Geochemistry Geophysics Geosystems G3
AN ELECTRONIC JOURNAL OF THE EARTH SCIENCES
Published by AGU and the Geochemical Society

Article
Volume 4, Number 12
27 December 2003
1108, doi:10.1029/2003GC000576
ISSN: 1525-2027

Geodynamic evolution of the Galápagos hot spot system (Central East Pacific) over the past 20 m.y.: Constraints from morphology, geochemistry, and magnetic anomalies

R. Werner
Tethys Geoconsulting GmbH, Wischhofstr. 1-3, 24148 Kiel, Germany (rwerner@geomar.de)

K. Hoernle
GEOMAR, Wischhofstr. 1-3, 24148 Kiel, Germany

U. Barckhausen,
Bundesanstalt für Geowissenschaften und Rohstoffe, Stilleweg 2, 30655 Hannover, Germany

F. Hauff
GEOMAR, Wischhofstr. 1-3, 24148 Kiel, Germany

[1] We report results of magnetic data from the Nazca Plate and of geochemical (major element and Sr-Nd-Pb-isotope) analyses of rocks dredged from the Galápagos hot spot tracks (Cocos, Carnegie, Malpelo and Coiba Ridges and adjacent seamounts) in the Central East Pacific. Magnetic anomalies indicate that the Malpelo and Carnegie Ridges were once attached and that seafloor spreading separated the two ridges between 14.5 Ma and 9.5 Ma. The variations in Sr-Nd-Pb isotopic composition show that three of the mantle components currently observed at the Galápagos (Central, Southern, and Eastern) existed in the hot spot for at least 20 m.y., whereas the Northern Galápagos mantle component has been present for at least ~15 Ma. Our data are consistent with the existence of a compositionally zoned/striped Galápagos plume since ~20 Ma. Combined constraints from the morphology of the hot spot tracks, the magnetic record, and the isotope geochemistry of the rock samples provide new insights into the hot spot-ridge geometry and interaction of the Galápagos hot spot with the Cocos-Nazca spreading center (CNS) over the past 20 m.y. At 19.5 Ma a ridge jump moved the spreading axis to the northern edge of the hot spot. Between 19.5 and 14.5 Ma, the spreading axis was located above the center of the hot spot. At 14.5 Ma, a new ridge jump moved the spreading axis to the south, splitting the paleo-Carnegie Ridge into the present Carnegie and Malpelo Ridges. The repeated ridge jumps reflect capture of the northwardly drifting spreading center by the Galápagos hot spot. At 11–12 Ma an offset of the spreading axis lay above the plume center. Spreading between the Carnegie and Malpelo Ridges continued until 9.5 Ma.

Components: 14,843 words, 9 figures, 3 tables.

Keywords: Galápagos Hot Spot; East Pacific; Plume-Ridge-Interaction; Major Element and Sr-Nd-Pb-Isotope Geochemistry; Magnetic Anomalies; Morphology.

Index Terms: 1040 Geochemistry: Isotopic composition/chemistry; 8120 Tectonophysics: Dynamics of lithosphere and mantle—general; 8155 Tectonophysics: Plate motions—general.

Received 8 May 2003; **Revised** 10 October 2003; **Accepted** 17 October 2003; **Published** 27 December 2003.

Werner, R., K. Hoernle, U. Barkckhausen, and F. Hauff, Geodynamic evolution of the Galápagos hot spot system (Central East Pacific) over the past 20 m.y.: Constraints from morphology, geochemistry, and magnetic anomalies, *Geochem. Geophys. Geosyst.*, *4*(12), 1108, doi:10.1029/2003GC000576, 2003.

1. Introduction

[2] The Galápagos Archipelago is located in the Central East Pacific Ocean about 1000 km west of Ecuador and just south of the Cocos-Nazca spreading center (CNS; also known as Galápagos Spreading Center), which represents the boundary where the Cocos and Nazca Plates separate (Figure 1). The archipelago is the surface expression of a hot spot or long-lived mantle plume whose interplay with the CNS during the Neogene has resulted in the formation of two hot spot tracks, the Cocos and Carnegie Ridges and associated seamounts on the Cocos and Nazca Plates, respectively [*Holden and Dietz*, 1972; *Hey*, 1977; *Lonsdale and Klitgord*, 1978; *Wilson and Hey*, 1995]. The Coiba and Malpelo Ridges are also believed to be products of the Galápagos hot spot. The history of the CNS begins at ~23 Ma when migration of a preexisting fracture zone over the Galápagos hot spot caused the breakup of the Farallon Plate into the Cocos- and Nazca Plates [*Handschumacher*, 1976]. Most of the tectonic record of the opening of the CNS has already been subducted beneath Central America and South America, respectively. The earliest model of the CNS evolution [*Holden and Dietz*, 1972] suggested that the aseismic Cocos and Carnegie Ridges were formed simultaneously while the CNS was in a stationary position over the Galápagos hot spot. However, it has become clear that the CNS has been constantly moving relative to the hot spot since its opening [*Hey*, 1977; *Lonsdale and Klitgord*, 1978; *Wilson and Hey*, 1995; *Wilson*, 1996; *Barckhausen et al.*, 2001]. Although major advances in the identification of magnetic seafloor spreading anomalies around the Cocos-Nazca Plate boundary have been made, a precise reconstruction of the plate tectonic development of the region for times before ~10 Ma is still lacking due to missing information about the tectonic record.

[3] During R/V Sonne cruise SO 144-3 in 1999, the first systematic rock sampling of the aseismic ridges and associated seamounts between Galápagos and Central and South America was conducted (Figure 1). Here we report results of geochemical (major element and Sr-Nd-Pb-isotope) analyses of the recovered volcanic rocks and interpretations of magnetic profiles recorded on this cruise. We show that the morphology and composition of Galápagos hot spot tracks probably reflect the relative position of the CNS to the hot spot and/or variations in plume flux. In addition, we combine the constraints from the magnetic record with the geochemical compositions of rock samples and the morphology of the hot spot tracks (1) to reconstruct the long-term geochemical zonation of the Galápagos plume and (2) to fill in the missing history of the hot spot - spreading axis geometry (plume-ridge interactions) over the past ~20 m.y. Hf isotope data [*Geldmacher et al.*, 2003] and trace element geochemistry [*Harpp et al.*, 2003] for the same samples are being published elsewhere.

2. Morphology of the Galápagos Hot Spot Tracks

2.1. Cocos Track

[4] The Galápagos hot spot track on Cocos Plate ("Cocos track") is the largest and most complex morphologic structure in the eastern Central Pacific. It comprises 2 major morphological domains: (A) Cocos Ridge, a highstanding broad NE-SW trending aseismic ridge and (B) the seamount domain adjacent to the northwestern flank of the ridge [*von Huene et al.*, 1995] (Figure 1).

[5] Cocos Ridge, oriented parallel to the recent motion of the underlying Cocos Plate, extends more than 1000 km from the CNS directly north of the Galápagos Platform to the trench off the coast of Costa Rica (Figure 1). Seamounts are scattered across the crest and the flanks of the

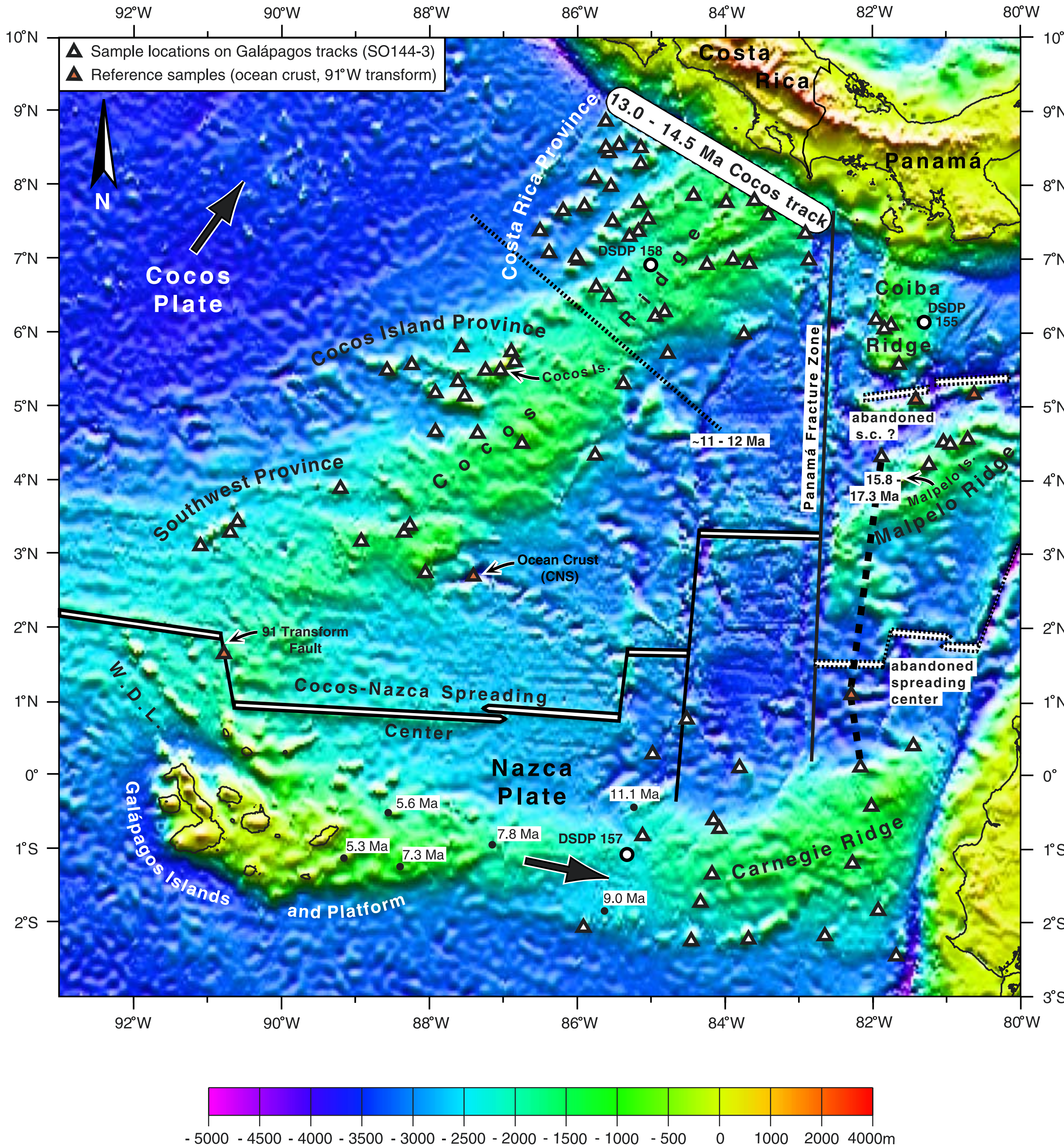


Figure 1. Bathymetric map of the study area and the morphologic and tectonic setting of the East Pacific between Galápagos Archipelago and Central and South America showing the Galápagos hot spot tracks: Cocos track (Cocos Ridge and seamount provinces to the northwest), and the Carnegie, Coiba and Malpelo Ridges). Sampling sites (triangles) and a magnetic profile from Malpelo to Carnegie Ridge recorded on cruise SO 144-3 (dashed line) are also denoted. Bathymetry based on the TOPEX data set by *Smith and Sandwell* [1997]. Age range of the Cocos track off the coast of Costa Rica are from *Werner et al.* [1999] and of Malpelo Island from *Hoernle et al.* [2002]; age data on Nazca Plate are from *Sinton et al.* [1996]. Relative plate motion according to *Kellogg and Vega* [1995]. W. D. L. = Wolf-Darwin-Lineament.

entire ridge. Off the coast of Costa Rica, the ridge is up to ~300 km broad and rises up about 2000 m above the adjacent ocean floor to depth of less than 1000 m. In this region the ridge crest is marked by steep scarps and an up to 25 km wide, sediment-filled graben striking sub-parallel to the ridge axis in its center [e.g., *von Huene et al.*, 1995]. Off the coast of Panamá, the Panamá fracture zone cuts diagonally across the southern part of Cocos Ridge (Figure 1). Further to the southwest, the ridge slightly narrows and shallows. A volume decrease of the ridge toward SW is evident from seismic profiles across the ridge [e.g., *Bialas et al.*, 1999; *Walther*, 2003; *Sallarès and Charvis*, 2003].

[6] The seamount domain comprises more than 30 major volcanoes (>1000 m in height) and numerous smaller volcanoes at the northwestern flank of the Cocos Ridge. The seamounts are not continuously arranged along the ridge flank but can be subdivided into 3 distinct seamount fields which differ in number, arrangement and orientation of the volcanic edifices (Figure 1):

[7] 1. The Costa Rica seamount province, adjacent to the Pacific coast of Costa Rica, is by far the largest of the 3 seamount fields comprising 18 major and numerous smaller seamounts. The major seamounts form two distinct chains which extend ~300 km from the trench to the southwest parallel to the axis of the Cocos Ridge (Figure 1). A third NE-SW-trending seamount chain is discernible a bit further north. Indentations along the Costa Rica continental rise and earthquake clusters along extensions of these seamount chains indicate that parts of these seamount chains have been subducted beneath Costa Rica [e.g., *von Huene et al.*, 1995, 2000] and thus were considerably longer than 300 km.

[8] 2. The Cocos Island seamount province comprises Cocos Island and an adjacent group of seamounts scattered west and southwest of the island. This seamount field consists of 7 major and several smaller seamounts. Most of these seamounts form a acute-angled triangle which extends from Cocos Island ~200 km toward the west. An approximately east-west trending valley near Cocos Island (Figure 1) corresponds to the location of a spreading center abandoned at ~1.8 Ma [*Meschede et al.*, 1998].

[9] 3. The southwest seamount province, located west of the southwestern end of Cocos Ridge, consists of a group of 5 large seamounts at ca. 3°20′N and 91°W, a single major seamount at 3°50′N and 89°15′W, and a few small seamounts. These seamounts are spread over a large area characterized by normal ocean floor.

[10] Coiba Ridge is a broad north-south trending structure approximately 150 km long by 100 km wide. Multibeam echo sounding data obtained during SO 144-3 cruise proved that satellite altimetry-derived bathymetric maps are inaccurate over much of the ridge. In particular, large seamounts shown rising from the central, southeastern and eastern parts of the ridge do not exist, and the topography in those areas has minimal relief. Instead, Coiba Ridge appears to be a large, sediment-covered plateau with steep western and southern flanks up to 1500 m high and a gently dipping eastern slope. The western flank of the ridge is subparallel to the Panamá fracture zone.

2.2. Carnegie Track

[11] Carnegie Ridge is a highstanding, broad, east-west-trending ridge approximately 600 km long and up to 300 km wide. This ridge, oriented approximately parallel to the recent motion of the underlying Nazca Plate, represents the continuation of the Galápagos Platform to the east and extends to the Colombian trench off the coast of Ecuador (Figure 1). Bathymetry and seismic profiles [e.g., *Sallarès and Charvis*, 2003, and references therein] clearly indicate that height, width and volume of the Carnegie Ridge increases significantly to the east. Many seamounts rise from the ridge. Most of them do not exceed several hundred meters in height, are relatively smooth with gentle slopes, and are covered by sediments. Single large seamounts are scattered on and close to the flanks of the ridge. Five large seamounts on the southern flanks between ~86° and ~82°W appear to be aligned in an east-west direction. Large seamount

clusters as observed on the Cocos track do not occur on the Carnegie Ridge.

[12] Malpelo Ridge is an elongated, NE-SW trending aseismic block approximately 300 km long by 100 km wide. The block is bisected by a central graben that divides a narrow, steep-sided northwest ridge from a more extensive southeast plateau [*Lonsdale and Fornari*, 1980].

3. Background

3.1. Galápagos Islands and Hot Spot Tracks

[13] The main islands of the Galápagos Archipelago are located on a shallow submarine platform. Isolated volcanic islands and seamounts are located north of the platform ("Wolf-Darwin triangle" bounded by the Wolf-Darwin lineament [WDL] in the west, the CNS in the north and the 91°W transform fault in the east [Figure 1]). They are aligned in three sub-parallel, curved SE-NW trending seamount lineaments that radiate from the region around Pinta Island, intersecting the CNS at their northwestern ends [*Christie et al.*, 2001; *Harpp and Geist*, 2002]. The Galápagos Islands display a complex geochemical zonation. Enriched plume material forms a horseshoe-shaped region with depleted material, similar in composition to mid ocean ridge basalt, in its inner part [e.g., *White and Hofmann*, 1978; *Geist et al.*, 1988; *White et al.*, 1993]. The enriched horseshoe-shaped region can be subdivided into three distinct geochemical domains (Northern, Central, and Southern Galápagos Domains, typified by the islands of Pinta, Fernandina, and Floreana, respectively; *Hoernle et al.*, 2000). The Northern, Central, Southern, and Eastern Domains contain the "WD" (Wolf-Darwin), "PLUME", "FLO" (Floreana), and "DUM" (Depleted Upper Mantle) end-member compositions, respectively, as defined by *Harpp and White* [2000].

[14] Besides for a profile across the Cocos track off the coast of Costa Rica, only a few samples from the Cocos, Carnegie, Coiba, and Malpelo Ridges had been obtained by dredging or drilling previously. They comprise mainly alkali basalts and Fe-rich tholeiites but only scarce volcanological, petrological, and geochemical data are available [e.g., *Engel and Chase*, 1965; *van Andel et al.*, 1973; *Heezen and Rawson*, 1977; *Fornari et al.*, 1979; *Lonsdale and Fornari*, 1980; *Cann et al.*, 1983; *Castillo*, 1987; *Castillo et al.*, 1988; *Becker et al.*, 1989; *Hauff et al.*, 2000]. The rocks from Cocos Island, located on the northwestern flank of Cocos Ridge approximately halfway between the CNS and the Central America (Figure 1), show ocean-island-basalt (OIB)-type compositions similar to those of the enriched Galápagos domains but K/Ar and paleomagnetic dates indicate that the island is only 2 m.y. old [*Dalrymple and Cox*, 1968; *Bellon et al.*, 1983; *Castillo*, 1987; *Castillo et al.*, 1988]. *Castillo* [1987] concludes that this late-stage volcanism on Cocos Ridge was apparently caused by anomalously slow cooling of the lithosphere under the ridge whereas *Meschede et al.* [1998] postulate a second hot spot near Cocos Island.

[15] Ar-Ar age dating and morphological and geochemical studies of the profile across the Cocos track (Cocos Ridge and seamounts to the NW) off the coast of Costa Rica (Figure 1) demonstrated that the oldest (preserved) part of the Cocos track forms a now-drowned 13.0–14.5 m.y. old paleo-Galápagos Archipelago [*Werner et al.*, 1999; *Hoernle et al.*, 2000]. Volcanological studies of samples from the R/V Sonne 144-3 cruise show that islands existed continuously above the Galápagos hot spot over at least the last 17 m.y. [*Werner and Hoernle*, 2003]. The morphology and geochemical zonation of the 13.0–14.5 Ma paleo-archipelago into northern, central and southern plume domains are similar to those of the recent archipelago. The remarkable similarity in the composition and geographical distribution of the geochemical Galápagos Domains at the present hot spot and the Cocos track profile is intriguing and may suggest chemical zonation of the Galápagos plume for at least 14 m.y. [*Hoernle et al.*, 2000]. The crust underlying the paleo-Galápagos Archipelago ranges from 15 Ma in the south to 19 Ma in the north at the Fisher Ridge [*Barckhausen et al.*, 2001], as deduced from the magnetic anomalies. The Fisher Ridge, interpreted to represent a piece of uplifted ocean crust formed at the CNS, pro-

duced an age of 19.2 Ma [*Werner et al.*, 1999] in good agreement with the magnetic data.

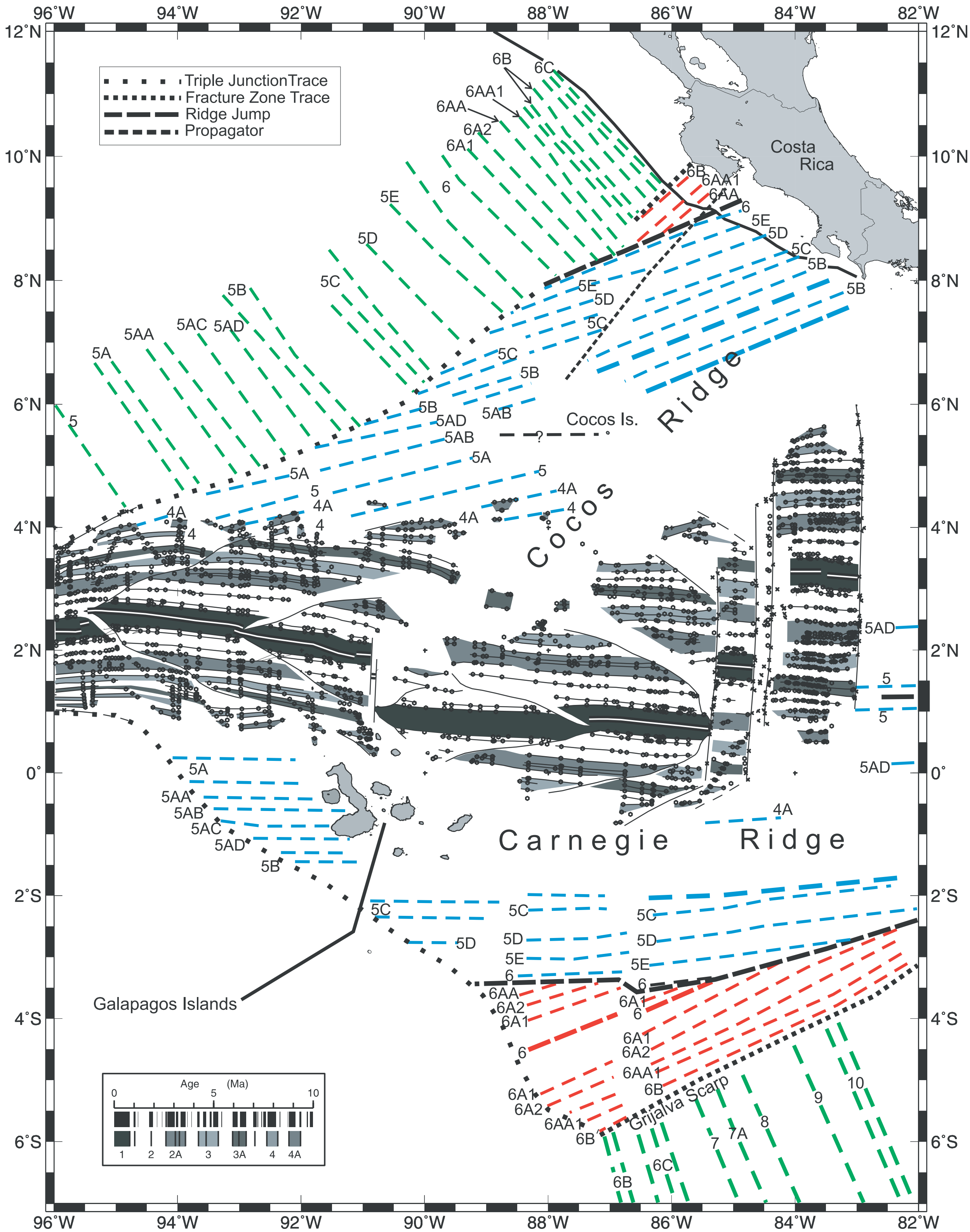
[16] The Coiba Ridge is believed to be an extension of the Cocos track offset by a transform fault, a predecessor of the Panamá fracture zone [e.g., *Hoernle et al.*, 2002]. The age of sediments overlying the Coiba Ridge have been dated paleontologically at 15 Ma, giving a minimum age for the Coiba Ridge [*van Andel et al.*, 1973]. Recent $^{40}Ar/^{39}Ar$ age results from Malpelo Island on the Malpelo Ridge (Figure 1) on the Nazca Plate south of Coiba Ridge yielded ages of 15.8–17.3 Ma, giving a minimum age for the underlying Malpelo Ridge of 17.3 Ma [*Hoernle et al.*, 2002]. The oldest parts of Carnegie Ridge off the coast of Ecuador are estimated to have formed ~20 m.y. ago [e.g., *White et al.*, 1993; *Meschede and Barckhausen*, 2001].

3.2. Plate Tectonic Evolution and Hot Spot - Spreading Axis Geometry

[17] Seafloor-spreading anomalies are reliably identified in major parts of the CNS area (Figure 2). Between 96°W and 84°W, CNS-derived anomalies from Recent to 4A (0–10 Ma according to the magnetic polarity timescale of *Cande and Kent* [1995]; this timescale is used throughout this paper) have been mapped in detail on both sides of the active CNS [*Wilson and Hey*, 1995]. This magnetic mapping allowed for a detailed reconstruction of the position of the spreading axis relative to the Galápagos hot spot for the past 8.2 Ma [*Wilson and Hey*, 1995]. The history of the hot spot - spreading axis geometry is quite complicated because the spreading center as a whole is constantly moving with components in eastern and northern directions. The eastern movement results from the fact that both the Cocos and Nazca Plates have a strong eastward component in their plate motion vectors. If the CNS axis were a straight line, this eastward movement would not affect the position of the spreading axis relative to the hot spot. However, the CNS axis is offset along N-S striking fracture zones in a number of places (Figure 1). Whenever one of these fracture zones moves east past the latitude of the Galápagos hot spot, a significant change in the position of the spreading axis relative to the hot spot occurs. The northward movement of the CNS is also a result of the Cocos and Nazca Plate motion vectors. The Nazca Plate at 5°S moves almost exactly east while the Cocos Plate at 5°N has a strong northward component [*DeMets et al.*, 1990; *Kellogg and Vega*, 1995]. With a roughly symmetrical generation of new oceanic lithosphere at the CNS (as confirmed by *Wilson and Hey* [1995] for ages <10 Ma and by *Barckhausen et al.* [2001] for older ages), the spreading axis moves northward at a rate that equals the half-spreading rate (Figure 3). The tectonic geometry is further complicated by a series of small jumps of the spreading axis to the south which slows down the northward movement and results in an asymmetric accretion of oceanic crust at the CNS [*Wilson and Hey*, 1995]. As a result of this complex tectonic geometry, the spreading axis has moved from a position directly on top of the Galápagos plume at 8.2 Ma to its present location ~170 km north of it [*Wilson and Hey*, 1995].

[18] Further in the past, it becomes very difficult to reconstruct the tectonic history of the CNS from the magnetic record with an accuracy that allows location of the position of the spreading axis relative to the Galápagos hot spot over time. At anomaly 4A (~10 Ma), the magnetic lineations in the Cocos Plate begin to swing around from an E-W to a NE-SW direction (Figure 2). This implies that the direction of Cocos Plate motion changed at that time and led to a counterclockwise rotation. Owing to the lack of data, the magnetic anomalies older than 10 Ma could not be mapped in the same

Figure 2. (opposite) Magnetic anomalies in the area of the CNS between 96°W and 82°W [modified from *Barckhausen et al.*, 2001]. The interpretation of anomalies 1 through 4A at the center of the map is from *Wilson and Hey* [1995], legend in the lower left corner of the figure. Older anomalies are labeled in the figure. Green dashed lines indicate seafloor spreading anomalies formed at the East Pacific Rise. Red dashed lines mark magnetic anomalies derived from CNS-1, blue dashed lines indicate magnetic anomalies formed at the CNS-2 after a ridge jump at 19.5 Ma. The interpreted magnetic anomalies, paleo plate boundaries, ridge jumps, and propagators reveal a complicated plate tectonic history.


96°W
94°W
92°W
90°W
88°W
86°W
84°W
82°W
12°N
10°N
8°N
6°N
4°N
2°N
0°
2°S
4°S
6°S
Triple JunctionTrace
Fracture Zone Trace
Ridge Jump
Propagator
Costa Rica
Cocos Is.
Cocos Ridge
Carnegie Ridge
Galapagos Islands
Grijalva Scarp
Age (Ma)
0
5
10
1
2
2A
3
3A
4
4A

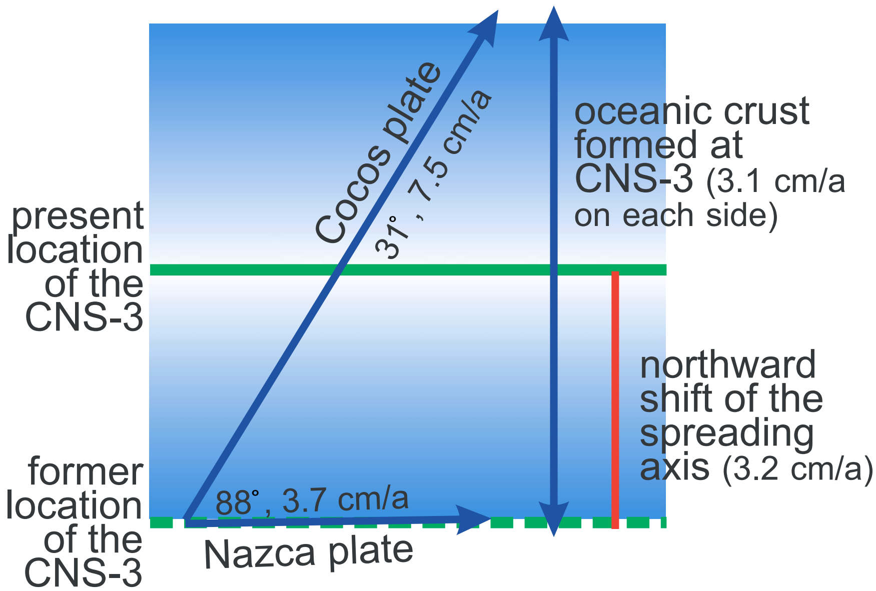


Figure 3. Absolute plate motion vectors of the Cocos and Nazca Plates [after *DeMets et al.*, 1990] used to calculate the amount of northward migration of the present CNS. The magnetic record proves that the CNS has been migrating northward for at least 10 m.y. but it is unclear if this is also true for older ages.

detailed manner with all fracture zones and propagators as the younger ones [*Barckhausen et al.*, 2001]. Critical parts of the magnetic record are buried and destroyed under the Cocos and Carnegie Ridges and only small amounts of older crust has not yet been subducted. Specifically on the Cocos Plate, only a tiny fraction of the crust formed during the break up of the Farallon Plate at ~23 Ma is preserved. From the identification of the magnetic anomalies older than 10 Ma around the CNS, however, the time of the break-up of the Farallon Plate could be derived and a general reconstruction of the following opening process in three major stages was possible [*Barckhausen et al.*, 2001]. The CNS initiated at 22.7 Ma, probably along an old SW-NE trending fracture zone of the Farallon Plate (CNS-1, Figure 4), when the fracture zone passed over the Galápagos hot spot. After a phase of fast and symmetric spreading, the spreading axis jumped to the south at 19.5 Ma and at the same time changed its strike direction by ~20° to almost E-W (CNS-2, Figure 4). Spreading continued at somewhat slower spreading rates until at ~14.5 Ma when another ridge jump to the south, possibly associated with a few degrees change in the strike direction of the spreading axis, again reshaped the plate tectonic configuration (CNS-3, Figure 4). Thereafter the current situation with symmetric spreading, increasing spreading rates to the east (leading to counterclockwise rotation of the Cocos Plate) and small ridge jumps to the south seems to have prevailed [*Barckhausen et al.*, 2001]. The southward jumps and realignments of the CNS probably reflect recapture of the northeastward drifting spreading center by the Galápagos plume. A plate tectonic reconstruction of the development of the Cocos Plate from 25 Ma to recent [*Meschede and Barckhausen*, 2000] brings together many of these findings but fails to give reliable positions of the CNS relative to the Galápagos hot spot before 10 Ma for the reasons discussed above.

4. Rock Sampling and Analytical Methods

[19] On RV Sonne cruise SO 144-3, 84 dredge and TV-grab stations were sampled on the flanks, scarps and seamounts of Cocos, Carnegie, Malpelo, and Coiba Ridges and volcanoes in the seamount domain (Figure 1, Table 1). The sampling sites are located in water depths between 3400 and 600 m below sea level (b.s.l.). Samples were also collected from major stratigraphic units

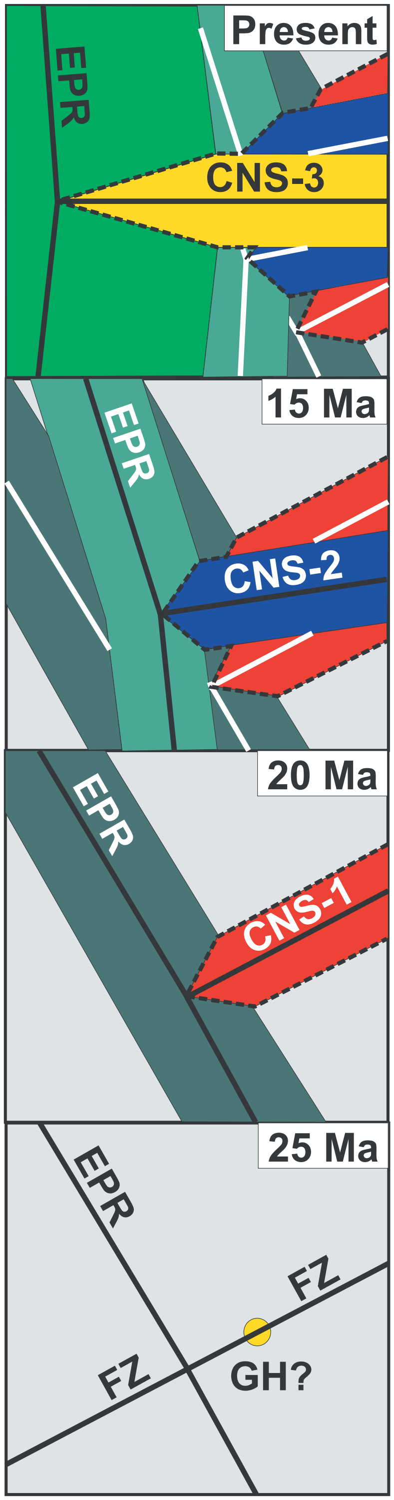


Figure 4. Schematic sketch of the development of the CNS in three stages with discontinuities at 22.7 Ma (onset of spreading along a preexisting fracture zone), 19.5 Ma (ridge jump from CNS-1 to CNS-2), and 14.7 Ma (ridge jump from CNS-2 to CNS-3).

on Cocos Island. The submarine base of the island was dredged at five stations to record the entire history of the Cocos Island volcano. Reference samples were dredged on the Cocos Plate (no. 37 DR-1: 2°35.32′N, 87°28.92′W) at a fault zone in the ocean crust formed at the CNS, on the Nazca Plate (no. 8a DR-5: 1°02′N, 82°12′W) close to a ridge-like structure believed to be an abandoned spreading center, at a fault zone north of the Malpelo Ridge (no. 2 DR-1: 5°06′N, 81°25′W), and on the CNS at the transform fault at 91°W (Figure 1, Table 1). During cruise SO 144-1, dredging on an off-axis seamount of the East Pacific Rise (EPR) off the coast of Nicaragua (no. SO 144-1: 11°06′N, 87°52′W) yielded reference samples for older (~25 Ma) crust formed at the EPR.

[20] Samples selected for geochemistry were first crushed to small pieces, then washed in deionized water and carefully handpicked under a binocular microscope. Major elements and some trace elements (e.g., Cr, Ni, Zr, Sr) of whole rock samples were determined on fused beads using a Phillips X'Unique PW1480 X-ray fluorescence spectrometer (XRF) equipped with a Rh-tube at GEOMAR.

[21] Sr-Nd-Pb isotope analyses were carried out on whole rock powders and glass chips that were leached in hot 6N HCl and cold 2N HCl (18 DR glass) respectively for one hour prior to dissolution in order to minimize the effects of alteration, in particular seawater alteration. Samples 13DR, 26TVG, 35bDR, 43DR, and 74DR were not leached (except for Sr-isotope analyses) because Pb loss into the leachate was too high in these samples to obtain sufficient Pb for analyses. Chemical separation procedures for Sr, Nd and Pb followed those described in *Hoernle and Tilton* [1991]. Sr, Nd and Pb isotope ratios were determined on a Finnigan MAT 262-RPQ2+ thermal ionization mass spectrometer at GEOMAR. Replicate analyses of Sr-Nd-Pb isotope ratios on the same samples were within the analytical uncertainties. Sr was measured in static mode and $^{87}Sr/^{86}Sr$ ratios are normalized within-run to $^{86}Sr/^{88}Sr$ = 0.1194. The long-term reproducibility of NBS987 over the course of this study gave $^{87}Sr/^{86}Sr$ = 0.710249 ± 0.000022 (N = 160; all

Table 1. Sample Locations

Sample ID	Location	Latitude	Longitude	Water Depth (on Bottom)
		Seamounts		
48 DR-1	Costa Rica seamount province	06°47.74′N	085°22.88′W	1517 m
60 DR-2	Costa Rica seamount province	07°23.20′N	085°11.18′W	1723 m
74 DR-1	Costa Rica seamount province	07°23.02′N	086°31.29′W	2210 m
78 DR-1	Costa Rica seamount province	08°06.88′N	085°47.50′W	1465 m
69 DR-1	Cocos Island seamount prov.	05°12.52′N	087°56.77′W	2077 m
71 DR-1	Cocos Island seamount prov.	05°30.96′N	088°34.79′W	1251 m
42 DR-1	Cocos Island seamount prov.	05°08.68′N	087°32.60′W	2050 m
Cocos 11	Cocos Island (Wafer Valley)			
Cocos 17	Cocos Island (Bahia Chatham)			
Cocos 27	Cocos Island (Bahia Chatham)			
Cocos 34	Cocos Island (Bahia Wafer)			
Cocos 36	Cocos Island (Bahia Wafer)			
Cocos 37	Cocos Island (Bahia Wafer)			
Cocos 39	Cocos Island (Bahia Wafer)			
Cocos 42	Cocos Island (Top of Cerro Iglesias)			
64 DR-1	Cocos Island (submarine base)	05°45.66′N	086°54.08′W	1802 m
30 DR-1	Southwest seamount province	03°08.51′N	091°06.00′W	2436 m
33 DR-1	Southwest seamount province	03°53.88′N	089°13.62′W	1694 m
		Ridges		
3 TVG-4	Malpelo Ridge	04°28.02′N	080°54.34′W	916 m
5 DR-1	Malpelo Ridge	04°33.94′N	080°41.98′W	1639 m
6 DR-4	Malpelo Ridge	04°09.32′N	081°16.51′W	1564 m
7 DR-1	Malpelo Ridge	04°19.92′N	081°52.48′W	3000 m
11a DR-1	Carnegie Ridge	00°03.33′N	082°07.34′W	1446 m
12 DR-1	Carnegie Ridge	00°23.89′N	081°27.18′W	2364 m
13 DR-1	Carnegie Ridge	00°26.20′S	081°59.51′W	1250 m
17 TVG-1	Carnegie Ridge	02°09.83′S	082°36.64′W	1899 m
18 DR-1	Carnegie Ridge	02°13.55′S	083°40.94′W	2449 m
26 TVG-1	Carnegie Ridge	00°18.01′N	084°58.54′W	1388 m
28 DR-1	Carnegie Ridge	02°04.26′S	085°55.00′W	2495 m
35b DR-1	S-Cocos Ridge	03°22.65′N	088°18.37′W	1710 m
38 DR-12	S-Cocos Ridge	04°21.59′N	085°47.05′W	2419 m
43 DR-1	N-Cocos Ridge	05°18.60′N	085°22.67′W	2066 m
44 DR-14	N-Cocos Ridge	05°58.10′N	083°40.03′W	2961 m
49a DR-1	N-Cocos Ridge	06°56.39′N	084°14.95′W	1615 m
53 DR-1	N-Cocos Ridge	07°36.24′N	083°25.21′W	1530 m
88 DR-1	Coiba Ridge	06°12.27′N	081°56.93′W	1848 m
90 DR-8	Coiba Ridge	05°35.55′N	081°35.07′W	1571 m
		Reference Samples		
2 DR-1	CNS-crust	05°06.33′N	081°25.02′W	3354 m
8a DR-5	CNS-crust	01°01.56′N	082°11.40′W	3375 m
37 DR-1	CNS-crust	02°35.32′N	087°28.92′W	3328 m
29a DR-5	91° transform (CNS)	01°35.20′N	090°47.31′W	2428 m
SO 144-1	Nicaragua-seamount	11°05.93′N	087°51.73′W	3300 m

reported errors are ±2sigma). The $^{143}Nd/^{144}Nd$ ratios are normalized within-run to $^{146}Nd/^{144}Nd$ = 0.7219 and measured in multi dynamic mode. The La Jolla standard yields a long-term average for $^{143}Nd/^{144}Nd$ of 0.511841 ± 0.000011 (N = 73). Our inhouse Nd standard Spex gives $^{143}Nd/^{144}Nd$ = 0.511709 ± 0.000013 (N = 134) over the same period. All Pb isotope analyses were corrected for fractionation using the NBS981 values of *Todt et al.* [1996].

5. Results

5.1. Composition of the Rock Samples

[22] The Cocos, Carnegie, Coiba and Malpelo Ridges and associated seamounts yielded a broad

spectrum of rock types including lava (e.g., pillow and sheet lava fragments), subvolcanic and plutonic rocks (e.g., gabbro), peridotite, volcaniclastic rocks (e.g., hyaloclastite, scoria, pumice) and sedimentary rocks (e.g., clay-, silt- and limestone, conglomerate, turbidite). The samples vary from fresh to deeply weathered. The most common alteration products are palagonite, iddingsite, chlorite, and iron oxides. Hydrothermal alteration involving silicification, development of clay minerals, and occasional development of pyrite ± pyrrhotite has affected some samples, in particular many of the gabbroic rocks.

[23] Petrographically, olivine-, olivine-pyroxene- and plagioclase-bearing lavas dominate. Gabbro occurs in a 100 km-wide band along the SE margin of the Cocos Ridge at the Panamá fracture zone suggesting that cross-sections through the ridge have been exposed, most likely by movement along the Panamá fracture zone.

[24] Analyzed samples from the ridges and seamounts range from basalt to trachytes with SiO_2 = 45–61 wt.% and MgO = 1.0–10.3 wt.%. There is a general difference in chemical composition between the seamount provinces and the ridge along the Cocos track (Figure 5). Samples from the Cocos Ridge are exclusively tholeiitic. The volcanic rocks from the seamounts range from tholeiitic to alkalic compositions, but most of them are alkalic. Lavas from the southwest province are tholeiitic basalts and basaltic andesites, whereas those from the seamounts off the coast of Costa Rica extend to higher contents of alkalies (Na_2O and K_2O) at similar SiO_2 and range from basalts to hawaiites. The volcanic rocks from the Cocos Island seamount province generally have alkalic compositions and range from alkali basalts and hawaiites to trachytes (Figure 5a). The samples from the Carnegie, Coiba, and Malpelo Ridges are generally tholeiitic and fall in a narrow field ranging from basalts to basaltic andesites (Figure 5b).

5.2. Sr-Nd-Pb-Isotope Geochemistry

[25] The Sr-Nd-Pb isotope data are presented in Tables 2a and 2b. With one exception (sample no. 28 DR-1 from Carnegie Ridge), all analyzed samples from the Galápagos hot spot tracks have higher Sr and Pb and lower Nd isotopic compositions compared to MORB from the CNS or EPR and plot closely to the four geochemical domains defined by the Sr-Nd-Pb isotopic composition of the present Galápagos Archipelago [hereafter referred to as Northern, Central, Southern, and Eastern Galápagos Domains as defined by *Hoernle et al.*, 2000] (Figure 6). It should be noted that the term domains simply refer to geographic regions in the Galápagos Archipelago in which the volcanic rocks have distinct isotopic compositions. The sample taken from the 91°W transform fault (no. 29a DR-5) at the CNS directly north of the Galápagos Islands has isotopically enriched signatures with Sr and Pb being more radiogenic and Nd being less radiogenic than CNS and EPR-MORB samples (samples no. 2, 8a, 37, and from the seamount off the coast of Nicaragua; Figure 6). The occurrence of geochemically enriched material at the 91° transform fault may suggest northward flow of Galápagos plume material to this area of the spreading center.

[26] The rocks analyzed from volcanoes of the seamount provinces have isotopic compositions that overlap with those of the Northern and Central Galápagos Domains (Figures 6 and 7). All samples from the Costa Rica seamount province [this study; *Hoernle et al.*, 2000] plot within or on an extension of the field of the Northern Galápagos Domain. The samples from the southwest seamount province and the Cocos Island seamount province fall within the relatively narrow field for the Central Galápagos Domain. The rocks from Cocos Island and its submarine base show very little variation in isotopic composition with $^{87}Sr/^{86}Sr$ = 0.70297 – 0.70306, $^{143}Nd/^{144}Nd$ = 0.51296 – 0.51299, $^{206}Pb/^{204}Pb$ = 19.12 – 19.29, $^{207}Pb/^{204}Pb$ = 15.57 – 15.59, and $^{208}Pb/^{204}Pb$ = 38.83 – 38.97, similar to the previously published Sr-Nd-Pb isotopic data from Cocos Island [*Castillo*, 1987; *Castillo et al.*, 1988].

[27] The samples analyzed from the Cocos Ridge show a wide range in isotopic composition overlapping all four geochemical Galápagos Domains (Figures 6 and 7). The northeastern and southwestern parts of the Cocos Ridge show significant

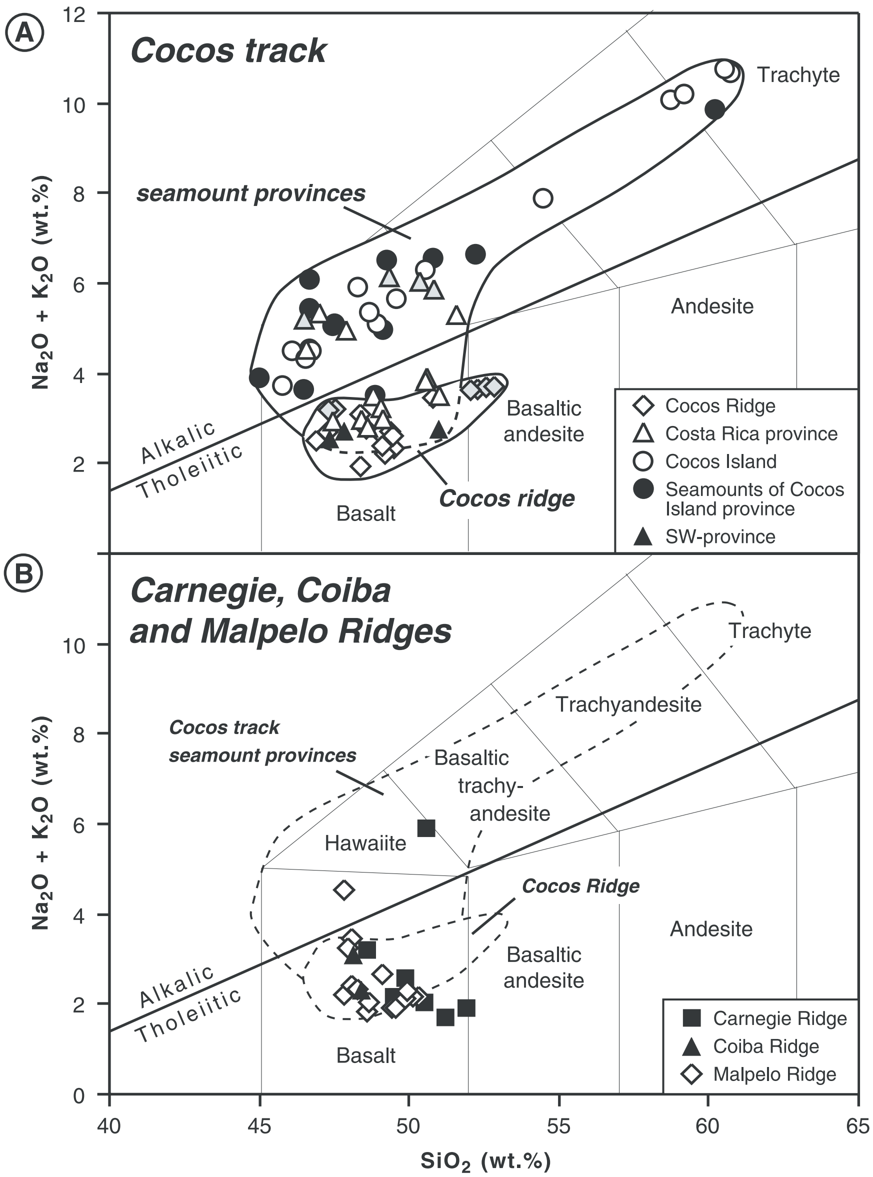


Figure 5. Major element data of whole rock samples from (a) Cocos track and (b) Carnegie, Coiba, and Malpelo Ridges illustrated by total alkali-silica diagrams after *Le Bas et al.* [1986]. Tholeiitic basalts dominate at Cocos, Carnegie, Coiba, and Malpelo Ridges, whereas volcanic rocks from the seamount provinces northwest of Cocos Ridge range from tholeiitic basalts and hawaiites to trachytes (fields for the seamount provinces and Cocos Ridge include data from the 13.0–14.5 Ma Cocos track, *Hoernle et al.*, 2000).

differences in isotopic composition. Samples from the southwestern part have similar isotopic compositions and fall in the field for the Central Galápagos Domain whereas those from the northeastern part [this study; *Hoernle et al.*, 2000] exhibit large variations (Figures 6 and 7). The westernmost samples of the northeastern part of the ridge fall into field of the Northern Galápagos Domain. The samples taken from the central part as well as a sample drilled nearby (DSDP Site 158, data from *Hauff et al.* [2000]) fall into the field of the Central Galápagos Domain and the samples taken a bit further east into the field for the Southern Galápagos Domain. The two samples dredged at the northeastern edge of the Cocos Ridge are relatively depleted in composition. Their

Table 2a. Sr-Nd-Pb Isotope Data for the Seamount Provinces Determined by Thermal Ionization Mass Spectrometry

Sample ID	Location	$^{87}Sr/^{86}Sr$	2σ	$^{143}Nd/^{144}Nd$	2σ	$^{206}Pb/^{204}Pb$	2σ	$^{207}Pb/^{204}Pb$	2σ	$^{208}Pb/^{204}Pb$	2σ
48 DR-1	Costa Rica seamount province	0.703359	0.000008	0.512917	0.000008	19.330	0.003	15.559	0.002	39.112	0.006
60 DR-2	Costa Rica seamount province	0.703554	0.000008	0.512885	0.000003	19.360	0.001	15.571	0.001	39.090	0.001
74 DR-1	Costa Rica seamount province	0.703982	0.000003	0.512978	0.000003	19.028	0.002	15.557	0.001	38.892	0.003
78 DR-1	Costa Rica seamount province	0.703572	0.000009	0.512838	0.000008	19.277	0.002	15.591	0.002	39.291	0.004
69 DR-1	Cocos Island seamount prov.	0.702974	0.000010	0.512986	0.000008	19.231	0.003	15.575	0.003	38.827	0.007
71 DR-1	Cocos Island seamount prov.	0.703163	0.000006	0.513018	0.000006	19.274	0.001	15.591	0.001	38.979	0.002
42 DR-1	Cocos Island seamount prov.	0.702924	0.000008	0.513007	0.000008	19.197	0.001	15.573	0.001	38.781	0.001
Cocos 11	Cocos Island	0.702972	0.000007	0.512972	0.000009	19.235	0.001	15.572	0.000	38.871	0.001
Cocos 17	Cocos Island	0.703057	0.000008	0.512963	0.000006	19.292	0.001	15.579	0.001	38.974	0.002
Cocos 27	Cocos Island	0.703023	0.000007	0.512977	0.000007	19.273	0.001	15.578	0.001	38.917	0.001
Cocos 34	Cocos Island	0.703010	0.000007	0.512988	0.000007	19.191	0.003	15.578	0.003	38.845	0.006
Cocos 36	Cocos Island	0.703003	0.000007	0.512970	0.000005	19.190	0.004	15.572	0.004	38.826	0.009
Cocos 37	Cocos Island	0.702994	0.000007	0.512981	0.000008	19.224	0.001	15.576	0.001	38.861	0.002
Cocos 39	Cocos Island	0.703063	0.000008	0.512964	0.000007	19.257	0.001	15.577	0.001	38.979	0.001
Cocos 42	Cocos Island	0.702995	0.000008	0.512987	0.000005	19.195	0.001	15.572	0.001	38.837	0.002
64 DR-1	Cocos Island (submarine base)	0.703040	0.000007	0.512976	0.000007	19.123	0.001	15.590	0.001	38.849	0.003
30 DR-1	Southwest seamount province	0.702999	0.000006	0.512960	0.000008	19.403	0.004	15.593	0.003	39.165	0.009
33 DR-1	Southwest seamount province	0.703161	0.000009	0.512943	0.000013	19.278	0.003	15.583	0.002	39.050	0.005

slightly more enriched composition compared to CNS and MORB and the occurrence of vesicular lavas and beach cobbles at these sites indicate shallow to subaerial eruption at a (paleo-) Galápagos Archipelago. Therefore we attribute these samples to the Eastern Galápagos Domain rather than to ocean crust formed at the CNS. The presence of Eastern Domain signatures exclusively on the southeastern flank of the Cocos Ridge suggests that it may reflect the composition of deeper portions of the ridge.

[28] The samples from Carnegie and Malpelo Ridges have isotopic compositions similar to those of the Southern, Central and Eastern Galápagos Domains; none fall into the Northern Domain. Three samples from the Carnegie Ridge are enriched and fall into the field for the Southern Galápagos Domain (Figures 6 and 7), whereas 4 samples have depleted compositions. Three of the depleted samples, as well as a DSDP sample drilled at Site 157 (data from *Hauff et al.* [2000]), are slightly enriched compared to CNS and MORB. The high vesicularity of the dredged rocks and the occurrence of conglomerates at station 13 suggest shallow water to subaerial eruptions at volcanic islands. Therefore we attribute these samples to the Eastern Galápagos Domain rather than to the ocean crust. Sample 28 DR-1, however, is a pillow fragment with small vesicles and falls into the field for CNS and MORB. It has been dredged from a seamount at the southern edge of Carnegie Ridge and it remains unclear whether it has been formed at the CNS or the Galápagos hot spot. The three samples plotting within the Southern Domain were dredged from the flanks of the Carnegie Ridge and thus may be derived from deeper levels of the ridge than the Eastern Domain samples from the top of the ridge, opposite of what was observed at the northeastern Cocos Ridge. Three of four analyzed samples from Malpelo Ridge have similar isotopic compositions and fall into the field for the Central Galápagos Domain. The remaining sample shows slightly more radiogenic Pb-isotope ratios and plots on the boundary with the Southern Galápagos Domain (Figures 6 and 7).

[29] The analyzed samples from Coiba Ridge have similar isotopic compositions to those from Mal-

Table 2b. Sr-Nd-Pb Isotope Data for Cocos, Carnegie, Malpelo, and Coiba Ridges and Reference Samples Determined by Thermal Ionization Mass Spectrometry

Sample ID	Location	$^{87}Sr/^{86}Sr$	2σ	$^{143}Nd/^{144}Nd$	2σ	$^{206}Pb/^{204}Pb$	2σ	$^{207}Pb/^{204}Pb$	2σ	$^{208}Pb/^{204}Pb$	2σ
				Isotope Data							
3 TVG-4	Malpelo Ridge	0.703139	0.000008	0.512953	0.000008	19.307	0.001	15.575	0.001	39.064	0.003
5 DR-1	Malpelo Ridge	0.703081	0.000008	0.512963	0.000005	19.429	0.026	15.632	0.020	39.225	0.050
6 DR-4	Malpelo Ridge	0.703514	0.000007	0.512949	0.000008	19.346	0.002	15.593	0.002	39.106	0.005
7 DR-1	Malpelo Ridge	0.703182	0.000006	0.512932	0.000008	19.325	0.003	15.590	0.002	39.049	0.006
7 DR-1 (D)	Malpelo Ridge	0.703204	0.000007	0.512920	0.000008	19.327	0.003	15.583	0.003	39.025	0.007
11a DR-1	Carnegie Ridge	0.703225	0.000007	0.512966	0.000013	19.621	0.011	15.615	0.009	39.226	0.023
12 DR-1	Carnegie Ridge	0.703227	0.000007	0.512955	0.000008	19.498	0.006	15.610	0.005	39.184	0.013
13 DR-1	Carnegie Ridge					18.885	0.001	15.615	0.001	38.760	0.002
17 TVG-1	Carnegie Ridge	0.703557	0.000007	0.513007	0.000010	20.364	0.005	15.700	0.004	39.854	0.010
18 DR-1	Carnegie Ridge	0.703094	0.000007	0.513082	0.000010						
26 TVG-1	Carnegie Ridge	0.702842	0.000003	0.513043	0.000003	18.873	0.001	15.526	0.001	38.254	0.002
28 DR-1	Carnegie Ridge	0.702813	0.000007	0.513066	0.000007	18.567	0.005	15.501	0.004	38.127	0.009
35b DR-1	S-Cocos Ridge	0.703212	0.000003	0.513035	0.000003	19.312	0.005	15.581	0.004	38.849	0.010
38 DR-12	S-Cocos Ridge	0.703059	0.000008	0.512934	0.000008	19.342	0.001	15.595	0.001	38.999	0.003
43 DR-1	N-Cocos Ridge	0.702852	0.000003	0.513048	0.000003	18.852	0.001	15.530	0.001	38.327	0.003
44 DR-14	N-Cocos Ridge	0.703219	0.000009	0.513024	0.000008	19.000	0.008	15.543	0.007	38.489	0.017
49a DR-1	N-Cocos Ridge	0.703188	0.000008	0.512960	0.000008	19.161	0.003	15.572	0.003	38.742	0.006
53 DR-1	N-Cocos Ridge	0.703269	0.000007	0.512946	0.000007	19.560	0.006	15.594	0.005	39.175	0.012
88 DR-1	Coiba Ridge	0.703067	0.000008	0.512975	0.000010	19.444	0.001	15.598	0.001	39.055	0.003
90 DR-8	Coiba Ridge	0.703049	0.000009	0.512959	0.000012	19.276	0.003	15.582	0.003	38.906	0.007
				Reference Samples							
2 DR-1	CNS-crust	0.702424	0.000007	0.513153	0.000009	18.347	0.004	15.484	0.003	37.901	0.008
8a DR-5	CNS-crust	0.702530	0.000003	0.513139	0.000003	18.462	0.005	15.500	0.004	37.948	0.009
37 DR-1	CNS-crust	0.702954	0.000009	0.513099	0.000009	18.590	0.003	15.514	0.002	38.129	0.006
29a DR-5	91° transform (CNS)	0.702803	0.000008	0.513041	0.000009	18.920	0.004	15.550	0.004	38.521	0.009
SO 144-1	Nicaragua-seamount	0.702668	0.000007	0.513124	0.000008	18.436	0.005	15.499	0.004	38.053	0.011
SO 144-1 (D)	Nicaragua-seamount	0.702684	0.000007	0.513110	0.000008	18.431	0.004	15.491	0.004	38.027	0.009

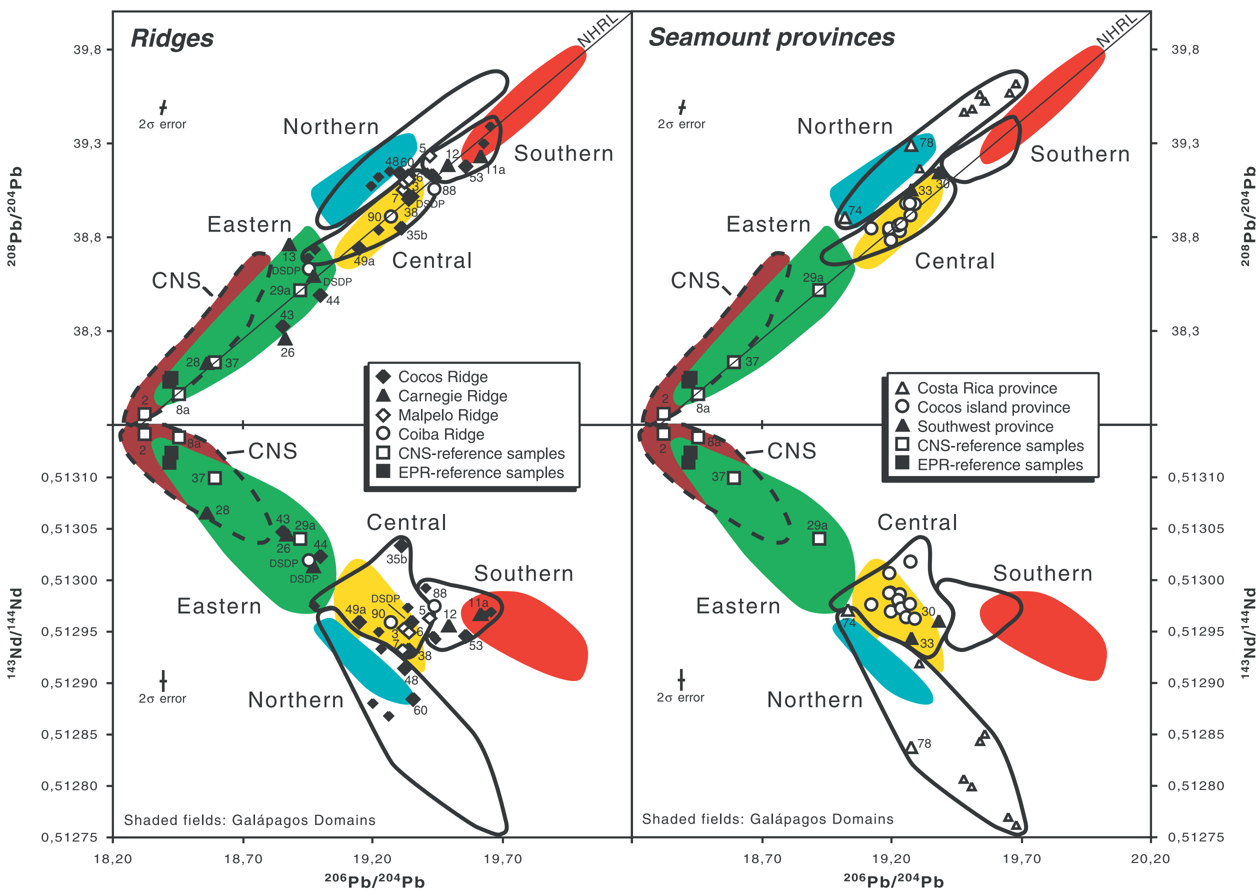


Figure 6. $^{206}Pb/^{204}Pb$ versus $^{208}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ versus $^{143}Nd/^{144}Nd$ isotope correlation diagrams illustrate that all analyzed samples from Cocos, Carnegie, Malpelo, and Coiba Ridges have isotopic compositions similar to those of Southern, Central, Northern, and Eastern Galápagos Domains (shaded fields). The analyzed samples from the seamount provinces overlap the fields for the Central and Northern Galápagos Domain. No samples from the Nazca Plate fall into the northern field. Compositions of selected reference samples for CNS and EPR are also shown. Numbers next to plot symbols refer to sample numbers, small symbols represent data of the 13.0–14.5 Ma Cocos track profile taken from *Hoernle et al.* [2000]. Fields for Galápagos Domains are according to *Hoernle et al.* [2000], Galápagos Island data and field for CNS are from *White et al.* [1993], DSDP-data are from *Hauff et al.* [2000].

pelo Ridge and overlap the field for the Central Galápagos Domain, whereas a DSDP sample drilled at Site 155 on the eastern flank of the Coiba Ridge (data from *Hauff et al.* [2000]) shows signatures of the Eastern Galápagos Domain.

[30] In summary, the samples from the northeastern part of the Cocos track exhibit the widest range in isotopic composition with signatures of the Northern, Central, Southern and Eastern Galápagos Domains, respectively, from NW to SE. Samples from the Coiba Ridge have Central and Eastern Domain compositions. The Eastern Domain compositions at both the northeastern Cocos and Coiba Ridges occurs only on the eastern flanks of the ridge, possibly reflecting derivation from a deeper stratigraphic level than the other samples. All samples from the southwestern part of the Cocos track fall exclusively in the field of the Central Galápagos Domain (Figure 7). Samples showing signatures of the Eastern Galápagos Domain dominate at the Carnegie Ridge; however, Southern Domain signatures were obtained from the flanks of the ridge, opposite of the northeastern Cocos and Coiba Ridges. Central Galápagos Domain signatures dominate at the Malpelo Ridge. Samples

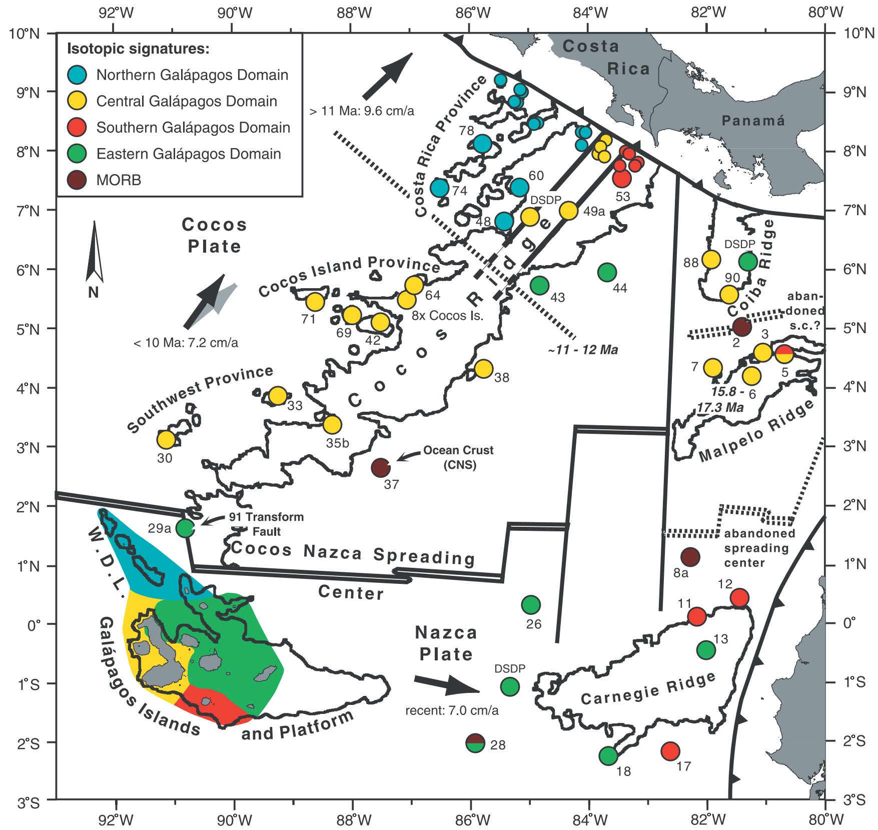


Figure 7. Overview map illustrating the geographic position of the geochemical Galápagos domains (according to *Hoernle et al.* [2000]) and their distribution on aseismic ridges and associated seamounts between the Galápagos Islands and Central and South America. The enriched Northern, Central, and Southern Domains of the present Galápagos Archipelago occur in the same relative geographic positions along the northeastern part of the Cocos track (small symbols represent data from *Hoernle et al.* [2000]), whereas the southwestern part of the Cocos track appears to be homogeneous in isotopic composition with signatures of the Central Galápagos Domain. The change in geochemical composition along the Cocos track (denoted by the dashed line) correlates with a change in morphology and can be dated at ∼11–12 Ma based on magnetic data and plate motion rates. On the Nazca Plate, samples with signatures of the Southern and Eastern Galápagos Domains dominate at the Carnegie Ridge and those with signatures of the Central Galápagos Domain at the Malpelo Ridge. Relative plate motion rates and directions for the Cocos Plate are from *Kellogg and Vega* [1995], *Wilson* [1996], and *Barckhausen et al.* [2001]; numbers next to sample locations refer to sample numbers.

with isotopic compositions similar to the Northern Domain were not found east of 90°W on Nazca Plate.

6. Discussion

6.1. Origin of the Malpelo and Coiba Ridges

[31] All samples from the Cocos track and the Carnegie, Malpelo, and Coiba Ridges have isotopic compositions similar to volcanic rocks of the Galápagos Archipelago, indicating an origin of these structures from the Galápagos hot spot (Figure 6). While the Cocos and Carnegie Ridges are "typical" hot spot tracks extending from the Galápagos hot spot in the direction of plate motion, the origin and evolution of the Coiba and Malpelo Ridges are still somewhat problematic.

6.1.1. Coiba Ridge

[32] The Coiba Ridge is located south of Panamá in the area where subduction ceased within the Neogene. The geochemistry of dredged rock samples and of a DSDP sample [*Hauff et al.*, 2000] confirms that it also formed as part of a Galápagos hot spot track. The age of the Coiba

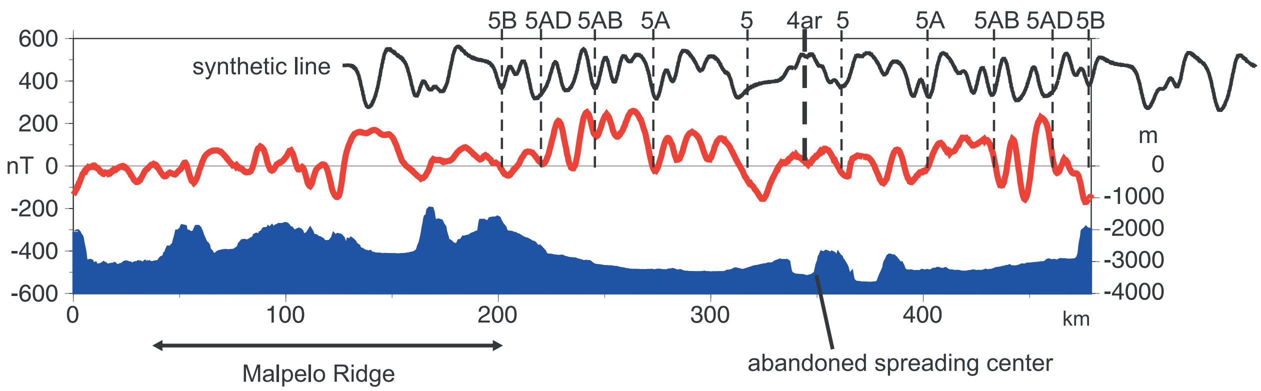


Figure 8. Magnetic profile acquired at 82.5°W between Malpelo and Carnegie Ridge with interpretation and bathymetry.

Ridge at the DSDP site 155 must be greater than 15 Ma based on the age of the sediment cover [*van Andel et al.*, 1973]. The crust underlying the ridge formed during the initial opening of the CNS as part of the Cocos Plate and is 22.7–21.0 m.y. old [*Barckhausen et al.*, 2001], placing a maximum age on the formation of the Coiba Ridge. The spreading center between the Coiba and Malpelo Ridges may have been abandoned during the plate tectonic reorganization at 19.5 Ma (jump from CNS-1 to CNS-2, Figure 4). We will discuss further constraints on the age and origin of the Coiba Ridge below.

6.1.2. Malpelo Ridge

[33] It has been suggested that the Malpelo Ridge originally formed as the oldest part of the Cocos Ridge and was later sheared off along the Panamá fracture zone and thus transferred from the Cocos to the Nazca Plate [e.g., *Hey*, 1977; *Sallarès and Charvis*, 2003]. However, an abandoned spreading center was identified south of the Malpelo Ridge and approximately halfway to the northern flank of the Carnegie Ridge (Figure 1) [*Lonsdale and Klitgord*, 1978]. Accordingly sample 8a DR-5, taken close to this ridge-like structure, clearly shows MORB-composition (Figure 6). A new magnetic profile acquired during cruise SO-144-3 confirms that the Malpelo Ridge was once attached to the northern flank of the Carnegie Ridge but was subsequently rifted away [*Pennington*, 1981; *Hardy*, 1991]. The interpretation of the data shows that seafloor spreading occurred between the two ridges in a time interval from approximately 14.5 Ma to 9.5 Ma (Figure 8). Spreading was almost symmetric at a half-spreading rate of 2.5 cm/yr. The age span during which the spreading axis was active covers exactly the time interval between the ridge jump of the main spreading axis at the Cocos-Nazca Plate boundary at 14.5 Ma (Figure 4) and the activation of the Panamá Fracture Zone at 9.5 Ma [*Hey*, 1977]. Therefore we suggest that at 14.5 Ma a segment of the Cocos-Nazca spreading axis jumped from a position north of the Carnegie Ridge (abandoned spreading center between Malpelo and Coiba Ridges) ~60 km to the south into the northern flank of the Carnegie Ridge. The spreading axis remained active at this position until the activation of the Panamá fracture zone at 9.5 Ma caused seafloor spreading in the eastern Panamá basin to be abandoned. The 15.8–17.3 Ma age of rocks from Malpelo Island [*Hoernle et al.*, 2002] matches very well the predicted age of the Carnegie Ridge [*White et al.*, 1993; *Meschede and Barckhausen*, 2001] in the region around 83°W where the Malpelo Ridge must originally have been attached.

[34] The morphology along the profile between Malpelo and Carnegie Ridges (Figure 8) displays a generally smooth oceanic crust to both sides of the abandoned spreading center. The former spreading axis is marked by a 500 m deep axial valley which is typical for abandoned slow spreading centers. A similar depression just 30 km to the south seems to have no major effect on the magnetic anomalies and may be the result of irregular

spreading processes shortly before the seafloor spreading was abandoned in this area. Malpelo Ridge has a rugged morphology and is clearly bounded against the smooth oceanic crust on its southern edge (profile km 200 in Figure 8). Close to the end of the profile, the northern edge of Carnegie Ridge is marked by a 1000 m high step which clearly separates the ridge form the smooth oceanic crust generated at the now abandoned spreading center and which is interpreted as the conjugate to the southern edge of Malpelo Ridge. The identical maximum crustal thickness of the Malpelo and eastern Carnegie Ridges (19.1 and 19.0 km, respectively [*Sallarès and Charvis*, 2003, and references therein]) provide additional support for this reconstruction.

6.2. Chemical Zonation of Hot Spot Tracks and Galápagos Plume

[35] One of the most striking features of the present Galápagos Archipelago is the spatial variation in chemical composition of the Galápagos lavas [e.g., *White and Hofmann*, 1978; *Geist et al.*, 1988; *Vicenzi et al.*, 1990; *White et al.*, 1993; *Hoernle et al.*, 2000; *Harpp and White*, 2001]. *White et al.* [1993] propose thermal entrainment of depleted asthenosphere by an enriched mantle plume bent by velocity shear in direction of the plate movement in the uppermost asthenosphere to explain the presence of depleted lavas within a horseshoe of more enriched material. This model predicts hot spot tracks on the Cocos and Nazca Plates with stripes of enriched Galápagos material bounding a depleted central stripe. Volcanic rocks with enriched compositions in the center of the hot spot tracks are presumably buried beneath those of depleted material as the plate moves away from the hot spot.

[36] *Hoernle et al.* [2000] subdivided the horseshoe-shaped region of plume components at the present Galápagos Archipelago into three distinct (enriched) geochemical domains (Northern, Central, and Southern Galápagos Domain) and showed that these same domains occur in the same relative geographic positions with respect to morphology at the 13.0–14.5 Ma Cocos track off the coast of Costa Rica. It was proposed that the same geographic pattern of geochemical zonation of the hot spot track off the coast of Costa Rica as at the present archipelago could reflect a long-term zonation of the Galápagos plume, implying laminar flow within the plume and possibly preservation of heterogeneities from the plume source in the lower mantle. A major goal of the SONNE 144-3 cruise was to determine if this zonation was continuous or episodic.

[37] Our data as well as those from *Hoernle et al.* [2000] show that the Cocos track (Cocos and Coiba Ridges) are dominated by the Northern and Central Galápagos Domains with Eastern Domain compositions being obtained from the eastern flanks of both ridges (Figure 7). On the other hand, the Nazca track (Carnegie and Malpelo Ridges) are dominated by the Central, Southern and Eastern Galápagos Domains with the Central and Southern Domain samples coming from the flanks of the ridges. Furthermore, the data presented here confirm that the northeastern Cocos track (northeastern Cocos Ridge and Costa Rica seamount province off the coast of Costa Rica) can be subdivided into stripes running parallel to the track axis with geochemical signatures of the enriched Northern, Central and Southern Galápagos Domains (from NW to SE, Figure 7) in the same geographic relationship as found for the enriched plume material above the Galápagos hot spot at present. Therefore in a crude sense, the present zonation of the Galapagos hot spot is preserved in the hot spot tracks. Nevertheless there are some significant discrepancies that need to be taken into consideration before continuous zonation of the Galápagos plume over the last 20 Ma can be confirmed.

[38] The main difference between the northeastern Cocos track and the <5 Ma Galápagos hot spot products is the apparent absence of the depleted Eastern Domain at the hot spot track. *Hoernle et al.* [2000] relate this difference to the relative position of the CNS to the plume in the Middle Miocene, i.e., to a position of the CNS south of the focus of the hot spot instead of to the north as is the present case. As plume material flows to the spreading center, it is depleted of enriched components through melt extraction [*Hoernle et al.*, 2000] and mixes with upper asthenospheric MORB-

source mantle (DMM) [*White et al.*, 1993], resulting in the more depleted compositions observed in the Eastern Domain of the Galápagos Archipelago. If the CNS is located south of the plume center, then the depleted lavas are buried by younger enriched lavas as the Cocos Plate moves to the northeast over the plume center [*Hoernle et al.*, 2000]. Accordingly, rocks which have been attributed to the Eastern Galápagos Domain have only been dredged at the base of northeastern Cocos Ridge (Figure 7, samples 43 and 44) where sections through the ridge appear to have been exposed by tectonic processes.

[39] On the paleo-Nazca track (i.e., before the Malpelo Ridge split off from Carnegie Ridge) geochemical signatures of the Southern and Eastern Galápagos Domains dominate in the southern part (present Carnegie Ridge) and those of the Central Galápagos Domain in the northern part (Malpelo Ridge) (Figure 7). A (voluminous) hot spot track on the Nazca Plate will only be formed if the CNS is located directly above or north of the center of the hot spot. Considering the eastward motion of the Nazca Plate, the Eastern Domain should dominate the composition of the hot spot track, since Eastern Domain lavas are erupted on lavas derived from the Southern, Central and Northern Domains to the west. The dominant component beneath the Eastern Domain volcanic rocks should be the Southern and possibly the Central Domain volcanic products, depending on the exact location of the CNS to the hot spot (cf. Figure 9). Lavas from the Northern Domain will be deposited on the Cocos Plate unless the CNS is well north of the center of the hot spot as is the case at the present but wasn't in the past. Consistent with the zoned plume model of *Hoernle et al.* [2000], only Eastern, Southern and Central Domain compositions occur on the Nazca Plate east of the Galápagos Platform. Interestingly, the Southern and Central Domain samples were only obtained on the margins of the Carnegie and Malpelo Ridges, where deeper stratigraphic levels of the ridges may have been exposed to dredging. Finally there is a clear change in the enriched domains from the Southern Domain at the Carnegie Ridge to the Central Domain at the Malpelo Ridge, once forming the northern part of the Carnegie Ridge.

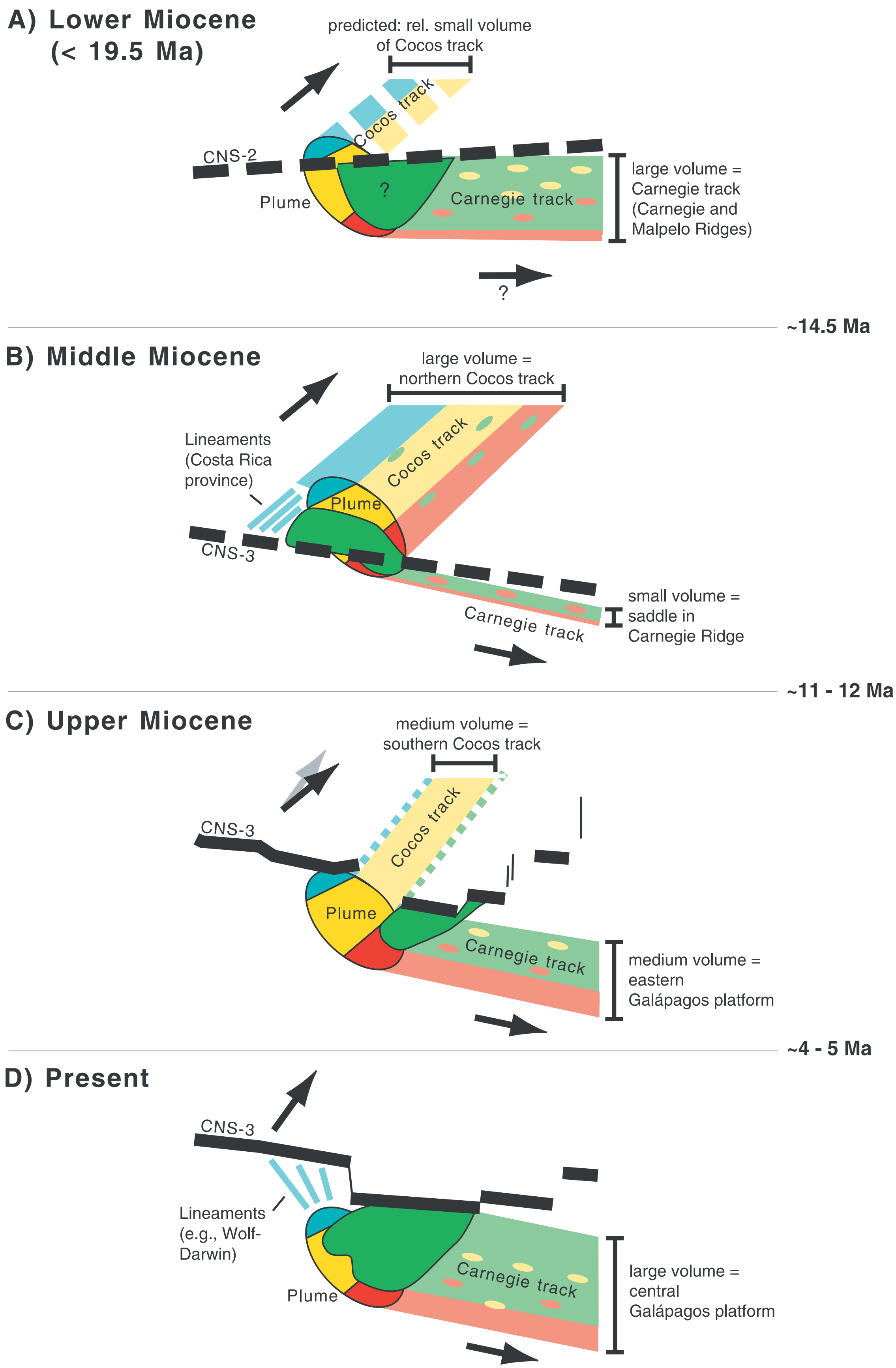
[40] In summary, the geochemical signatures of the northeastern Cocos track and of the Nazca track are consistent with the presently observed spatial variation in geochemistry above the Galápagos hot spot [*White et al.*, 1993; *Harpp and White*, 2001; *Hoernle et al.*, 2000] and provide strong support for the zonation of the Galápagos hot spot tracks over at least part of the past ~20 Ma. The southwestern part of the Cocos track (southwestern Cocos Ridge, Cocos Island seamount province, and southwest seamount province), however, differs significantly in morphology and geochemical composition from its northeastern part. We discuss possible explanations for these discrepancies in section 6.3.

6.3. Constraints on the Geodynamic Evolution of the Galápagos System Over the Past ~20 m.y.

6.3.1. Lower Miocene (>14.5 Ma): Carnegie, Malpelo, and Coiba Ridges

[41] The history of the interplay between the Galápagos hot spot and the CNS in the Lower Miocene is still somewhat ambiguous. Much of the Cocos track older than 14.5 m.y. has been

Figure 9. (opposite) Schematic sketches illustrating the respective hot spot-ridge geometry and their implications for the geochemical zonation, volume and morphology (a) in Lower Miocene, (b) in Middle Miocene, (c) in Upper Miocene, and (d) at present (see text for detailed discussion). The strike direction of the spreading axis of CNS-2 is after *Barckhausen et al.* [2001]. The proposed changes in the direction of plate movement of the Nazca plate are consistent with the change in the strike of the axis of Carnegie Ridge from E-W toward NNE-SSW and may be caused by the change in the strike direction of the spreading axis. For Upper Miocene the hot spot-ridge geometry is exemplified on the reconstruction for 8.2 Ma by *Wilson and Hey* [1995], the direction of plate motion for Cocos Plate is according to *Wilson* [1996] and *Barckhausen et al.* [2001]. The geometry of the geochemical zonation of the Galápagos plume at the present-day and at 13.0–14.5 Ma Cocos track is taken from *Hoernle et al.* [2000]. Colors indicate the four distinct geochemical domains of Galápagos as in Figures 6 and 7.


A) Lower Miocene (< 19.5 Ma)
predicted: rel. small volume of Cocos track
Cocos track
CNS-2
?
Plume
Carnegie track
large volume = Carnegie track (Carnegie and Malpelo Ridges)
?
~14.5 Ma
B) Middle Miocene
large volume = northern Cocos track
Lineaments (Costa Rica province)
Cocos track
Plume
CNS-3
Carnegie track
small volume = saddle in Carnegie Ridge
~11 - 12 Ma
C) Upper Miocene
medium volume = southern Cocos track
CNS-3
Cocos track
Plume
Carnegie track
medium volume = eastern Galápagos platform
~4 - 5 Ma
D) Present
CNS-3
Lineaments (e.g., Wolf-Darwin)
Plume
Carnegie track
large volume = central Galápagos platform

subducted beneath the Caribbean Plate. Subduction-type lavas from the Cordillera Central and the Cordillera de Talamanca in Costa Rica show Galápagos-type isotopic signatures beginning 5–8 m.y. ago [*Abratis and Wörner*, 2001], which are interpreted to be derived from the subducting Cocos track [*Hoernle et al.*, 2003]. The onset of uplift of the Cordillera de Talamanca began ≥5 m.y. ago [e.g., *Lonsdale and Klitgord*, 1978; *de Boer et al.*, 1995; *Gräfe et al.*, 2002]. Both of the aforementioned observations indicate that the Cocos track began subducting beneath Costa Rica ~5–8 m.y. ago and that the oldest parts of the Cocos Ridge subducted beneath Costa Rica are likely to be ~20 m.y. old. If the Coiba Ridge was offset from Cocos Ridge along a predecessor of the Panamá fracture zone [*Hoernle et al.*, 2002], then it is likely to be ≥20 Ma but <22.7 Ma, the age of the oldest crust beneath the Coiba Ridge. Therefore at least parts of the Galápagos hot spot tracks existed on the Cocos Plate from >20 to ~4 Ma, implying continuous supply of magma from the Galápagos plume to the Cocos Plate since approximately the initiation of the CNS.

[42] The oldest well-documented event of the CNS history is the ridge jump to the south from CNS-1 to CNS-2 at 19.5 Ma. Since this jump was associated with a change in the strike direction of ~20°, the western portion of the new CNS-2 spreading axis lay north and the eastern portion south of the old CNS-1 spreading axis (Figure 4) [*Barckhausen et al.*, 2001]. From the magnetic record, it is impossible to tell how this affected the position of the spreading axis relative to the hot spot. Things become even more complicated because little is known about the positions and the offsets of transform faults along the CNS-1 and CNS-2 spreading axes.

[43] More constraints on the hot spot-spreading axis geometry in the Lower Miocene come from the hot spot track on the Nazca Plate, i.e., the Carnegie and Malpelo Ridges. When attached, they formed a voluminous hot spot track. Geochemically, signatures of the Central Galápagos Domain dominate in the northern part of the track (represented by the Malpelo Ridge) and those of the Southern and Eastern Galápagos Domain in its southern part (Figure 7). Several features of the geochemical zoning of the Carnegie track are consistent with a position of the CNS above the northern part of the plume or north of the plume between 19.5 Ma (change from CNS-1 to CNS-2) and the next ridge jump from CNS-2 to CNS-3 at 14.5 Ma (Figure 9a): (1) the large volume of the attached Carnegie and Malpelo Ridges, (2) the occurrence of stripes parallel to the track axis of material with geochemical signatures of the Central and Southern/Eastern Galápagos Domains, and (3) absence of evidence for the Northern Domain signature on the Carnegie track. However, at least minor volumes of plume magmas were also deposited on the Cocos Plate during this time period (Figure 9a), the only surviving example being the Coiba Ridge. The simultaneous formation of a voluminous Nazca track and (probably) a less voluminous Cocos track suggests a position of the CNS on the northern edge of the plume in Lower Miocene (Figure 9a).

6.3.2. Middle Miocene (14.5–~11 Ma): Northeastern Cocos Track

[44] The ridge jump from CNS-2 to CNS-3, being the youngest and best documented in the Lower Miocene, moved the CNS to the south and was possibly associated with a slight change in the strike direction of the spreading axis (Figure 4) [*Barckhausen et al.*, 2001]. As a consequence, magma production rates on the Nazca Plate decreased significantly, as reflected by the decreased volume represented by the saddle in the Carnegie Ridge between ~84–87°W (Figure 1). Between ~11–14.5 Ma (see below), nearly the entire hot spot track occurs on the Cocos Plate, as is evident from the northeastern Cocos track which reflects the complex morphology and geochemical zonation in Sr-Nd-Pb-Hf isotope ratios of the present-day Galápagos Archipelago as it was observed for the 13.0–14.5 Ma Cocos track off the coast of Costa Rica [*Werner et al.*, 1999; *Hoernle et al.*, 2000; *Geldmacher et al.*, 2003]. The ridge and the volcanic centers on it are analogous to the main Galápagos Islands and the underlying platform, whereas the long seamount chains of the Costa Rica seamount province exhibit similar morphology and

isotope geochemistry to the Wolf-Darwin triangle, suggesting that both seamount fields may have formed by similar processes. Possible explanations include flow of plume material to the spreading center and/or structural control through lithospheric faults [e.g., *Verma and Schilling*, 1982; *Sinton et al.*, 2001; *Christie et al.*, 2001; *Harpp and Geist*, 2002]. Our observations therefore suggest that the ridge jump of CNS-2 to CNS-3 moved the CNS to the southern edge of the hot spot at 14.5 Ma (Figure 9b).

6.3.3. Upper Miocene (<∼11 Ma): Southwestern Cocos Track

[45] The transition from the northeastern to the southwestern part of Cocos track, situated about 300 km southwest of the trench, occurred ∼11–12 Ma ago assuming plate motion rates of 9.6 cm/a for the Cocos Plate between ca. 11 and 17 Ma [*Wilson*, 1996; *Barckhausen et al.*, 2001]. Around 11 Ma (chron 5), a change in the strike direction of Cocos Plate magnetic lineations is observed [*Barckhausen et al.*, 2001], which is another indication for a change in the plate motion at that time. Possibly this was the onset of the northward migration of the CNS observed today (Figure 2).

[46] The most obvious features which distinguish the southwestern (Upper Miocene) from the northeastern (Middle Miocene) Cocos track are (1) the lack of continuous seamount chains adjacent to the northwestern flank of Cocos Ridge (e.g., Figure 1), and (2) its apparent homogeneous isotopic composition with the signature of the Central Galápagos Domain (Figure 7). We note, however, that Nd isotope ratios (1) from basaltic glasses taken on the southern flank of Cocos Ridge (at 3°08.08′N and 87°12.73′W) are higher and (2) from a sample taken on a seamount in the Cocos Island seamount province are lower than those of the Central Galápagos Domain [*Castillo*, 1987]. The glasses from the southern flank of the southwestern Cocos Ridge show Nd isotopic signatures similar to samples that we sampled on the southern flank of the northeastern Cocos Ridge and may also suggest the presence of Eastern Domain material at deeper stratigraphic levels of the Cocos Ridge. Alternatively they may represent uplifted pieces of ocean crust derived from the CNS. The lower Nd isotope ratios from a Cocos Island seamount suggest that volcanic rocks with Northern Domain signatures may exist in the Cocos Island seamount province. The few samples analyzed from the eastern Galápagos Platform [*Harpp and White*, 2001] and the saddle between the eastern platform and the Carnegie Ridge, which cover an age range of 5.3 to 11.1 Ma (see Figure 1) [*Sinton et al.*, 1996], have isotopic compositions similar to those of the Eastern Galápagos Domain and may overlie older Southern Domain volcanic rocks.

[47] Cocos Island is ∼2 m.y. old and therefore anomalously young compared to the expected age of the hot spot track here [*Dalrymple and Cox*, 1968; *Bellon et al.*, 1983; *Castillo*, 1987; *Castillo et al.*, 1988]. Therefore at least the upper part of the Cocos Island volcano could not have formed above the Galápagos hot spot. Magnetic anomalies west of Cocos Island suggest that associated volcanoes of the Cocos Island seamount province may also be younger [*Meschede et al.*, 1998]. Moreover, *Fornari et al.* [1979] and results from the SO 144 cruise reveal abundant very fresh volcanic rocks and thin sediment cover on several volcanoes, suggesting young ages for these structures also. Preliminary age data indicate that anomalously young volcanism may be widespread on southwestern Cocos track, in particular in its peripheral areas [*O'Connor et al.*, 2002]. Accordingly parts of the Upper Miocene hot spot track on the Cocos Plate may be covered by younger volcanism. Therefore samples obtained by dredging may not provide information on the composition of the underlying hot spot track.

[48] Another major difference between the southwestern Cocos track and its northeastern counterpart is the non-continuous appearance and arrangement of the seamount fields along the southwestern Cocos Ridge. Taking the young volcanism into account, only few (possibly no) isolated volcanoes may have existed along the northwestern edge of the southwestern Cocos track. Furthermore, it appears that the volume of the hot spot track on the Cocos Plate may have been significantly lower in the Upper Miocene as compared to the Middle Miocene. Therefore the

transition from the northeastern to the southwestern Cocos track may reflect a major event in the history of the Cocos track. It may either reflect episodic magma supply from the plume and/or interplay of the CNS with the Galápagos hot spot, i.e., changes in the hot spot - spreading axis geometry.

[49] The relative position of the CNS to the Galápagos hot spot and its geometry are well constrained for ages up to 8.2 Ma [e.g., *Wilson and Hey*, 1995; *Wilson*, 1996; *Barckhausen et al.*, 2001]. During this time interval, the center of the hot spot was located south of the ridge axis. At 8.2 Ma a western ridge segment bounded the northern tip of the hot spot, whereas an eastern ridge segment was located at the northeastern edge of the hot spot (Figure 9c). The location of the hot spot in such an offset of the CNS, as postulated by *Wilson and Hey* [1995] at 8.2 to ~4 Ma, would imply that the majority of the plume material was erupted on the Nazca Plate (Figure 9c). The easternmost part of the Galápagos Platform represents this part of the hot spot track. Plume material erupted on the Cocos Plate would have been mainly produced from the center of the plume and therefore show the geochemical signature of the Central Galápagos Domain. Only minor portions of magmas with signatures of the Northern Domain may have been deposited on the Cocos Plate with much of the northern plume material being diverted westward along the western ridge segment (Figure 9c). This scenario also predicts that an equivalent to the Wolf-Darwin triangle and the Costa Rica seamount province would not have formed on the Cocos Plate. Taken together, a location of the hot spot within an offset of the CNS could explain the major features of the southwestern Cocos track, i.e., the dominance of lavas with signatures of the Central Galápagos Domain, and its relatively low volume, and the lack of continuous seamounts chains adjacent to its northwestern flank (Figure 9c). Therefore the morphological and compositional change of the Cocos track may be attributed to a southward jump of the ridge segments of the CNS at ca. 11–12 Ma.

[50] Alternatively the central component may have dominated the plume from 11–12 to ~4 Ma. The northern and southern plume components may be discontinuous heterogeneities/stripes in the plume, i.e., the northern and southern components came up with the plume in Upper (?) to Middle Miocene and Pliocene/Quaternary but not at all or only in small amounts between 11–12 to ~4 Ma. Both hypothesis could be tested by more detailed sampling and/or by drilling on the northwestern edge of the southwestern Cocos track and on the western Galápagos Plateau. On the basis of the available data, we conclude that a major event happened on the Cocos track at the Middle-Upper Miocene boundary and that at least magmas with geochemical signatures of the Central and Eastern Galápagos Domain exist continuously since Lower Miocene.

6.3.4. Origin of Anomalous Young Volcanism

[51] Unlike any volcanic rocks from the present-day Galápagos Islands and Platform, Costa Rica and Cocos Island seamount provinces are unique in that they primarily have incompatible-enriched, alkalic compositions. Late-stage, post-erosional or rejuvenated-stage alkalic volcanism however is an almost universal feature on ocean island volcanoes [e.g., *Clague and Frey*, 1982; *Clague and Dalrymple*, 1987; *Hoernle and Schmincke*, 1993a, 1993b]. Late-stage volcanism is characterized by small degrees of melting in the garnet stability field, generating incompatible-element enriched, alkalic melts. Despite low production rates, late-stage volcanism in many cases covers much of the exposed parts of ocean island volcanoes, since these are the last erupted products. It's origin, however, remains enigmatic.

[52] We now briefly evaluate some hypothesis which may explain the origin of late-stage volcanism in the Cocos Island seamount province and along the Cocos track. *Meschede et al.* [1998] postulate a second hot spot near Cocos Island. The results presented in their paper however also allows another possible explanation for late-stage volcanism near Cocos Island. West of Cocos Island, a ~120 km wide area of E-W striking, high amplitude magnetic anomalies is observed [*Meschede et al.*, 1998]. The strike direction of these anomalies dif-

fers significantly from the SW-NE strike direction of the surrounding CNS-2 anomalies and their high amplitudes suggest that they (as well as the seamounts in this region) are younger than the surrounding ocean floor. *Meschede et al.* [1998] tentatively correlated the sparse magnetic anomalies in this area with anomalies 2 to 2A (1.8–3 Ma) and postulated a small and short-lived Cocos Island spreading system, which was initiated by high magmatic activity related to the Galápagos hot spot located more than 500 km away at that time. In accordance with this scenario, Cocos Island and related seamounts may have formed during a late-stage spreading episode of the ocean crust in this area. A second Galápagos-related plume and late-stage spreading west of Cocos Island may apply to the anomalously young volcanism in the Cocos Island seamount province but does not account for the widespread late-stage volcanism along the southwestern Cocos track, in particular not for the areas located "upstream" with respect to plate motion.

[53] Some studies have linked late-stage volcanism associated with volcanoes on older crust to the lithospheric mantle [e.g., *Clague and Frey*, 1982; *Class and Goldstein*, 1997]. We note however that the rare earth element data from alkalic rocks from the Costa Rica and Cocos Island seamount provinces show that they were formed with garnet in the residuum [*Hoernle et al.*, 2000; *Harpp et al.*, 2003]. Considering the young age of the Cocos Plate, it is unlikely that the lithosphere extends into the garnet stability field. Furthermore, melting of the lithospheric mantle also requires a mechanism to cause melting (e.g., heat source).

[54] Recent results from numerical experiments however suggest another possibility. *Hall and Kincaid* [2003] show that as upwelling plume material melts and dehydrates, it becomes viscous and readily accretes to the overlying lithosphere, forming a "viscous plug" above the plume. This viscous plug will deflect upwelling plume material at subsolidus depths, allowing pristine plume material to flow horizontally until it reaches the edge of the plug where it can rise and melt by decompression. If the plume is beneath the spreading center or close to the spreading center, such a viscous layer could conceivably block upwelling beneath parts of the spreading center, in some cases even permitting plume material to flow beneath a spreading center to the opposite plate. Alternatively the viscous layer (and the plume material beneath it) could have passed beneath the spreading center at an offset. This scenario would be consistent with the hypothesis for the evolution of the southwestern Cocos track in the Upper Miocene as discussed above (cf. Figure 9c). The viscous layer is also likely to stay attached to the plate and move with it. An occasional disturbance of the layer, for example extension or spreading of the overlying lithosphere, could allow pristine plume material traveling laterally beneath it to rise to shallower depths. Decompression melting of the upwelling mantle could generate small degree, incompatible-element enriched, alkalic melts long after that portion of the plate has moved away from the hot spot, providing a possible explanation for late-stage volcanism. Such a model also allows plume material from other parts of a zoned plume to move laterally into another zone before crossing its solidus, such a process is particularly likely for late stage melting.

6.3.5. Implications for the History of Galápagos Islands

[55] The present Galápagos Islands are 3–4 m.y. old [e.g., *White et al.*, 1993], which has been considered for a long time by some to be the maximum time available for the evolution of the endemic biota [e.g., *Hickman and Lipps*, 1985]. The existence of older islands formed above the Galápagos hot spot has first been reported by *Christie et al.* [1992]. These authors discovered now-drowned, up to ~9 m.y. old Galápagos Islands east of the Galápagos Platform. Detailed bathymetric, geophysical, volcanological, and geochemical studies of the Cocos track off the coast of Costa Rica revealed a 13.0–14.5 m.y. old drowned archipelago very similar in morphology and geochemistry to the present Galápagos Archipelago [*Werner et al.*, 1999; *Hoernle et al.*, 2000]. As discussed earlier in this paper, this paleo-Galápagos Archipelago existed at least during the entire

Middle Miocene. Moreover, the common occurrence of guyot-shaped seamounts, paleo-beach or inter-tidal wave-cut platform deposits, the structure and texture of volcanic rocks, and low sulfur contents of fresh glasses dredged at the seamounts and ridges along the Cocos and Nazca tracks imply that ocean islands have most likely existed continuously above the Galápagos hot spot for at least the past 17 m.y. [*Werner and Hoernle*, 2003]. Taken together, these data may significantly extend the time period over which the unique endemic Galápagos fauna could have evolved.

[56] The existence of anomalous young volcanoes at least along the southwestern Cocos track, however, may suggest that several of the former shallow water or island volcanoes did not form above the Galápagos hot spot, implying possibly a gap in the history of Galápagos Islands which in turn would significantly reduce the speciation times for the Galápagos biota. This gap could have existed from the apparent disappearance of the paleo-archipelago at ∼11–12 Ma until ∼9 Ma (i.e., oldest drowned islands described by *Christie et al.* [1992]). Dredging on SO 144 cruise, however, revealed subaerial volcanism even on the central part of Cocos Ridge [*Werner and Hoernle*, 2003], where no evidence has been found for late-stage volcanism. Shallow water volcanism has also been documented on Carnegie track in the area between 86° and 85°W [*Werner and Hoernle*, 2003] where the available ages of seamounts vary between 8.7 and 11.1 Ma [*Sinton et al.*, 1996]. Finally, the younger volcanism may simply form a thin veneer over paleo-islands, as is observed on many older volcanic ocean islands. Therefore we conclude that islands are likely to have existed continuously above the Galápagos hot spot for at least the past 17 m.y., even if anomalously young volcanism is widespread on Cocos track.

7. Conclusions

[57] Our studies are consistent with the morphology and geochemical composition of the Galápagos hot spot tracks reflecting the relative position of the CNS to the hot spot and variable interaction of the hot spot with the CNS. We cannot rule out changes in the composition and/or zonation of the plume since the Lower Miocene; however, our data do not require them and are consistent with the existence of a compositionally zoned/striped Galápagos plume since ∼20 Ma. The Coiba Ridge appears to be the oldest part of the preserved Galápagos hot spot track, probably having formed on the Cocos Plate between ∼20–22 Ma. The jump from CNS 1 to CNS 2 at 19.5 Ma moved the spreading axis southward to the northern edge of the plume. During this time the main hot spot track (combined Carnegie and Malpelo Ridges) were formed on the Nazca Plate. Afterward the CNS migrated southward over the plume center. At 14.5 Ma, a major southward jump of the CNS moved the spreading axis to the southern edge of the hot spot again where the axis most likely remained for ∼3 m.y. From >17.3 Ma (minimum age of the Carnegie track beneath and east of Malpelo Island) to ∼11 Ma, the geochemical signatures of the Galápagos hot spot tracks are consistent with the presently observed spatial variation in geochemistry above the Galápagos hot spot. After ∼11 Ma, the Galápagos plume center may have been located in or south of an offset of the CNS until ∼4 Ma. The evolution of the Galápagos system in the Upper Miocene, however, remains somewhat enigmatic. On the basis of the presently available data, it cannot be ruled out that the Central Galápagos component dominated the plume composition between 4–11 Ma at the expense of the Northern and Southern components. From the results of our morphological, geophysical and geochemical studies, we draw the following additional conclusions on the evolution of the Galápagos system:

[58] 1. Sr-Nd-Pb isotopic compositions confirm that the aseismic ridges and associated seamounts between the Galápagos Islands and Central and South America formed from the Galápagos hot spot.

[59] 2. Magnetic anomalies indicate that Malpelo and Carnegie Ridges were once attached and that seafloor spreading separated the two ridges between 14.5 Ma to 9.5 Ma as a result of a southward ridge jump at 14.5 Ma (CNS 2 to CNS 3).

[60] 3. The morphological and geochemical differences between the northeastern and the southwest-

ern Cocos track cannot be exclusively attributed to anomalous young volcanism but reflect a major event in the evolution of the Galápagos system at the Middle-Upper Miocene boundary. This event may be related to plate tectonic processes and/or non-continuous plume supply.

[61] 4. Southern (FLO), Central (PLUME) and Eastern (DUM)-type Galápagos mantle has been associated with the plume for at least the last ~20 Ma, whereas the Northern (WD)-type Galápagos mantle has existed for at least ~15 Ma.

Acknowledgments

[62] We thank S. Vetter, D. Rau and M. Thöner for technical assistance and D. Ackermand, chief scientist of cruise SO 144/3a, and the SO 144-1, 3a and 3b crews and Shipboard Scientific Parties for the support necessary to carry out this study. We thank the Governments of Costa Rica and Ecuador for granting permission to work in their territorial waters and on Cocos Island and gratefully acknowledge the help of G. Alvarado, B. Sassen, and E. Santana in obtaining these permissions. We are grateful to Dennis Geist and Paterno Castillo for their detailed and constructive reviews. This study was supported by the German Ministry of Education and Research (BMBF; Grant PAGANINI). Several Figures were prepared with GMT public domain software [*Wessel and Smith*, 1995].

References

Abratis, M., and G. Wörner, Ridge collision, slab-window formation, and the flux of Pacific asthenosphere into the Caribbean realm, *Geology*, *29*, 127–130, 2001.

Barckhausen, U., C. R. Ranero, R. von Huene, S. C. Cande, and H. A. Roeser, Revised tectonic boundaries in the Cocos Plate off Costa Rica: Implications for the segmentation of the convergent margin and for plate tectonic models, *J. Geophys. Res.*, *106*, 19,207–19,220, 2001.

Becker, K., et al., *Proceedings of Ocean Drilling Program Scientific Results*, vol. 111, Ocean Drill. Program, College Station, Tex., 1989.

Bellon, H., R. Saenz, and J. Tournon, K-Ar radiometric ages of lavas from Cocos Island (Eastern Pacific), *Mar. Geol.*, *54*, 17–23, 1983.

Bialas, J., E. Flueh, and G. Bohrmann (Eds.), *FS SONNE Cruise Report SO144/1&2 PAGANINI*, 437 pp., GEOMAR, Kiel, 1999.

Cande, S. C., and D. V. Kent, Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic, *J. Geophys. Res.*, *100*, 6093–6095, 1995.

Cann, J. R., M. G. Langseth, J. Honnorez, R. P. von Herzen, S. M. White, et al., *Initial Report Deep Sea Drilling Project*, vol. 69, U.S. Gov. Printing Off., Washington D. C., 1983.

Castillo, P. R., Geology and geochemistry of Cocos Island, Costa Rica; Implications for the evolution of the aseismic Cocos Ridge, Ph.D. thesis, Washington Univ., Saint Louis, Miss., 1987.

Castillo, P. R., R. Batiza, D. Vanko, E. Malavassi, J. Barquero, and E. Fernandez, Anomalously young volcanoes on old hotspot traces: I. Geology and Petrology, *Geol. Soc. Am. Bull.*, *100*, 1400–1414, 1988.

Clague, D. A., and G. B. Dalrymple, The geology of the Hawaiian-Emperor Volcanic Chain, *U.S. Geol. Surv. Prof. Pap.*, *1350*, 5–49, 1987.

Clague, D. A., and F. A. Frey, Petrology and trace element geochemistry of the Honolulu Volcanics, Oahu: Implications for the oceanic mantle below Hawaii, *J. Petrol.*, *23*, 447–504, 1982.

Christie, D. M., R. A. Duncan, A. R. McBirney, M. A. Richards, W. M. White, K. S. Harpp, and C. G. Fox, Drowned islands downstream from the Galápagos hotspot imply extended speciation times, *Nature*, *355*, 246–248, 1992.

Christie, D. M., R. Werner, B. B. Hanan, P. Wintersteller, F. Hauff, K. A. Hoernle, and Shipboard Scientific Party, Galápagos plume-ridge interaction Part 2: Variations in seamount morphology around the Galapagos Platform, *Eos Trans. AGU*, *82*(47), Fall Meet. Suppl., Abstract T42B-0936, 2001.

Class, C., and S. L. Goldstein, Plume-lithosphere interactions in the ocean basins: Constraints from the source mineralogy, *Earth Planet. Sci. Lett.*, *150*, 245–260, 1997.

Dalrymple, G. B., and A. Cox, Paleomagnetism, potassium-argon ages and petrology of some volcanic rocks, *Nature*, *217*, 323–326, 1968.

de Boer, J. Z., M. S. Drummond, M. J. Bordelon, M. J. Defant, H. Bellon, and R. C. Mauri, Cenozoic magmatic phases of the Costa Rican island arc (Cordillera de Talamanca), in *Geologic and Tectonic Development of the Caribbean Plate Boundary in Southern Central America*, vol. 295, edited by P. Mann, pp. 35–55, Geol. Soc. of Am., Boulder, Colo., 1995.

DeMets, C., R. Gordon, D. Argus, and S. Stein, Current plate motions, *Geophys. J. Int.*, *101*, 425–478, 1990.

Engel, C. G., and T. E. Chase, Composition of basalts from seamounts off the west coast of Central America, *U.S. Geol. Surv. Prof. Pap.*, *525-C*, 161–163, 1965.

Fornari, D. J., A. Malahoff, and B. C. Heezen, Visual observations of the volcanic micromorphology of Tortuga, Lorraine, and Tutu seamounts and petrology and chemistry of ridge and seamount features in and around the Panamá basin, *Mar. Geol.*, *31*, 1–31, 1979.

Geist, D. J., W. M. White, and A. R. McBirney, Plume-asthenosphere mixing beneath the Galápagos Archipelago, *Nature*, *333*, 657–660, 1988.

Geldmacher, J., B. B. Hanan, J. Blichert-Toft, K. Harpp, K. A. Hoernle, F. Hauff, R. Werner, and A. C. Kerr, Hafnium isotopic variations in volcanic rocks from the Caribbean Large Igneous Province and Galápagos hotspot tracks, *Geochem. Geophys. Geosyst.*, *4*(7), 1062, doi:10.1029/2002GC000477, 2003.

Gräfe, K., W. Frisch, I. M. Villa, and M. Meschede, Geodynemaic evolution of southern Costa Rica related to low-angle

subduction of the Cocos Ridge: Constraints from thermochronology, *Tectonophysics*, *348*, 187–204, 2002.
Hall, P. S., and C. Kincaid, Melting, dehydration, and the dynamics of off-axis plume-ridge interaction, *Geochem. Geophys. Geosyst.*, *4*(9), 8510, doi:10.1029/2002GC000567, 2003.
Handschumacher, D. W., Post-Eocene plate tectonics of the eastern Pacific, in *The Geophysics of the Pacific Ocean Basin and Its Margin*, *Geophys. Monogr. Ser.*, vol. 19, edited by G. H. Sutton, M. H. Manghnani, and R. Moberly, pp. 177–202, AGU, Washington, D. C., 1976.
Hardy, N. C., Tectonic evolution of the easternmost Panamá Basin: Some new data and inferences, *J. South Am. Earth Sci.*, *4*, 261–269, 1991.
Harpp, K. S., and D. Geist, Wolf-Darwin lineament and plume-ridge interaction in northern Galápagos, *Geochem. Geophys. Geosyst.*, *3*(11), 8504, doi:1029/2002GC000370, 2002.
Harpp, K. S., and W. M. White, Tracing a mantle plume: Isotopic and trace element variations of Galápagos seamounts, *Geochem. Geophys. Geosyst.*, *2*, Paper number 2000GC000137, 2000.
Harpp, K. S., V. D. Wanless, R. H. Otto, and K. A. Hoernle, The Cocos and Carnegie a seismic ridges: A trace element record of long-term plume-spreading center interaction, *J. Petrol.*, in press, 2003.
Hauff, F., K. A. Hoernle, P. van den Boogard, G. E. Alvarado, and D. Garbe-Schönberg, Age and geochemistry of basaltic complexes in Western Costa Rica: Contributions to the geotectonic evolution of Central America, *Geochem. Geophys. Geosyst.*, *1*, Paper number 1999GC0000207, 2000.
Heezen, B. C., and M. Rawson, Visual observations of contemporary current erosion and tectonic deformation on the Cocos Ridge crest, *Mar. Geol.*, *23*, 173–196, 1977.
Hey, R. N., Tectonic evolution of the Cocos-Nazca spreading center, *Geol. Soc. Am. Bull.*, *88*, 1404–1420, 1977.
Hickman, C. S., and J. H. Lipps, Geologic youth of Galápagos islands confirmed by marine stratigraphy and palaeontology, *Science*, *227*, 1578–1580, 1985.
Hoernle, K. A., and H.-U. Schmincke, The petrology of the tholeiites through melilite nephelinites on Gran Canaria, Canary Islands: Crystal fractionation, accumulation and depths of melting, *J. Petrol.*, *34*, 573–597, 1993a.
Hoernle, K. A., and H.-U. Schmincke, The role of partial melting in the 15 Ma geochemical evolution of Gran Canaria: A blob model for the Canary hotspot, *J. Petrol.*, *34*, 599–626, 1993b.
Hoernle, K. A., and G. R. Tilton, Sr-Nd-Pb isotope data for Fuerteventura (Canary Islands) basal complex and subaerial volcanics: Applications to magma genesis and evolution, *Schweiz. Mineral. Petrogr. Mitt.*, *71*, 3–18, 1991.
Hoernle, K. A., R. Werner, J. P. Morgan, D. Garbe-Schönberg, J. Bryce, and J. Mrazek, Existence of complex spatial zonation in the Galápagos plume for at least 14 m.y., *Geology*, *28*, 435–438, 2000.
Hoernle, K. A., P. van den Bogaard, R. Werner, F. Hauff, B. Lissinna, G. E. Alvarado, and D. Garbe-Schönberg, Missing history (16–71 Ma) of the Galápagos hotspot: Implications for the tectonic and biological evolution of the Americas, *Geology*, *30*, 795–798, 2002.
Hoernle, K. A., S. Sadofsky, H. Nichols, M. Portnyagin, P. van den Bogaard, and G. Alvarado, Volatile, trace element and isotopic variations of mafic arc volcanic rocks from Nicaragua and Costa Rica, *Eos Trans. AGU*, *84*(46), Fall Meet. Suppl., Abstract V32H-08, 2003.
Holden, J. C., and R. S. Dietz, Galápagos core, NazCoPac triple junction and Carnegie/Cocos Ridges, *Nature*, *235*, 266–269, 1972.
Kellogg, J. N., and V. Vega, Tectonic development of Panamá, Costa Rica, and the Colombian Andes: Constraints from global positioning system geodetic studies and gravity, in *Geologic and Tectonic Development of the Caribbean Plate Boundary in Southern Central America*, vol. 295, edited by P. Mann, pp. 75–90, Geol. Soc. of Am., Boulder, Colo., 1995.
Le Bas, M. J., R. W. Le Maitre, A. Streckeisen, and B. Zanettin, A chemical classification of volcanic rocks based on the total alkali-silica diagram, *J. Petrol.*, *27*, 74–750, 1986.
Lonsdale, P., and D. Fornari, Submarine geology of Malpelo Ridge, Panamá basin, *Mar. Geol.*, *36*, 65–83, 1980.
Lonsdale, P., and K. D. Klitgord, Structure and tectonic history of the eastern Panamá Basin, *Geol. Soc. Am. Bull.*, *89*, 981–999, 1978.
Meschede, M., and U. Barckhausen, The plate tectonic evolution of the Cocos-Nazca spreading center, *Proc. Ocean Drill. Program Sci. Results*, *170*, 1–10, 2000. (Available at http://www-odp.tamu.edu/publications/170_SR/chap_07/chap_07.htm)
Meschede, M., and U. Barckhausen, The age of submarine ridges in the eastern Panamá basin: Constraints from palinspastic restorations, *Int. J. Earth Sci.*, *90*, 386–392, 2001.
Meschede, M., U. Barckhausen, and H.-U. Worm, Extinct spreading on the Cocos Ridge, *Terra Nova*, *10*, 211–216, 1998.
O'Connor, J. M., P. Stoffers, J. Wijbrans, D. Ackermand, and T. Worthington, PAGANINI SO 144/3, rep., Christian-Albrechts-Univ., Kiel, 2002.
Pennington, W. D., Subduction of the eastern Panama basin and seismotectonics of the northwestern south America, *J. Geophys. Res.*, *86*, 10,753–10,770, 1981.
Sallarès, V., and P. Charvis, Crustal thickness constraints on the geodynamic evolution of the Galápagos volcanic province, *Earth. Planet. Sci. Lett.*, *214*, 545–559, 2003.
Sinton, C. W., D. M. Christie, and R. A. Duncan, Geochronology of Galápagos seamounts, *J. Geophys. Res.*, *101*, 13,689–13,700, 1996.
Sinton, J. M., R. S. Detrick, J. P. Canales, G. Ito, M. Behn, T. Blacic, B. Cushman, and J. Dixon, Correlated geophysical, geochemical, and volcanological manifestations of plume-ridge interaction along the Galápagos spreading center, 90,5-98°W, *Eos Trans. AGU*, *82*(47), Fall Meet. Suppl., Abstract T41D-02, 2001.
Smith, W. H. F., and D. T. Sandwell, Global seafloor topography from satellite altimetry and ship deep soundings, *Science*, *277*, 1956–1962, 1997.
Todt, W., R. A. Cliff, A. Hanser, and A. W. Hofmann, Evaluation of a ^{202}Pb-^{205}Pb double spike for high precision lead isotope analyses, in *Earth Processes*: *Reading of the Isotopic Code*, *Geophys. Monogr. Ser.*, vol. 95, edited by A. Basu and S. Hart, pp. 429–437, AGU, Washington, D. C., 1996.

Verma, S. P., and J.-G. Schilling, Galápagos hot spot-spreading center system, 2, $^{87}Sr/^{86}Sr$ and large ion lithophile element varaitions (85°W–101°W), *J. Geophys. Res.*, *87*, 10,838–10,856, 1982.

Vicenzi, E. P., A. R. McBirney, W. M. White, and M. Hamilton, The geology and geochemistry of Isla Marchena, Galápagos Archipelago: An ocean island adjacent to a mid-ocean ridge, *J. Volcanol. Geotherm. Res.*, *40*, 291–315, 1990.

van Andel, T. H., et al., *Initial Report Deep Sea Drilling Project*, vol. 16, U.S. Gov. Printing Off., Washington, D. C., 1973.

von Huene, R., et al., Morphotectonics of the Pacific convergent margin of Costa Rica, in *Geologic and Tectonic Development of the Caribbean Plate Boundary in Southern Central America*, vol. 295, edited by P. Mann, pp. 291–307, Geol. Soc. of Am., Boulder, Colo., 1995.

von Huene, R., C. R. Ranero, W. Weinrebe, and K. Hinz, Quaternary convergent margin tectonics of Costa Rica, segmentation of the Cocos Plate, and Central American volcanism, *Tectonics*, *19*, 314–334, 2000.

Walther, C. H. E., The crustal structure of the Cocos ridge off Costa Rica, *J. Geophys. Res.*, *108*(B3), 2136, doi:10.1029/2001JB000888, 2003.

Werner, R., and K. A. Hoernle, New volcanological and volatile data confirm the hypothesis for the continuous existence of Galápagos Islands for the past 17 m.y., *Int. J. Earth Sci.*, in press, 2003.

Werner, R., K. A. Hoernle, P. van den Bogaard, C. Ranero, R. von Huene, and D. Korich, A drowned 14-m.y.-old Galápagos Archipelago off the coast of Costa Rica: Implications for tectonic and evolutionary models, *Geology*, *27*, 499–502, 1999.

Wessel, P., and W. H. F. Smith, New version of the Generic Mapping Tools released (abstract), *Eos Trans. AGU*, *76*(29), 329, 1995. (Available as http://www.agu.org/eos_elec/95154e.html)

White, W. M., and A. W. Hofmann, Geochemistry of the Galápagos Islands: Implications for mantle dynamics and evolution, *Year Book Carnegie Inst. Washington*, *77*, 596–606, 1978.

White, W. M., A. R. McBirney, and R. A. Duncan, Petrology and geochemistry of the Galápagos Islands: Portrait of a pathological mantle plume, *J. Geophys. Res.*, *98*, 19,533–19,563, 1993.

Wilson, D. S., Fastest known spreading on the Miocene Cocos-Pacific plate boundary, *Geophys. Res. Lett.*, *23*, 3003–3006, 1996.

Wilson, D. S., and R. N. Hey, History of rift propagation and magnetization intensity for the Cocos-Nazca spreading center, *J. Geophys. Res.*, *100*, 10,041–10,056, 1995.