The plate tectonic evolution of the Cocos-Nazca spreading center

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7. Plate Tectonic Evolution of the Cocos-Nazca Spreading Center[1]

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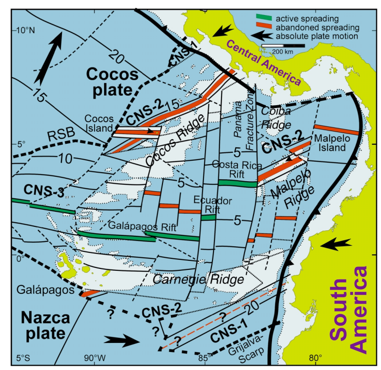
ABSTRACT

Paleogeographic restorations for the oceanic crust formed by the Cocos-Nacza spreading center and its precursors were performed in steps of 0.5 m.y. The breakup of the Farallon plate into the Cocos and Nazca plates occurred at ~23 Ma and was followed by three subsequent spreading systems: CNS-1, ~23–19.5 Ma; CNS-2, 19.5–14.7 Ma; and CNS-3, 14.7 Ma–present. Based on the spreading history, we reconstructed the evolution and ages of submarine aseismic ridges in the Eastern Pacific Basin—the Carnegie, Coiba, Cocos, and Malpelo Ridges, which overprint oceanic crust formed at the subsequent Cocos-Nazca spreading system. The mophological bipartition of the Carnegie Ridge reflects the jump from CNS-2 to CNS-3 at 14.7 Ma and the later increasing distance of the CNS-3 spreading axis from the Galápagos hotspot. The Cocos Ridge is mainly composed of products from the Galápagos hotspot but also contains material from a suggested less productive second center of volcanic activity that is located ~600 km northeast of Galápagos. The Malpelo Ridge is a product of the second center of volcanic activity, whereas the Coiba Ridge probably formed directly 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 CNS-3 system since its formation at 14.7 Ma.

INTRODUCTION

The Cocos and Carnegie Ridges are two prominent submarine aseismic ridges that dominate the basin morphology of the eastern Panama Basin (Fig. F1). The Cocos Ridge is an ~1000-km-long and up to 200-

F1. Overview of the eastern Pan ama Basin, p. 7.



[1]Meschede, M., and Barckhausen, U., 2000. Plate tectonic evolution of the Cocos-Nazca spreading center. *In* Silver, E.A., Kimura, G., and Shipley, T.H. (Eds.), *Proc. ODP, Sci. Results,* 170: College Station, TX (Ocean Drilling Program), 1–10 [Online]. Available from World Wide Web: <http://www-odp.tamu.edu/publications/170_SR/VOLUME/CHAPTERS/SR170_07.PDF>. [Cited YYYY-MM-DD]
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km-wide positive morphological feature on the ocean floor of the Cocos plate. It reaches elevations of <1000 m below sea level and is thus considerably shallower than the surrounding oceanic crust of the Cocos plate with water depths of >4000 m. Its northeast trend (45°) is almost normal to the strike of the Middle America Trench, along which it is being subducted off Costa Rica and Panama. The indentation into the Central America landbridge leads to strong uplift and exhumation of deep crustal stockworks (Graefe et al., 1997; Graefe, 1998; Meschede et al., 1999). A paleogeographic restoration juxtaposes the smaller Malpelo Ridge, today located east of the Panama Fracture Zone on the Nacza plate (Fig. **F1**), in prolongation of the Cocos Ridge (Hey, 1977; Lonsdale and Klitgord, 1978; Meschede et al., 1998). An ~250 km missing part of the once-continuous Cocos-Malpelo Ridge system has already been subducted beneath the Central America landbridge. The Coiba Ridge south of Panama has been suggested to have been formed not as a hotspot trace but rather by uplift beside a long meridional transform fault during the late Miocene and Pliocene (Lonsdale and Klitgord, 1978). Its origin, however, remains unclear because of the lack of data.

The Carnegie Ridge is an ~1350-km-long and up to 300-km-wide structure on the ocean floor of the northern Nazca plate (Fig. **F1**). It is separated into two elongated triangular-shaped parts and includes the Galápagos archipelago at its western end. Its east-west trend is almost normal to the strike of the Peru-Chile Trench, along which it is being subducted beneath the South American plate. Although in contrast to the Cocos Ridge, uplift and exhumation of the upper plate are not observed at the indentation front of the Carnegie Ridge; therefore, the indentation of the ridge into South America is interpreted to have started at ~2 Ma (Gutscher et al., 1999).

The Cocos, Malpelo, and Carnegie Ridges are interpreted to be hotspot traces that began to form when the Galápagos hotspot initiated at ~20–22 Ma (Hey, 1977; Lonsdale and Klitgord, 1978). Meschede et al. (1998) demonstrated that the products of hotspot volcanism overprinted a complex pattern of oceanic crust formed at three subsequently active and differently oriented spreading systems where, in contrast to older reconstructions (e.g., Hey, 1977; Lonsdale and Klitgord, 1978), symmetric spreading occurred. The identified extinct spreading systems represent precursors of the presently active Cocos-Nazca spreading center (Fig. **F1**).

During the late Oligocene, the Farallon plate split into the Cocos and Nazca plates as a result of global rearrangement of plate boundaries (e.g., Silver et al., 1998). Based on interpretations of magnetic anomalies, the oceanic crust of both the Cocos and Nazca plates was formed along the presently active Cocos-Nazca spreading center (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 geomagnetic polarity time scale of Cande and Kent, 1995), and thus dating the splitting of the Farallon plate to this time period. The first spreading system (CNS-1) was active until 19.5 Ma, when the orientation of the spreading axis changed from northwest–southeast to east-northeast–west-southwest. The second spreading system (CNS-2) was abandoned at 14.7 Ma, when the presently active east-west–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 boundary between oceanic crust formed at the Cocos-Nazca spreading center and the East Pacific Rise is marked by the rough/smooth boundary (RSB in Fig. F1).

PALEOGEOGRAPHIC RESTORATIONS

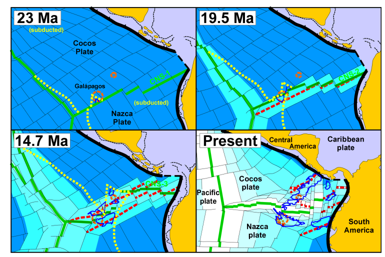
We performed paleogeographic restorations based on a slightly modified age model (Fig. F1) for the oceanic crust formed by the Cocos-Nazca spreading center and its precursors, given by Meschede et al. (1998). The plate motion vectors were calculated according to the absolute plate motion reference frame (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 neglected. A series of 50 restorations (dating back to 25 Ma in 0.5-m.y. steps) shows the breakup of the Farallon plate and the spreading history of the Cocos and Nazca plates (Fig. F2; animated illustration) since their formation at ~24–23 Ma. The first pictures (25–24 Ma) demonstrate the situation directly before the split of the Farallon plate. The hotspot traces subsequently overprinted the oceanic crust formed at the three 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 the last 10–15 m.y. When spreading started at CNS-3 at 14.7 Ma, the transform faults connecting the Ecuador and Costa Rica rifts with the Galápagos rift (see Fig. F1 for location) were located only a little distance to the west of the hotspot (see Fig. F2; 14.5 Ma) and the rift axis was directly north of it. Because of 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 came into a position on or south of the hotspot. At ~11–12 Ma, the rift axis finally shifted north of the hotspot. As a result, a considerable portion of hotspot products formed after the beginning of CNS-3 spreading (14.7 Ma) has been deposited on the Cocos plate side of the CNS-3 rift now forming a part of the Cocos Ridge, which is located far north of the presently active axis.

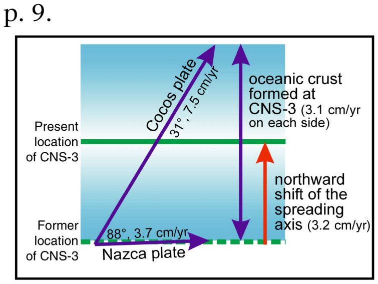
A simple calculation based on the present absolute plate motion vectors of the Cocos and Nazca plates (Tamaki, 1997) demonstrates the continuous northward shift of the CNS-3 axis (Fig. F3) and the deposition of products. The 7.5 cm/yr north-northeast motion (31°) of the Cocos plate and the 3.7 cm/yr east motion (88°) of the Nazca plate add to a 3.1 cm/yr half-spreading rate at symmetric CNS-3. Because the CNS-3 axis is east-west and the Nazca plate moves towards the east, the resulting northward shift of the spreading axis equals the spreading rate.

The northward shift of the CNS-3 axis decreased the amount of hotspot products that were formed on the Cocos plate side of CNS-3 with time. This is mirrored in the triangular shape of the Carnegie Ridge: its maximum width (~270 km) is at the Galápagos Islands (related to the –2000 m bathymetric line), and its thinnest part is below the –2000 m line at 85.5° (Fig. F1), where ages of >11 Ma have been determined from drowned islands (Christie et al., 1992; Sinton et al., 1996). The material missing from the middle part of the Carnegie Ridge is today represented in the northeastern part of the Cocos Ridge, where similar ages were obtained (13.0–14.5 Ma) (Werner et al., 1999). The animated illustration Figure F4 demonstrates the principal evolution of

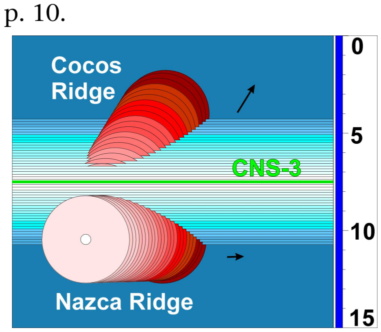
F2. Paleogeographic restoration of the plate tectonic evolution of the Cocos and Nazca plates, p. 8.



F3. Absolute plate motion vectors of the Cocos and Nazca plates, p. 9.



F4. Evolution of the two hotspot traces during the past 15 m.y., p. 10.



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 CNS-3. In this simplified sketch, a constant and symmetric spreading rate during the last 14.7 m.y. 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 Cocos Ridges (cf. Figs. **F1** and **F4**). Applying this simple model to our paleogeographic restorations, we can explain the missing bathymetric connection between the two ridges and the triangular shape of the western Carnegie Ridge, all based on symmetric spreading and the resulting northward shift of the rift axis.

Before 14.7 Ma, the axis of the CNS-2 system was ~200 km north of the Galápagos hotspot and resembled the present situation (Fig. **F2**). Accordingly, most of the hotspot products formed during the later stage of CNS-2 activity (19.5–14.7 Ma) are located south of its spreading axis and are thus part of the eastern Carnegie Ridge, which is much wider than the eastern end of the triangular western Carnegie Ridge segment (Fig. **F1**). The bipartition of the Carnegie Ridge 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. **F2**) shows that it was located at the center of the CNS-2 spreading axis ~500 km from the Galápagos hotspot. According to this restoration, direct relation to the Galápagos hotspot is not possible and a second center of volcanic activity must be considered. The location of this second center, which might be connected to the Galápagos hotspot in the upper mantle, coincides with the position where later-stage Cocos Island volcanoes (Castillo et al., 1988) have formed. Since the width of the Malpelo Ridge (~80–90 km) is much smaller than the Cocos Ridge (~200 km), we suggest lower activity at the second center. Based on magnetic anomalies and bathymetric data, the Malpelo Ridge has been interpreted to have formed on CNS-2 oceanic crust (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. A critical test for this part of our model will be to obtain new age data from Malpelo Ridge, where up to now no age data have been available.

Before 19.5 Ma (Fig. **F2;** 20 Ma), the CNS-1 axis was located south of the Galápagos hotspot. Because most of the subsequent CNS-2 and CNS-3 axes are located north of the CNS-1 axis and of Carnegie Ridge, most of the CNS-1 crustal material has been transferred to the Nacza plate. Most of the remnants of CNS-1 are thus suggested to be located today south of the Carnegie Ridge on the Nazca plate (Fig. **F1**). Only a small remainder of CNS-1 oceanic crust exists in front of the Nicoya Peninsula north of the CNS-2–related part of the Cocos plate (Fig. **F1**) (Meschede et al., 1998). A possible remainder of the oldest part of the Galápagos hotspot trace preserved on the Cocos plate side may be the Coiba Ridge south of Panama (Fig. **F1**). The relation of this submarine ridge to the evolution of the hotspot traces, however, remains unclear because the only available age data from this environment (Deep Sea Drilling Project [DSDP] Site 155, drilled at the eastern flank of the ridge; Shipboard Scientific Party, 1973) revealed 15-Ma sediment overlying basaltic bedrock. The age of the bedrock is not known. The assumption that Coiba Ridge represents a remainder of the Galápagos hotspot trace is thus based only on the paleogeographic restoration of Figure F2 (20 Ma). This restoration demonstrates that the ridge lay in close connection to the Galápagos hotspot at ~20 Ma. It is, therefore, predicted that Coiba Ridge contains ~20-Ma Galápagos hotspot material. The alkali basaltic composition of basaltic samples from DSDP Site 155 (Shipboard Scientific Party, 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) and related ridges.

CONCLUSIONS

Conclusions are as follows:

1. Three subsequent spreading systems formed the oceanic crust of the Cocos and Nazca plates: CNS-1, ~23–19.5 Ma; CNS-2, 19.5–14.7 Ma; and CNS-3, 14.7 Ma–present;
2. Hotspot traces overprint oceanic crust formed at the subsequent spreading centers of the Cocos-Nazca spreading system;
3. Main production of hotspot material occurred at the Galápagos hotspot; and
4. Because of the northward shift of the Cocos-Nazca spreading system, the amount of hotspot material transferred to the Cocos plate and represented by the Cocos Ridge decreased.

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Figure F1. Overview of the eastern Panama Basin (modified from Meschede et al., 1998). Numbers indicate the ages of oceanic crust. The distribution of extinct spreading systems is from Meschede et al. (1998). CNS = Cocos-Nazca spreading system. RSB = rough/smooth boundary.

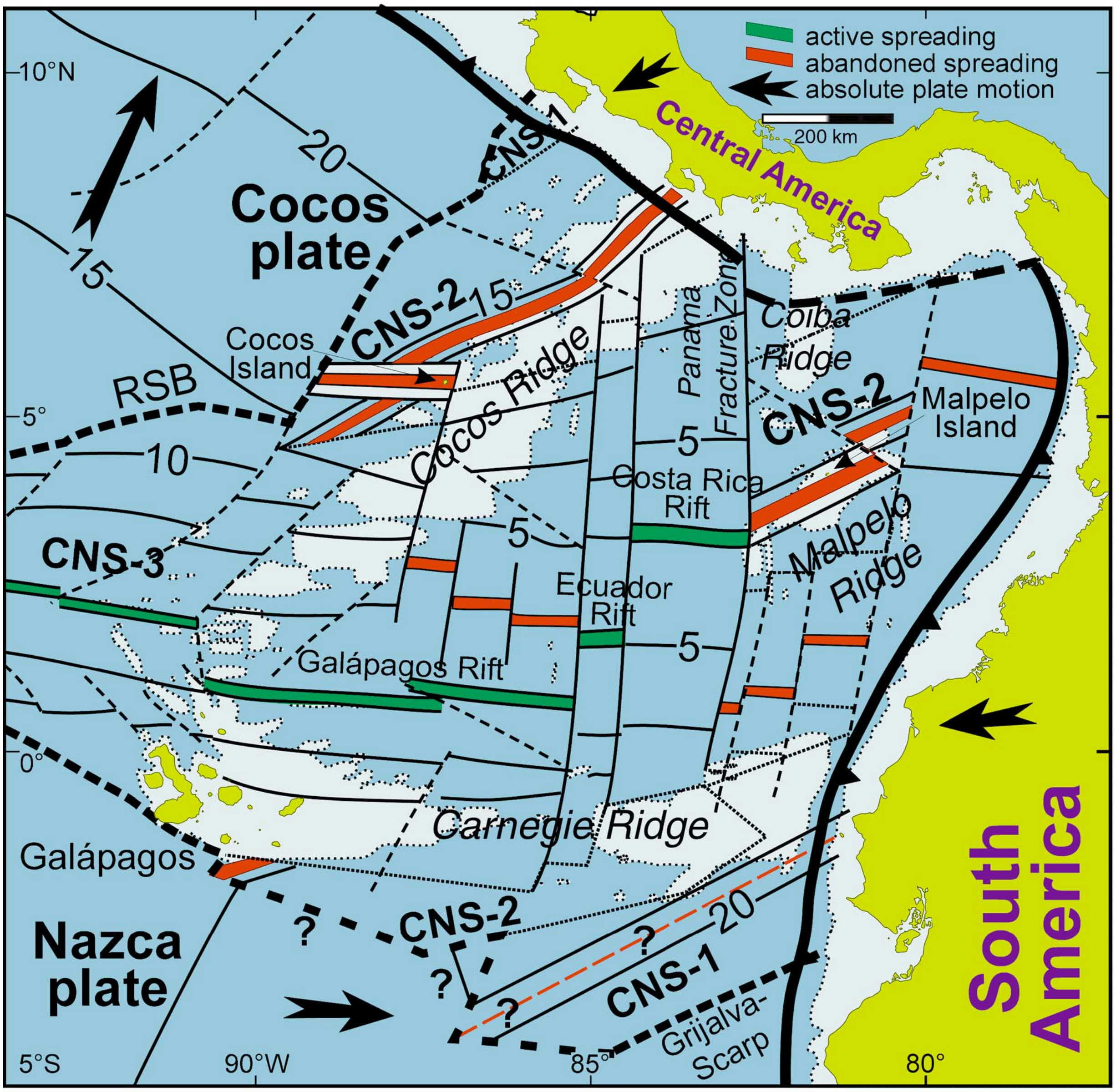


Figure F2. Animated illustration of paleogeographic restoration of the plate tectonic evolution of the Cocos and Nazca plates. The restoration is based on the age model of oceanic crust from Meschede et al. (1998). The plate motion is calculated after Tamaki (1997). The location of the Galápagos hotspot is taken as fixed. The evolution of the Central America landbridge is adopted from Coates and Obando (1996). Dotted line = outline of present plate boundary. At 23 Ma: breakup of Farallon plate into Cocos and Nazca plates and formation of CNS-1; 19.5 Ma: formation of CNS-2; and 14.7 Ma: formation of the still-active CNS-3. (Windows and Macintosh users: view QuickTime movie, **fast version:** ~40 s, no explanations; **slow version:** ~2.5 min, with explanations. UNIX users: view animated GIF in Web browser, **fast version;** view **slow version.**)

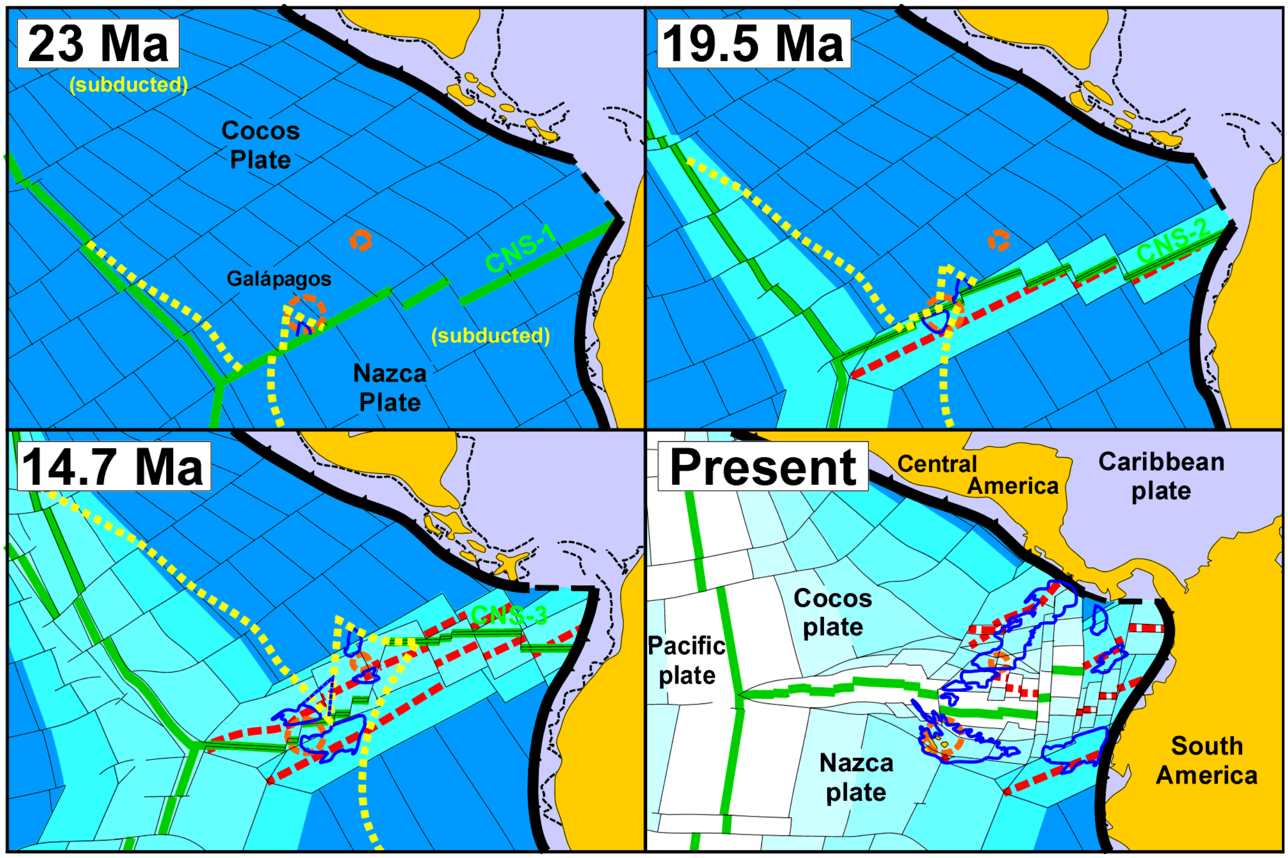
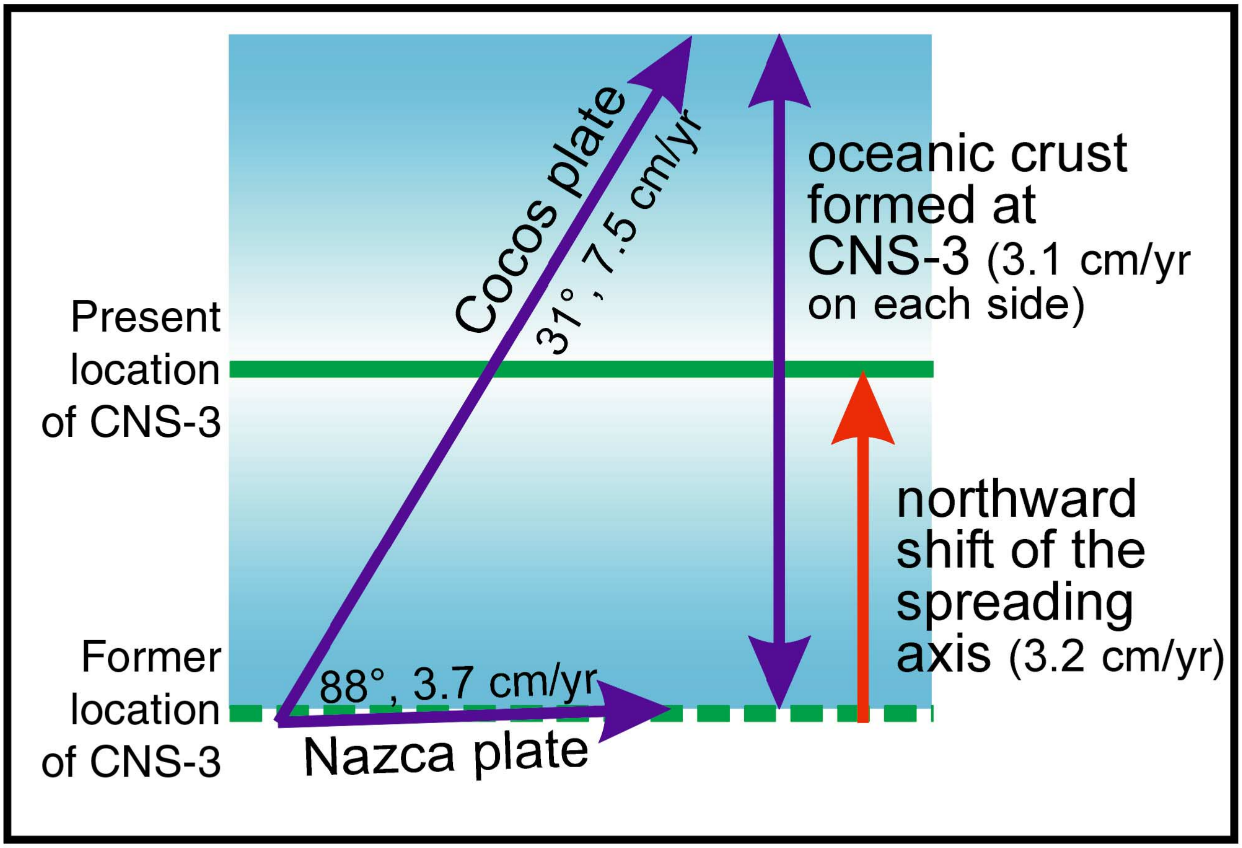
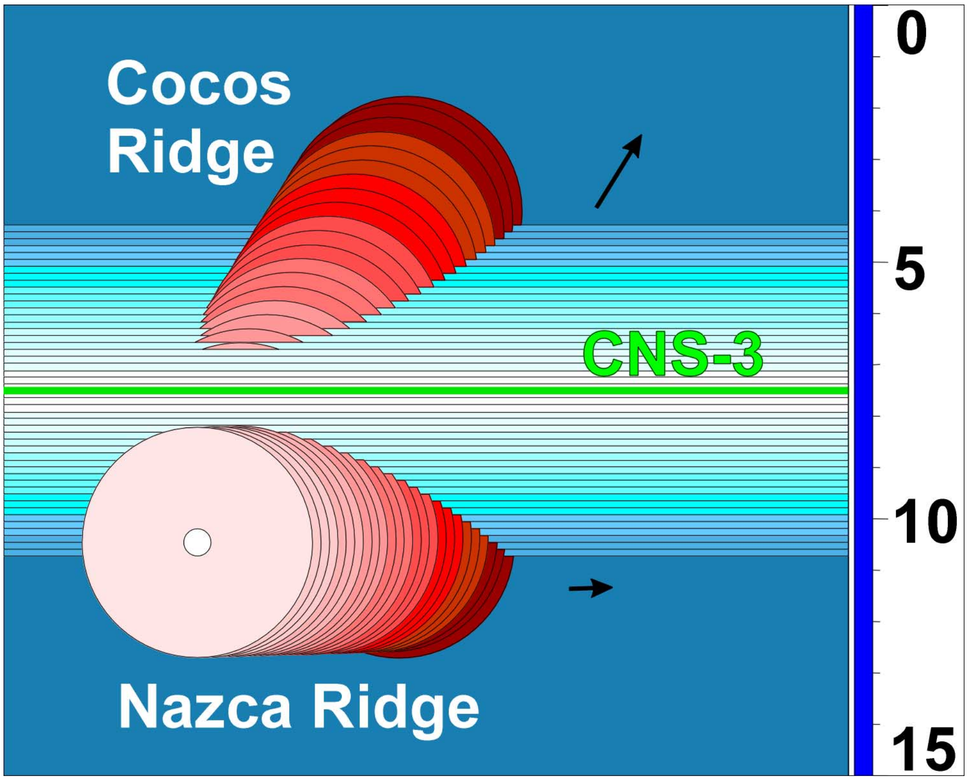


Figure F3. Absolute plate motion vectors of the Cocos and Nazca plates (after Tamaki, 1997) used to calculate the amount of northward shift of the CNS-3 axis.




Cocos
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