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# Characterization and tectonic implications of Mesozoic-Cenozoic oceanic assemblages of Costa Rica and Western Panama

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**ABSTRACT**

The Pacific face of Costa Rica and western Panama has been extensively studied because of the wide occurrence of oceanic assemblages. In Northern Costa Rica, the Santa Elena Nappe made by ultramafic and mafic associations overthrusts the Santa Rosa Accretionary Complex. The Nicoya Complex corresponds to a pre-Campanian oceanic plateau association, cropping out in the Nicoya Peninsula and the outer Herradura Block. The 89 Ma high MgO Tortugal Komatiitic Suite corresponds to 14-km long, 1.5-km wide body, with no clear relation with to the Nicoya Complex. The Tulín Formation (Maastrichtian to Lower Eocene) forms the main edifice of an accreted ancient oceanic island of the Herradura Block. The Quepos Block was formed by the accretion of a late Cretaceous-Paleocene seamount. In the Osa and Burica peninsulas, Caño Island and Golfito area, a series of Upper Cretaceous to Eocene accreted plateau and seamount blocks crop out. In western Panama, the oceanic assemblages range from Upper Cretaceous to Miocene, and their geochemical signature show their oceanic plateau association. The Costa Rica and western Panama oceanic assemblages correspond to a fragmentary and disrupted Jurassic to Miocene sequences with a very complicated geological and geotectonic history. Their presence could be interpreted as a result of accretionary processes rather than tectonic erosion; despite this last process is nowadays active in the Middle American Trench. The whole picture has not been completed yet, but apparently, most of the igneous rocks have a geochemical signature similar to the Galapagos mantle plume. The later has been acting in pulses, or otherwise the outcropping occurrences could be part of several plateaus somehow diachronically formed in the Pacific basin.

***KEYWORDS*** **Costa Rica. Panama. Oceanic assemblage. Galapagos. Basalts. Gabbros. Radiolarites. Peridotites.**

## INTRODUCTION

The Pacific face of Costa Rica and western Panama is characterized by extensive occurrences of oceanic assemblages (Fig. 1). Many authors have discussed their origin and tectonic significance since the 70's. Nowadays, geologists and petrologists are applying updated methodology to understand the geotectonic environment of formation of these rocks. However, this is a wide-open field of research and much more needs to be done to have a clear

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geotectonic picture. The oceanic crust outcrops are one of the most important records for the understanding of the origin and geotectonic history of the Middle American convergent margin. Today, the Middle American Trench separates the Cocos and Caribbean plates, and the Panama Fracture Zone delimits the Cocos from the Nazca plates. Convergence rates of nearly 10 cmy-1 have been measured across the Costa Rican segment of the trench (DeMets et al., 1990), and several subduction processes have been proposed that range from smooth subduction off the Nicoya Peninsula to collision, where the Cocos Ridge meets the Middle American Trench (Gardner et al., 1992).

Fundamental controversy exists about the geotectonic setting related to the formation and emplacement of the oceanic suites, which is directly related to the regional models involved in the formation of the Caribbean Plate. Malfait and Dinkelman (1972), Donnelly et al. (1973), Donnelly (1973) and later Burke et al. (1978) hypothesized that a large part of the present Caribbean Plate was formed in the Pacific as anomalously thick, buoyant crust that later was displaced northeast, between the Americas. Duncan and Hargraves (1984) hypothesized that the Galapagos mantle plume was responsible for the thickened Caribbean crust.

In opposition to the above models of a general allocthony of the Caribbean, Frisch et al. (1992) and Meschede and Frisch (1998) proposed a fixist model for the formation of the Caribbean Plateau by the separation of North and South America. This model was based on paleomagnetic work by Sick (1989), who concluded the Peninsula to belong genetically to the Caribbean plate. His interpretation locates the Nicoya Peninsula in a position close to South America from its formation in the Jurassic until the Coniacian/Turonian Caribbean Plateau event.

In contrast, the paleomagnetic data from DeBoer (1979), DiMarco (1994) and DiMarco et al. (1995) show rotation and shift. DeBoer (1979) presented 87 basaltic paleomagnetic data that he interpreted have gradual clockwise rotation from an E-W-trending aeromagnetic pattern in N-Nicoya Peninsula. DiMarco (1994) reconstructed the Campanian-Maastrichtian to Paleogene magneto-stratigraphy at several sites in Costa Rica and Pana-

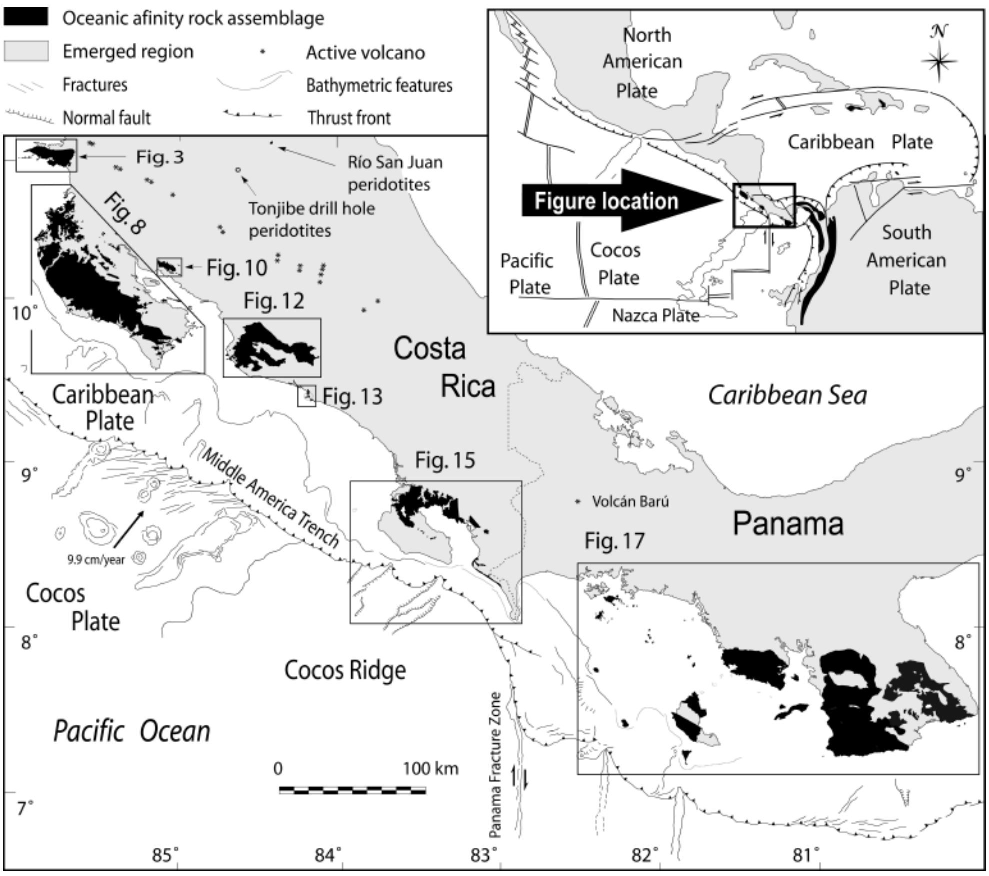


FIGURE 1 | **Present day geotectonic setting of Central America and the Caribbean, showing the oceanic assemblages of Costa Rica and western Panamá. The different areas described in this paper are marked and they are detailed in the following figures. Ocean floor features from Ranero and von Huene (2000).**

ma, and determined the existence of four terranes: Chorotega, Nicoya, Golfito, and Burica (Fig. 2). Following, the conclusions of DiMarco (1994) and DiMarco et al. (1995) are exposed. The Chorotega Terrane comprises most of the territory of Costa Rica and Panama, inclusive part of the Nicoya Peninsula. This terrane is characterized by mean paleomagnetic directions approximately parallel to present day Earth's field that implies an origin close to its present latitude and no significant rotation relative to South America from the Late Cretaceous to present. The Nicoya Terrane comprise the Santa Elena and Nicoya pennsulas; it was positioned around 16° latitude south respect to the Chorotega Terrane in the Late Cretaceous. The Golfito Terrane extends from Golfito area in southern Costa Rica to the Azuero and Soná peninsulas, Panama. The paleomagnetic data from the Golfito Terrane indicate Late Cretaceous equatorial latitude and a counterclockwise rotation of 60° respect to the Chorotega Terrane. The Burica Terrane form the Burica Peninsula; its paleomagnetic data locate a south equatorial origin of this terrane, and 90° of counterclockwise rotation, which implies 15° of northward shift from the Paleocene to Eocene.

More recent geochemical works and $Ar^{39}/Ar^{40}$ dating by Sinton et al. (1997), Alvarado et al. (1997), Hauff et al. (1997), Hauff et al. (2000) and Hoernle et al. (2004) have largely confirmed the view of the Nicoya Peninsula as a portion of the Caribbean Plateau or as a plateau geochemically similar to the Eastern Pacific.

Concerning the petrological-geochemical studies, the comparison of the different authors is very difficult because of the great progress and rapid changes in geochemical analyses technology. It is impossible to use the geotectonic interpretations that were made before the use of trace elements and rare earths. However, Wildberg (1984) did the first systematic analysis of igneous geochemistry in the Nicoya Peninsula. He concluded that both MORB and primitive island arc rocks were present in the Peninsula. Meschede and Frisch (1994) published one of the major data bases of geochemical analyses from various basaltic units along the Costa Rican Pacific coast. They found mid-ocean ridge basalts, island arc tholeiites, within-plate tholeiites and alkali basalts. Hauff et al. (1997), Sinton et al. (1997), Beccaluva et al. (1999), Hauff et al. (2000), Arias (2003), and Hoernle et al. (2004) carried out some of the modern studies. Despite the different methodology and terminologies used, they conclude that the majority of the complexes of the Pacific face of southern Central America are part of the Caribbean Large Igneous Province (CLIP), with a clear affinity to the Galapagos hotspot. More recent geochemical work and $Ar^{39}/Ar^{40}$ dating by Sinton et al. (1997), Alvarado et al. (1997), Hauff et al. (1997), Hauff et al. (2000), Hoernle et al. (2002) and Hoernle et al. (2004) has largely confirmed the view of the Nicoya Peninsula as a portion of the Caribbean Plateau or as a plateau geochemically similar to the East Pacific. In this paper, we do not consider the K-Ar radioisotopic dating, because they are no trusty as $Ar^{39}/Ar^{40}$ in altered samples. In general, the oceanic assemblages cropping out along the pacific coast of Costa Rica and western Panama were part of aseismic ridges, seamounts, volcanoes, portions of ancient island arcs, and mantle fragments that probably represent old suture zones. Remarkable also is the presence of several accretion complexes and mélanges that nowadays represents a well understood part of the very complicated history of the Pacific active margin.

Several authors have considered an ophiolitic model, basically, in relation to the Nicoya Complex cropping out in the Nicoya Peninsula together with the ultramafics of Santa Elena Peninsula (DeBoer, 1979; Kuijpers, 1980; Berrangé and Thorpe, 1988; Beccaluva et al., 1999); some of them use the term "Nicoya Ophiolite Complex". Other authors (Berrangé et al., 1989) extended the name of Nicoya Complex to refer to other oceanic occurrences of the Pacific face of Costa Rica, despite of their different ages and origin. However, we consider, as is explained further, to use the term of Nicoya Complex restricted to the Lower Campanian-Santonian sequences described originally by Dengo (1962), with redefinition by Kuijpers (1980), Tournon (1984) and Baumgartner (1984).

Our work along the Pacific margin of Central America has been focused on the understanding of subduction-accretion processes back in time to the Jurassic. However, we faced basic difficulties to integrate the whole information. There are two principal issues. Firstly, the large amount of different hypothesis that have been proposed through the last 40 years, based on a very diverse type of

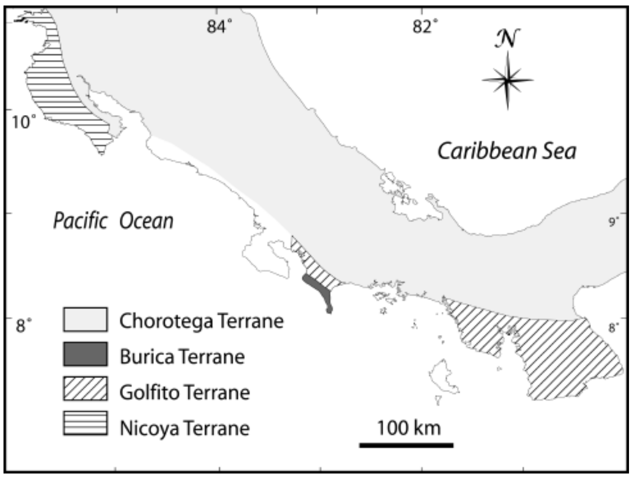


FIGURE 2 | **Late Cretaceous-Paleogene terranes distribution of Costa Rica and Panama, after DiMarco (1994) and DiMarco et al. (1995).**

analysis and different research approach, which mean the existence of quite contradictory theories. Secondly, the big difference of the research detail, northern Costa Rica has been very detailed studied in comparison to the lack of information in southern Costa Rica and Panama. In despite of these difficulties the objective of this paper is to put on the table the main differences in age and source of the occurrences of the oceanic assemblages, which are cropping out through the Pacific margin of Costa Rica and western Panama, emphasizing on the unsolved problems. We consider necessary to have a view of the whole picture to begin to understand the real significance of each particular component, which is the main purpose of this paper. From geochemical point of view, we did a comparison of chondrites normalized REE from each area. We summarize the biochronologic ages and radioisotopic $Ar^{39}/Ar^{40}$ dating which have been done at the region. To really solve one or more of the regional problems will required a future integrate geochemical, structural, stratigraphic and $Ar^{39}/Ar^{40}$ radioisotopic campaign.

## SANTA ELENA PENINSULA

The Santa Elena area structurally consists of a nappe (Fig. 3), which placed an ultramafic and mafic allochtonous unit above a basaltic-radiolaritic assemblage (Azéma and Tournon, 1980). The vergence of folds in the autochthonous unit indicates that emplacement of Santa Elena Nappe occurred from north to south relative to the autochthonous underneath unit (Azéma et al., 1985). Frisch et al. (1992) through fabrics studies, indicate a south to west southwest emplacement direction as well. The rudist reef limestone growing up on top of the exhumed peridotites suggest that overthrusting occurred in the pre-late Campanian (Schmidt-Effing 1980; Seyfried and Sprechmann, 1985). On the other hand, the nappe was emplaced after Cenomanian, the age of the youngest dated radiolarite in the underlying sediments (DeWever et al., 1985).

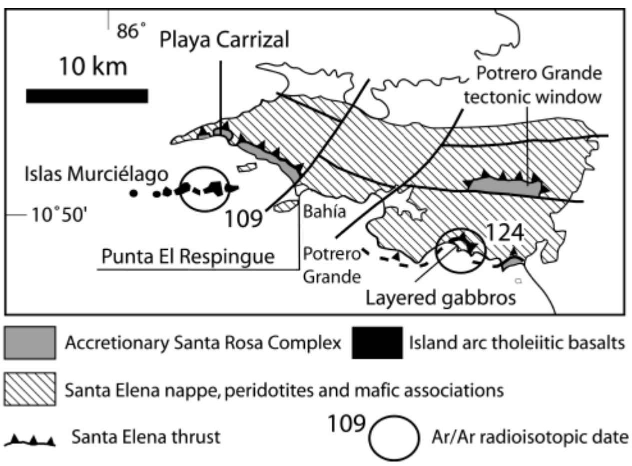


FIGURE 3 | **Simplified geologic map of the Mesozoic oceanic assemblages of the Santa Elena peninsula. Modified after Tournon (1994), and Tournon and Alvarado (1997), and include radioisotopic dates after Hauff et al. (2000).**

The allochthonous sequence is composed of mafics, ultramafics, dyke swarms and plagiogranites. The ultramafic sequence consist of peridotites, mostly diopside bearing harzburgites (Tournon, 1994). Layered gabbros and plagiogranites are cropping out in part of southern peninsula (Fig. 3). The layered gabbros consist of centimeter to meter thick layers of gabbros, different from one to another according to the ferromagnesian abundance (Tournon, 1994). Radioisotopic $Ar^{39}/Ar^{40}$ dating was done on a gabbro sample from this unit, and it gives an age of 124.0 ± 4.0 Ma (Hauff et al., 2000). Plagiogranites are very acidic and low in potassium (Tournon, 1984; Wildberg, 1984). The peridotites are cut by a numerous series of mafic dikes (Desmet et al., 1985; Tournon, 1994; Fig. 4).

The autochthonous unit is cropping out in the Potrero Grande tectonic window and southern shoreline, and they represent the deepest erosion levels. The igneous rocks are alkaline pillow and massive lavas, micro-gabbros, dolerites, lamprophyres, tuffs, and very scarce trachytes (Tournon, 1994). Radiolarites and pelagic siliceous limestones are present in the Potrero Grande tectonic window. The radiolarian fauna were assigned to the Callovian, Hauterivian and Cenomanian (Schmidt-Effing, 1980; DeWever et al., 1985). The southwest cliffs outcrops, between Playa Carrizal and Punta El Respingue (Fig. 3), have radiolaria that ranges from late Early or early Middle Jurassic to Albian-Cenomanian (Tournon, 1984; DeWever et al., 1985).

We consider the relative autochthonous lower unit of Santa Elena as an accretion complex, due it does not represent a continuous stratigraphic succession, but a tectonically complex assemblage that may be interpreted as a pile of several heterogeneous tectonic slabs, constituting the Santa Rosa Accretionary Complex.

The geotectonic significance of the igneous assemblages in the Santa Elena peninsula has been interpreted in different ways, representing a sea mount/ocean island complex or a tectonic mélange (Frisch et al., 1992; Tournon, 1994). Beccaluva et al. (1999) consider the basalts and gabbros at the Santa Rosa Accretionary Complex and the Santa Elena Nappe as typical N-MORB. Hauff et al. (2000) found two different geochemical affinities, first as an ocean island basalt (OIB), with a strong light rare earth elements (LREE) enrichment in the Santa Rosa Accretionary Complex, Carrizal-Respingue section and Potrero Grande tectonic window, and second as

FIGURE 4 | **Numerous parallel dikes cutting the peridotites in Bahía Potrero Grande.**

island arc basalts in southeastern peninsula shoreline cliffs. Based on the available geochemical analyses (Beccaluva et al., 1999; Hauff et al., 2000), the layered gabbros (Fig. 3) and the primitive island arc affinity dikes show a remarkable depleted LREE pattern (Fig. 5A), which is not common in the rest of the areas described in this paper.

Geochemically, the basalts forming the Islas Murciélago (Fig. 3) are very different from the autochthonous Santa Elena peninsula igneous rocks, but similar than the allochthonous unit (Fig. 5A), nevertheless the structural relationship of the Islas Murciélago with the allochthonous unit is not clear. The Islas Murciélago igneous rocks form a continuous ten kilometers long archipelago, consisting of columnar (Fig. 6), pillow (Fig. 7) and massive basalts, with a general steep northward dip. Hauff et al. (2000) presented a radioisotopic $Ar^{39}/Ar^{40}$ date of 109.0 ± 2.0 Ma and related their origin to a primitive island arc.

## Other peridotite occurrences

Serpentinized peridotites found in the Tonjibe drill hole and close the Río San Juan (Fig. 1), along the Costa Rica/Nicaragua border (Astorga, 1992; Vargas and Alfaro, 1992; Tournon et al., 1995) have not been well explained. They have similar structures and mineral composition as Santa Elena, and could be part of an ancient E-W suture zone (Tournon et al., 1995). However, the suture hypothesis does not explain the Siuna (northeastern Nicaragua) peridotite ocurrences, described previously by Venable (1994) and Rogers (2003), which are in a non-studied association with radiolarites and basalts.

## NICOYA PENINSULA

The Nicoya Peninsula is dominated by the Nicoya Complex (Fig. 8). This unit was defined by Dengo (1962), and was redefined by Kuijpers (1980). The Nicoya Complex represents a basaltic sequence older than Lower Campanian-Santonian (>74m.y.), which composed mainly of olivine tholeiites that occur as massive and pillow flows, dikes, and hyaloclastic pillow breccias. Subordinate rocks include gabbros, diabases and plagiogranites (Tournon and Azéma, 1980). Deep-sea radiolarian cherts were deposited from the Middle Jurassic to the Late Cretaceous (Baumgartner, 1984), but their contact with the volcanics is almost always tectonic or disturbed by intrusions of diabases and gabbros. Based on available geochemical analyses (Ragazzi, 1996; Sinton et al., 1997; Beccaluva et al., 1999; Hauff et al., 2000) the igneous Nicoya Complex shows a typical flat rare earth elements (REE) plateau, with more fractionated patterns belonging to plagiogranites and other intrusions (Fig. 5B).

Several emplacement hypotheses have been formulated from the 70's to explain the Nicoya Complex on the Nicoya Peninsula. We consider, based on Sinton et al. (1997), Hauff et al. (1997), Hauff et al. (2000) and Hoernle et al. (2004), that the Nicoya Complex is a plateau, geochemically similar to the Caribbean Plateau. The Nicoya Peninsula represents an incomplete cross section of the Nicoya Complex, where the deepest levels of the plateau crop out in NW-Nicoya. The top of the Plateau crops out in the southern Nicoya Peninsula. The $Ar^{39}/Ar^{40}$ magmatic radioisotopic data (139 Ma to 83 Ma) by Sinton et al. (1997), Hauff et al. (2000) and Hoernle et al. (2004), and radiolarites ages in N-Nicoya. Baumgartner (1984) identify stratigraphically incoherent Blocks within magmatic bed rock (Fig. 9). We interpreted this whole picture as a Jurassic-Cretaceous chert sediment pile disrupted and detached from its original basement by multiple magmatic intrusions during the formation of the Caribbean Plateau.

## TORTUGAL AREA

High MgO (26-29%) komatiitic-like and picritic suite lavas have been reported in the Tortugal area (Alvarado et al., 1997; Alvarado and Denyer, 1998). They occur as a large, elongated (14 km long, 1.5 km wide, Fig. 10) N60OºW striking body of 89.7 ± 1.4 Ma, based on $Ar^{39}/Ar^{40}$ dating (Alvarado et al., 1997). These rocks contain olivine megacrystals ($Fo_{71-85}$), complexly zoned clinopyroxene (augite, $Wo_{37-45}En_{45-53}Fs_{7-15}$), orthopyroxene (enstatite, $En_{80}$), some with spinifex texture (Fig. 11), spinel, and rare ilmenite and plagioclase ($An_{56-68}$) phenocrysts. Their chemistry and mineralogy are characteristics of a primary magma with an estimate eruption temperature of 1300-1400EC (Alvarado and Denyer, 1998).

This suite is intruded by centimeter and meter thick-dykes of trachybasalts, and partially surrounded and over-

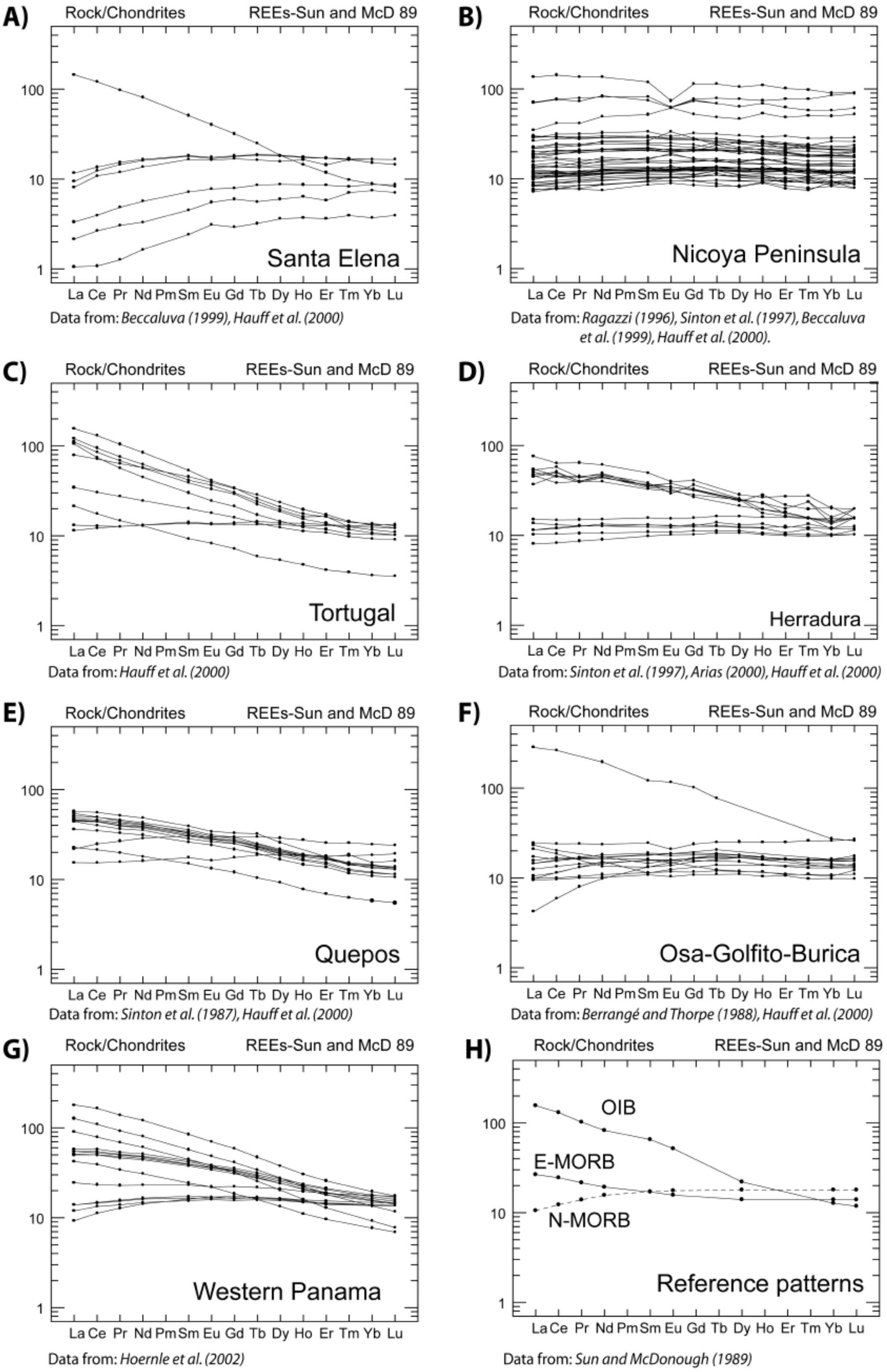


FIGURE 5 **Chondrites normalized REE comparison between the different areas described in this paper. The data source is indicated in each diagram. E-MORB, N-MORB, and OIB reference patterns are included in H.**

lain by massive basalts, trachybasalts and basaltic trachyandesite flows and breccias. Associated subvolcanic rocks (diabases and amphibole trachybasalts) are all geochemically similar.

In contrast to the well-known Gorgona komatiites (Echeverría, 1980) with macroscopic spinifex olivine texture, the Tortugal ultramafic lavas have microspinifex pyroxene and glass surrounding olivine megacrystals. Interstitial plagioclase is also present. Hauff et al. (2000) noted the similarities in trace element and isotopic compositions between alkaline rocks from Santa Elena and Tortugal, and also consider both as part of the Chortis Block. The Tortugal komatiites are characterized by an OIB-like source similar to the common plume component ("C" component of Hanan and Graham, 1996) (Fig. 5C), whereas the Gorgona komatiites have a MORB-like source. Tortugal ultramafic and mafic lavas are part of the mantle source that created this piece of the Caribbean Plateau during the initiation of the Galápagos hotspot circa 90 Ma (Alvarado et al., 1997; Hanan et al., 1998).

## HERRADURA BLOCK

The Herradura Block is a huge area (Fig. 12), bigger than 1000 km$^2$, with altitudes up to 1500 m. It has been recently mapped by Arias (2003), whose map shows two oceanic assemblage units, Nicoya Complex and Tulín Formation.

### Nicoya Complex

The Nicoya Complex crops out in the southeast edge of the Herradura Block (Fig. 12), the geochemical signature is consistent with the Caribbean Ocean Plateau (Hauff et al., 2000; Arias, 2003), as is shown in Fig. 5D. Two $Ar^{39}/Ar^{40}$ radioisotopic ages reported 83.2 ± 1.8 Ma (Sinton et al., 1997), and 86.0 ± 2.0 Ma (Hauff et al., 2000).

### Tulín Formation

This unit was defined by Malavassi (1967) and MIEM (1982) and was redefined by Arias (2003) as a Maastrichtian to Lower Eocene basaltic sequence, based on micropaleontological dates of interbedded sediments (Fig. 12). Tulín overlies the Nicoya Complex, and it is dominated by vesicular pillow basalts with microdoleritic texture (Arias, 2003). Geochemically, Tulín Formation can be distinguished from the Nicoya Complex, due its enrichment in high field strength elements (HFS) and in LREE pattern corresponding to an OIB like signature, while Nicoya Complex basalts are poor in HFS elements and show a typical flat REE plateau pattern (Fig. 5D). Gabbros with similar geochemical signatures are scarce. Olivine

FIGURE 6 **Flexured Columnar structures (botton-right) and pillow basalts (top-left) at Islas Murciélago. It is remarkable that the whole sequence is tilted almost 90°.**

FIGURE 7 **Vertical pillow basalts of Islas Murciélago. Horizontal faulting is obvious.**

cumulates (Fo85) with affinity to the basalts occur as small pockets over the entire region (Arias, 2003).

Epiclastic sediments, breccias, sandstones and tuffs are interbeded with the basalts. They are rich in juvenile volcanic fragments, and also contain foraminifera and radiolarians. In the unit also occur larger foraminifera and rudists (Arias, 2003), suggesting the existence of an oceanic shallow water zone from the Maastrichtian to the Lower Eocene, covered during the Upper Eocene by a calcareous platform. Tulín Formation was likely formed during the Middle Eocene, either as a beheaded oceanic island or as a block related to an ancient transform fault (Arias, 2003).

## QUEPOS BLOCK

The Quepos Block is formed by vesicular pillow basalts, dolerites, picrites, and rare gabbros (Fig. 13). It is relatively younger than the Caribbean Basaltic Event. It corresponds to a late Cretaceous-Paleocene seamount (Azéma et al., 1978; Bolz and Calvo 2003) piled up on the western flank of the Caribbean plate. The isotopic ratios of the Quepos lavas evidence a similar mantle source to the Nicoya Complex (Sinton et al., 1997). Geochemically, the basalts show a LREE enrichment in comparison with the flat pattern of the gabbros (Fig. 5E).

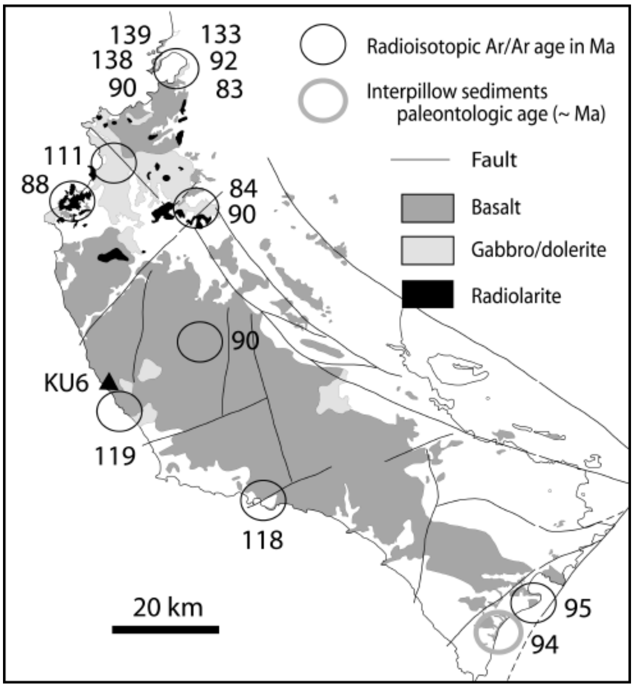


FIGURE 8 **Generalized geological map of the Nicoya Peninsula that shows the different lithologies of the Nicoya Complex. The radioisotopic Ar39/Ar40 dates after Sinton et al. (1997), Hauff et al. (2000) and Hoernle et al. (2004). Interpillow sediments dating after Azéma et al. (1985).**

FIGURE 9 **Baked and leached radiolarite pocket in igneous assemblage at the southern edge of Playa Conchal. Both magmatic and tectonic contacts are observed.**

Hauff et al. (2000) proposed a OIB Galápagos related mantle source.

The volcanic stratigraphy provides evidence for the emergence of a submarine volcanic edifice above sea level (Baumgartner et al., 1984). The ocean island could have been active between 59.4 ± 1.8 Ma and 65.0 ± 0.4 Ma, as is shown by the $Ar^{39}/Ar^{40}$ radioisotopic dates (Sinton et al., 1997; Hauff et al., 2000; Hoernle et al., 2002). These dates are consistent with the age of the intrapillow sediments (Fig. 14) paleontologically identified by Azéma et al. (1978). Baumgartner et al. (1984). Arias (2003) correlated these basalts to the Tulín Formation.

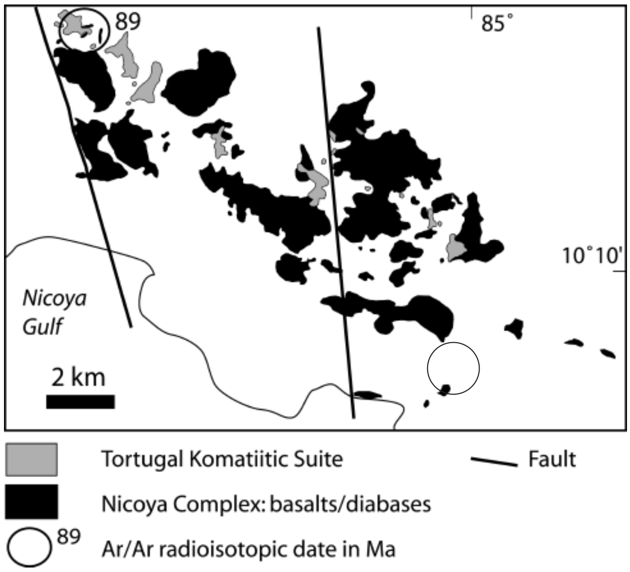


FIGURE 10 **Schematic geologic map of Tortugal Komatiitic-like Suite. The radioisotopic age is from Alvarado et al. (1997).**

## OSA AND BURICA PENINSULAS AND CAÑO ISLAND

The geologic conception of this area has changed considerably through time. First, it was considered as part of the Nicoya Complex, as earlier authors (Berrangé et al., 1989) conceptually mapped all the Osa peninsula and Caño island as belonging to Nicoya Complex. Later, DiMarco (1994) restricted the igneous sequence to the very inner part of Osa peninsula, and most of this peninsula corresponds to the Osa-Caño Accretionary Complex (Fig. 10).

Finally, the oceanic assemblage was divided into five tectonic units (DiMarco, 1994; DiMarco et al., 1995; Buchs and Stucki, 2001; Buchs and Baumgartner, 2003), with different origins (Fig. 15).

### Golfito Terrane

The Golfito Terrane was defined by DiMarco et al. (1995). It is characterized by oceanic basalts and dolerites, which are overlaid by Campanian-Maastrichtian pelagic limestones. Based on geochemical data from Hauff et al. (2000), it corresponds to an accreted plateau segment, and it is characterized by a flat REE patterns (Fig. 5F).

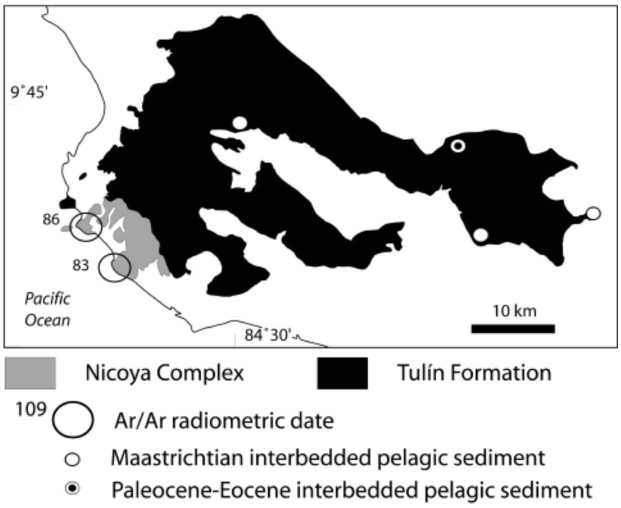


FIGURE 12 **Simplified geological map of the Mesozoic-Paleogene oceanic assemblages of the Herradura Block. Radioisotopic data from Sinton et al. (1997) and Hauff et al. (2000). Micropaleontological dates after Arias (2000).**

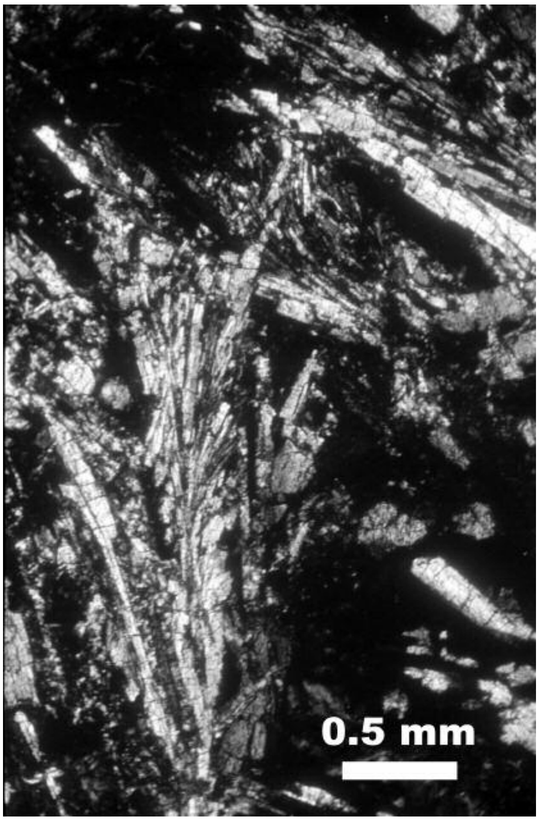


FIGURE 11 **Microscopic spinifex texture of the Tortugal Komatitic Suite.**

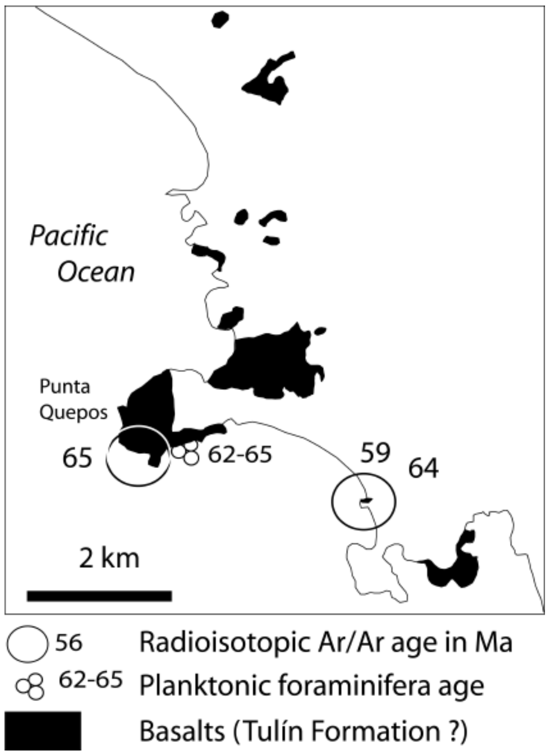


FIGURE 13 **Upper Cretaceous-Paleocene geological sketch of Quepos Block. Radioisotopic dates after Sinton et al. (1997), and Hauff et al. (2000). Micropaleontological dates after Azéma et al. (1978), Baumgartner et al. (1984) and Bolz and Calvo (2003).**

FIGURE 14 | **Paleocene pelagic limestone lens between basalt flows in Punta Quepos.**

## Burica Terrane

The Burica Terrane forms the western edge of the Burica peninsula (Fig. 10). It has been interpreted as an accreted seamount (Obando, 1986). Also, Frisch et al. (1992) interpreted it as a structurally high piece of primitive island arc. The available geochemical data (Hauff et al., 2000) implies a plateau origin with its typical flat pattern (Fig. 5F).

DiMarco et al. (1995) micropaleontogically dated it as Upper Cretaceous to Paleogene in age. One radioisotopic $Ar^{39}/Ar^{40}$ radioisotopic age of 64.2 ± 1.1 Ma has been recorded (Hoernle et al., 2002).

## Rincón Block

The Rincón Block (Fig. 10) is an accreted igneous sequence, formed by oceanic basalts varying in age from the Upper Cretaceous to the Early Eocene. It has been divided into two major units.

The first unit corresponds to a suite of accreted seamounts, with scarce but significance alkaline subaerial basalts. It is Early Paleocene to Early Eocene in age, based on microfossils (Buchs and Stucki, 2001). Two different $Ar^{39}/Ar^{40}$ radioisotopic dates for Violines island are 54.5 ± 1.7 Ma and 62.1 ± 0.6 Ma, which correspond to Paleocene (Hauff et al., 2000; Hoernle et al., 2002).

The second unit matches the age of a Campanian-Maastrichtian basaltic plateau (Buchs and Stucki, 2001; Buchs and Baumgartner, 2003). The plateau origin of this unit is well supported by the available geochemical data (Hauff et al., 2000), with a remarkable flat REE pattern (Fig. 5F).

## Osa-Caño Accretionary Prism

This prism has been defined and studied by DiMarco (1994), DiMarco et al. (1995), Buchs and Stucki (2001), and Buchs and Baumgartner (2003). It is a mélange predominantly consisting of sedimentary rocks, cropping out trench-ward of basaltic basement blocks, which now form the trailing edge of the Caribbean Plate. Its exposures in the outer Osa Peninsula (Fig. 10), less than 30 km northeast of the Middle America Trench, have been uplifted for the last ~3.5 Ma from a depth of 2 500 m to a maximum altitude of 650 m in response to the subduction (Collins et al., 1995, Kolarsky et al., 1995). This mélange has been variously interpreted in the geological literature. Moreover, several authors confused the predominant, highly compacted basaltic sandstones with basalts and, therefore, called it Nicoya Complex as mentioned above. Some geo-

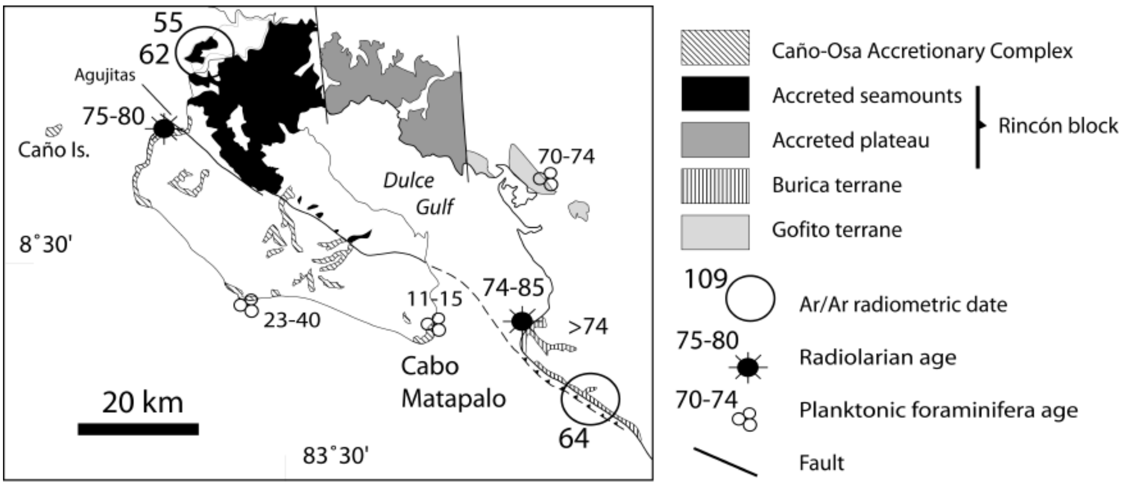


FIGURE 15 | **Map of the oceanic assemblages of Golfito, Osa and Burica peninsulas and Caño island. Radioisotopic dates after Hauff et al. (2000). Micropaleontological dates after DiMarco et al. (1995), Buchs and Stucki (2001), and Diserens (2002).**

chemical analyses (Berrangé and Thorpe, 1988; Hauff et al., 2000) from different blocks of the mélange show a plateau signature, and in less proportion depleted LREE patterns, and OIB affinities (Fig. 5F). This variability is congruent with an accretionary prism.

Sedimentary and tectonic characteristics suggest that the Osa-Caño Accretionary Prism represents a mélange formation. It appears that the Osa-Caño mélange is composed principally of hemipelagic calcareous mudstones, volcanic sediments and shallow water calcareous rocks embedded in the mélange, which form 75% of the volume of the mélange of NW Osa. Areas with abundant sediments contrast with areas containing crushed igneous mega blocks (>10 m in diameter). The sedimentary nature of the mélange is well shown by the constant block-in-matrix texture and a diminutive concentration of matrix when the size of the allochthonous resedimented elements increases from small ashy particles up to igneous mega blocks. A clast-in-matrix texture at different scales can be observed, that draws a fractal image typical of a sedimentary origin. This is the result of the emplacement of gravity flows and rock that fell into the trench. Arc-derived volcanic sediments, shallow water calciturbidites (Fig. 16) and debris flows, breccias and igneous mega blocks were emplaced at a high rate during continuous background sedimentation (hemipelagic calcareous mudstones). The fractal construction of the mélange reflects the degree of catastrophism, as more energetic massflows carried bigger clasts, forming coarser textures compared to less energetic events (Buchs and Baumgartner, 2003).

The origin of the sediments has been resolved by a numerical analysis of the clastic lithologies. This approach indicates that the major part of the material constituting the Osa-Caño accretionary mélange was eroded from the forearc region which comprised an evolved volcanic island arc and an emerged igneous backstop (mostly basaltic in composition). The material was gravitationally emplaced downslope; it reworked partially lithified slope deposits and accumulated in the trench. Both trench fill and pieces of seamounts were sheared off by the downgoing plate at shallow depths and added to the upper plate. The reworked material includes Late Cretaceus-Paleocene pelagic limestones and cherts and Eocene shallow water limestones. The background sedimentation represented by the hemipelagic calcareous mudstones (matrix of the mélange) is pene-contemporaneous to the accretion. It has been dated by radiolarians in NW Osa as late Paleocene to middle Eocene. The youngest, middle Miocene, pelagic sediments of the Osa-Caño Accretionary Complex are found near Cabo Matapalo. Redeposited shallow water-derived lithologies contain larger foraminifera of middle to late Eocene age. Thus, the accretion must have occurred during the Middle/Late Eocene to Middle Miocene (Buchs and Baumgartner, 2003).

FIGURE 16 **Hydro-fractured Eocene calciturbidite of Agujitas is part of the Osa-Caño Accretionary Complex.**

Structural observations indicate that the prism seems to be disorganized at a <50 m scale but shows good arrangement of the orientations of fractures, and lithologically coherent domains consistent with off-scraping and accretion. A good lateral continuity of the lithologies is observed between the Caño Island and the Osa coast, which may be related to a combination of both sedimentary and accretionnary mechanisms (Buchs and Baumgartner, 2003).

## WESTERN PANAMA

In western Panama are numerous occurrences of oceanic assemblages (Fig. 17), which are known as the Azuero-Soná Complex. It has been mapped using different nomenclature as distinct units (e.g. Soná, Playa Venado, Quebro, Tiribique, Lovaina and Tiribique; DelGiufice and Recchi, 1969; Tournon et al., 1989; DGRM, 1991; Kolarsky et al, 1995). They crop out in the Azuero and Soná peninsulas, and various islands of the Chiriquí and Montijo gulfs, (e.g. Coiba, Cébaco, Montuosa, Ladrones, Parida, Boca Brava, Contreras). Some of these outcrops seem to be very undisturbed tectonically, with marked developed pillow (Fig. 18) and columnar (Fig. 19) structures.

Comprehensive mapping of almost all areas was done (DelGiudice and Recchi, 1969; DGRM, 1991; Kolarsky et al., 1995). Lithologically, the Azuero-Soná Complex consists of massive, columnar and pillow basalts with some interbedded radiolarites. Schistose amphibolites (Tournon et al., 1989) are exposed as slivers along the Azuero-Soná fault zone (Kolarsky et al., 1995). Additionally, metabasalts and metatuffs with a pronounced shear foliation and tectonic mélanges were found by Tournon et al. (1989). This metamorphic basement is covered by pil-

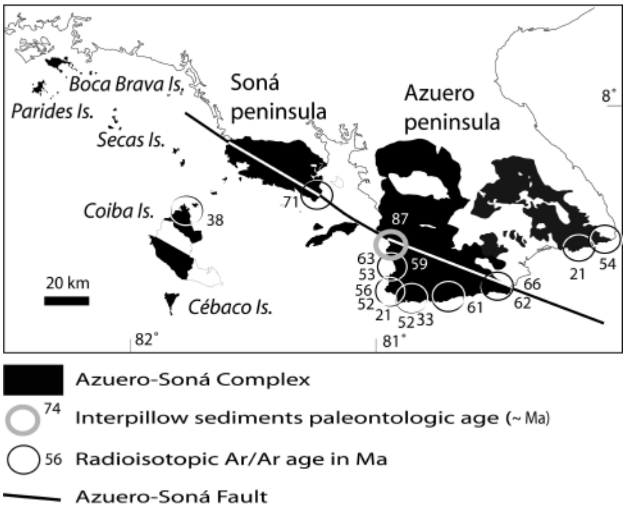


FIGURE 17 | **Oceanic assemblages of western Panamá, including the Zoná and Azuero peninsulas, Cébaco and Coiba islands, and other small islands. Radioisotopic ages from Hoernle et al. (2002). Micropaleontologic age included in Kolarsky et al. (1995).**

low basalts and is cut by doleritic dykes. Tournon et al. (1995) consider that metabasites of Azuero and Soná are unique evidence for a regional metamorphism prior the intra-Senonian tectonic phase that affected the rest of Mesozoic formations cropping out along the Pacific coast (Tournon et al., 1989).

One Coniacian radiolarite has been reported in the Azuero peninsula (Kolarsky et al., 1995). The $Ar^{39}/Ar^{40}$ radioisotopic dates of lava flows and pillow basalts from Panama range from 21 Ma to 71 Ma. The 21-66 Ma basalts of Azuero, Soná and Coiba are interpreted as accreted pieces of the subducted Galápagos hotspot track, while the 71.3 ± 2.1 Ma basalt of Soná peninsula belongs to the Caribbean Igneous Province (Hoernle et al., 2002). Geochemical data from Hoernle et al. (2002) shows LREE enrichment and, in less abundance, flat patterns that confirm the ocean island and plateau affinities (Fig. 5G).

## DISCUSSION AND CONCLUDING REMARKS

The oceanic assemblages cropping out in the Pacific coast of Costa Rica and western Panama have been relatively well studied, specially the northwest of Costa Rica, although, they are relatively poorly understood because the extreme complexity of the processes taking place in an active oceanic margin. Micropaleontological, geochemical and petrological techniques have been applied to these units in the 60's of the last century. However, the history of oceanic assemblages of the pacific margin of southern Central America is very incomplete. It seems to consists of portions of the whole material already subducted during Mesozoic and Cenozoic. The presence of huge volumes of oceanic related rocks means that the accretion process has been very important in the emplacement of these oceanic complexes.

The serpentinized mantle peridotites of Santa Elena Peninsula, Río San Juan, Tonjibe drill hole and Siuna are one of the most intriguing pieces of the southern Central America oceanic occurrences. Only the Santa Elena Peninsula has been studied in detail. They could easily be interpreted as suture zones, but the genetic relationships are not clear and the trends are not known, although a E-W suture zone have been suggested between Santa Elena Peninsula and Río San Juan occurrences. We consider that more research and mapping must be done in order to understand the significance of all these occurrences in the oceanic plateau model.

Apparently, most of the igneous Mesozoic-Cenozoic assemblages have a geochemical signature similar to the Galapagos mantle plume, as suggested by the last geo-

FIGURE 18 | **Dipping pillow basalts at Parides islands.**

FIGURE 19 | **Columnar basalts of Parides islands.**

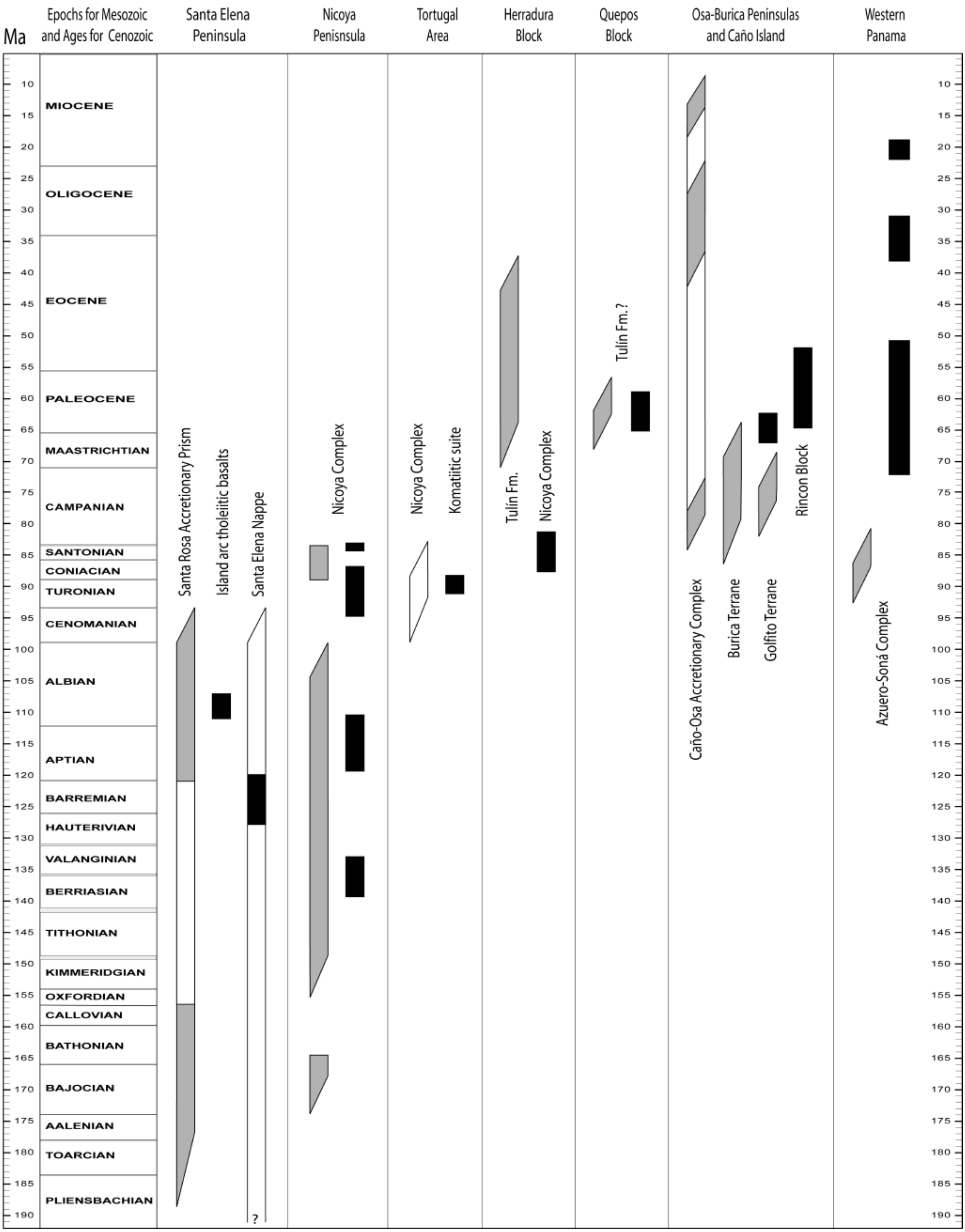


FIGURE 20 **Synoptic age comparison of the Costa Rica and western Panama oceanic assemblages. $Ar^{39}/Ar^{40}$ radioisotopic ages in black, biochronologic age ranges in gray, stratigraphic inferences in white. Oblique upper and lower field ends indicate age uncertainties.**

chemical results (Sinton et al., 1997; Beccaluva et al., 1999; Hauff et al., 2000; Hoernle et al., 2002, 2004). If so, the Galapagos hotspot must have been much larger than today during the Caribbean Basalt Event, or there were several thermal spots occurring at the same time and distributed widely enough, to thicken the crust of the newborn Caribbean plate. The interpretation of several pulses of this thermal source happening during 140 Ma (Hoernle et. al., 2002., 2004) is also difficult to imagine in the actual geotectonic framework. We consider premature the presumption that all oceanic assemblages came from the same source. The geotectonic history of this area could be more complicated, and there could be several plateaus with similar signatures piled up along the eastern side of the active margin.

In order to have a comprehensible terminology, less susceptible to confusion, we think that the term “Nicoya Complex” must be restricted to the pre-Campanian oceanic plateau occurrences of the Nicoya Peninsula and surroundings. The Tortugal Komatiitic Suite is a very particular assemblage, with no clear relationship to the Nicoya Complex, but with a geochemical signature closer to basaltic rocks of the Santa Elena Peninsula (Hauff et al., 2000).

The mechanism of emplacement of the seamounts and the volcanic edifices is not very well understood. Tulín Formation and Quepos Block appear to be mega-structures reaching today altitudes up to 1500 m above sea level.

The hypothesis of a continuous Jurassic-Cretaceous oceanic sequence in the Santa Elena Peninsula relatively autochthonous did not withstand detailed field analysis. Thus, the presence of numerous thrust faults causing repetitions of pelagic, detrital and igneous facies and chaotic collapse breccias favour the accretionary prism interpretation.

The outer Osa peninsula and the Caño Island have been mapped as igneous assemblages, but actually are composed by sedimentary mega-breccias (DiMarco et al., 1995) that are now named the Osa-Caño Accretionary prism. The Golfito Terrane (Upper Cretaceous) and the Burica Terrane (Upper Cretaceous-Paleogene) represent segments of oceanic plateau assemblages. The Rincón Block is an Upper-Cretaceous-Eocene seamount and oceanic plateau sequences (Hauff et al., 2000; Buchs and Baumgartner, 2003).

In western Panama, the outcrops of Soná and Azuero peninsulas and several islands of Chiriquí gulf correspond to a Mesozoic-Cenozoic igneous assemblage including an amphibolitic regional metamorphic sequence. This is the least studied of all the areas described in this article. Western Panamá, Nicaraguan and Guatemala assemblages, not described in this paper, are also fundamental pieces to understand the whole geotectonic significance of the Central American oceanic assemblages.

The terranes that have been identified by DiMarco et al. (1995) represent a first step in the study of the different blocks or terranes that have been piled to conform the Costa Rica and Panama basement. We predict that further research will confirm the existence of more exotic terranes. Just looking into the stratigraphic differences in the Cretaceous sedimentary sequences, it is obvious that these differences are incompatible with a single event of formation. These tectonostratigraphic elements may have been transported, accreted and sutured together as they arrived to their present position.

The age synthesis (Fig. 20) shows clearly that the oldest oceanic assemblages crops out in the northern part of the region, Santa Elena and Nicoya peninsulas. In the Nicoya Peninsula is possible to distinguish at least three main magmatic pulses, the latest corresponds to the Caribbean Large Igneous Province and it is also present in the Tortugal area and the base of the Herradura Block. Tulín Formation (Paleocene) of Herradura and Quepos blocks are contemporaneous to the Rincón Block and the initial stage of western Panama, which extends trough the Oligocene, showing three pulses. These different pulses could be interpreted as different stages of the Galapagos hot spot but this is not totally understood because more data are needed.

From the geochemical point of view, based on the available data, the whole picture of the region seems to be very variable. There are evidences of accreted seamounts with an OIB (LREE enrichment pattern) in the Jurassic-Cretaceous Santa Rosa Accretionary Complex, Upper Cretaceous-Eocene Tulín Formation in the Herradura and Quepos blocks, and the Upper Cretaceous- Miocene Caño-Osa Accretionary Complex. This source is also present in the not well-known Upper Cretaceous Tortugal Komatiitic Suite. The plateau signature (flat REE pattern) is present in the Jurassic-Cretaceous Nicoya Complex, cropping out in the Nicoya Peninsula, Tortugal area and the base of the Herradura Block. This source is also interpreted from the Upper Cretaceous-Miocene magmatics of the Osa and Burica peninsulas. The Upper Cretaceous-Oligocene oceanic assemblages of western Panama show a wide range of REE patterns, with a predominance of OIB source, possibly representing accreted seamount tracks.

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