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Martin Meschede · Udo Barckhausen

The relationship of the Cocos and Carnegie ridges: age constraints from paleogeographic reconstructions

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Abstract Paleogeographic restorations for the oceanic crust formed by the Cocos-Nacza spreading center and its precursors were performed to reconstruct the history and ages of the submarine aseismic ridges in the Eastern Pacific Basin, the Carnegie, Coiba, Cocos, and Malpelo ridges. The bipartition of the Carnegie ridge reflects the shift from a precursor to the presently active Cocos-Nazca spreading center. The Cocos ridge is partly composed of products from the Galápagos hotspot but may also contain material from a second center of volcanic activity which is located approximately 600 km NE of Galápagos. The Malpelo ridge is a product of this second hotspot center, whereas the Coiba ridge probably formed at the Galápagos hotspot. The geometric relationship of the Cocos and Carnegie ridges indicates symmetric spreading and a constant northward shift of the presently active Cocos-Nazca spreading center.

Keywords Eastern Pacific · Galápagos hotspot · Oceanic crust · Plate tectonic evolution · Cocos ridge · Carnegie ridge · Malpelo ridge · Coiba ridge · Hotspot trace

Introduction

The Cocos and Carnegie ridges are two prominent submarine aseismic ridges that dominate the basin morphology of the Eastern Panama Basin (Fig. 1). The Cocos ridge is an approximately 1000-km-long and up to 200-km-wide positive morphological feature on the ocean floor of the Cocos plate. It reaches elevations of less than 1000 m below sea level and is thus considerably shallower than the surrounding oceanic crust of the Cocos plate with water depths of more than 4000 m. Its trend (N45°E) is almost normal to the strike of the Middle American trench, along which it is being subducted off Costa Rica and Panamá. The indentation into the Central American landbridge leads to strong uplift and exhumation of deep crustal sections (Graefe et al. 1997; Graefe 1998; Meschede et al. 1999). A paleogeographic restoration juxtaposes the smaller Malpelo ridge, presently located east of the Panama Fracture zone on the Nacza plate (Fig. 1), in prolongation of the Cocos ridge (Hey 1977; Lonsdale and Klitgord 1978; Meschede et al. 1998). A missing part of approximately 250 km of the once continuous Cocos-Malpelo ridge system has already been subducted beneath the Central American landbridge. The Coiba ridge south of Panama has been suggested to be formed not as a hotspot trace but rather by uplift beside a long meridianal transform fault during late Miocene and Pliocene time (Lonsdale and Klitgord 1978). Its origin, however, remains unclear due to the lack of data.

The Carnegie ridge is an approximately 1350-km-long and up to 300-km-wide structure on the ocean floor of the northern Nazca plate (Fig. 1). It is separated into two elongated triangular-shaped parts, including the Galápagos archipelago at its western end. Its trend (E–W) is almost normal to the strike of the Peru–Chile trench, along which it is being subducted beneath the South American plate. In contrast to the Cocos ridge, uplift and exhumation of the upper plate are not observed at the collision front of the Carnegie ridge; however, the indentation of the ridge into South America is interpreted to have started approximately 2 Ma ago (Gutscher et al. 1999).

M. Meschede (✉)
Institut für Geologie und Paläontologie, Universität Tübingen, Sigwartstrasse 10, 72076 Tübingen, Germany
E-mail: meschede@uni-tuebingen.de
Fax: +49-7071-5059

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

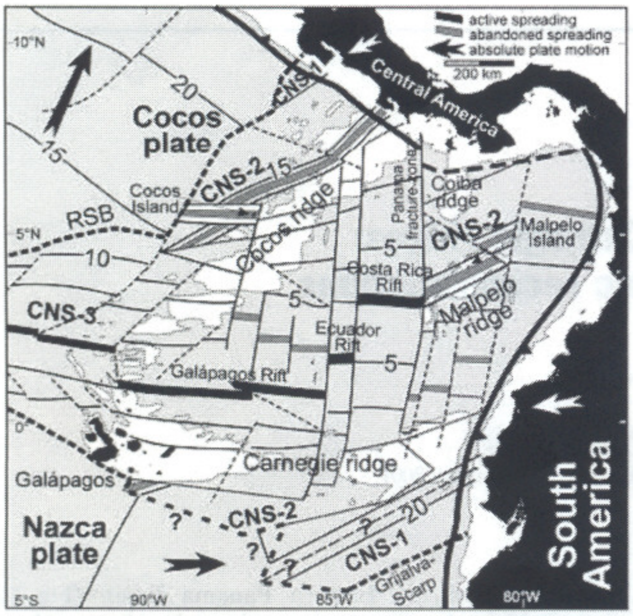


Fig. 1 Overview of the Eastern Panama Basin (modified from Meschede et al. 1998). *Numbers* indicate ages of oceanic crust. Distribution of extinct spreading systems from Meschede et al. 1998. *CNS* Cocos-Nazca spreading system; *RSB* rough smooth boundary

The Cocos, Malpelo, and Carnegie ridges have been interpreted to be hotspot traces which began to form when the Galápagos hotspot initiated at approximately 20–22 Ma (Hey 1977; Lonsdale and Klitgord 1978). Meschede et al. (1998) have demonstrated that the products of the hotspot volcanism overprinted a complex pattern of oceanic crust formed at three subsequently active, symmetric spreading systems of different orientation, which is in contrast to older reconstructions (e.g., Hey 1977; Lonsdale and Klitgord 1978). The identified extinct spreading systems represent precursors of the presently active Cocos-Nazca spreading center (Fig. 1).

The origin of the Cocos-Malpelo ridge system, however, remains unclear since the geometry seems to preclude a direct relation to the Galápagos hotspot. The Cocos-Malpelo ridge system has thus tentatively been interpreted to be related to a second center of hotspot volcanism, which may be connected to the Galápagos hotspot in the upper mantle (Meschede et al. 1998).

The goal of the present study is to outline a geometric solution of the Cocos and Nazca plate tectonic evolution which particularly focuses on the overprinting of normal oceanic crust by hotspot volcanism. Such a model has the potential to predict the ages of the volcanic rocks which form the hotspot traces.

Age relations

During the Late Oligocene the Farallon plate split into the Cocos and Nazca plates as a result of global rearrangement of plate boudaries (e.g., Silver et al. 1998). The oceanic crust of the Cocos and Nazca plates was formed along four spreading centers: the presently active Cocos-Nazca ridge (CNS-3); its two precursors CNS-2 and CNS-1 (Meschede et al. 1998); and the East Pacific Rise. The oldest magnetic anomalies which belong to the CNS-1 system are identified as anomaly 6B, giving an age of 22.8 Ma (according to the magnetic reversal timescale of Cande and Kent 1995). Hence, the splitting of the Farallon plate has been dated to this age (Barckhausen et al., 2001). The first spreading system (CNS-1) was active until 19.5 Ma when the orientation of the spreading axis changed from NW–SE to ENE–WSW (Meschede et al. 1998). The second spreading system (CNS-2) was abandoned at 14.7 Ma when the presently active, E/W-oriented CNS-3 started its activity. Sharp and discordant contacts of magnetic anomalies (Barckhausen et al. 1998; Meschede et al. 1998) indicate abrupt changes in spreading direction.

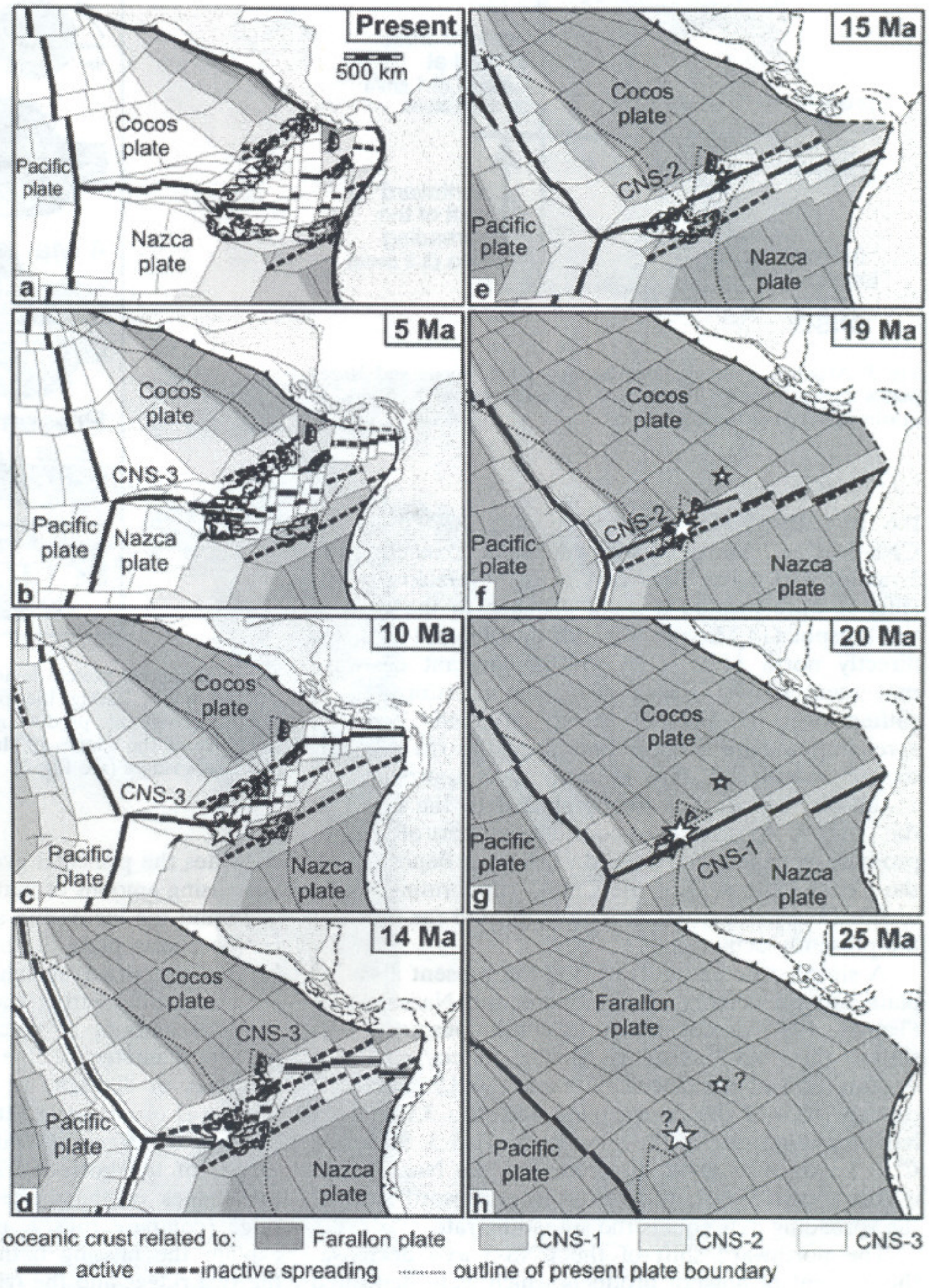
The age of the Carnegie ridge is relatively well constrained (Christie et al. 1992; Sinton et al. 1996), whereas the Cocos ridge has only recently been investigated in its northeasternmost part (Werner et al. 1999). The youngest part of the Carnegie ridge is at its western end in the Galápagos archipelago where active volcanism related to the Galápagos hotspot is observed. A clear and continuous age trend from recently formed volcanic rocks to ages of more than 11 Ma obtained in the middle part of the ridge suggests an origin from a hotspot. Since the Carnegie ridge is directly connected to the Galápagos hotspot and is in line with the plate movement vector of the Nazca plate (Tamaki 1997), its formation at this hotspot is evident (Christie et al. 1992; Sinton et al. 1996).

Due to the paucity of dredge samples along the Cocos ridge any similar age trend has yet to be established. Werner et al. (1999) determined ages from 13.0 to 14.5 Ma directly in front of the Costa Rican convergent margin. Pliocene alkaline volcanism is observed at Cocos Island (2 Ma; Castillo et al. 1988) which is located on the western flank of the Cocos ridge approximately 480 km southwest of Costa Rica (Fig. 1). Meschede et al. (1998) interpreted the area around Cocos Island as that part of the Cocos ridge which moved over a second center of hotspot activity during the Pliocene.

Paleogeographic restorations

Paleogeographic restorations for the oceanic crust formed by the Cocos-Nacza spreading center and its

Fig. 2a–h Paleogeographic restoration of the plate tectonic evolution of the Cocos and Nazca plates. Restoration based on the age model of oceanic crust from Meschede et al. (1998). Plate motion calculated after Tamaki (1997). Location of the Galápagos hotspot is taken as fix. Evolution of the Central American landbridge adopted from Coates and Obando (1995)



precursors are based on an age model (Fig. 1) modified from Meschede et al. (1998). The plate motion vectors were calculated according to the absolute plate motion reference frame (Tamaki 1997; DeMets et al. 1990; Gripp and Gordon 1990) and were used to move the plates back to their respective positions. As a reference, the location of the Galápagos hotspot was taken as fixed in all restorations. The restorations were performed on a cylindrical projection where distortions at the edges were negligible. A series of seven restorations (Present, 5, 10, 14, 15, 19, and 20 Ma) show the spreading history of the Cocos and Nazca plates (Fig. 2a–g) since their formation at approximately 23 Ma ago, whereas one restoration reconstructs the situation directly before the split-up of the Farallon plate (25 Ma; Fig. 2h). The hotspot traces have subsequently overprinted the oceanic crust formed at the different Cocos-Nazca spreading systems.

The paleogeographic restorations indicate that the distance between the location of the Galápagos hotspot and the CNS-3 axis has been increasing during

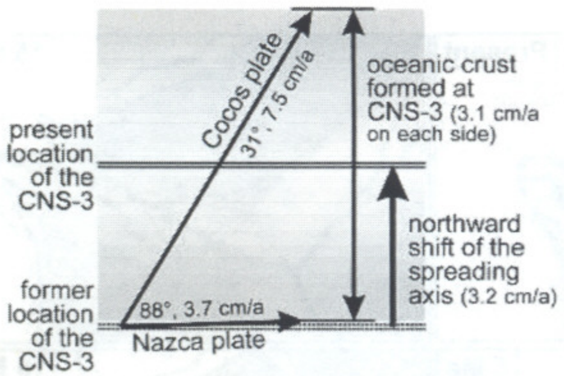


Fig. 3 Absolute plate motion vectors of the Cocos and Nazca plates (after Tamaki 1997) used to calculate the amount of northward shift of the CNS-3 axis

the past 10–15 Ma. When spreading started at the CNS-3 at 14.7 Ma the transform faults connecting the Ecuador and Costa Rica rifts with the Galápagos rift (Fig. 1) were located a small distance to the west of the hotspot (14 Ma; see Fig. 2d) and the rift axis was directly north of it. Due to the constant eastward movement of the Nazca plate, the transform faults shifted over the hotspot shortly after the onset of spreading and for a short time span the rift axis was on or south of the hotspot. At approximately 11–12 Ma the rift axis finally shifted to the north of the hotspot. As a result, a considerable part of hotspot products younger than 14.7 Ma has been deposited on the Cocos plate side of the CNS-3 rift forming a part of the Cocos ridge, which is now located far north of the presently active axis.

A simple calculation based on the present absolute plate motion vectors of the Cocos and Nazca plates (Tamaki 1997) demonstrates the continuous northward shift of the CNS-3 axis (Fig. 3). The 7.5 cm/year NNE motion (31°) of the Cocos plate and the 3.7 cm/year E motion (88°) of the Nazca plate add to a 3.1 cm/year half spreading rate at the symmetric CNS-3. Since the CNS-3 axis is in E–W direction and the Nazca plate moves towards east, the resulting northward shift of the spreading axis equals the spreading rate.

The northward shift of the CNS-3 axis decreases the amount of hotspot products which were deposited on the Cocos plate side of the CNS-3 with time. This is mirrored in the triangular shape of the Carnegie ridge: Its maximum width of approximately 270 km is at the Galápagos Islands (related to the –2000-m isobath) and its narrowest part is below the –2000-m isobath at 85.5°W (Fig. 1) where ages of more than 11 Ma have been determined from drowned islands (Christie et al. 1992; Sinton et al. 1996). The material missing in the middle part of the Carnegie ridge is presently represented in the northeastern part of the Cocos ridge where similar ages were obtained (13.0–14.5 Ma; Werner et al. 1999). Figure 4 demonstrates the principal evolution of the two ridges: the decreasing amount of material deposited on the Cocos plate and the increasing amount of material deposited on the Nazca plate during the opening of the CNS-3. In this simplified sketch, a constant and symmetric spreading rate during the past 14.7 Ma as well as a constant amount of volcanic production represented by the diameter of the circle (corresponding to a diameter of 300 km) is assumed. Holocene volcanic activity is observed in the Galápagos archipelago at a distance of 250 km (White et al. 1993). The resulting shapes of the hotspot traces are strikingly similar to the shapes of the western Carnegie and the Cocos ridge (compare Figs. 1 and 4). Thus, the model may explain the missing bathymetric connection between the two ridges and the triangular shape of the western Carnegie ridge, all based on symmetric CNS spreading and the resulting northward shift of the rift axis.

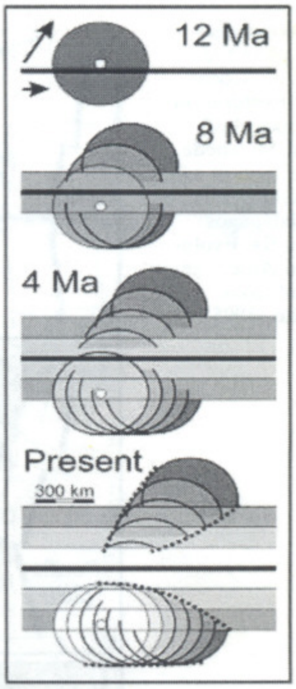


Fig. 4 Simplified sketch demonstrates the evolution of the two hotspot traces during the past 15 m.y. Spreading rates and amount of volcanic production are taken as constant. Note the similarity of the shapes of the traces to the western Carnegie and Cocos ridges (see Fig. 1)

Before 14.7 Ma the axis of the CNS-2 system was to the north at a distance of approximately 200 km from the Galápagos hotspot and resembled the present situation (Fig. 2f). Accordingly, most of the hotspot products formed during the later stage of activity of the CNS-2 (19.5–14.7 Ma) were deposited south of its spreading axis. They formed what is presently the eastern Carnegie ridge which is much wider than the eastern end of the triangular western Carnegie ridge segment (Fig. 1). The partitioning of the Carnegie ridge into two parts and the formation of the Cocos ridge is, therefore, the most visible result of the jump of the spreading axis at 14.7 Ma.

The Malpelo ridge has been suggested to be the older part of the Cocos ridge (Hey 1977; Lonsdale and Klitgord 1978; Meschede et al. 1998). The paleogeographic restoration at 15 Ma (Fig. 2e) shows that it was located at the center of the CNS-2 spreading axis at a distance of approximately 500 km to the Galápagos hotspot. In contrast to the Cocos ridge, however, a direct relation to the Galápagos hotspot is not possible and we suggest formation at a second center of volcanic activity, whose location coincides with the position where, at a later stage, the Cocos Island volcanoes were formed. Since the width of the Malpelo ridge (~80–90 km) is much smaller than that of the Cocos ridge (~200 km), we suggest a lower activitiy for the second center. From magnetic anomalies and based on bathymetric data, the Malpelo ridge has been interpreted to have formed on oceanic crust of the CNS-2 (Meschede et al. 1998). The central part of the ridge, which overprints the CNS-2 axis, is, therefore, suggested to be younger than 14.7 Ma.

Before 19.5 Ma (20 Ma; Fig. 2g) the CNS-1 axis was located south of the Galápagos hotspot. Since most of the subsequent CNS-2 and CNS-3 axes are located north of the CNS-1 axis and north of the Carnegie ridge, most of the CNS-1 crustal material has been transferred to the Nacza plate. Most of the remnants of the CNS-1 are thus suggested to be presently located south of the Carnegie ridge on the Nazca plate (Fig. 1). Only a small piece of CNS-1 oceanic crust exists in front of the Nicoya peninsula north of the CNS-2 related part of the Cocos plate (Fig. 1; Meschede et al. 1998; Barckhausen et al., 2001). A possible remnant of the oldest part of the Galápagos hotspot trace preserved on the Cocos plate side may be the Coiba ridge south of Panama (Fig. 1). The relation of this submarine ridge to the evolution of the hotspot traces, however, remains unclear since the only available age data from this environment, which was drilled at its eastern flank (DSDP Site 155; van Andel et al. 1973), revealed 15-Ma-old sediment overlying basaltic bedrock. The age of the bedrock is not known. The assumption that Coiba ridge represents a remnant of the Galápagos hotspot trace is thus only based on the paleogeographic restoration of Fig. 2g at 20 Ma. This restoration demonstrates that the ridge was close to the Galápagos hotspot at approximately 20 Ma. It is, therefore, predicted that the Coiba ridge contains approximately 20-Ma-old Galápagos hotspot material. The alkali basaltic composition of the samples from DSDP Site 155 (van Andel et al. 1973) may be an indication of hotspot material. Rocks older than 23 Ma, which would have formed on the Farallon plate, are not known from the Galápagos hotspot (Christie et al. 1992) or from related ridges.

Geometric constraints indicate that a considerable part of the Cocos ridge has been formed at the Galápagos hotspot when the CNS-3 spreading axis was located near this hotspot (Fig. 2c, d). However, based on the existing data, we consider three indications for a second center of hotspot activity: (a) the age of Cocos Island (2 Ma); (b) the location of the Malpelo ridge, which cannot be explained by formation at the Galápagos hotspot in our model; and (c) the size of the Cocos ridge, which seems to be too large to have been formed completely at the Galápagos hotspot. One hotspot center in the neighborhood of the CNS-3 should produce two complementary ridges. When the hotspot was on the Cocos plate side of the CNS-3, a wide Cocos ridge and a narrow Carnegie ridge were formed at the same time (Fig. 4). Whereas the western segment of the Carnegie ridge with its increasing width toward the west follows this geometric constraint, the Cocos ridge keeps its width from the Central American landbridge to a position approximately 500–600 km to the NE of the Galápagos center (Fig. 1).

The Pliocene ages of the Cocos Island volcanism preclude a direct relation to Galápagos (Meschede et al. 1998), although geochemically the volcanic rocks clearly indicate hotspot characteristics. We argue that a second center of volcanic activity exists approximately 500–600 km to the NE of the Galápagos center. The position of this second center, which was less productive than Galápagos and probably only sporadically active, remains stable in relation to Galápagos from its first occurrence at the Malpelo ridge until formation of Cocos Island. Further investigations may provide more detailed age data from the Cocos ridge helping to understand the area around Cocos Island

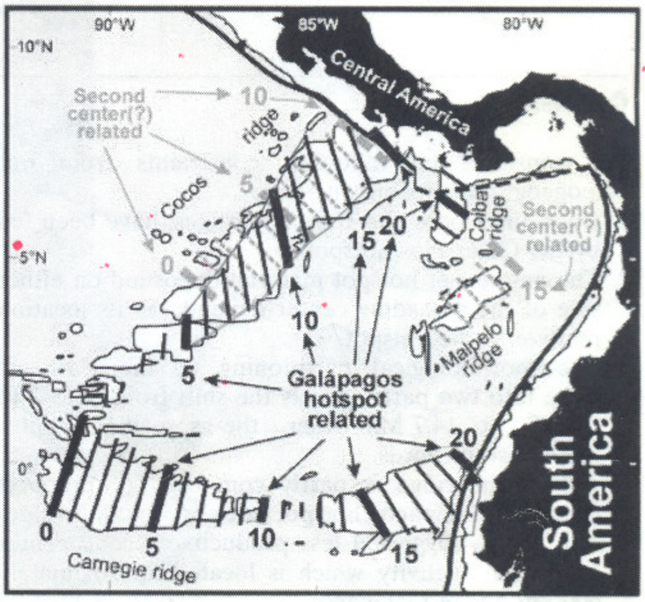


Fig. 5 Predicted ages of hotspot products on the Galápagos hotspot traces. *Black lines* indicate Galápagos age trend; *gray lines* indicate second center age trend

and the nearby short-lived spreading center with its problematic connection to the CNS-3 spreading.

Transferring the sketch model of Fig. 4 to the paleogeographic restorations we developed a map of age predictions for the two hotspot traces (Fig. 5). We assumed a radius of 150 km around the center of hotspot activity at Galápagos where volcanic material thickened the pre-existing oceanic crust. The radius is represented by the age lines in Fig. 5. The shorter the age lines of the Galápagos trend on the Carnegie ridge, the longer they are on the Cocos ridge representing the amount of material deposited on each side of the CNS-3. The sum of both lines at the same age is always 300 km. Whereas the Carnegie ridge is characterized by an increasing age trend towards the east, the Cocos ridge has two age trends: the older, predominant one is related to the Galápagos hotspot; it ends with ages around 15 Ma in front of the Central American landbridge. This is in agreement with the results of Werner et al. (1999). The younger age trend is approximately 5 m.y. younger than the Galápagos trend and is related to the second center of hotspot activity, which, however, is suggested to be much less productive and thus represented by shorter age lines. Because of this second center of activity, it is possible that ages differing by 5–10 m.y. will be found on the Cocos ridge at the same location. This critical test of our model can only be performed with future age dating of rock samples from the Cocos ridge. Ages on the Malpelo ridge, which is suggested to have formed on CNS-2 oceanic crust, are expected to be 15 Ma in its northeastern part with a decreasing age trend toward southwest. According to our paleogeographic restorations the Coiba ridge was formed on CNS-1 crust and its material is derived from the Galápagos hotspot (Fig. 2f,g).

Conclusion

We consider the following constraints from our paleogeographic reconstructions:

1. Both, the Cocos and Carnegie ridges, have been fed by the Galápagos hotspot.
2. The amount of hotspot material deposited on either side of the spreading center depends on its location relative to the hotspot.
3. The morphological partitioning of the Carnegie ridge into two parts reflects the shift from CNS-2 to CNS-3 at 14.7 Ma when the spreading center jumped southwards.
4. The Cocos ridge is partly composed of products from the Galápagos hotspot but also contains material from a suggested less productive second center of volcanic activity which is located approximately 600 km NE of Galápagos.
5. The Malpelo ridge has been formed at the second center of volcanic activity.
6. The Coiba ridge is suggested to have formed at the Galápagos hotspot and may contain the oldest Galápagos material preserved in the suboceanic ridges of this area.
7. The geometric relationship of the Cocos and Carnegie ridges indicates symmetric spreading and a constant northward shift of the presently active Cocos-Nazca spreading center.

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