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Magmatic and geotectonic significance of Santa Elena Peninsula, Costa Rica

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ABSTRACT

We present a new integrated interpretation of the geochemistry and geotectonic significance of the Santa Elena Peninsula, which is divided in three units: 1) an overthrust allocthonous unit of ultramafic and mafic rocks, the Santa Elena Nappe; 2) an autochthonous basaltic sedimentary suite, resting immediately below the overthrust, the Santa Rosa Accretionary Complex; and 3) Islas Murciélago pillow and massive basaltic flows. In the Santa Elena Nappe three petrological affinities have been recognized: 1) the ultramafic complex, that corresponds to depleted (MORB-like) mantle serpentinizated peridotites, with very low TiO_2 and high Ni and Cr; 2) the pegmatitic gabbros, layered gabbros and plagiogranites and basaltic dikes with low TiO_2 (< 0.89%) contents and high LREE depletions; and 3) the doleritic dykes with higher TiO_2 (>0.89%). These mafic associations have geochemical signatures that suggest an island arc origin and petrographic evidences of low grade metamorphism and hydrothermal alteration. The Santa Rosa Accretionary Complex includes pelagic and volcanoclastic sediments, tuffs and alkaline magmatic rocks, originated by low degree melting of enrichment OIB mantle source, and probably related with seamount portions incorporated into the accretionary prism. Islas Murciélago pillow and massive basalts show no clear structural relationship with the rest of the units, but are geochemically similar to the dolerites of the Santa Elena Nappe. Sr, Nd, and Pb isotopic ratios of the Santa Elena Nappe and the Santa Elena Accretionary Complex samples do not correspond to the Galapagos Mantle array, and have different mantle reservoirs and geochemical characteristics than the Nicoya Complex.

KEYWORDS **Santa Elena Peninsula. Oceanic assemblages. Ultramafic Complex. Geochemistry. Accretionary complex.**

INTRODUCTION

Costa Rica is located in the southern part of Central America, in the convergent margin of the Cocos and Caribbean plates. The western margin of the Caribbean Plate was formed by tectonic juxtaposition of the Chortis, Chorotega, and Chocó Blocks (Dengo, 1973). The Santa Elena Peninsula has an east-west orientation, this is probably unrelated to the modern (northwest-southeast) trench axis (Fig. 1).

Traditionally the magmatic rocks at Santa Elena Peninsula have been related to the Nicoya Complex (Dengo, 1962; Kuijpers, 1980), an oceanic basaltic sequence that includes pillow and massive basalts, breccias, dolerites, gabbros, plagiogranites, and radiolarites of Middle Jurassic to Late Cretaceous age (Baumgartner, 1987; Gursky, 1994) that extends along the entire Pacific margin of Costa Rica (Fig. 1). Geochemistry and petrological studies suggest mid-ocean rift, hotspot, and primitive island arc tectonic affinities (Appel et al., 1994; Meschede and Frisch, 1994; Sinton et al., 1997; Beccaluva et al., 1999; Hauff et al., 2000). Recent theories relate the Nicoya Complex with the Galapagos hotspot (Hauff et al., 1997; Alvarado and Denyer, 1998; Beccaluva et al., 1999).

FIGURE 1 | **Tectonic and geological setting of the Santa Elena Peninsula.**

Harrison (1953) presented the first geological description of the Santa Elena Peninsula and mentioned the presence of an ultramafic massif cut by mafic dikes and a sedimentary cover in the northern part of the peninsula. Dengo (1962) interpreted that the ultramafic and mafic rocks stratigraphically represent lateral equivalents of the Nicoya Complex. Later, petrological and structural data by Tournon and Azéma (1980) and Tournon (1994) suggest that the ultramafic complex represents the base of an ophiolitic sequence that is thrust over an autochthonous unit (Fig. 2) of alkaline volcanic and sedimentary rocks (radiolarites, greywakes and tuffs). The allocthonous unit (Fig. 2) consists of serpentinized peridotites, pegmatitic gabbros, cumulate gabbros, and plagiogranites, which is cut by different generations of dolerites and basaltic dikes (Tournon, 1980; Beccaluva et al., 1999). Tournon (1994) presented detailed microprobe analysis of minerals of both units.

The ultramafic complex had been correlated with peridotites cropping out in both sides of the Costa Rican – Nicaraguan border (Río San Juan and San Carlos, Nicaragua) and with the base of the Tonjibe 1 petroleum exploration drill hole (Fig. 1). These ultramafic suites have been interpreted as an east-west, sutured zone (Fig. 1) between the Chorotega and Chortis blocks (Tournon et al., 1995). Nevertheless, the suture hypothesis does not explain the Siuna peridotite occurrences (northeastern Nicaragua, Fig. 1) associated with radiolarites and basalts described by Venable (1994) and Rogers (2003).

Hauff et al. (2000), based on ^{39}Ar/^{40}Ar dating, geochemistry, and Sr, Nd and Pb isotopes, considered that the 124-109 Ma units of Santa Elena were originated in a primitive island arc setting, related to the subduction zone of the Chortis Block. They correlated Santa Elena and Tortugal (Fig. 1) alkaline volcanic rocks, and proposed that the Chortis Block extends southwards the Hess Escarpment. They also described the geology and tectonic possition of the Santa Elena peninsula rock suites, and the previous hypothesis are evaluated. The aim of this paper is to present a new integrated interpretation of the geochemistry and geotectonic significance of the Santa Elena Peninsula, based on the pool of geochemical analyses made in the past 25 years. This research represents an actualized synthesis of the magmatic units of the region, which are geologically characterized. Thus, this paper set the actual state of the art in this region.

METHODOLOGY

The Santa Elena Peninsula is one of the key localities in the study of the geological evolution of Costa Rica and the western Caribbean edge. To contribute to that study,

TABLE 1 | **Source and type of chemical analyses used in this paper.**

Source	No. samples	Majors	Traces	Sr-isotopes	Nd-isotopes	Pb-isotopes
Kussmaul et al. (1982)	23	X				
Tournon (1984)	11	X				
Wildberg (1984)	23	X	X			
Meschede & Frisch (1994)	19	X	X			
Ragazzi (1996)	17	X	X			
Beccaluva et al. (1999)	7	X	X	X	X	
Arias (2000)	26	X	X	X	X	
Hauff et al. (2000)	14	X	X			X

we present a systematic interpretation of the magmatic, metamorphic and hydrothermal processes. We compiled, plotted, and reinterpreted 140 chemical analyses, from Kussmaul et al. (1982), Wildberg (1984), Tournon (1984), Meschede and Frisch (1994), Ragazzi (1996), Beccaluva et al. (1999), Arias (2002), and Hauff et al. (2000). These analyses were made by diverse laboratories with different techniques and standards. In order to validate these chemical analyses we compare data from same localities, and they agree well enough within the error range. The amount and type of data used are summarized in Table 1. The database used in this paper is available on request.

For the classification and discussion of the petrological units we used HFSE (high field strength elements) and REE (rare earth elements) because of their "immobile" character.

THE SANTA ELENA NAPPE: PETROGRAPHY AND GEOCHEMISTRY

Ultramafic Complex

The ultramafic complex represents the magmatic rocks of larger extension in the peninsula. Most of these rocks are

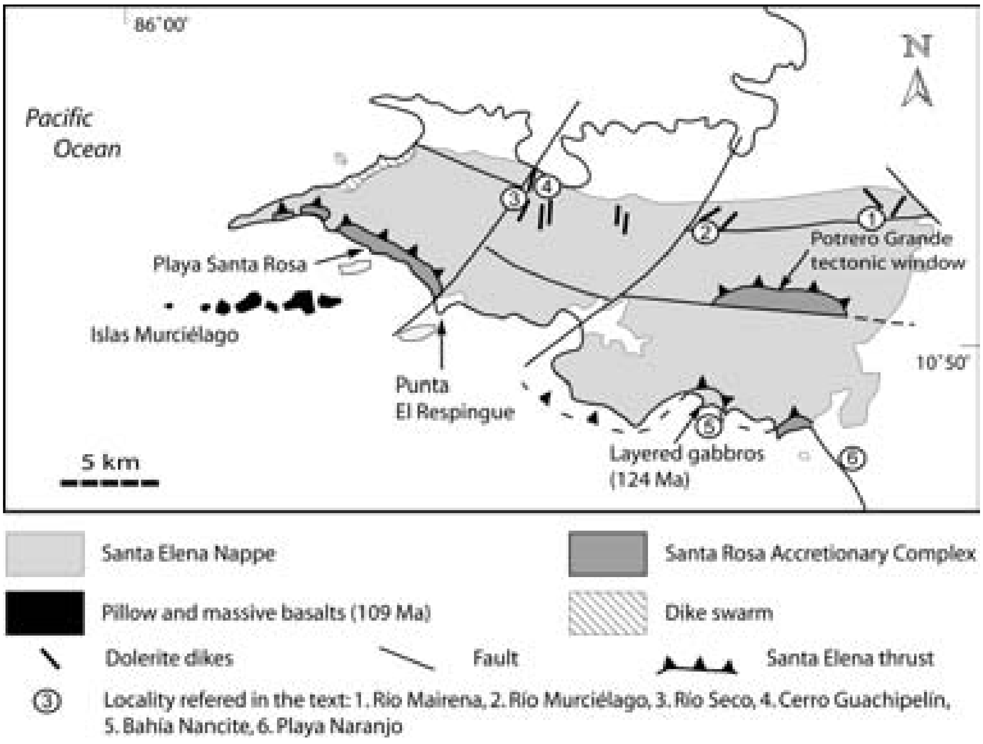

FIGURE 2 | **Geological map of the Santa Elena Peninsula. Modified after Tournon (1994).**

highly serpentinized; nevertheless some peridotites have preserved some of the original paragenesis, which permits their classification as spinel harzburgites. Along the road North of Cerro Guachipelin, meter wide exposures of dunitic layers with chromite mineralization occur in the peridotites (Fig. 2). Tournon (1994) mentioned that meter wide patches of plagioclase bearing lherzolites, pyroxenites and dunites are also common. In the major fault zones the peridotites have been transformed to pseudotachylite.

The peridotites and the ultramafic associations have low TiO_2 (0.01-0.14%), Zr (3-25 ppm) (Fig. 3), V (41-95 ppm), and very high MgO (34-45%), Cr (1931-2471 ppm) and Ni (1993-2380 ppm).

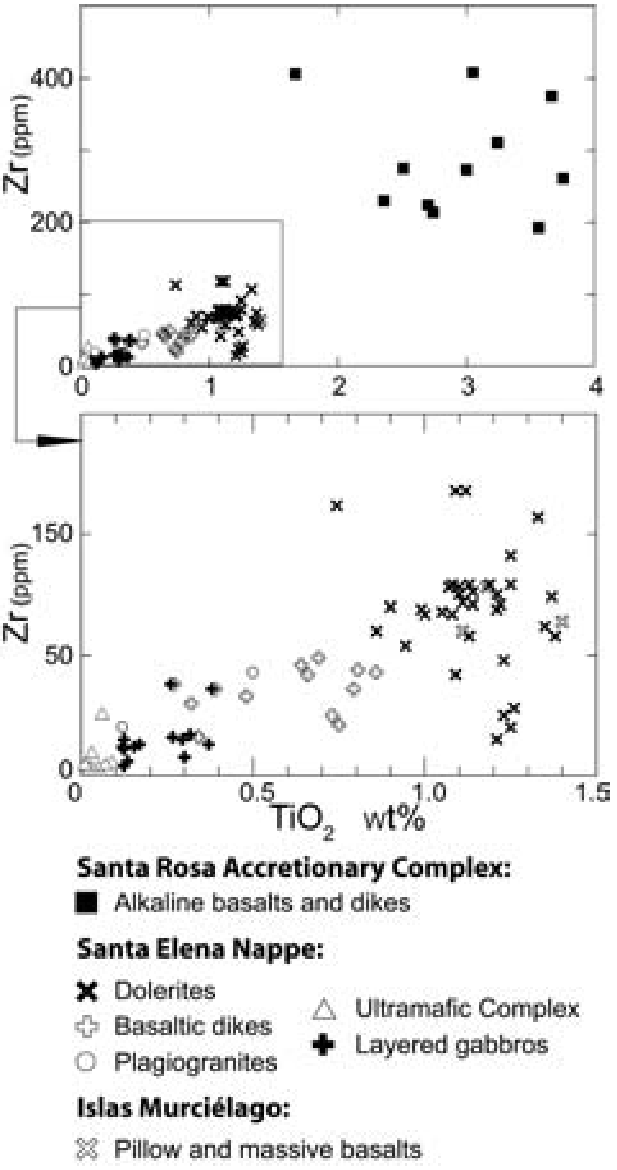

FIGURE 3 | **Zr/TiO_2 variation diagram of the Santa Elena Units. The lower diagram is an amplification form TiO2 0-1.5% and Zr 0-200 ppm. Data from Wildberg (1984), Meschede and Frisch (1994), Ragazzi (1996), Beccaluva et al. (1999) and Hauff et al. (2000).**

Pegmatitic Gabbros

These rocks are characterized by abundant plagioclase, light green amphibole (pargasite-actinolite), clinopyroxene, and olivine, with apatite and titanite as accessories. The occurrence of the clinopyroxene-amphibole transition, pyrite, zeolites, and serpentine, indicates low temperature alteration. Individual minerals are tectonically fractured and folded; some plagioclases have secondary tectonic twins. There are at least two generations of pegmatitic gabbroic dikes (2 cm to 10 m in thickness). Any of them show chilled margins with the peridotites and therefore they were likely emplaced when the peridotite was still hot and plastic.

Tournon and Azéma (1980) have provided a chemical analysis, showing that these gabbros are high in Al_2O_3, MgO, and low in TiO_2, similar to the layered gabbros sequence of Bahía Nancite (Fig. 2)

Dolerites

These dikes represent a later magmatic episode because they cut the peridotites and the pegmatitic gabbros, and show chilled margins with the hostrock. Río Mairena dolerites have labradorite plagioclase, light green uralite, and clinopyroxene as the main mineralogical association. The Río Murciélago dikes have bytownite and pargasite-actinolite, with relicts of clinopyroxene. At Río Seco at least two amphibolitic dikes occur, and they are related to a major northeast-southwest fault structure (Fig. 2). These dikes present foliations of aligned actinolite and bytownite; accessory minerals are apatite, titanite and magnetite. The abundance of doleritic dikes increases towards the west coast, where they constitute a dike swarm (Tournon, 1994). All the samples have secondary pyrite and zeolites. A secondary amphibol yields a radioisotopic K/Ar date of 88 ± 4.5 Ma (Bellon and Tournon, 1978).

These dikes range from basalts, basaltic-andesites to trachy-basalts, and display tholeiitic to transitional calc-alkaline affinities. They are characterized by $TiO_2 \geq 0.86$ %, and have higher Zr contents at a same value of TiO_2 % than the basaltic dikes and the layered gabbros (Fig. 3). MgO contents vary from 4.80 to 10.12%; these results, along with the low Cr ($\leq$206 ppm) and Ni ($\leq$104 ppm) contents, indicate that these rocks are fractionated relative to primitive magmas (Fig. 4). They are also depleted in LREE and HFSE, and enriched in LILE and Pb (Fig. 5A and 5B).

Layered gabbros and plagiogranites

The layered gabbros and plagiogranites are located along the southern coast, near Bahia Nancite (Fig. 1). The various layered rocks differ in the relative abundance of ferromagnesian minerals and plagioclase. Ultramafic cumulates (plagioclase bearing peridotites and pyroxenites) are also present (Tournon, 1994, Arias, 2002). Actinolite and tremolite occur as secondary phases. The plagiogranites are composed of abundant quartz, labradorite and actinolite. Hauff et al. (2000) report a ^{40}Ar/^{39}Ar date of the layered gabbros as 124.0 ± 4.0 Ma.

The layered gabbros are characterized by very high MgO (8.41-39.07%), Cr (72-2096 ppm) and Ni (74-296 ppm), and low TiO_2 (0.01-0.38%) and lower Zr contents compared to the dolerites and the basaltic dikes. Their TiO_2 contents are higher than in ultramafic rocks (Figs. 3 and 4). The layered gabbros are strongly depleted in LREE and HFSE, and enriched in LILE and Pb (Fig. 5C and 5D). The plagiogranites are also depleted in LREE and HFSE. These depletions respond to the cumulative sequence, where these cumulates are more depleted than the evolved liquids or even than the original basaltic liquid from which they fractionated. One of the samples presents a positive Eu anomaly that indicates plagioclase accumulation. The rest of the samples that have Eu negative anomalies indicate plagioclase fractionation processes (Fig. 5C and 5D).

Basaltic Dikes

Basaltic dikes cut the layered gabbros at Bahía Nancite, and the dike swarm along the eastern coast. They show an ophitic to subophitic texture and are composed of plagioclase, clinopyroxene, olivine and magnetite. Based on field observations, Tournon (1994) suggested that these rocks represent the latest magmatic phase of the Santa Elena Nappe.

These dikes are tholeiitic to transitional calc-alkaline basalts and basaltic-andesites; with primitive to fractionated features, high MgO (6,71-11,44%), Cr (61-555 ppm), Ni (74-208%) and low TiO_2 ($\leq$0.86%). Their Zr content, at a same value of TiO_2, are lower than those of the dolerites, and higher than those of the layered gabbros (Figs. 3 and 4). They show depletions in LREE, HFSE and enrichment in LILE and Pb. One sample has a negative Eu anomaly, indicating strong plagioclase fractionation (Figs. 5A and 5B).

Metamorphic and metasomatism processes

Metamorphism of mafic and ultramafic rocks requires metasomatic aqueous fluids in areas exposed to heat flow related to magmatic activity (Miyashiro, 1972).

The ultramafic and mafic association of the Santa Elena Nappe show evidence of hydrothermal alteration (presence of pyrite in most of the samples), and ocean floor metamorphism, which resulted in the serpentinization of the peridotites and development of secondary amphiboles in the dolerites, the layered gabbro complex, the pegmatitic gabbros, and in lesser degrees, in the basaltic dikes. The secondary paragenesis of albite + epidote + actinolite + chlorite indicates zeolites to green schist metamorphic facies. The serpentinization of the peridotites and the presence of amphibole in the dolerites increase along the major fault zones (Fig. 2).

The dike swarm on the west coast also has low temperature alteration minerals (epidote + clinozoisite + chlorite + quartz) that suggest low degree of ocean floor metamorphism.

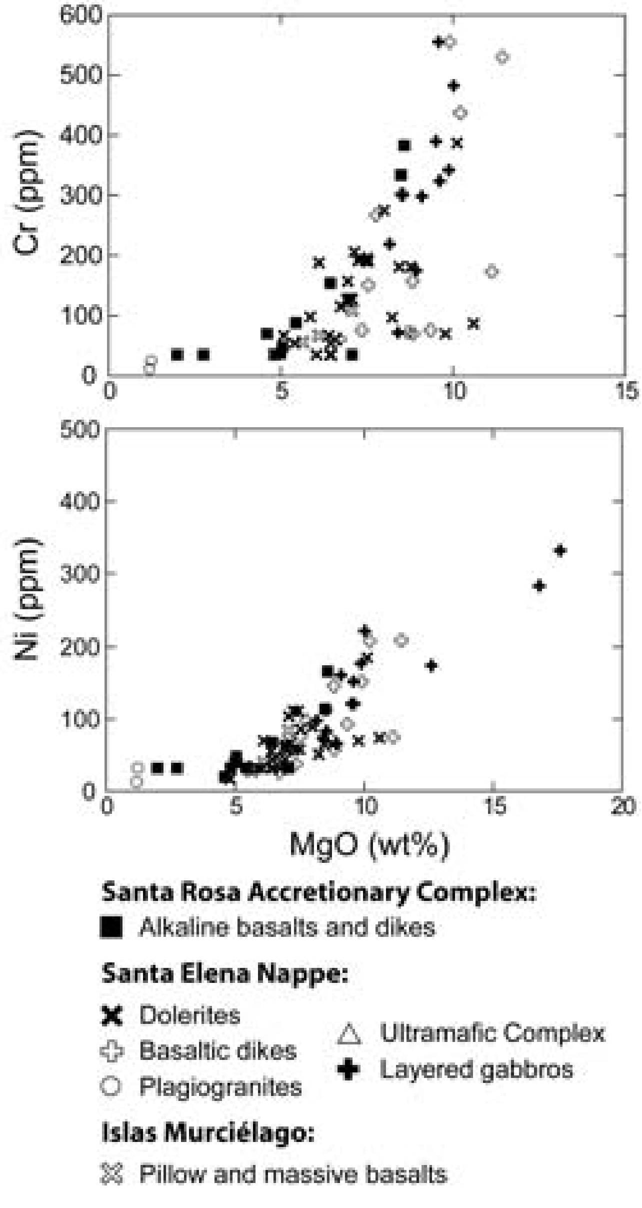

FIGURE 4 | **Cr/MgO and Ni/MgO variation diagrams showing the primitive and fractionated features of the Santa Elena units. Data from Wildberg (1984), Meschede and Frisch (1994), Ragazzi (1996), Beccaluva et al. (1999) and Hauff et al. (2000).**

THE SANTA ROSA ACCRETIONARY COMPLEX: DESCRIPTION AND GEOCHEMISTRY

This unit directly underlies the basal thrust of the Santa Elena Nappe. It is exposed in the tectonic-erosional window of Río Potrero Grande and along the southern coast of the Santa Elena Peninsula (Fig. 2). This unit includes pillow lavas, radiolarian cherts (principally of late Aptian to Cenomanian age) along with reworked cherts of Middle and Late Jurassic age (Schmidt-Effing, 1980; DeWever et al., 1985). Pelagic limestones also occur at one outcrop north of Playa Naranjo. At Playa Carrizal, the sequence is made up of alkaline pillow lava flows, minor black shales, and Aptian-Cenomanian radiolarites (Azéma and Tournon, 1980; Tournon, 1994). At Santa Rosa, radiolarian cherts are cut by alkaline dikes. At Playa Respingue, the sequence is made up of a thick pile of massive and pillow basalts, dikes, trachytes and tuffs. East of Bahía Nancite the sequence includes sandstones and microconglomerates composed of volcanic lithoclasts that suggest the proximity of intermediate to felsic volcanism (Tournon and Azéma, 1980; Tournon, 1994).

The alkaline basalts have phenocrysts of partially altered olivine, clinopyroxene (titaniferous augite), plagioclase and magnetite. They range from basanites to phonolites, all with a strong alkaline affinity. They are typified by high TiO_2 (1.25-3.66%), Ba (> 300 ppm), and

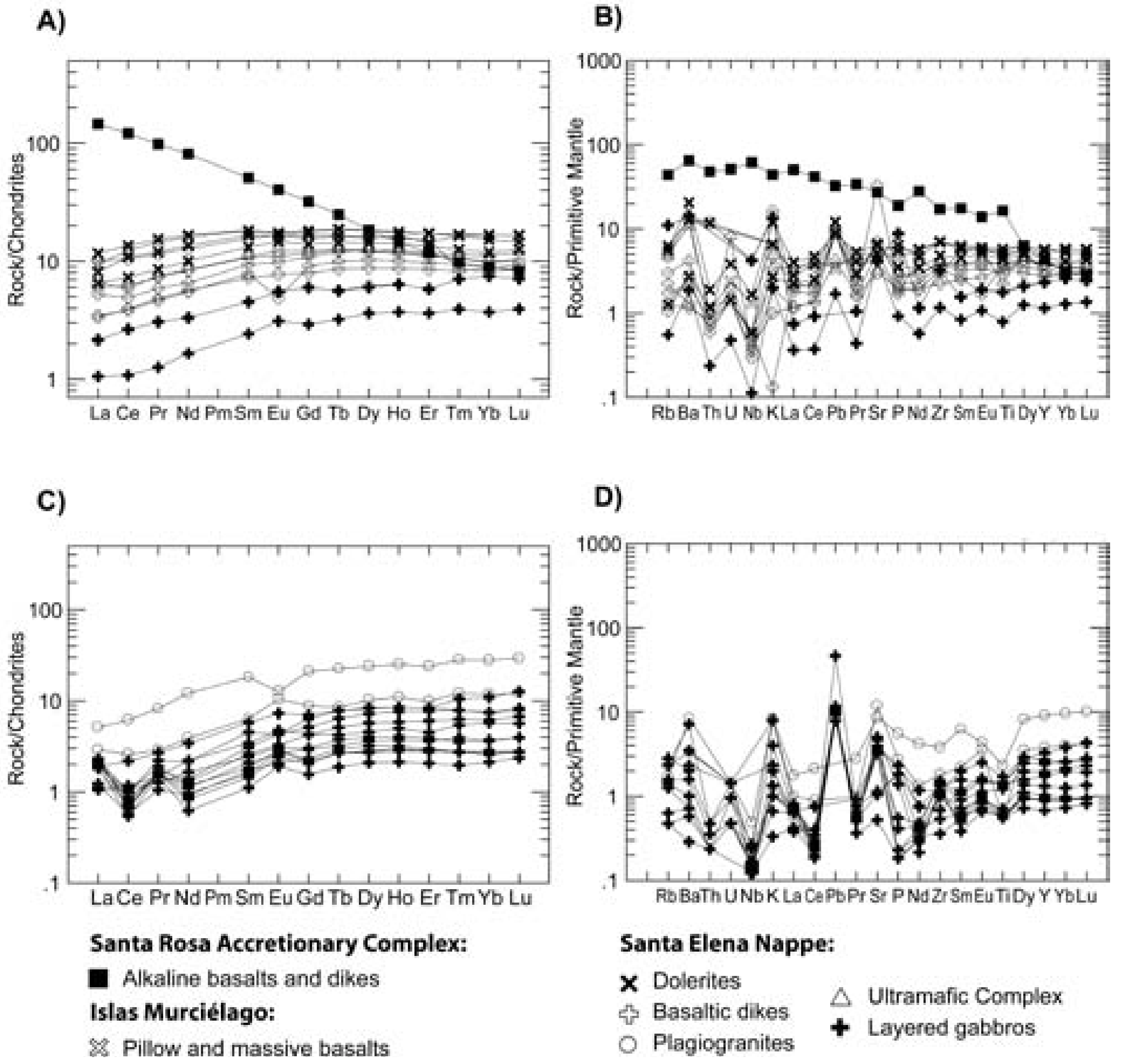

FIGURE 5 | **Santa Elena Nappe and Santa Rosa Accretionary Complex, chondrite and primitive mantle normalized diagrams (Sun and McDonough, 1989). The geochemical data are from Beccaluva et al. (1999) and Hauff et al. (2000) for A and B, and from Arias (2002) for C and D.**

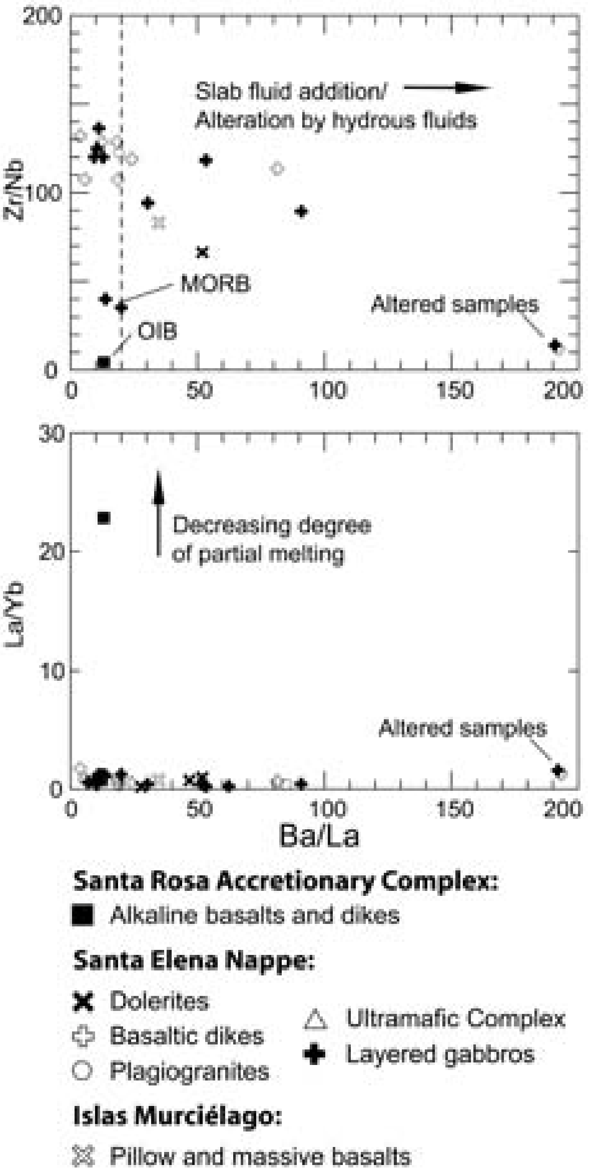

FIGURE 6 | **Zr/Nb-Ba/La and La/Yb-Ba/La ratios diagrams. Data from Ragazzi (1996), Beccaluva et al. (1999) and Hauff et al. (2000).**

Zr (> 200 ppm) contents, LREE enrichment (Fig. 5A) and variable MgO (1.99-8.49%), Cr (35-383) and Ni (20-166) contents (Figs. 3 and 4).

ISLAS MURCIÉLAGO

The structural relation of the Islas Murciélago with the rest of the units is unknown. The archipelago (Fig. 1) is made up of a subvertical and steep northward tilted sequence of tholeiitic pillow and massive basalts and trachy-basalts. Their geochemistry is similar to the dolerites from the Santa Elena Nappe. They have higher Zr and TiO_2 than the basaltic dikes and the layered gabbros. These basalts are fractionated from primitive magmas, with MgO varying from 5.64 to 7.49%, low Cr (≤388 ppm) and low Ni (≤84ppm) (Figs. 3 and 4). They are depleted in LREE and HFSE, and enriched in LILE (Fig. 5A and 5B). A pillow basalt from Islas Murciélago yields a $^{40}Ar/^{39}Ar$ date of 109.0 ± 2.0 Ma (Hauff et al., 2000).

RESULTS AND DISCUSSION

Petrological units and general interpretation

The Santa Elena Nappe shows 3 different petrological affinities: 1) The ultramafic complex: depleted MORB (Mid-Ocean Ridge Basalt) mantle, with very low TiO_2, and high Ni and Cr. 2) Pegmatitic gabbros, layered gabbros and plagiogranites and basaltic dikes, with low TiO_2 content (< 0.86 %) and depleted to strongly depleted in LREE. 3) The dolerite dikes yield higher TiO_2 (> 0.86 %) and other HFSE and LREE than the rest of the magmatic rocks at the Santa Elena Nappe. This third unit is similar to Islas Murciélago pillow and massive basalts; however the structural relationships between the Islas Murciélago and the Santa Elena Nappe are not clear.

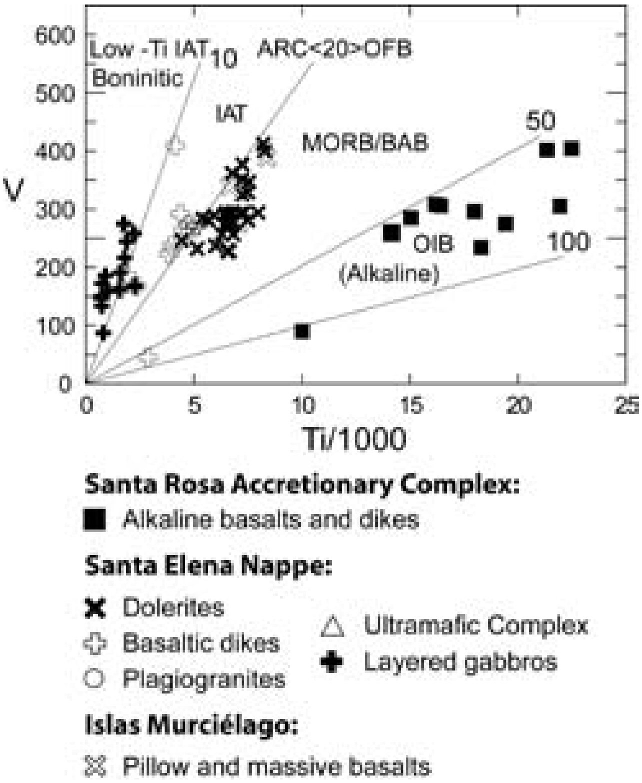

FIGURE 7 | **V/Ti discrimination diagram after Shervais (1982). Data from Wildberg (1984), Meschede and Frisch (1994), Ragazzi (1996), Beccaluva et al. (1999) and Hauff et al. (2000). IAT: Island-Arc Tholeiite; OFB: Ocean-Floor Basalt; MORB: Mid-Ocean Rift Basalt; BAB: Back-Arc Basalt; OIB: Ocean-Island Basalt.**

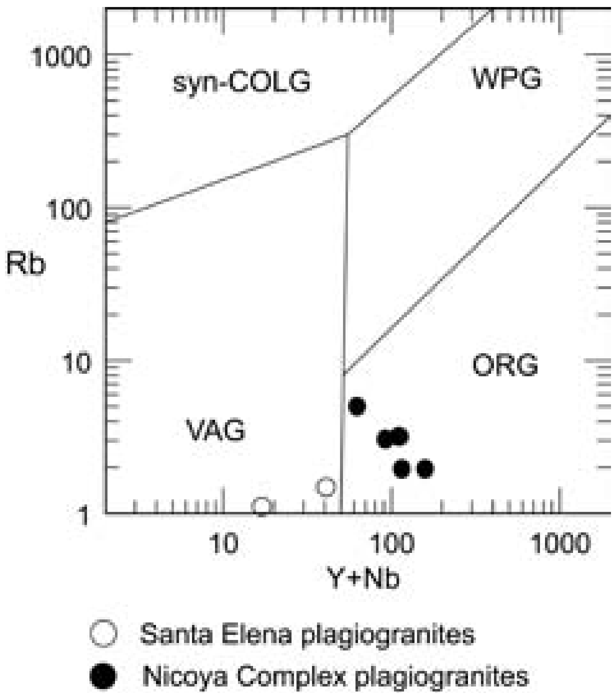

FIGURE 8 | **Rb/(Y+Nb) discrimination diagram (after Pearce et al., 1984) for Nicoya and Santa Elena plagiogranites. Geochemical data from Widberg (1984) and Arias (2004). Syn-COLG: Syn-Collisional Granites; WPG: Within-Plate Granites; VAG: Volcanic-Arc Granites; ORG: Ocean-Rift Granites.**

The mafic rocks from the Santa Elena Nappe have La/Yb ratios <5 that indicate high degrees of melting; the Zr/Nb ratios >30 and the variable Ba/La (up to 90 in the fresh samples) ratios evidence a MORB-like subduction "modified" mantle source (Fig. 6). Primitive mantle normalized spider diagrams show LILE enrichment and HFSE depletion, typical patterns of island arcs (Figs. 5B and 5 D). The same affinity is also confirmed by the V/Ti diagram (Fig. 7). High Ba/La ratios, up to 200 (Fig. 6), and negative Ce anomalies in the layered gabbros (Fig. 5C) are related to alteration of the samples (Haskin, 1984).

There are two areas with outcropping plagiogranites in the Costa Rican basaltic oceanic assemblages, one in the Nicoya Peninsula and other in the layered gabbros at the Santa Elena Nappe. The Rb/Y+Nb diagram shows that these rocks reflect different tectonic origins. This diagram suggests that the Nicoya Complex plagiogranites have affinities to ocean-rift (or plateau?) and the ones from Santa Elena to a volcanic arc (Fig. 8).

We interpret the autochthonous unit beneath the Santa Elena Nappe as the Santa Rosa Accretionary Complex. This interpretation takes into account the variety of rock types that are tectonically associated. The alkaline magmatic rocks of the Santa Rosa Accretionary Complex display LREE enrichment and high La/Yb (>20) ratios that indicate low degrees of melting. The Zr/Nb ratios (<10) and the V/Ti diagram (Figs. 6 and 7) provide evidence for an OIB (Ocean-Island Basalt) mantle source. Hauff et al. (2000) proposed that these rocks represent an accreted seamount, which is consistent with our understanding as an accretionary complex.

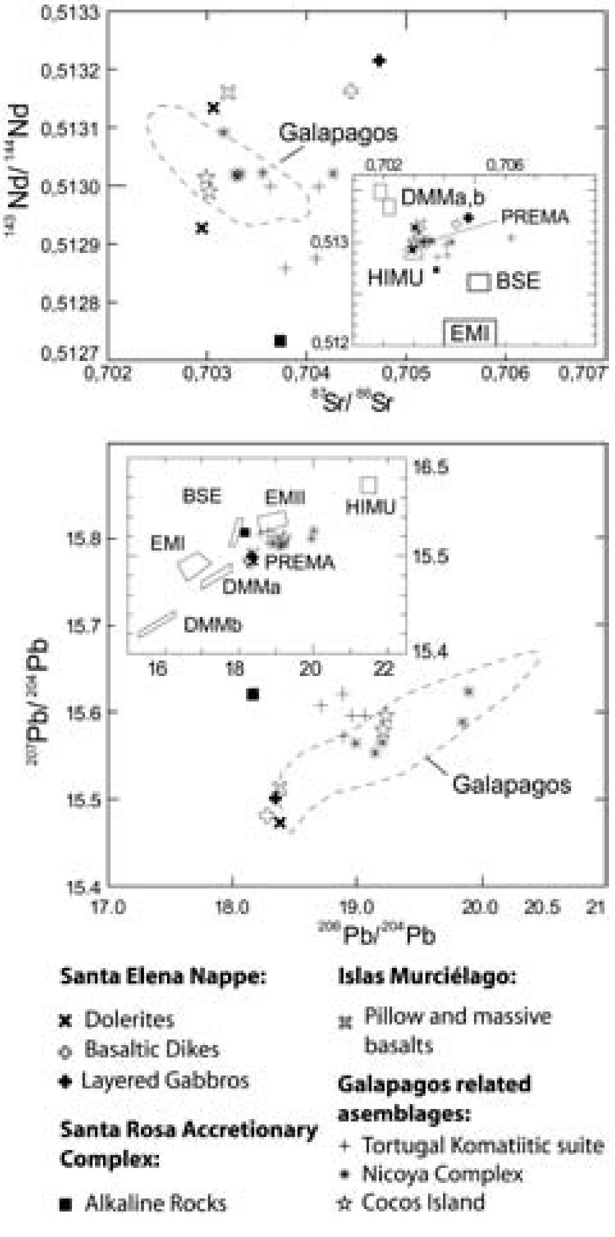

FIGURE 9 | **Sr, Nd and Pb isotopic diagrams for Santa Elena Peninsula, Nicoya Complex, Tortugal Komatiitic Suite and Cocos Island basaltic assemblages. Data from Castillo et al. (1988), Beccaluva et al. (1999) and Hauff et al. (2000). Galapagos array after Zinder and Hart (1986) and Castillo et al. (1988). Mantle reservoirs after Zinder and Hart (1986). DMM (a, b): Depleted Mantle a and b; PREMA: Prevalent Mantle; HIMU: High U/Pb ratio mantle; BSE: Bulk Silicate Earth; EMI and EMII: Enriched Mantle I and II.**

Isotopic relations and mantle reservoirs

The Santa Elena Nappe and Islas Murciélago samples generally have higher $^{87}Sr/^{86}Sr$ at the same value of $^{143}Nd/^{144}Nd$ and lower $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ compared to the Galapagos related assemblages represented by the Nicoya Complex, Tortugal Komatiitic Suite and the Cocos Island (Fig. 9). The isotopic ratios of the Santa Elena Nappe and Islas Murciélago are more typical of island arcs magmas than of a hot spot tectonic setting. The alkaline basalt sample from the Santa Rosa Accretionary Complex has lower $^{206}Pb/^{204}Pb$ and $^{143}Nd/^{144}Nd$ and high $^{207}Pb/^{204}Pb$ ratios compared to the Santa Elena Nappe, Nicoya Complex, the Cocos Island and Tortugal Komatiitic Suite samples. Any of the Santa Elena samples (Fig. 9) fall in the Galapagos array from Zinder and Hart (1986) and Castillo et al. (1988).

Based on Pb isotopes, the mantle reservoir for the Santa Elena Nappe units is PREMA (Prevalent Mantle). The sample of the alkaline rocks of the Santa Rosa Accretionary Complex is close to BSE (Bulk Silicate Earth) and the Galapagos related assemblages samples are close to EMII (Enriched Mantle II) with a HIMU (high U/Pb ratio mantle) component (Fig. 9).

CONCLUSIONS

The Santa Elena Ultramafic complex represents a relative depleted metasomatized MORB mantle. The mafic associations of the Santa Elena Nappe are depleted to strongly depleted in LREE and HFSE, enriched in LILE and show a range from primitive to fractionate compositions. These magmas originated by a high degree melting of a depleted, subduction modified MORB source. They were affected by low-grade metamorphism and hydrothermal alteration. The geochemical data suggest a primitive island arc tectonic setting for these magmatic rocks.

The alkaline rocks of the Santa Rosa Accretionary Complex are interpreted as low-degree melts of an OIB mantle source and probably represent accreted portions of a seamount.

Traditionally the Santa Elena Peninsula magmatic rocks were included in the Nicoya Complex, however we believe that these assemblages should be considered as a separated unit because the Santa Elena Nappe and the Santa Rosa Accretionary Complex samples were derived from different mantle reservoirs with distinctive Sr, Nd, and Pb isotopic ratios, than the Nicoya Complex and other Galapagos related rocks.

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