S) is composed by the miocene sedimentary basin of the Gulf of Guayaquil.

The area of the ridge-trench junction is defined by tensional fault-induced structure related to the down-bending of the lithosphere parallel to the Ecuador trench. The slope is unstable, because rotational slumps deform the sediment [*Collyot et al.*, 2000]. This area is composed of calcareous, biogenic siliceous, and siliciclastic sediments. The shallow ridge-trench axis controls the distribution of sediments by its interaction with thermohaline circulation [*Lonsdale*, 1978]. The sill depth (maximum depth at which direct flow occurs) acts as a partial barrier for the northward Panama Basin inflow current [*Lonsdale*, 1977a]. In the north area of the ridge-trench junction, recent sediment is absent, and Pleistocene calcareous oozes from Carnegie are exposed, as was indicated in previous core studies by *Lonsdale* [1978].

The thickness of sediments covering the area located at the northeastern wedge in the shallower zone is thinner than the rest of the east ridge. They were recently formed as a product of the outer rise formation [*Lonsdale*, 1978], caused by the flexing of an elastic lithosphere. This feature modified the regional sediment distribution of the area, and the bare peaks in this area

were possibly formed by recent eruptions along tensional fractures [Lonsdale, 1978]. The tectonics of the region closest to the subduction zone, and the possibly enhanced current activity at shallower depths, are directly important local factors controlling the distribution of sediments near the volcanic peaks of the east ridge.

Lonsdale [1978] found no evidence of an accretionary prism. However, a recent study showed that accretionary prisms could be found in areas where the sediment is being subducted [Collyot *et al.*, 2002]. The Ecuador Trench is shallow in the vicinity of the Carnegie Ridge, enabling the movement of materials eroded from the highest parts of the ridge to move downslope to the north, toward Panama Basin. Deep currents travel at a speed of 33 cm/s [Lonsdale, 1976], and the high slope angle adds to the erosional environment. On the southwestern flank, the stratigraphy of the sediment sequence is evident and the flat blankets are affected in small areas by migrated sections (Figure 51) as a result of the bottom water flow.

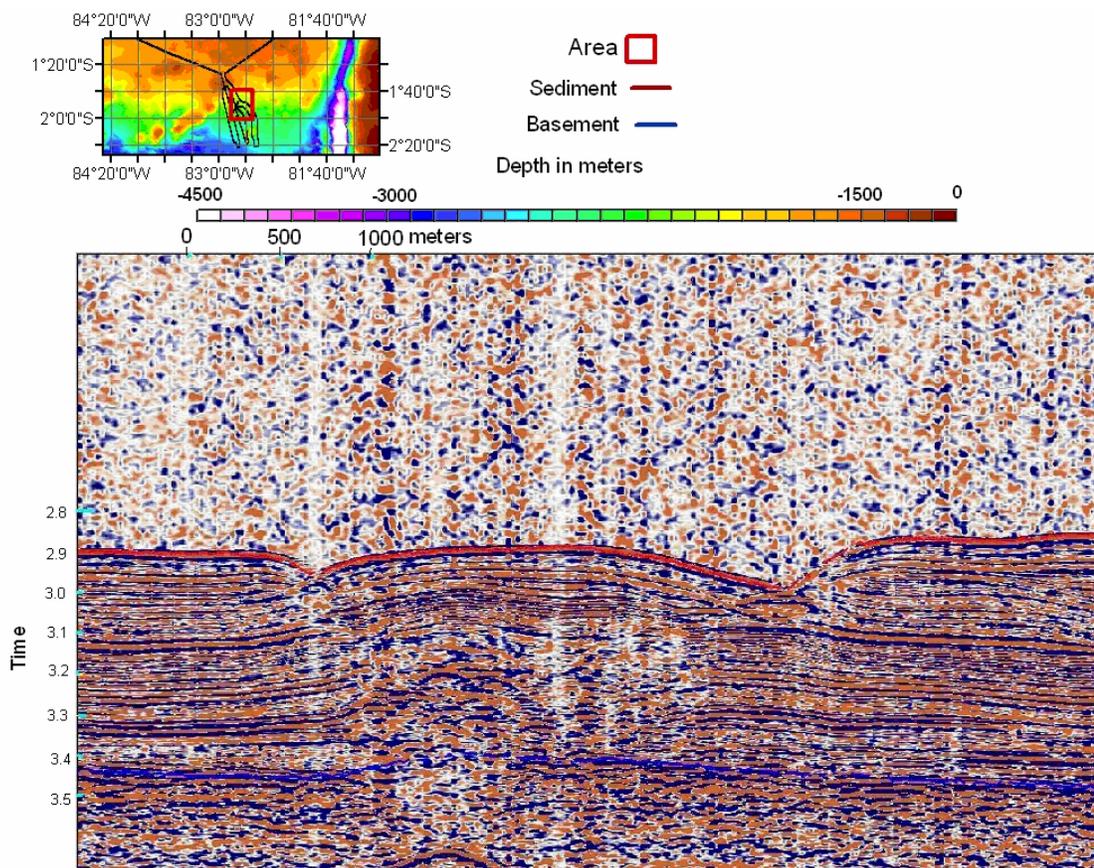


Figure 51. Migrated sections on the southeastern flank of the east ridge. Erosion produced by bottom water flow can be identified as the origin of those formations in the sediment sequence.

Depositional sedimentary environment

The depositional sedimentary environment is used to determine under what biological, chemical, oceanographic and bathymetric conditions material was deposited. Combined, these factors show a predominate pelagic (carbonate) content in the sediments deposited along the west ridge and saddle area, while the carbonate, biogenic silicious and siliciclastic sediments are more important in the northeast ridge and the adjacent abyssal plain. The depositional environment, based on the almost continuous sediment sequence is categorized by number of different factors, such as productivity along the ridge, steepness of slope, and the location of the lysocline and CCD (Figure 52).

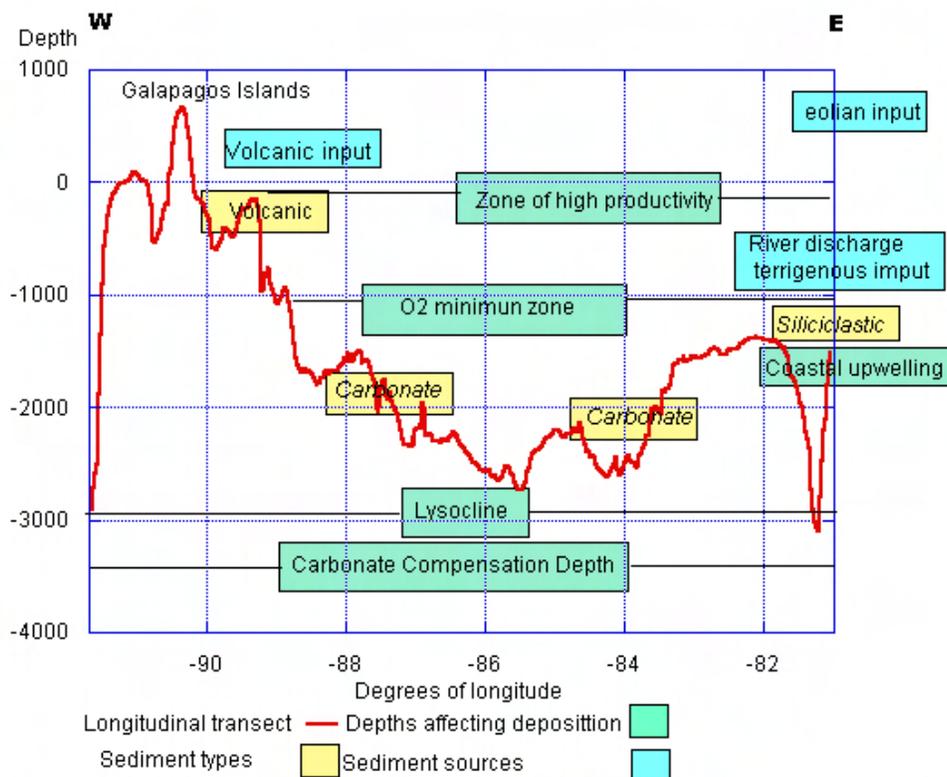


Figure 52. Sources distribution on Carnegie Ridge. Sediment source types are represented in a longitudinal transect from the Ecuador Trench to the Galapagos Volcanic Platform.

The association between sediment composition grid distribution, sediment thickness, and bathymetry has been used to define the depositional environment in terms of characteristics that reproduce the geometry, location, and energy of the depositional area. Carnegie Ridge is located in an area of moderate to rapidly accumulating pelagic sediments. The increase in sedimentation rate and decrease of organic carbon creates depositional environments formed by facies types, mainly identified as cherts, chalks, or ooze units. These facies types are aimed at the formation of distinct depositional products, based on intensity and duration [Reinek and Singh, 1980] such as the fine sediment on the slope of the saddle area's north flank, and the coarse material at the hilltops. The environment where sediment is deposited is affected by the geotectonic structural character. The tectonically active zone is influenced by the Galapagos Spreading Center hotspot interactions, the subduction of the east ridge that modifies the sediment cover, and the bottom oceanographic conditions and climatic processes in the area.

The location of the high productivity zone is important because it is based on the upwelling strength, which creates inter-regional and seasonal factors that influence the depositional processes.

Most of the physical factors in the saddle area and in the ridge-trench junction that are considered most important are driven by the bottom current. The non-conformities in the sedimentary structure [Lonsdale, 1976], size distribution patterns [Malfait, 1974], and bottom current deposits create surfaces of erosion with local re-deposition.

The sedimentary environments examined in this study are represented by ridge hill tops, areas of smooth seafloor (flat terraces), channels in the saddle area [Van Andel and Malfait, 1980] and lateral slope (steep scarp), and the abyssal plain surrounding the ridge. The central saddle area is part of the ridge hill. The specific environments are characterized by their physical conditions and depositional processes. Table 3 classifies the depositional processes locally influencing several parts of the ridge. The differences between these environments are based on susceptibility to erosion (related to the bottom water flow) and dissolution in the middle slopes.

Table 3. Brief definitions of the depositional processes in the Carnegie Ridge area, and estimation of general physical properties such as bottom velocity and sedimentation rate.

Depositional processes	Transport and sediment support mechanics	Slope	Sedimentation Rate	Bottom Water Velocity
Non-depositional	Sediment accumulates on hollows, gentle slope	Steep	Low	15 cm/s [<i>Van Andel and Malfait, 1980</i>]
Normal Canyon Current	Flows down slopes, canyons, and channels	Moderate	Low	33.2 cm/s [<i>Lonsdale, 1976</i>]
Bottom Currents	Deep slow flow driven by thermohaline circulation	Gentle slope	Medium	33.2 cm/s [<i>Lonsdale, 1976</i>]
Deep surface Currents	Intermediate slow flows of North Pacific Intermediate Water	Gentle slope	Medium	15-20 cm/sec [<i>Van Andel et al., 1971</i>]
Pelagic Settling	Vertical settling of grains through water column	Flat terraces	High	0.002-0.005 cm/s settling rate [<i>Stow, 1986</i>]

CHAPTER IX

DISCUSSION

Carnegie ridge has been examined in regional studies of sedimentation of the Eastern Equatorial Pacific, and also as part of the Panama Basin. These works have clarified the nature of the ridge faulting [Van Andel *et al.*, 1971], and the assumption of latitudinal transport at the regional scale [Lyle, 1992]. This study examines the relationships between sediment distribution and morphology, sediment thickness and sediment composition. Depositional processes vary along and across the ridge by the boundary faults and pre-existing morphology. The processes of formation and the composition of sediments are important to explain the sediment distribution on this accreted ridge, formed as a hot spot tracer. The Carnegie Ridge is in an area of high productivity since their formation, and shows a latitudinal pattern of sedimentation. This is primarily caused by the convergence of south equatorial currents and their equatorial divergence.

Sediments have high pelagic content in the high production areas (250-500 and >500 mg of carbon $\text{m}^{-2} \text{day}^{-1}$) of the upper ocean [Lisitzin, 1996]. The deep sea sediments on the Carnegie Ridge are controlled by the upwelling intensity, which increases the density of nutrients, and the input of pelagic sediments. Over the Carnegie Ridge, these variations are controlled by the strength of the trade winds [Loubere *et al.*, 2004], and by the lateral changes of advection of cold water from the Peru Current through the South Equatorial Current. Lyle [1992] and Mix [1999] reviewed the changing in upwelling based on this advection of colder waters.

Climatic conditions control the biochemical activity and affect the accumulation of calcium carbonate and silica particles in the Eastern Equatorial Pacific. Loubere [1999] and Lyle [1988] had discussed the importance of changes in CaCO_3 accumulation due to the variation of productivity in surface waters provoked by upwelling changes. Conversely, Berger [1973] proposed that dissolution provoke changes in the CaCO_3 . Dissolution in the area can be originated by the variation in deep water corrosiveness [Farrell and Prell, 1989] or by changes in the supply of organic carbon [Archer, 1991]. Based on bare sediments primarily on the east ridge and saddle area and drape sediment primarily on the west ridge on the hilltops, circular depressions on flanks and sediment composition the west ridge have major interconnectivity with the increase in productivity of surface water. This area is affected by the South Equatorial Current and the Equatorial Undercurrent. The north and south flanks of the east ridge are more affected by the inflow of bottom water, and are therefore more susceptible to dilution due to

increases in deep water corrosiveness (Appendix 3.5). The east ridge also has a higher supply of organic carbon.

The dispersal mechanisms related to the relief of the seafloor are also directly influenced by the northward Pacific Bottom Water at the south flank and the adjacent basin; in turn, hilltops are affected by the intermediate current (Pacific Central Water). These processes determine the character of the sediment deposited. However, there is no persistence of carbonate sediment (variability 17 to 94 weight percent) for the length of core (Sites 1238 and 1239) on the east ridge, suggesting that sediments are not related to the effects of deep currents on summit terraces.

Thickness and compositional distribution

The sediment accumulation and thickness are greatest at the outer flanks of the Carnegie Ridge, and in terraces between fault blocks. Exceptions are present at parts of the south flank affected by bottom water flow (non-deposition areas and development of embayment). The northern border of the ridge has a large blanket of sediment on its top, and there the basement is rough and sediment accumulation is high. The sediment is composed of hemipelagic particles near the northeast corner of the ridge [Heath *et al.*, 1974], as opposed to the mainly pelagic composition on the west (excluding the Galapagos Volcanic Platform, where the input of dust and volcanic glass material can modify sediment composition).

The grid on sediment thickness was constrained by the NGDC dataset and restricted to areas where seismic profiles exist. The scarce distribution of seismic profiles limits resolution. Sediment distribution is not completely correlated to negative gravity anomalies, making it more difficult to identify sediment thickness using homogeneous areas below a specific gravity contour. Seismic profiles show that the basement hill remains exposed to fluid exchange for a much longer time than the flanks and abyssal plains surrounding the ridge. This fluid change is within the range of North Pacific Intermediate water current and remains of the Antarctic Intermediate water current [Mix *et al.*, 2002]. Thus, the sediment composition can vary, based on the hydro chemical conditions of the water column that the ridge is exposed to.

Terrigenous input occurs close to the coast and to the Galapagos Volcanic Platform. Significant variations in concentration exist between the east ridge and the central saddle area: carbonate can vary up to 40%, and opal can vary by as much as 30%. These variations are caused by dilution of carbonate sediments by terrigenous input. For instance, the carbonate distribution map shows that the highest the percentage of CaCO_3 occurs on hills and on the west ridge. In

these areas, natural conditions for accumulation are affected by the pre-existing morphology (Appendix 3.1), and by active bottom water flow (Appendix 3.2). *Lyle* [2003] determines that most of variability on the Eastern Equatorial Pacific is due to CaCO₃ production than to dissolution using spatially coherent patterns of CaCO₃ deposition. These can be explained by the percent of variance in the dataset and their relationship to a dominated signal (production).

Process and environmental control on sedimentation history

In this accreted ridge affected by dissolution and productivity the pelagic setting that controls the sedimentation is located in different environments such as flanks, summit terraces, hill tops and adjacent basins. These environments are interactive, and sedimentation is highly depending on the land and volcanic influences. The main controls in those environments are: Tectonic, Bathymetric, bottom water flow at deep (Pacific Deep Water) and intermediate water circulation (Pacific Central Water), and underwater dissolution [*Van Andel et al.*, 1971; *Lonsdale*, 1976; *Mix et al.*, 2003].

Tectonic control

Basement relief is important to the sediment accumulation. In this area, sedimentation occurs over a volcanic basement. The relief of the seafloor determines the character of the sediments deposited and their post-depositional deformation. The crust where sediment has been deposited is affected by thermal subsidence: the east ridge formed of one magmatic episode related to the location of GHS below the Nazca Plate [*Christie et al.*, 1992; *Werner and Hoernle*, 2003; *Michaud et al.*, 2004; *Sallares and Chavis*, 2003] is local isostatically compensated. The uplift is present on the west ridge affected by the hotspot influence area (350 km around its actual location) (*Sallares and Chavis*, 2003). The east ridge at its eastern end is affected by the formation of the outer rise (in the work of *Lonsdale* [1978] was shown an outer rise to be deposited 300 m shallower than would be expected). The saddle area also affected by thermal subsidence is related to the location of GHS below the Cocos Plate [*Sallares and Chavis*, 2003]. These combined factors are modifiers of the sedimentation processes because change the depositional environment. Adjustments are identified as local deformations observed mainly in discontinuous surfaces of the depositional sequence such as non-conformities in the sediment sequence [*Lonsdale*, 1976] and offsets produced by the fault blocks [*Van Andel et al.*, 1973].

The bare sediments on the hilltops in the east ridge have been associated to subaerial erosion

related to the east ridge subsidence [*Michaud et al.*, 2004]; the greatest sediment thicknesses were found in flat terrace areas with minimal tectonics variations. Hills are bounded by scarps produced by normal faulting [*Van Andel et al.*, 1971]. High sediment thicknesses exist in the basement lows, while lower thicknesses are found in the basement highs. This is observed directly from single reflection profiling and seismic channels.

Bathymetric control

The Carnegie ridge, due to its natural elongate shape, is a natural barrier for bottom water moving northwards. This natural morphologic feature is an important point [Lonsdale, 1976] in the bathymetric control of the sediment distribution. Areas of non-deposition and re-deposition are related to the relief at the south flank and in the sill areas. The shallow waters in this region are close to 1000 meters in the east ridge hilltops and up to 1000 meters in the west ridge seamounts. It is inferred that the saddle area now at 2300 m has been underwater during the whole ridge formation, as suggested from previous aseismic ridges studies that the ridge subsidence to 1000 m within 10 m.y. after formation [*Detrick et al.*, 1977; *Michaud et al.*, 2004].

Sediments associated with topographic variations are located in the southern ridge-trench junction, below the CCD, and in the southeast ridge showing vertical zonality because the depth in this area affects the type and amount of pelagic sediment [Lonsdale, 1978]. Likewise, the lateral distribution of fine material eroded from the crest of the ridge and relocated downslope close to the source are function of the general relief. The intrusion of bottom-water flow through the central sill and the Ecuador Trench plays an important part in the reorganization of sediments. Channels formed from pre-existing morphology are used to modify the original deposition environment. These were identified as local factors controlling the sediment deposition [Lonsdale, 1978].

Dispersal paths of sediments, identified from the concentration of grain size modes in silt fraction [*Van Andel*, 1973a], were used to explain the location of coarse sand and silt on the hills due to winnowing. The high content of sediment in suspension on the north flank, shown by the high light scattering values near the bottom [*Plank et al.*, 1973], confirms a lateral sediment flux. The presence of dunes composed of quaternary foraminiferal sand is also physical evidence of active transport. Depositional environments are different based on the depth: Hilltops and summit terraces are affected by Pacific Central Water and North Intermediate Pacific Water, which affects the shallowest areas in the east and west ridge. Flanks and adjacent abyssal are affected

by Pacific Deep Water

Bottom water circulation

The dominant deep current flows northward [Lonsdale, 1977a] and the inflow into Panama Basin occurs at the central saddle and Ecuador trench. Likewise, bottom water flow on sedimentation is observed on the west ridge, with non-deposition or sediment transport [Jhonson *et al.*, 1976; Feighner and Richards, 1994]. This is due to the advected flow around the ridge to the west. The south flank at the saddle central area shows scouring effects, evidence of erosion produced by a bottom water flow. Erosion related to active currents results in the scouring of basement structures, and bottom water deflection (Appendix 3.3).

Sediment transport is directly related to the location of the areas of erosion and accumulation. Sediment transport is mainly produced by deep bottom currents and reinforced by sedimentary gravity flows in the flanks close to bottom channels. Both the hard grounds formed by manganese-encrusted chalk stratum and the abyssal dunes formed by calcareous ooze described by Lonsdale and Malfait [1974] show unconsolidated sediment sand related to flows in the erosional north valley surrounding the saddle area. This bottom water flows command the most important processes in re-deposition.

Underwater dissolution

The northward moving Pacific Bottom Water has a higher CO₂ content due to be water out of contact with the surface for a long period of time. It is also characterized by a cooler temperature between (1.8° to 2° C), and by the high organic content at the equator (high productivity) and close to mainland areas. These conditions increase corrosiveness of bottom water over calcareous sediments. The underwater dissolution was described as the origin of the depression on the Carnegie sedimentary blanket (Michaud *et al.*, 2004). The location of depressions on the east ridge is consistent with more coastal condition described in chapter VII. Van Andel and Malfait [1980] identified exposed sediments in the saddle area by analyzing underwater photography. These were related to Karst topography in which sediments are strongly eroded and dissolved. Michaud *et al.* [2004] associated circular depressions to a shoaling CCD occurred during of ~11.2 to 7.5 Ma [Farrell *et al.*, 1995], and attributed to changes in the bottom water flow through the Panama seaway. Indeed, the lysocline has fluctuated up to 800 m. during the last 800 (k.y.) in response to changes in carbonate supply and the corrosive nature of bottom

water. All these facts stress that the ridge is locally affected by a higher degree of dissolution on the east ridge than in the west ridge.

Dominant processes controlling sediment deposition

Factors controlling deposition were identified based on extrapolations from areas with similar composition, similar sediment types, and the identification of continuities in significant reflectors. The Carnegie Ridge is above the calcium carbonate compensation depth, and the slope gradient is an important factor influencing the depositional processes (Appendix 1, 2). The dominant factor influencing depositional process is the high pelagic settling. Pelagic sedimentation on Carnegie Ridge follows the basin fill sediment sequence, deposited in the topographic lows, or concentrated there by a product of reworking from upper slope. Similar sediment sequences in the east ridge and saddle area were observed using seismic profiles, particularly in areas where the crust is uniform. Pelagic drape sediment observed in the north area surrounding the ridge at the saddle area as a product of high rate accumulation, where even settling ignores rough topography. On the west ridge, the sediment is deposited on hilltops and basins and sediment on the flanks is deposited directly in topographic lows.

Small variations between thicknesses of reflectors in the sediment sequences are evidence of uniform deposition in the ridge. Seismic profiles in the east ridge reveal relatively constant sedimentation rates. Sediments are distributed through geological time despite varying oceanographic conditions and climatic processes, such as enhanced equatorial productivity [Pisias *et al.*, 2000]. On the east ridge shallow flank, sediments do not appear truncated. Therefore, they ignore topography during the original deposition [Lyle *et al.*, 2004]. In the outer south ridge, the reflectors show a slope, indicating erosion, produced by the bottom water flows at the outer rise.

Other important factors determining the sediment distribution are changes in the productivity linked to the strength of the south equatorial current.

In the west ridge sediments follow the paleo-track of the Nazca plate in direction to the subduction, causing differences in the sediment sequence. The primary processes of sedimentation in the Carnegie Ridge area are identified in the literature are the following:

- bottom currents re-deposited sediments through lateral transport, with a gradual decrease in size of particles since the original position;
- high energy south-western facies producing non-deposition at the bottom of the slope

- with a major volcanic basement exposed;
- mass flow deposits northward of the central saddle and ridge-trench junction formed by lateral transport from the hilltops;
 - high noncarbonated sediments input deposited in the areas surrounding the river discharge and crossing the trench, and north east from the Galapagos Islands;
 - pelagic sediments deposited in the south western side and in the east ridge input of terrigenous sediments modified the general pattern;
 - pre-existing morphology (normal faults and rough volcanic basement) affecting sediment distribution, produces vertical separation on the seabed creating zones of chaotic sediments downhill;
 - the age of the basement where the sediment was deposited is older at the eastern end and the sediments in that area are affected by the outer rise;
 - water masses affects deposition, in the shallow environment is affected by Pacific Central Water and in the deep environment by Pacific Deep Water; and
 - underwater dissolution processes are affecting the Ridge along the flanks due to variation of depositional environment produced by increase of water corrosiveness and high organic carbon content.

Environmental factors affecting deposition

Along slope, the bottom-flow currents are an important factor affecting deposition. Such currents have been correlated to lateral transport of sediments. Bottom currents associated with the inflow of water into the Panama Basin transported sediments northward [Lonsdale, 1977a]. Sand and gravel are part of the hardgrounds of channels along the flanks of the saddle area, while on the hilltops there is evidence of winnowing [Kowsman, 1973a and 1973b]. Submarine bedforms observed in a northward slope from the central saddle area are physical evidence of bottom current. A 30 cm/s bottom current [Lonsdale and Malfait, 1974] was found in the saddle area. On the saddle area adjacent basin a short supply of coarse sediments because they are located far away from depositional centers. The sediment is transported across the north flank before it goes down into the Panama Basin, leaving a pattern of ripples across the branches [Lonsdale, 1976]. These are bedforms on the ocean floor generated by water flow, leaving crescent tips in a northward direction [Lonsdale and Malfait, 1974]. Similar bedforms are generally free from pelagic and hemipelagic sediments [Stow, 1994]. They are produced by

bottom currents which vary in frequency and velocity. These currents are locally intensified by flow restriction in the central saddle area and in the ridge-trench junction. Active currents were observed at the saddle area (Appendix 3.2) and submarine valleys with a north–south direction (Figure 42).

Fine-grained turbidite currents are found on the slope of the Galapagos Islands and on sediments adjacent to the islands [Wynn and Stow, 2002]. The northeast side of the Galapagos Platform has higher sediment supply from the islands [Lyle, 1992], where the subsurface equatorial undercurrent moving eastward control their distribution [Ninkovich and Shackelton, 1975]. The basement location, according to the age reconstruction, has modified the sediment composition throughout its sequence due to the back track of the Nazca Plate movement. Sediment now has higher organic carbon content and lower carbonate content (ODP Sites 1238 and 1239). The variations in the inflow of waters had switched from Peru Basin to Panama Basin, recalling its original position [Lonsdale, 1977a]. The areas susceptible to erosion have been identified using the high slope, faults influence, and flowpaths because these three were considered as important factors to determine susceptible erosion areas. Their distribution and influence tendency are:

- On the west ridge, high slopes can be found in the south and west areas surrounding the Galapagos Islands (Figure 53). The Galapagos Volcanic Platform can be represented as a flat blank, where the southern boundary is a major erosional area due to the existence of faults, and flowpaths. There is no evidence of slide deposits on the adjacent abyssal plain analyzed by multibeam bathymetry.

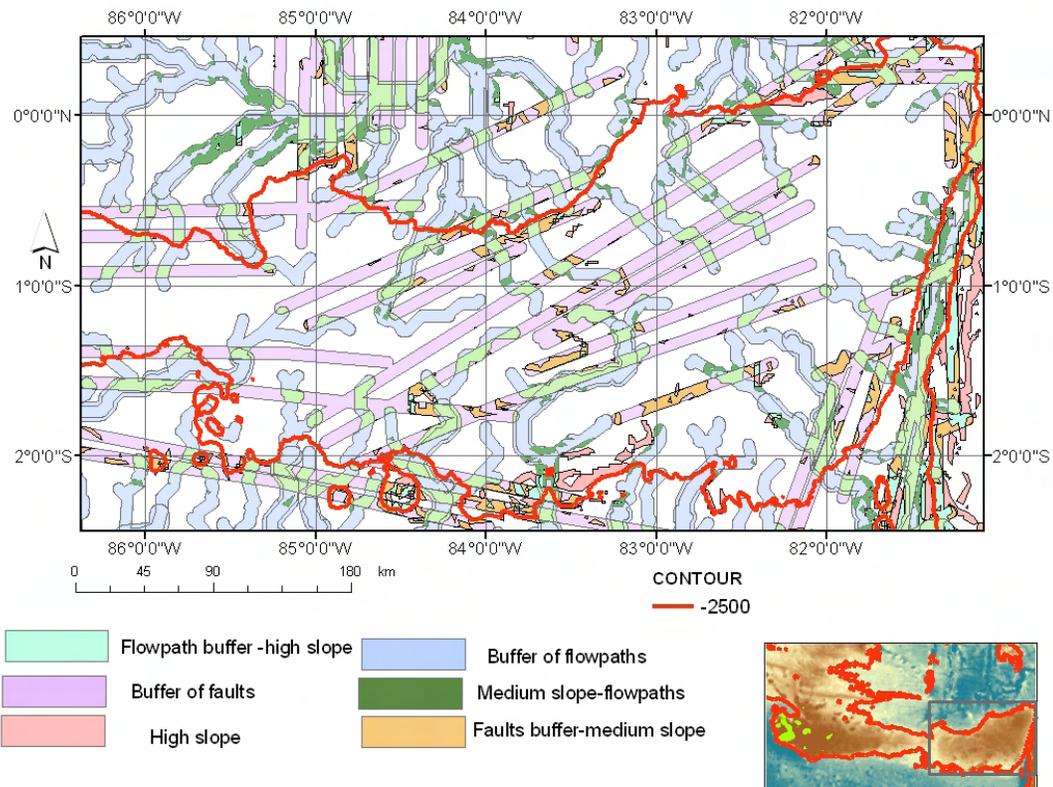


Figure 53. Erosional areas of the east ridge. Areas more vulnerable to erosion are marked with different colors, based on the high slope angle, fault influence in the high angle, and flowpaths.

- In the saddle area, erosion occurs mainly in the canyons created from pre-existing morphology by the inflow of bottom water into Panama Basin and the location of faults (Figure 54).

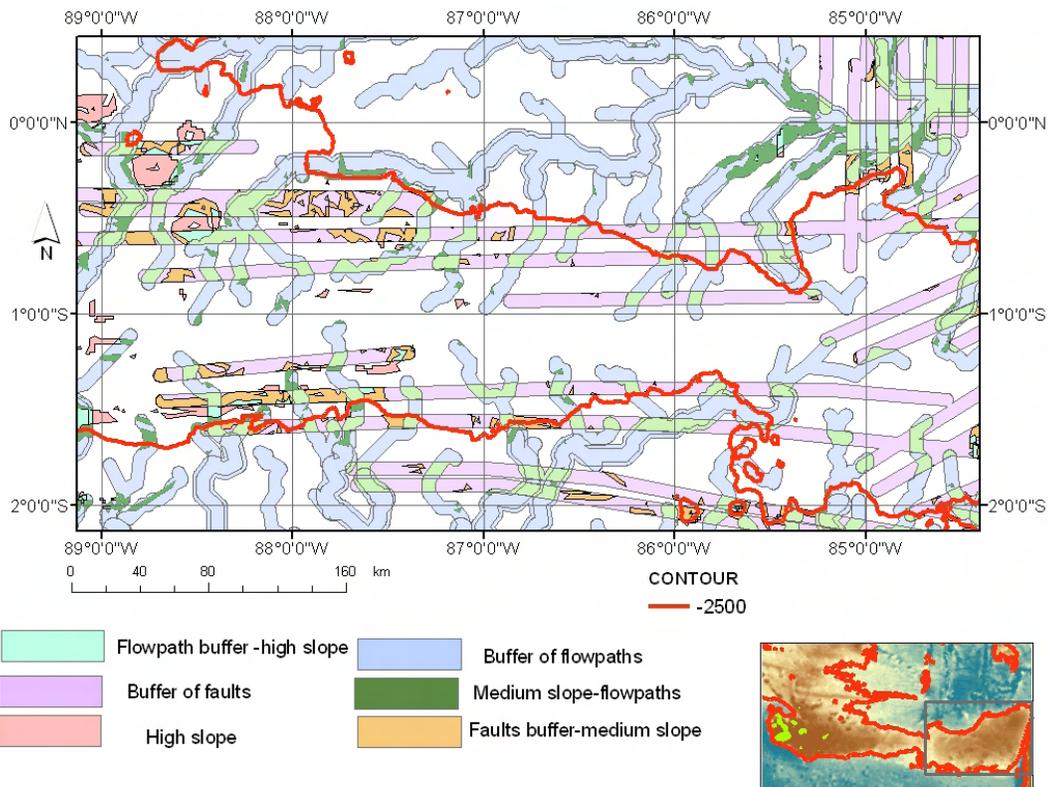


Figure 54. Erosional zones in the saddle area. Areas more vulnerable to erosion are marked with different colors, based on the high slope angle, fault influence in the high angle, and flowpaths.

- The east ridge is mainly controlled by fault blocks with a northeast-southwest trend; the ridge-trench junction is dominated by the tensional faults and flowpaths to the trench. On the eastern end the erosion due to the inflow of bottom water is concentrated near the Ecuador Trench (Figure 55).

This general classification permit to establish areas of major tendency to re-deposition on the flanks, and adding the bottom water flow the south flank is more susceptible to sediment transport.

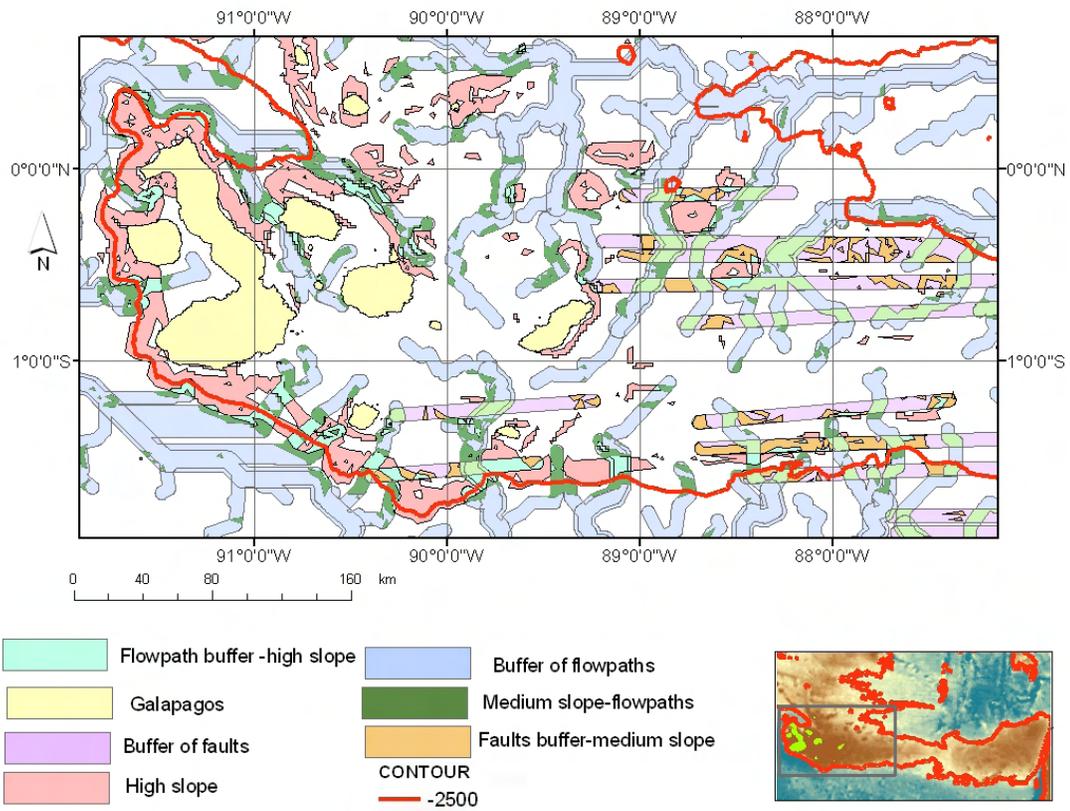


Figure 55. Erosional areas of the west ridge. Areas more vulnerable to erosion are marked with different colors, based on the high slope angle, fault influence in the high angle and flowpaths.

CHAPTER X

CONCLUSION

Summary and conclusions

The capability to assemble bathymetry, swath bathymetry, core data, sub-bottom data, seismic profiles and published single-channel profiles has improved interpretations of the sediment distribution and depositional processes on the Carnegie Ridge. Based on their comparative analysis, this thesis intended to explain current day sedimentary environment. The constant changes in sediment sequences and composition, as well as the importance of carbonate sediments in the ridge area were recognized as significant elements for the identification of depositional processes on the Carnegie Ridge.

The type of sediments in the Carnegie Ridge vary in accordance with their geographic location, water depth, age, underwater dissolution, and bottom water flow. The geographic location creates special conditions of deposition due to the distance to diverse environments between different sources. Terrigenous sediments diluted carbonate sediments close to the mainland, and eroded volcanic debris around the Galapagos Volcanic Platform. The major variables related to carbonate sediment in the Carnegie Ridge are their location relatively to the general area of dissolution (CCD and lysocline), and the general input from areas of high productivity.

The south flank of the west section of the ridge, the saddle area, and the trench-ridge junction reveal an environment dominated by bottom water flows. Deposition of recent sediment in these areas is occurring on top of sediments adjacent to the Panama Basin or Peru Basin because sediments are noncohesive. Winnowed material deposited on the adjacent Panama Basin after erosion of the northeast crest is evidence of lateral sediment transport. This sediment transport produces distinct lithofaces changes in the sediment composition, such as varying non-carbonate inputs. Presence of quantities of silicic volcanic glass shards of the Ecuador mainland origin, and basaltic ash content is located around the Galapagos Islands are resulted of non-carbonate inputs.

Sediment composition has been an important variable to differentiate recent depositional processes. Based on this study, the following can be concluded:

Carbonate distribution is classified as high content (80-100 weight percent) in the southern

saddle area and summit terraces, moderate content (50-80 weight percent) in the flanks and upper slope, deficient content (30-50 weight percent) in the lower slope and the sill of the central saddle area, and low content (0-30 weight percent) around the Galapagos islands and southern and northern edges of the ridge-trench junction. Siliciclastic distribution is linked to the distribution of quartz. The high values observed close to the mainland are related to the enrichment of organic carbon weight percent. The eastern part of the ridge is affected by dilution by terrigenous material. Organic carbon distribution is higher near the mainland and latitudinally along the equator due to the south equatorial current influence, which is related to the high pelagic sediments from productivity waters. Opal concentrations are high in the south-western part of the ridge coinciding with the high productivity area.

Tectonics is an important factor in the depositional processes along the ridge. Its aseismic origin presents different, tectonic and volcanic history than the adjacent basin constraining regional age and structural models. The geotectonic structural character of the Galapagos Spreading Center and its redistribution of mass through the faults are important tectonic factors influencing the northern border of the west ridge. The ridge subsided as a result of the long-term cooling varying depositional environment. Circular depressions on the flanks of the east ridge are physical evidence of the dissolution of sediments with depth, and flat seamounts are evidence of erosion near shallow environments (Appendix 3.4). Based on these considerations, the Carnegie Ridge changed depositional environments as the ridge moved away from the GHS and subsided. As a result the sediments that have less carbonate content and more organic carbon content are observed on top of east ridge.

Fault scarps, depressions, and channels produce discontinuities in the sediment thickness. The chaotic sediment environment observed in the upper part of the escarpment, especially in areas of instability located at the boundaries of flat terraces, can be defined as sediment creeping downhill. Seismic profiles provide evidence of homogeneous stratigraphic sequences in the flat blankets on the summit terraces. Over the ridge, pelagic drape is observed on the hilltops, basin fill is observed from the hilltops to the deepest basement on the eastern flank, and on the west ridge sediment is deposited on hilltops, basins and sediment on the flanks deposited directly in topographic lows. Undisturbed sediment stratigraphic sequences are explained by the lack of overpressure or fluid circulation on terraces and flanks. Migrated sections on seismic profiles are observed on the southeast ridge and can be related to erosion linked to bottom water flow. The blanket of pelagic sediments in summit terraces, and the flanks show regular horizons in the

seismic profiles.

Sediment deposits on Carnegie Ridge can be described as an irregular sedimentary cover ranging from the bare peaks and the infill of topographic lows, to the eroded material trapped in the terraces. The heaviest components have been removed by gravity forces to the adjacent basins. These conditions of deposition affect distinct particle input and re-deposition by bottom water flow and have generated sedimentary deposits with distinct composition along the ridge. Sedimentary deposits are found over ridge hill tops, flat terraces with smooth seafloor, channels (mainly in the saddle area), escarpment, and the abyssal plain surrounding the ridge, and this distribution defines the sediment environment.

Bathymetric variations provided details of the morphology. Multibeam surveys in the saddle area and east ridge were used to identify the dominant component in the deposition. This morphological analysis of the seafloor using 3D representation of multibeam sonar bathymetry provides a realistic view which enables the identification of physiographic units and prediction of mass movements, such as slump and slides. The general swath bathymetry does not show evidence of slide deposits at the lower flanks of the ridge boundaries. Pre-existing morphology originated from the volcanic basement is affecting sediment distribution (Appendix 3.1) and NE-SW trending lineation produce deformation and bending on the seafloor sediment at the edge of flanks. Channel formation provides information on lateral transport and basin fill on gravity flow. Inflow of bottom water remove sediments on the Topographic lows in the saddle area enhanced by bottom water flow, non-conformities and hardgrounds are physical evidence of erosion. Mechanical differentiation results from the size distribution of deposited particles in the flanks by dynamic conditions, with abyssal dunes [Lonsdale, 1976; and Malfait, 1974] as a physical evidence of this sediment transport. On the flanks, dissolution of sediments produced by corrosive waters and by fluctuations of lysocline can be one factor for the formation of circular depressions is also augmented by bottom water flow.

The shape of the ridge is important in sediment transport due to hydrodynamic affects produced by the water bottom flow. The nature and thickness of sediments are different in areas affected by bottom water flow, where sediment distribution is more affected by coarse sediments in the channels to silt sediments in adjacent basin. Locally, abyssal circulations in the southern of Panama Basin and over the sills on Carnegie Ridge modified the sediment accumulation. The local productivity and the corrosiveness of water properties in conjunction with bottom water flow are controlling the deposition.

The latitudinal distribution of the climate in the mainland produces different input of sediments to the adjacent seafloor due to variations from northern dry to southern humid tropical climate, accentuated by variations in river discharges in these two areas. However, the major sediment input is the pelagic input, affecting the whole elongate shape of Carnegie Ridge. Sediments in regions distant from the mainland exhibit an increase in CaCO_3 concentration as well as an increase in SiO_2 , which occurs in high productivity zones.

Dissolution by corrosive waters and re-deposition as evidence of water bottom flows are characteristic of the current sedimentary environment of Carnegie Ridge, which is dominated by high sediment input.

Finally, over the ridge, the thickness and composition of sediment covering the rough basement are controlled by the pre-existent morphology (volcanic constructional processes and faulting), the crustal age, the geographical location and distance to mainland or the Galapagos Islands. These different sources of sediments create different depositional environments. The transitions from silt to silt clays in areas of siliciclastic deposition close to the mainland to calcareous deposition in the south-west side are present in the sediment composition on the ridge. Their distribution is controlled by local erosional factors linked to dissolution and bottom water flow.

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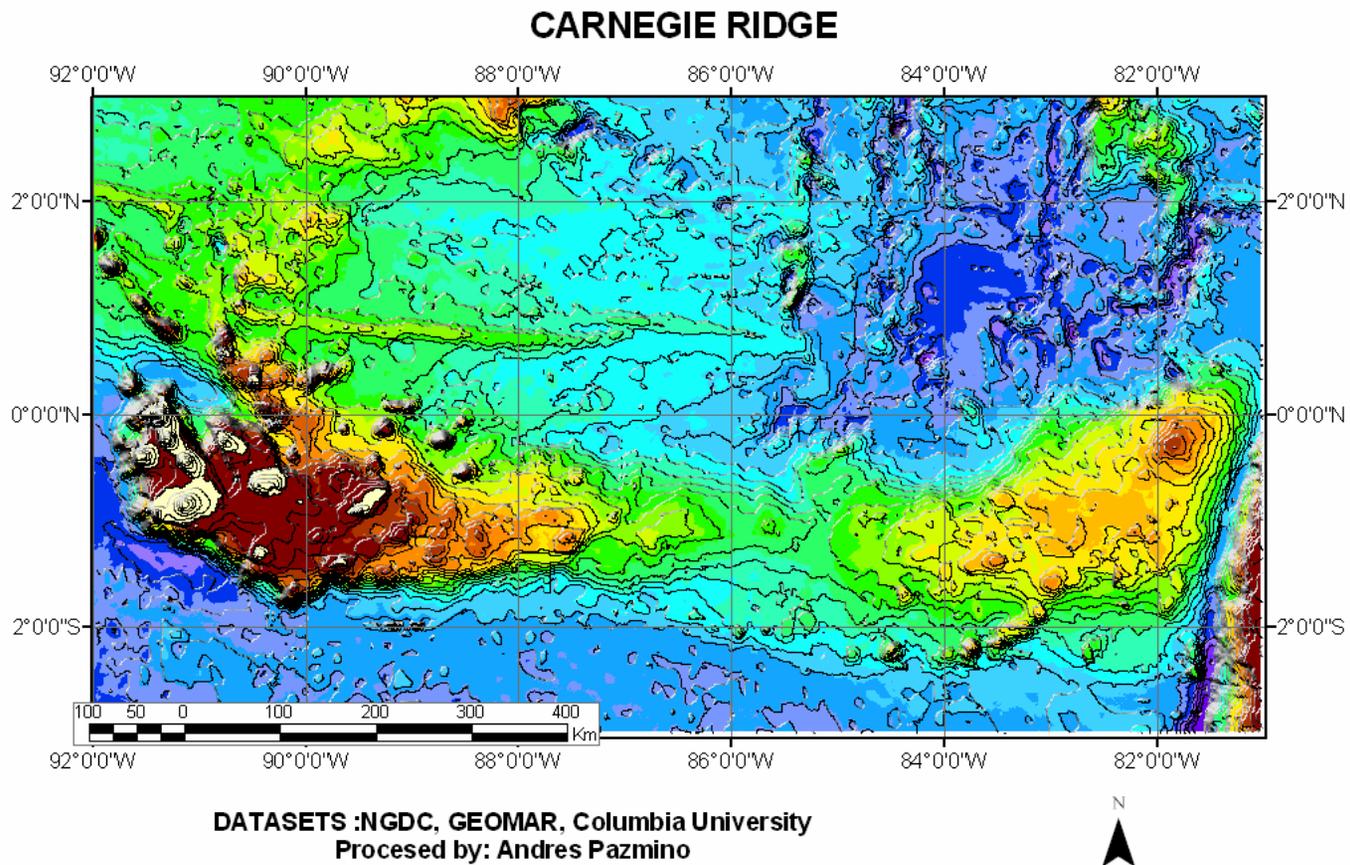
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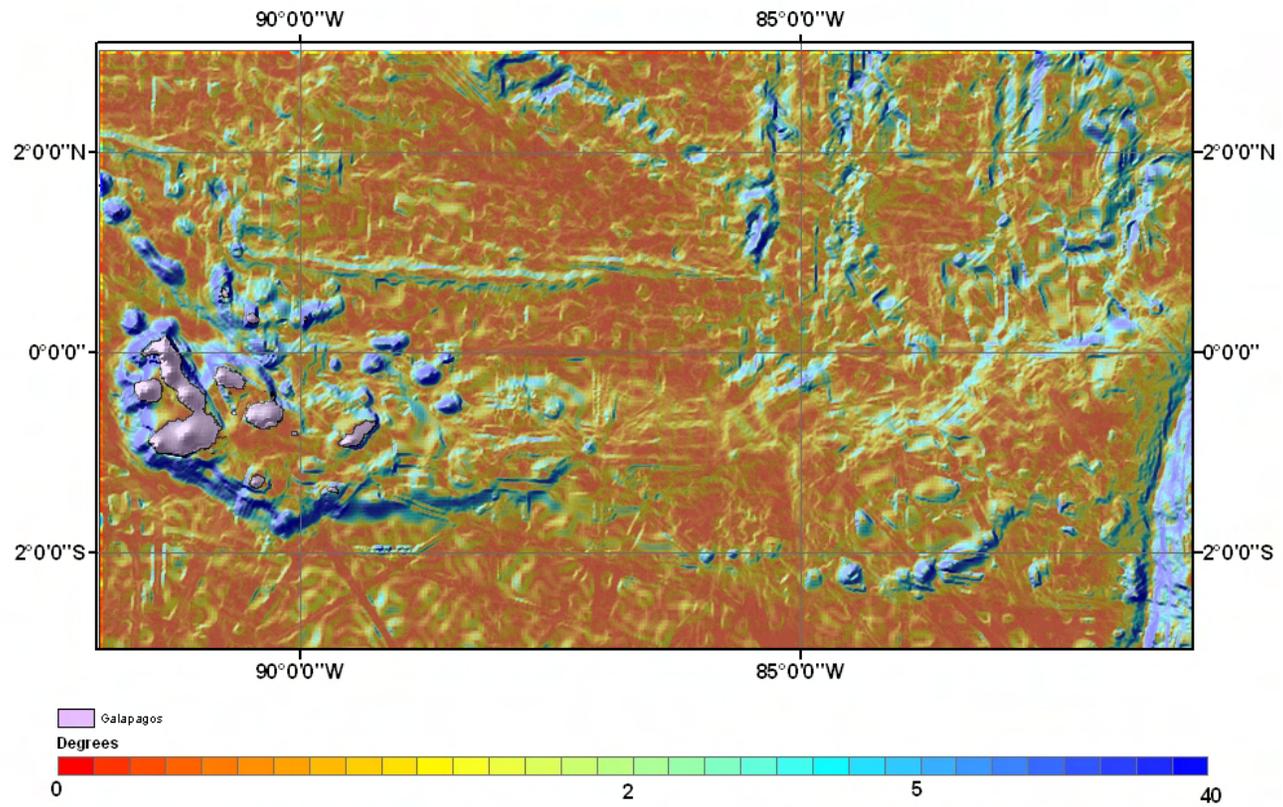
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APPENDIX 1



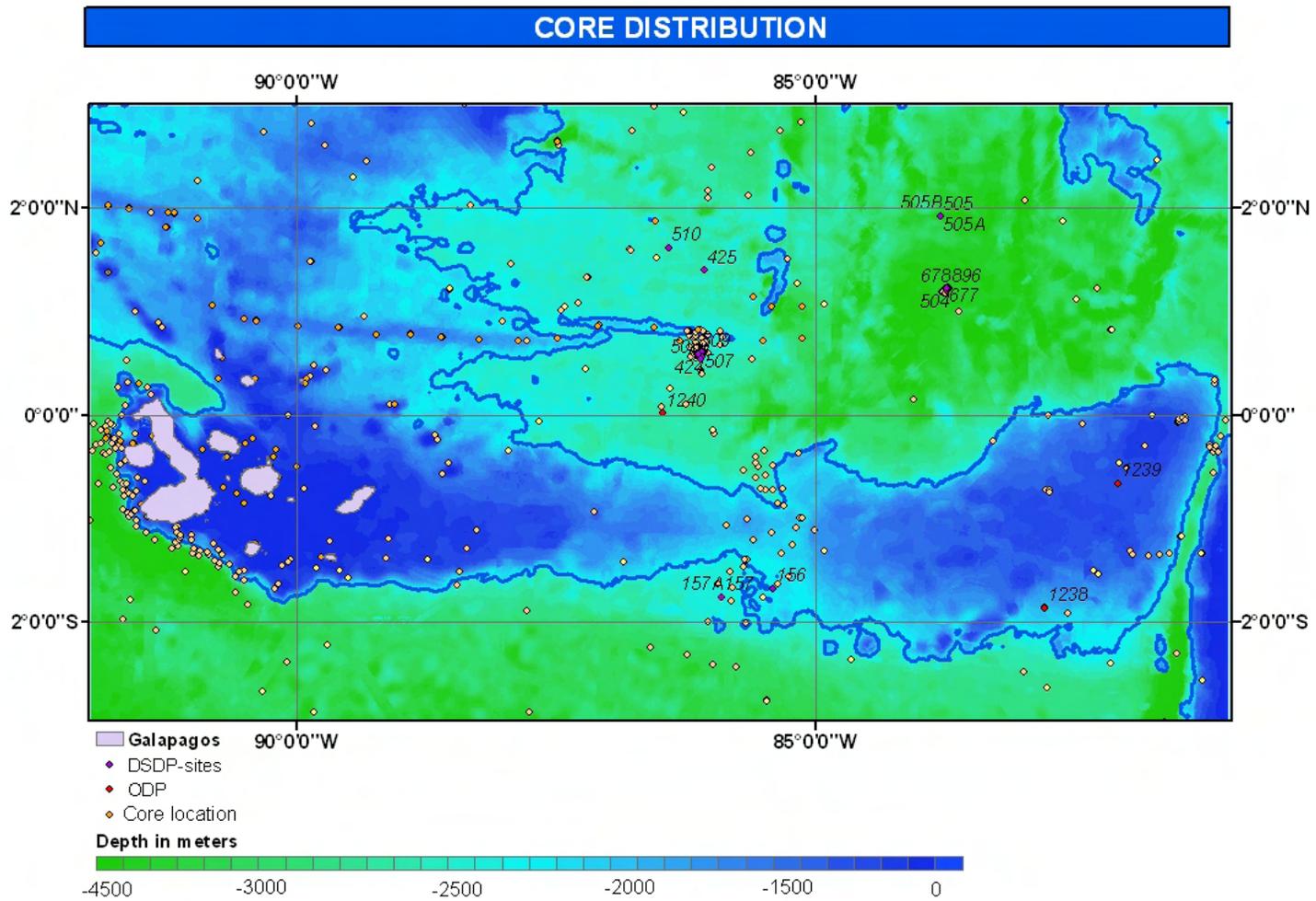
1. Seafloor map of the Carnegie Ridge. The deeper the water is associated to the deeper blue.

SLOPE DISTRIBUTION ON THE CARNEGIE RIDGE REGION

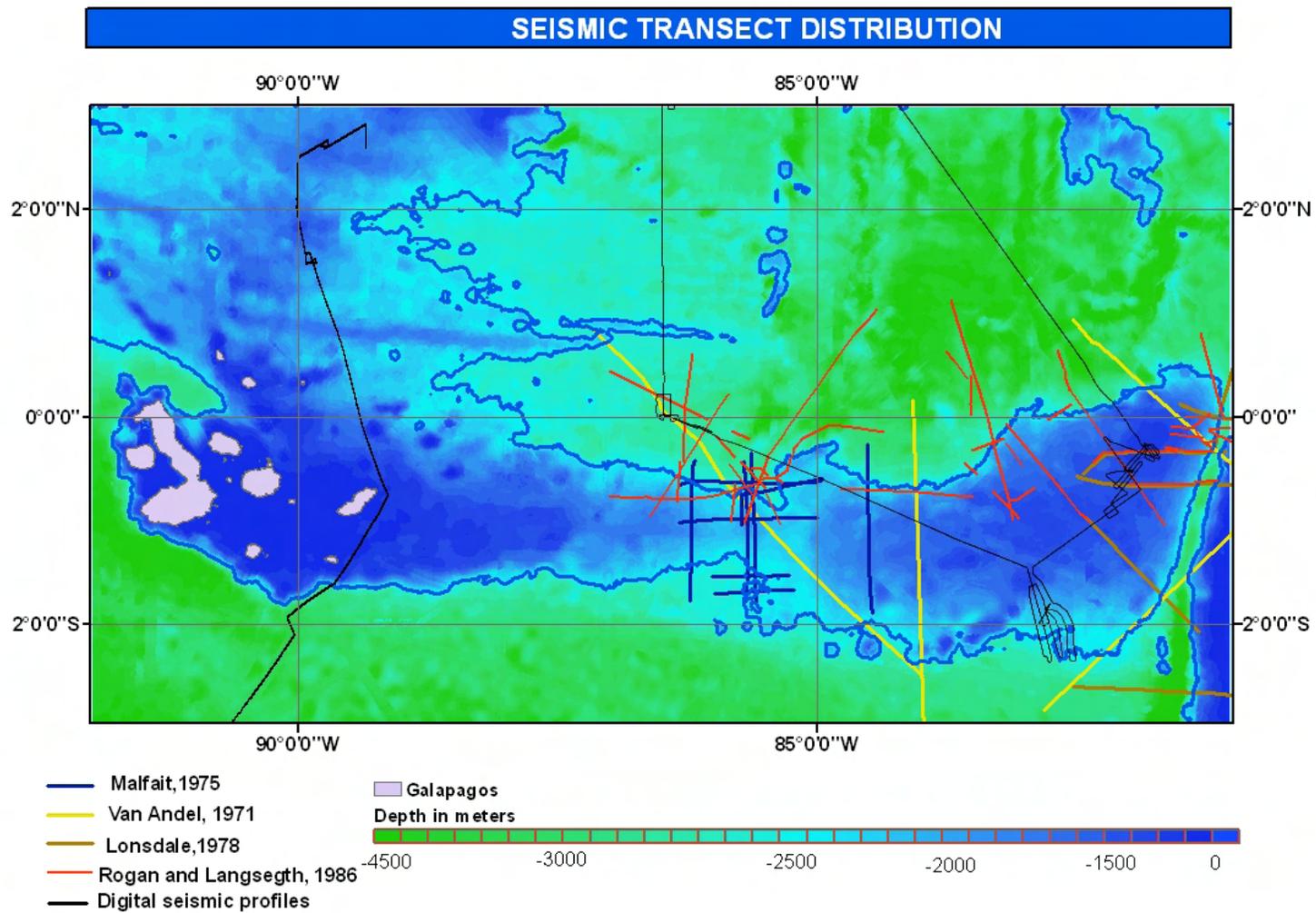


2. Slope distribution of the Carnegie Ridge. The higher slope is associated to the deeper blue.

APPENDIX 2

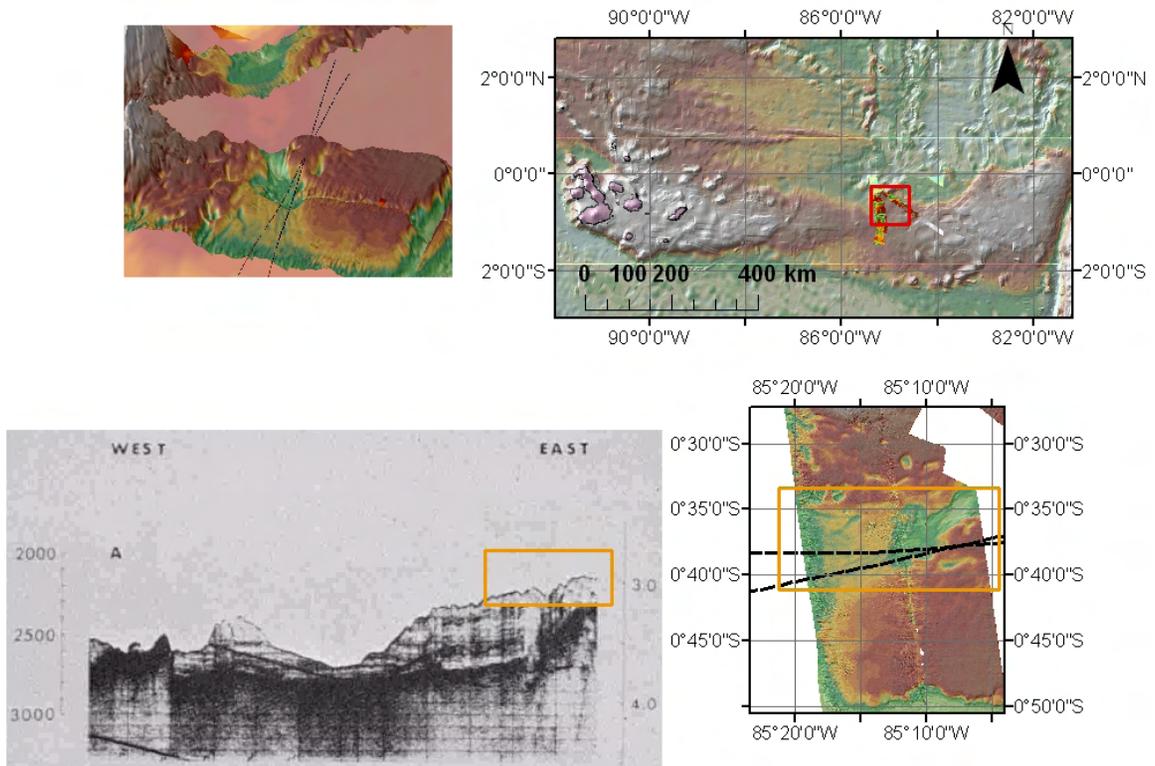


1. Core location (yellow dots). ODP Sites (red dots). DSDP Sites (purple dots).

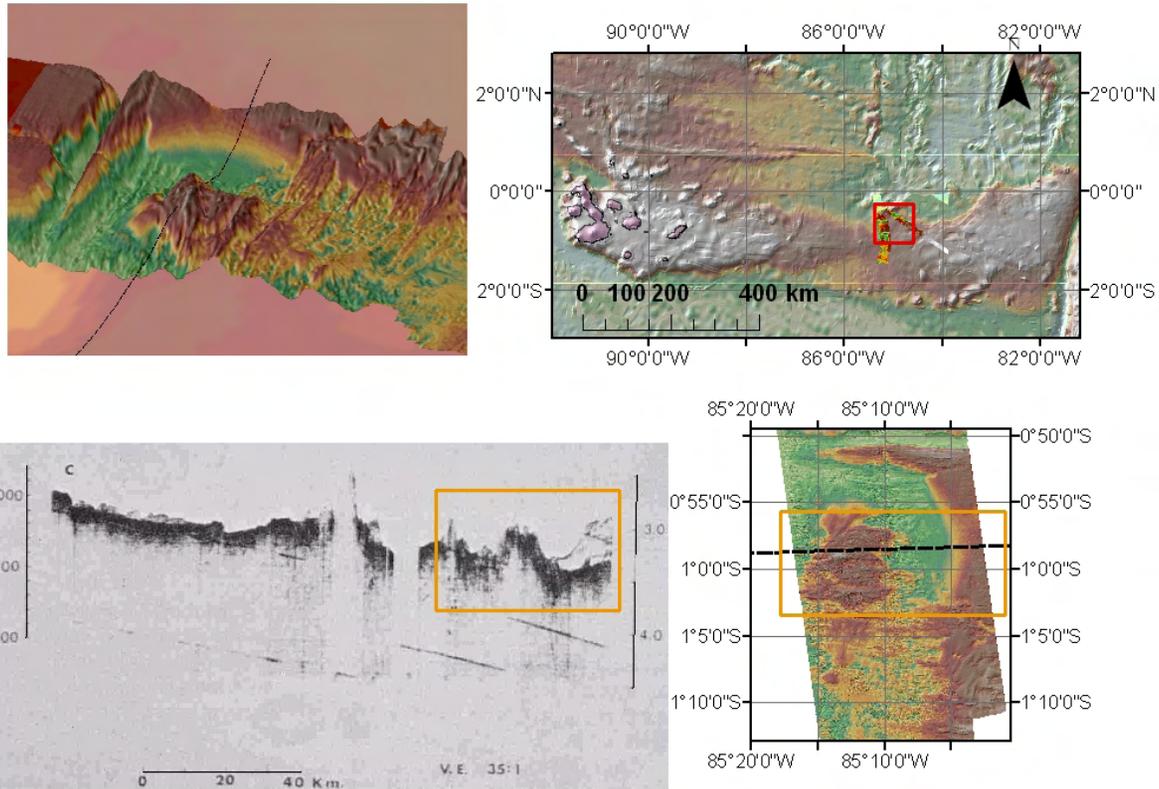


2. Seismic profiles and single channel profiles location.

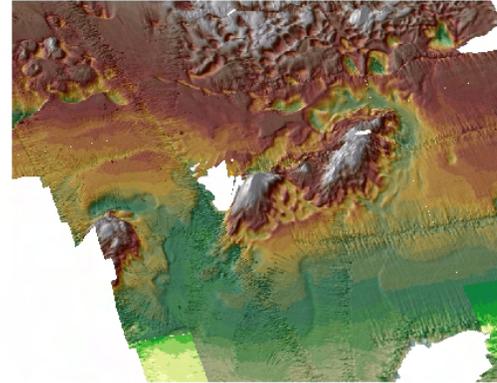
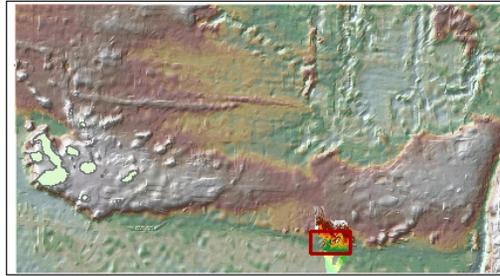
APPENDIX 3



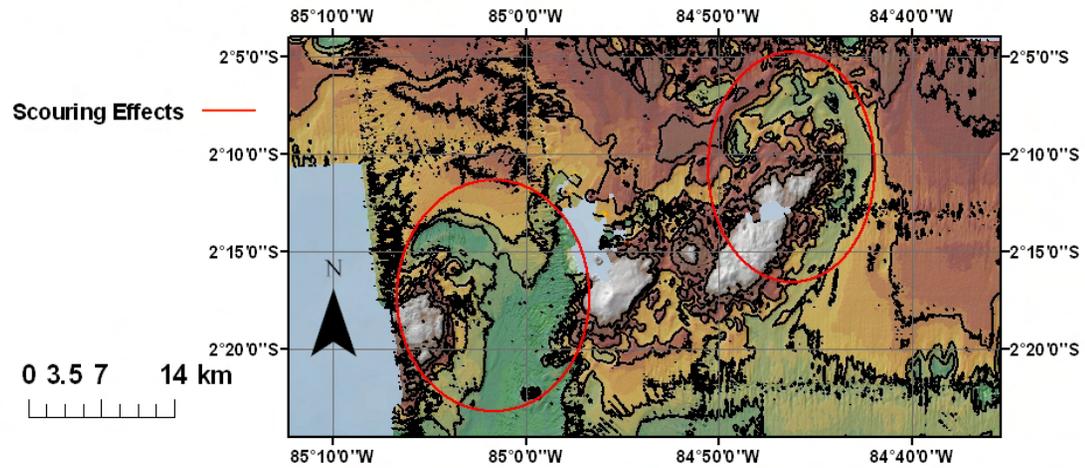
1. NE-SW trending lineations represent the pre-existing morphology, which is considered to be the local depositional process on the Carnegie Ridge. Seismic profile (Malfait and Van Andel, 1980, reprinted by permission of the Blackwell Publishing Ltd.)



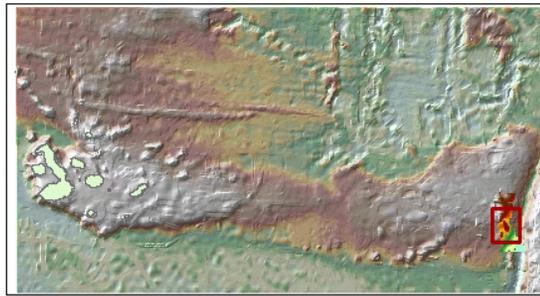
2. Evidence of active bottom water flow are considered to be the a local depositional process on the Carnegie Ridge. Seismic profile (Malfait and Van Anel, 1980, reprinted by permission of the Blackwell Publishing Ltd.)



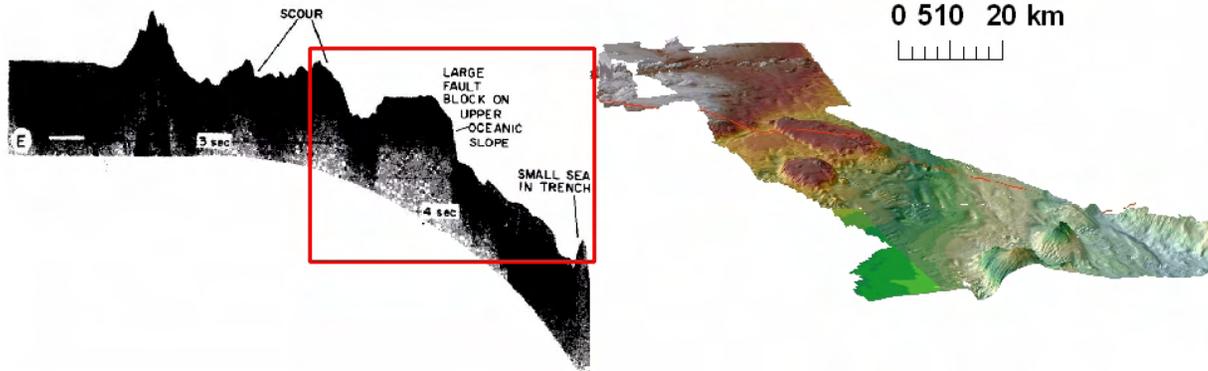
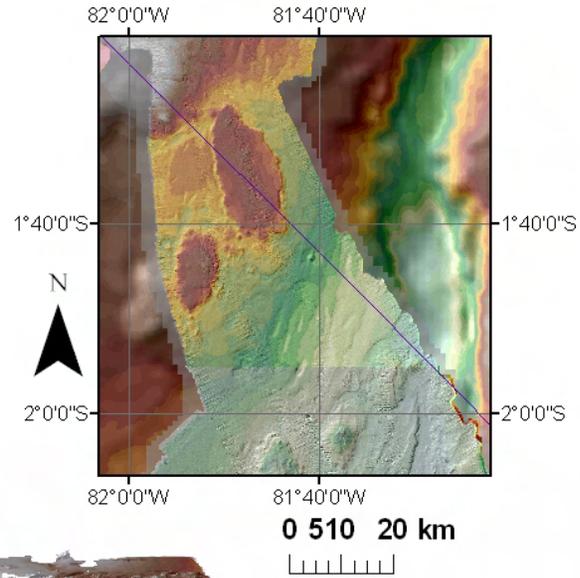
**Cold bottom waters which flow northward are eroding the seafloor.
The erosion along the southwestern side are forced to the west around the Carnegie Ridge**



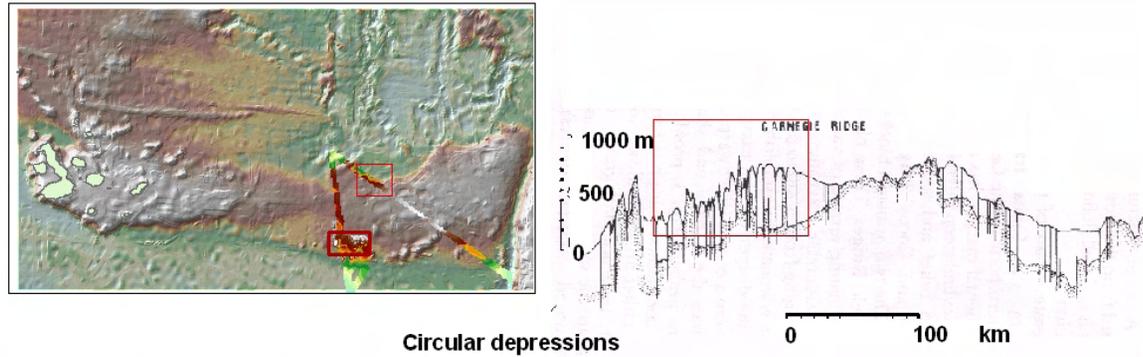
3. Scoured channel near the south border of the Carnegie Ridge suggesting rotational effects dominate the dynamics of the flow around this area, allowing us to predict a strong erosive process.



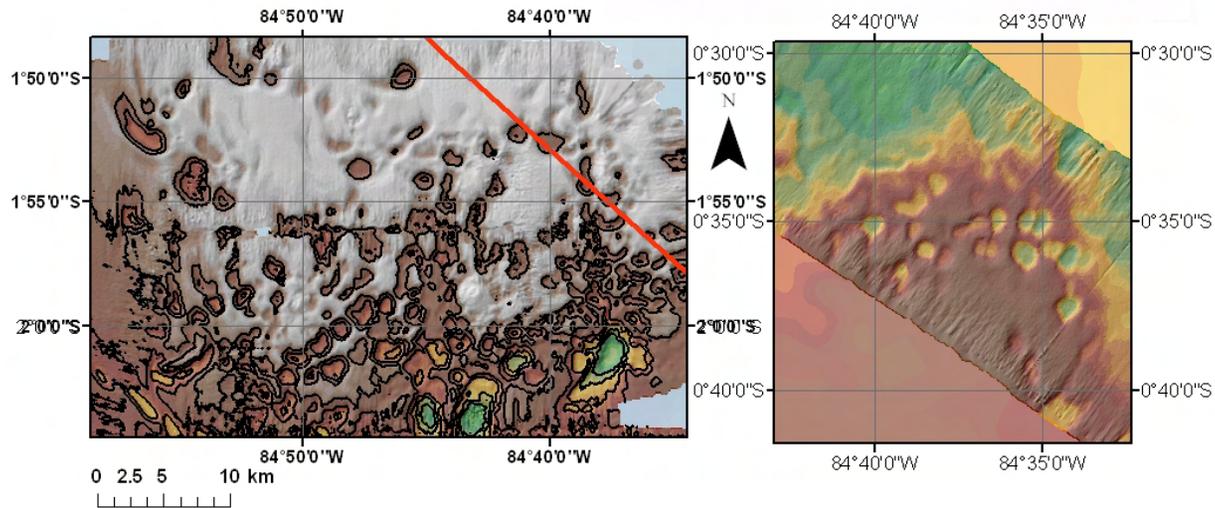
**SEDIMENT FREE VOLCANIC PEAKS,
AND IS EXPOSED TO BOTTOM CURRENT
ON THE RIDGE-TRENCH JUNCTION**



4. Eastern flank area without sediment and exposed to bottom water flow. Seismic profile (Lonsdale, 1978, reprinted by permission of the AAPG)



Circular depressions



5. Circular depressions as an evidence of chemical dissolution are formed on the Carnegie Ridge are the environment deposition is affected by their location. Seismic profile (From Van Andel et al., 1971, reprinted by permission of the Geological society of America).

VITA

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Education

B.S., December, 1992, Naval Science, Escuela Superior Naval, Salinas, Ecuador.

M.S., 1996, Ecuadorian Navy Oceanographic Institute, Hydrographer.

M.S., 2005 Oceanography, Texas A&M University.

Professional Experience

Chair of the Cartography Department, Ecuadorian Navy Oceanographic Institute, 1997-2000.

Supervisor/Chair of Hydrographic School, Ecuadorian Navy 1999-2000.

Geographical Information System IGAC Agustin Codazzi, Colombia, 1998.

Electronic Nautical Chart SHIO, Valparaiso, Chile, March 2000.

Cruise Experience

Regional cruise in the Eastern Equatorial Pacific Ocean, and Galapagos area B/I Orion (2000).

Coast Guard Patrol Commander (Ship "LAE 3 de Noviembre"), Galapagos Islands, 1995.

Coastal Survey of Guayas River, January-February 1998.

Coastal Multibeam Survey, INOCAR-NAVOCEANO, Manta Port, April-May 2000.

Teaching Experience

Digital Cartography, Ecuadorian Navy Oceanographic Institute, Hydrographic School, 1999.