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THE SOUTHERN CENTRAL AMERICA PUZZLE: CRONOLOGY AND STRUCTURE
A REVIEW

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ABSTRACT: From northern Costa Rica to eastern Panama oceanic rocks are extensively exposed along the Pacific margin of Isthmic Central America. For the past 30 years, their nature and significance were subject to debate. This study distinguishes numerous units using the following criterions: ages of igneous and sedimentary rocks, petrological and geochemichal features, structural setting and ages of the sedimentary "covers". New field, radiometric and stratigraphical data are compared with available data published in recent papers. Strong disparities are noticed for ages, from Lias-lower Dogger to Eocene and petrological patterns: mantle peridotites, several tholeiitic and alkaline series. Various units are mélange formations made of exotic blocks unknown elsewhere. We propose that these disparate units were emplaced by two contrasting processes: 1) Closing of a Mesozoic northern oceanic basin by northward convergence and emplacement of an E-W 150 km ophiolitic suture 2) successive accretions of terranes originated in the Pacific plate and corresponding to possible oceanic plateau basalts and seamounts.
Keywords: Central America, oceanic plateau basalts, Santa Elena and Nicoya peninsulas, $^{40}K/^{40}Ar$ ages

RESUMEN: Rocas oceánicas afloran ampliamente en las margenes pacíficas de América Central Ístmica, desde el norte de Costa Rica hasta el este de Panamá. Desde 30 anos sus índoles y orígenes han sido objeto de debates contradictorios. Este artículo define o redefine numerosas unidades usando varios criterios: cronología de rocas magmáticas y sedimentarias, petrología, estructura tectónica, edades de las coberturas sedimentarias. Los nuevos datos presentados se comparan con los recientemente publicados. Las edades se extienden desde el Lias-Dogger hasta el Eoceno, mientras que las características petrológicas cubren una amplia gama de composiciones tanto toleíticas como alcalinas. Varias unidades son formaciones de mélange en mayor parte constituidos de bloques exóticos desconocidos en otras partes. Se propone que el emplazamiento de estas unidades heterogéneas resulto de dos eventos tectónicos: 1) el cierre de una cuenca posiblemente protocaribe o Tethys, por S-N convergencia y obducción de una sutura ofiolítica de 150 km de largo; 2) accreciones sucesivas de unidades originadas en el Pacífico y que corresponden a fragmentos de depósitos profundos y actividad magmática intraplaca.
Palabras clave: América Central, basaltos oceánicos de *plateau*, prnínsulas de Santa Elena y Nicoya, $^{40}K/^{40}Ar$.

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INTRODUCTION

Two domains are classically defined in Central America (Weyl, 1980). From Guatemala to northern Nicaragua, Nuclear Central America displays outcrops of continental crust and is regarded as a fragment of North America. On the other hand, in Isthmic Central America, Costa Rica and Panama, the oldest outcrops are made of Mesozoic pelagic sediments and mafic rocks (Fig. 1).

Harrison (1953) first described a large peridotitic massif in the Santa Elena Peninsula. Then, Dengo (1962) defined the "Nicoya Complex" in the Nicoya Peninsula that is made of basalts, intrusive rocks and pelagic sediments.

Besides the Nicoya basalts, extensive outcrops of submarine basaltic flows were noticed in central and southern Costa Rica, Panama, Colombia, and Ecuador. They were regarded as an oceanic basement located on the Pacific margins (Pichler et al., 1974).

Further to the development of the ophiolitic model, many authors assigned the peridotites of Santa Elena to the "Nicoya Ophiolitic Complex" (de Boer, 1979; Galli, 1979; Kuijpers, 1980). Beccaluva et al. (1999) emphasized this model and assigned all the rocks from Santa Elena and Nicoya to a sole complete cogenetic ophiolite pile including peridotites, gabbros, dolerites, basalts and a radiolaritic cover.

However, Wildberg (1984) substituted to a single ophiolitic model to a two stages model involving a "Lower Nicoya Complex" formed at an oceanic ridge and an "Upper Nicoya Complex" corresponding to a possible subduction related settlement. The latter was interpreted as an inland witness of the Caribbean Sill Event (Meschede & Frisch, 1994).

Alternative interpretation considered that all the basaltic rocks from the Nicoya Peninsula are accreted fragments of the Caribbean Plateau formed at a Pacific hotspot (Donnely, 1994; Hauff et al., 1996; Sinton et al., 1997; Hauff et al., 2000).

On the other hand, the extensive basaltic outcrops from central and southern Costa Rica were also assigned to the "Nicoya Ophiolite Complex" (Berrangé & Thorpe, 1988) even though they are younger (Berrangé et al., 1989; Tournon, 1984; Di Marco,1994). These basaltic units, as the Nicoya basalts were later interpreted as fragments of basaltic plateaus, Cretaceous to Paleogene in age,

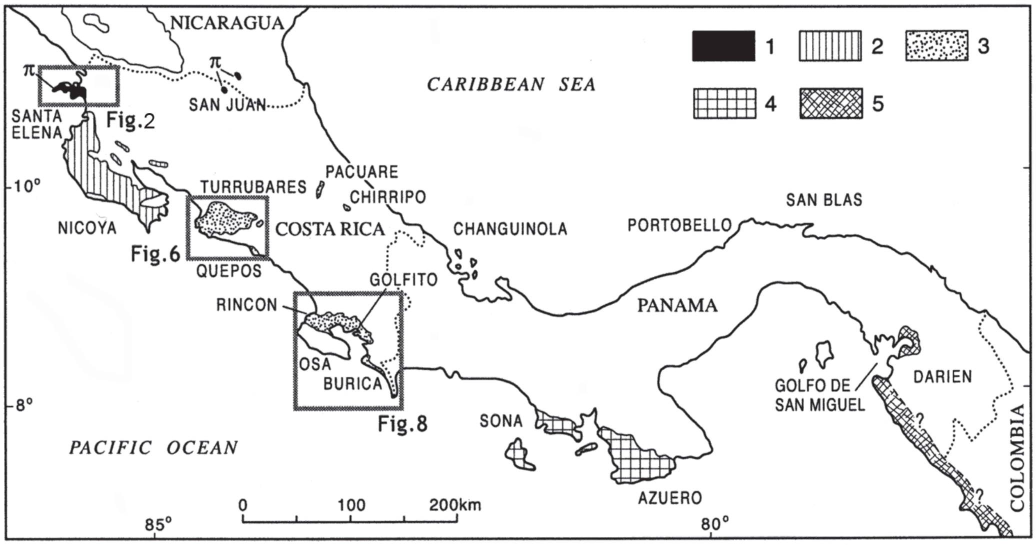


Fig. 1: Ultramafic and mafic complexes in Ishtmic Central America. 1: Mantle peridotites, Santa Elena Peninsula and Río San Juan area. 2: Pre-Campanian mafic rocks and pelagic sediments, Nicoya Peninsula and Tempisque Basin. 3: Late Cretaceous to Eocene basaltic complexes, Central and southern Costa Rica. 4: Metamorphic rocks and pre-Campano-Maastrichtian basalts, Western Panama. 6: Basaltic complex of Darién, Eastern Panama.

formed at the Galapagos hotspot (Hauff et al., 1997; Hauff et al., 2000). This latter model ruled out the ophiolitic one.

Otherwise, the presence of alkaline basaltic series or enriched light REE tholeiitic basalts (Tournon, 1984 and 1994; Hauff et al., 2000) suggest that various basaltic units were possibly generated in other geodynamic settings such as seamounts or even rifts.

Despite numerous data published the nature and significance of these “oceanic series” remain much debated particularly concerning the opposition between the “ophiolitic” and the “plateau” models. Recently a critical synthetic review was carried out which emphasizes the role of accretion (Denyer et al., 2006). Similar processes are attempted in this paper.

Since 1969, Jean Tournon, carried out field work studies from the Nicaraguan border to eastern Panama. Stratigraphic, structural and petrographic data allow us to attempt a comparative description of all the “oceanic” complexes listed in the Central America isthmus. First, we define each unit using structural and chronological criteria. ^{40}K/^{40}Ar datings by Hervé Bellon of selected rocks have completed the data set. Dating of basalts was only attempted on the scarce samples which display an unaltered mesostasis and most chronological data for basalts were traced in sedimentary intercalations within the basaltic successions. These results are completed by ^{40}K/^{40}Ar dating of the intrusives on both whole-rocks and separated mineral fractions. Our own results will be compared with the data available in literature. Then we will discuss the implications for chronological and geodynamic reconstructions.

ANALYTICAL METHODS

Whole-rock, separated mineral and/or groundmass ^{40}K/^{40}Ar ages were performed at the Geochronology Laboratory at the Université of Bretagne Occidentale in Brest. Analyses were done on whole-rocks and/or separated minerals fractions. After crushing and sieving, the grain fraction of 0.3 to 0.15 mm was cleaned with distilled water and then retained for analytical purposes: (i) one aliquot was powdered for K analysis by atomic absorption after fluorhydric acid digestion, and (ii) 0.3 to 0.15 mm grains were used for argon isotopic analysis. Argon extraction was performed by induction heating of a molybdenum crucible containing the grains in a high vacuum Pyrex line, where the extracted gases were cleaned on two titanium spunge furnaces and finally purified by using two Al-Zr SAES getters. Isotopic composition of argon and concentrations of radiogenic ^{40}Ar were measured using a 180°-geometry stainless steel mass spectrometer equipped with a 642 Keithley amplifier. The isotopic dilution method was applied using a 38Ar spike buried as ions in aluminium targets along the original procedure described by Bellon et al. (1981).

Ages are calculated using the constants recommended by Steiger & Jäger (1977) and 1σ errors are calculated following the equation of Mahood & Drake (1982); they are listed in Table 1 with the more characteristic parameters and reported in the general chronology presented in Fig. 10. Geographical names of sites of sampling for geochemical analyses and isotopic geochronology are in tables 1, 2 and 3.

Geochemical analyses for major and trace elements were partly performed at the Université of Bretagne Occidentale in Brest, using Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES). Samples were finely powdered in an agate grinder before the acid digestion. International standards were used for calibrations tests (ACE, BEN, JB-2 and Mica-Fe). Rb was measured by flame emission spectroscopy. Relative standard deviations are ±2% for major elements and ca. 5% for trace elements. Detection limits are ca. 2 ppm for Cr, Ni, Co, V, Ba, Ce, Zr, Nd; 1 ppm for Rb, Nb, La, Er; 0.5 ppm for Sr, Y; and 0.2 ppm for Sc, Eu, Dy, Yb. The precise analytical steps of the applied techniques are described in Cotten et al., (1995).

Another set of geochemical analyses was performed at CRPG in Nancy (France) using ICP-AES for major elements and ICP-MS for trace elements. Detection limits are 4 ppm for Sr; 3 ppm for Ba; 1 ppm for Rb; 0.5 for Rb; 0.15 ppm for Nd; 0.10 ppm for Nb; 0.05 ppm for Ce, La, Dy,Y; 0.04 ppm for Pr, Er; 0.03 ppm for Yb; 0.02 ppm for Eu.

Table 1

^{40}K/^{40}Ar isotopic ages for Costa Rica and Panama magmatic rocks

	Rock ref.	An. ref	Age (Ma) ± error	$^{40}Ar_R$ e^{7-} cm^3/g	$^{40}Ar_R$ (%)	K_2O (wt%)	^{36}Ar exp. $e^{-9}cm^3$	Weight fused (g)
Sta. Elena allochtonous unit	CR745(wr)	B3091	83.4±2.4	6.05	34.0	0.22	1.22	0.3092
	CR316(wr)	B3082	92.7±2.9	3.37	34.0	0.11	1.33	0.6059
Allochtonous unit mafic rocks	SE4(wr)	B2938	80.1±1.7	12.14	74.9	0.4b’	1.55	0.6113
	SE10(amp)	B3047	98.8±3.6	5.56	31.3	0.17	0.83	0.2026
		B3090	101.3±2.5	5.71	47.3	0.17	0.44	0.2044
Plutonic Comp. Bahia Nancite	SE10(Pl)	B4803	78.8±2.3	9.05	66.6	0.35	0.96	0.4012
	SE9(wr)	B3191	122.5±10	2.04	9.9	0.05	3.82	0.6111
		B0524	131.3±8.3	2.19	13.3		4.85	1.0018
	SE17(wr)	B3190	130.0±8.5	4.35	12.7	0.10	6.42	0.6375
		B0525	133.8±3.4	4.47	32.4		3.24	1.0241
Alk. sills within radiolarites	SE78(m)	B2918	74.7±1.4	83.38	83.2	3.39	2.04	0.2045
			84.7±1.4	94.72	93.5		1.46	0.5042
	SE78(amp)	B3087	159.5±3.5	61.81	74.0	1.15	1.01	0.1512
		B2917	149.9±3.0	57.96	77.9		2.09	0.2005
		B4799	155.4±3.6	60.16	96.7		0.51	0.2223
	CR564(wr)	O2998	127.4±2.7	113.2	94.2	2.66	3.23	1.5114
	CR573(wr)	O2924	126.9±2.7	233.2	91.5	5.5	2.60	0.4046
		O2923	130.5±2.8	240.0	92.4	5.5	3.73	0 6143
	CR774(amp)	B4798	158.7±3.6	69.52	98.2		0.43	0.2008
Trachyte	CR580(wr)	O2922	87.4±1.9	150.4	84.2	5.21	5.61	0.623--:
		B3220	86.2±2.0	148.3	57.8		7.88	0.2157
		B4829	83.4±1.9	143.4	98.6		0.89	0.8019
		B4841	83.7±1.9	143.9	97.9		0.76	0.4065
	CR580(fk)	B3080	99.2±3.3	75.62	27.2	2.3	13.9	0.2033
		B4842	80.7±2.5	61.22	32.7		6.75	0.1507
Nicoya intrusive rocks	N226B(wr)	B3089	80.5±1.9	3.71	49.2	0.14	1.01	0.5087
	N220B(wr)	B3089	78.4±2.3	3.36	33.7	0.13	1.70	0.6067
	CN11C(pl)	B2593	78.5±1.7	2.46	72.3	0.095	0.32	0.5023
	N284(pl)	B2607	76.2±2.1	4.14	58.9	0.165	0.62	0.5084
Herradura basalt	CR366(wr)	B4805	91.7±5.2	1.21	38.5	0.043	0.87	0.8017
		B3221	91.8±5.2	1.21	39.7		0.85	0.8034

Table 1 (continuation)

	Rock ref.	An. ref	Age (Ma) ± error	$^{40}Ar_R$ e^{7-} cm^3/g	$^{40}Ar_R$ (%)	K_2O (wt%)	^{36}Ar exp. e^{-9}cm^3	Weight fused (g)
Osa Peninsula	950(wr)	B4847	45.5±2.5	5.35	73.4	0.36	0.83	0.7360
		B4849	45.6±2.5	5.36	74.5		0.78	0.7022
Mafic dyke within schists-Azuero	P147(wr)	B2764	39.4±2.7	3.34	28.6	0.26	3.25	1.0092
		B2941	40.5±2.0	3.44	38.6		1.75	0.6150
		B2929	41.3±2.1	3.50	36.3		1.82	0.6045
calcalkaline intrusive	P182(wr)	O3316	58.9±1.4	16.39	57.1	0.85	4.19	1.0050
		B2961	57.4±1.7	15.97	61.7		1.45	0.4107
San Blas, calcalkaline intrusive	P218(wr)	B1950	63.1±3.2	3.82	55.1	0.185	1.37	1.0170
San Miguel gulf (Darien) pillow	P49(wr)	B2927	21.7±0.5	8.59	62.0	1.22	1.15	0.6150
		B3206	23.0±0.5	9.11	64.3		0.69	0.4017
		B4822	22.7±0.5	8.98	99.9		0.27	0.8024

Whole-rock: wr. Amphibole: amp. Plagioclase: pl. Alkali feldspar: fk. Mesostasis: m.

Location. **CR 745:** X 330.00, Y 322.30; **CR 316:** 357.50, 321.30; **SE 4:** 347.40, 319.80; **SE 10:** 347.65, 318.75; **SE 9 and SE 17:** 347.10, 310.60; **SE 78:** 330.95, 318.30; **CR 564:** 330.50, 310.35; **CR573 and 774:** 330.85, 318.20; **CR580:** 332.25, 317.60. **N 226:** 347.35, 281.20. **N 220:** 348.00, 281.30; **CN 11c:** 347.45, 281.10; **N 284:** 343.00, 280.10; **CR 366:** 390.35, 400.35; **P147:** 509.75, 855.20; **P182:** 538.00, 844.70; **P218**, Rio Azucar, coast opposite to Nargana island, San Blas; **P49:** Punta Hueca, Golfo de San Miguel, Darien.

THE MASSIFS OF MANTLE PERIDOTITES AND ASSOCIATED UNITS

The only mantle-derived rocks known in the Central America isthmus are exposed in the Santa Elena Peninsula and the Rio San Juan area (Fig. 1). These peridotite massifs are 150 km away from one another and stand on an E-W trend on both sides of the Quaternary volcanic cordillera.

THE RÍO SAN JUAN PERIDOTITES

Several occurences of ultramafic rocks, poorly exposed, were noticed along the Costa Rica – Nicaragua border at Tiricias (Costa Rica) and near El Castillo (Nicaragua), where radiolarites also occur (Astorga, 1992). The peridotites are totally serpentinized, except in one Nicaraguan outcrop (Las Brenes), where the primary paragenesis is partially preserved. Textures and compositions of the main phases (olivine, orthopyroxene, clinopyroxene and spinel) are typical of mantle peridotites and similar to that of the Santa Elena peridotites (Tournon et al., 1995).

THE SANTA ELENA PENINSULA

The Santa Elena peninsula (Fig. 2) is mainly composed of a large peridotitic massif (300 km2) elongated E-W along 30 km (Harrisson, 1953). Azéma & Tournon (1980, 1982) distinguished various structural units, eg. from the base to the top:

A - A relative autochtonous unit directly thrust by the massif of mantle peridotites. We interpret this unit as a chaotic unit (“mélange”) composed of sedimentary and magmatic blocks of all sizes within a more or less abundant detrital matrix.

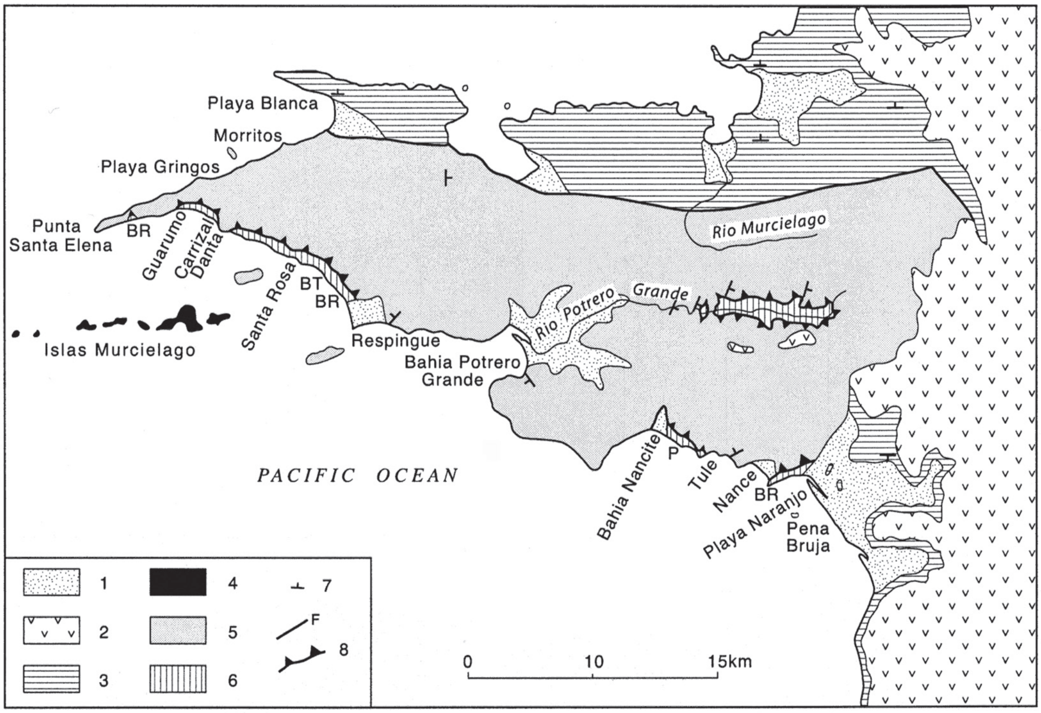


Fig. 2: The Santa Elena Peninsula. 1: Alluvial deposits. 2: Ignimbritic slab. 3: Sedimentary cover (late Cretaceous to Eocene). 4: Islas Murcielago basalts. 5: Allochtonous Unit, mantle peridotites. 6: Relative autochtonous unit, Santa Elena Melange. 7: Dips of foliation planes within peridotites, dips of the cover. F: Fault. 8: Thrust. BR: breccias. BT: Respingue basalts and trachytes. P: Bahía Nancite plutonic block.

B - An allocthonous unit made of mantle peridotites cut by mafic dykes.

C - A sedimentary cover from Campanian to Eocene in age.

D - An ignimbritic slab resting on the sedimentary cover or directly on the allochtonous unit.

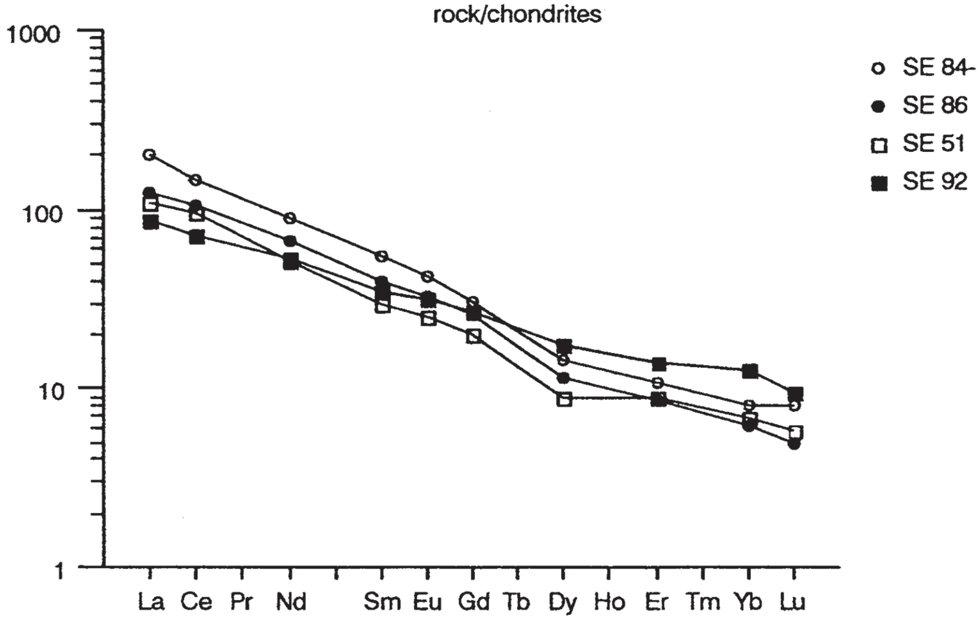
First, we will show some major patterns concerning the mélange and the peridotite nappe, then we will discuss their emplacement.

A - The Santa Elena Relative Autochtonous Unit, a mélange formation

The Santa Elena peridotitic nappe is thrust onto a relative autochtonous unit which is exposed within a tectonic window in the center of the Peninsula (Potrero Grande valley) and within half windows along the southern coast (Fig. 2).

In the Potrero Grande window, poor and discontinuous outcrops display cherts, pillow basalts, detrital sediments and radiolarites bearing Callovian–Oxfordian, Early Lower Cretaceous and Cenomanian fauna (Schmidt–Effing, 1980; de Wever et al., 1985). The contacts with the overlying peridotites are subhorizontal and penetrate within the ravines in both the northern and southern sides. Westwards of this ten km in length tectonic window appears a small window made of radiolarites surrounded with peridotites.

Along the southern coast, the peridotites crop out from sea level up to above 60 m. The contact above the autochtonous unit is marked by shistosed serpentinites and is northward dipping. The autochtonous unit crops out in four half tectonic windows: 1) the Guarumo-Carrizal window (radiolarites, shales, basalts); 2) the Santa Rosa-Respingue window (radiolarites, cherts, basalts,



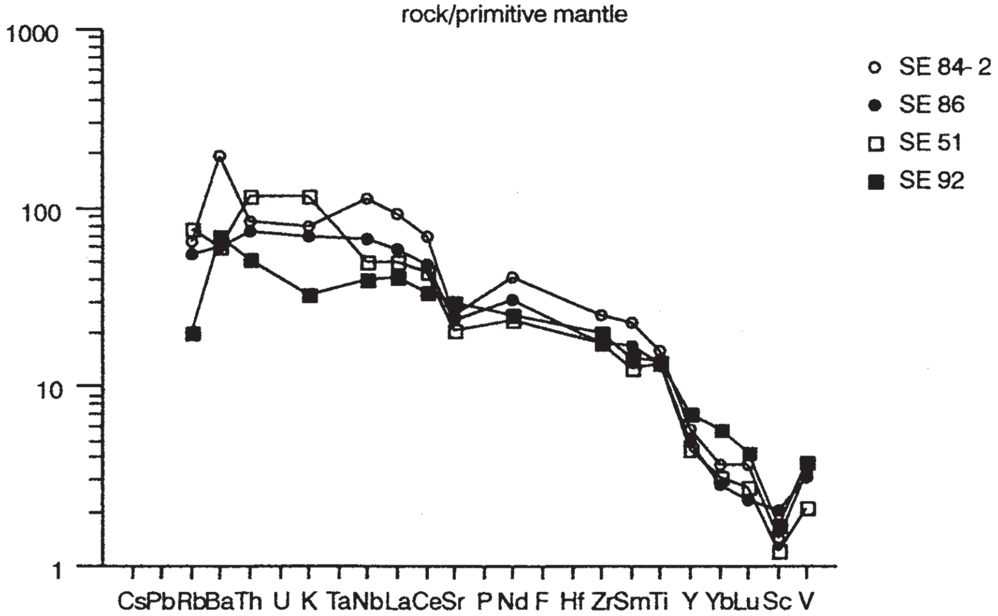


Fig. 3: Chondrite normalized REE-patterns and primitive mantle normalized spidergram for alkaline rocks from the Santa Elena autochthonous Unit.
Sills within the Sitio Santa Rosa Block: SE 84-2 and SE 86. Pillow basalt, Playa Carrizal: SE 51. Massive basalt, Respingue Block: SE 92.

breccias; 3) the Bahia Nancite window (plutonic rocks, detrital sediments; 4) the Playa Naranjo window (breccias).

The relative autochtonous unit outcrops fairly well in the coastal cliffs. Some outcrops are breccias made of centimetric to metric clasts and blocks. These breccias are exposed on the southern coast of Punta Santa Elena, Respingue and Playa Naranjo. However, most of the part relative to the autochtonous unit displays metric outcrops, sometimes up to 100 m and made of a wide range of sedimentary and igneous rocks. Structural features like directions of beds in layered radiolarites and polarity of pillow basalts are not coherent from one outcrop to another. Detrital rocks "tuffs" or sands are more or less abundant and more often display subvertical contacts with radiolarites or magmatic rocks.

Baumgartner & Denyer (2006) interpret this structural unit as an accretionary prism. However, the presence of fragments from the allochtonous unit and of a detrital matrix rounding large blocks suggests that this possibly accretionary prism was reworked in a mélange formation.

We interpret the relative autochtonous unit as a chaotic formation made of breccias (centimetric to metric clasts and blocks) or large blocks; some of them being several hundred meters in length directly juxtaposed or surrounded with a detrital matrix. This chaotic formation may correspond to a Mélange formation that results from tectonic and sedimentary processes (McCall, 1983). Some components of the mélange are serpentinites and dolerites reworked from the peridotitic nappe, but most are exotic blocks unknown elsewhere.

The breccias

On the southern coast of Punta Santa Elena outcrop metric blocks of serpentinites and dolerites directly covered by serpentinites.

The Respingue breccias crop out on 40 m of coastal cliffs. They consist of centimetric to metric blocks in a grey clayed matrix. The blocks are serpentinites, dolerites and metagabbros made of hornblende phenocrysts and prehnite. These products of a low temperature static metamorphism were not observed elsewhere in the peninsula.

At Playa Naranjo, along 1 km of coastal cliffs, occurs a complex association of tectonic and sedimentary breccias: (i) a tectonic breccia made of blocks of dolerites and serpentinites in a crushed serpentinic matrix; (ii) a decametric block of serpentinite with anastomozed dykes of pegmatitic pyroxenites; (iii) a sedimentary breccia which consists of serpentinitic blocks within pelagic limestones; (iv) a block of well stratified sandstones and conglomerates and (v) a breccia made of igneous pebbles in a sandy matrix that are similar to the rocks of the Bahia Nancite layered complex (cumulates, gabbros, plagiogranites and olivine basalts). The "low Ti basalts" described by Wildberg (1984) were possibly collected in this formation.

The matrix of the Mélange

The matrix is made of unstratified sands, more or less fine, already described as "tuffs" (Azéma & Tournon, 1980). This sandy-type matrix outcrops extensively in the Guarumo area where it contains elongated fragments of well-stratified radiolarites. This setting suggests that the radiolaritic fragments were first slided and then deposited within the detrital sediments.

At Bahia Nancite, a large plutonic block outcrops from sea level up to 60 meters where it is covered by a sandy sediment, which is directly thrust by the peridotites of the allochtonous unit. Eastward, the plutonic rocks are in vertical contacts with these sandy sediments, which outcrop extensively and contain scarce angular blocks of basalt.

Argillaceous matrix was also observed. In Carrizal, pillow basalts are covered with 6 meters of red brown argillaceous sediment with small blocks of serpentinites and basalts, which is directly thrust by peridotites.

No fossil have been noticed in these detrital matrix.

Characteristics and chronology of some blocks

The blocks show a very large diversity of magmatic and sedimentary rocks. Abundant sampling allows us to understand the precise chronological and petrological features. In addition, the large size of some blocks allows us to reconstruct stratigraphic succesion up to one hundred meters thick.

Most blocks are made of sedimentary, volcanic or plutonic rocks known only in this mélange formation.

1 - Sedimentary rocks

Most sedimentary blocks are made of siliceous rocks, red radiolarites well stratified in centimetric beds, brown to grey cherts. Various outcrops of red radiolarites display well-preserved radiolarian fauna.

Metric blocks of red radiolarites are quite common. In Playa Carrizal, radiolarites display recumbent isoclinal folds with thin bituminous intercalations. They display radiolarian fauna Upper Aptian–Lower Albian in age (de Wever et al., 1985).

Large blocks allow us to observe various stratigraphical successions over hundred meters in thickness.

In Sitio Santa Rosa, a well stratified unit showing subvertical dips crops out along one km of coastal cliffs. It consists of layered red radiolarites, grey cherts alternating with metric beds of sedimentary breccia composed of radiolaritic and basaltic clasts. The central radiolaritic sequence is Lias–Lower Dogger in age, while on the eastern and western side of the block the microfauna are Barremian to Cenomanian (de Wever et al., 1985). This symmetric setting suggests a fold. The Lias–Lower Dogger radiolarites are the oldest rocks known in isthmic Central America. They are intruded by numerous sills of potassic alkaline basalts (Azéma & Tournon, 1980; Tournon, 1994).

Contrasting with the radiolaritic and chert sequences are blocks made of coarse detrital rocks. In the Playa Naranjo breccias is a decametric block made of stratified conglomerates. Between Playa Nancite and Playa Tule, a well stratified detrital series directly thrust by serpentinites is exposed and it consists of a succesion of lutites, sandstones and micro conglomerates. The clasts are made of lavas, cherts, large zoned plagioclase, idiomorphic quartz and possible fragments of lamellibranchia and echinids. The large zoned plagioclases and the idiomorphic quartz possibly originated from a calc-alkaline volcanism. These detrital rocks are intruded by dykes, which display chilled margins. They are altered orthopyroxene-bearing. microgabbros

2 - Volcanic rocks

Potassic alkaline sills

In Sitio Santa Rosa, numerous sills are intrusive within the red layered radiolarites. They are 1 to 10 m in thickness and display chilled margins. Ultramafic cumulates occur in their central parts. The basalts contain iddingsitized olivine, clinopyroxene and plagioclase phenocrysts within a groundmass of kaersutite, clinopyroxene, plagioclase, scarce biotite, titanomagnetite, apatite and alkaline feldspar. Clinopyroxene phenocrysts may be strongly zoned with ferrous augite as core rounded with titan augite and thin rim of acmite. The presence of ferrous clinopyroxene cores suggests xenocrysts removed from diferentiated magmas while unusual occurence of acmite in basaltic rocks emphazises their strong peralkaline evolution. The K2O (up to 2 wt%) and LREE (La/Yb: 30-38) contents are high (Table 2, Fig. 3). The presence of K-kaersutite phenocrysts and biotite shows the primary origin of high potassium contents of these basalts.

More leucocratic lamprophyres occur as veins within the thick basaltic sills and are made of abundant kaersutite and minor clinopyroxene phenocrysts in a groundmass that consists of alkaline feldspar and devitrified glass. The basaltic rocks correspond to the uncommon lavas called sannaites, which display both potassic and lamprophyric features (Lemaitre, 2004).

Whole-rock and mineral ^{40}K/^{40}Ar ages have been carried out on mafic and leucocratic sills. Kaersutite separated from lamprophyres CR 574 and SE 78 yield mean ages of 165.1 ± 3.7 and 157.5 ± 3.6 Ma, respectively. The groundmass SE 78 is dated at 84.7 ± 1.4 Ma, while lamprophyre CR 573 and basalt CR 564 yield whole-rock ages of 128.7 ± 2.8 and 133.6 ± 6.2 Ma, respectively. Amphibole ages are preferred to the whole-rock ones, because these possibly result from the mixing of thermally rejuvenated ages of groundmass and the age of well preserved amphibole phenocrysts. Amphibole

Table 2

Representative geochemical analyses of rocks from the Santa Elena peninsula

Sample wt%	97-39*	CR537	SE4	CR316	CR738*	97-76*	97-90b*	97-93*	SE86+	SE51+	SE92+
SiO2	45.98	51.00	50.00	50.00	51.49	47.19	50.17	68.38	41.14	47.11	45.17
TiO2	0.24	1.14	0.82	1.00	1.15	0.30	0.37	0.50	2.97	2.97	3.08
A1A	20.88	16.35	16.20	16.84	16.06	19.06	16.06	15.32	11.46	16.15	15.28
FeA	4.12	9.93	9.75	9.20	11.09	5.63	8.31	2.14	12.83	10.96	12.53
MnO	0.06	0.17	0.16	0.15	0.16	0.09	0.14	0.03	0.17	0.32	0.19
MgO	9.59	6.28	7.55	7.15	5.37	9.88	10.02	1.20	7.48	4.13	4.41
CaO	14.39	10.85	11.45	11.40	8.02	10.33	9.94	8.09	13.64	7.35	6.80
Na2O	0.98	3.00	2.51	2.94	4.23	3.12	2.65	3.21	1.86	2.91	4.75
K2O	0.32	0.11	0.45	0.08	0.12	0.07	0.06	0.25	2.00	3.42	0.96
P2O5	0.05	0.12	0.07	0.11	0.12	0.05	<0.05	0.12	0.64	0.77	0.51
LOI	3.56	1.64	1.59	1.52	1.99	4.29	2.51	1.19	5.23	3.88	4.84
Total	100.17	100.59	100.55	100.39	99.80	100.01	100.23	100.43	99.42	99.97	98.52
ppm											
Cr	184	110	114	173	29.9	342	482	10.6	564	186	12
Ni	498	48	58	70	27.8	177	222	11.6	145	40	20
Co	36.3	34	40	33	35.7	33.1	39.2	8.20	40	26	35
V	147	290	375	267	328	216	258	19.1	269	187	328
Rb	4.97				1.20	<1.00	<1.00	1.46	38	52	14
Ba	51.9	19	58	46	38.7	16.2	24.2	23.4	418	411	467
Sr	290	130	104	139	141	83.1	79.1	182	555	494	712
Nb	<0.10	0.8	0.2	1.1	0.68	<0.10	0.11	0.35	50	37	30
Zr	5.79	58	22	17	72.9	7.65	13.0	42.8	194	193	224
Y	13.5	28.5	16.6	24	29	7.89	14.8	41.3	23	21	33
La	0.252	2.1	0.8	1.5	2.01	0.260	0.454	1.21	40.94	35.35	28.91
Ce	0.512	8.5	4	6	6.88	0.719	1.33	3.76	90.34	81.60	62.05
Nd	0.681	7.5	3	1.1	6.77	1.03	1.59	5.67	41.52	32.47	34.07
Eu	0.207	0.95	0.5	0.8	1.00	0.274	0.421	0.734	2.54	1.96	2.42
Dy	1.76	4.4	2.4	3.6	4.16	1.15	2.09	6.06	4.53	3.88	6.41
Er	1.31	2.8	1.6	2.3	2.79	0.741	1.38	3.93	1.95	1.97	3.15
Yb	1.58	2.75	1.7	2.25	2.75	0.973	1.85	4.75	1.36	1.51	2.71
La/Yb	0.16	0.76	0.47	0.66	0.76	0.26	0.24	0.25	30.10	23.53	10.66

Total iron as Fe_2O_3. ICP AES, Université de Bretagne Occidentale, Brest. * ICP MS, CRPG, Nancy. + ICP for REE, CRPG, Nancy.

Allochtonous unit, 97-39: pegmatitic gabbro dyke within peridotites, X 346.25, Y 320.50. CR 537 and SE 4: dolerites dykes with preserved magmatic texture within peridotites, 349.60, 320.50 and 347.40, 319.80. CR 316: metamorphic amphibolite,. 357.50, 321.30. CR 738: dolerite, dyke swarm of the western coast, 330.45, 322.60. Blocks within the relative autochtonous unit (mélange) Bahia Nancite Block 97-76: gabbro, 346.55, 310.90. 97-90b: gabbro, 346.75, 210.60,. 97-93: clinopyroxene bearing plagiogranite 346.75, 210.60. SE 86: basalt (LOI including CO_2: 2.51%), sill within radiolarites, Sitio Santa Rosa, 330.90, 318.30. SE 51: pillow basalt with globules of calcite (analyses recalculated to 100 wt% substracting calcite, CO_2: 11.71%), Playa Carrizal, 327.60, 319.90. SE 92: basalt, Respingue Volcanic Block, 332.30, 317.60.

phenocrysts ages, which are the oldest recorded for igneous rocks in Isthmus Central America, are in accordance with the setting of these sills that are apparently restricted to the Lias - Lower Dogger radiolarites.

Pillow basalts from the Guarumo-Carrizal and Santa Rosa windows

The highly vesicular pillow basalts show high K and Na contents, but primary phases are strongly weathered (albitization of plagioclase). However, compositions of the fresh clinopyroxenes (SiO_2: 41-48 wt%, Al_2O_3: 5-9 wt%, TiO_2: 3-6 wt%) and high LREE (La/Yb: 23) contents suggest that they are alkaline basalts (Table 2, Fig. 3). Similar pillow basalts are exposed east of Punta Danta.

The Respingue Volcanic series

This block is made of a thick subvertical volcanic sequence of alternating massive and pillowed flows cut by basaltic dykes, and scarce trachytes. Sedimentary intercalations or matrix of pillows were not observed. Basalts (Table 2, Fig. 3) display weak alkaline patterns (La/Yb: 10), some are plagioclase-rich and may correspond to fractionated lavas (low Mg, Cr and Ni contents). Trachytes (CR 580) contain hedenbergite and abundant alkali feldspar phenocrysts in a groundmass with hedenbergite microlites and recrystallized feldspar and quartz. $^{40}K/^{40}Ar$ ages (Table 1) for both whole-rock and separated alkali feldspar phenocrysts (albite with orthose exsolutions) are nearly similar at 83.5 ± 1.9 and 80.7 ± 2.5 Ma, respectively. These data possibly concern subsolidus recrystallizations and then provide a minimum age for the Respingue volcanic series.

3 - Plutonic rocks

Blocks of serpentinites are present in the Guarumo-Carrizal window and in the Respingue and Playa Naranjo breccia. In the latter is a large block of serpentinized peridotite cut by anastomozed dykes of pegmatitic pyroxenites. They are made of idiomorphic crystals of diopside, 1 to 5 cm length, and scarce xenomorphic orthopyroxene. Such pyroxenites with cumulate texture were not observed in the Allochtonous unit.

The Bahia Nancite Block, a layered igneous sequence

The Bahia Nancite igneous complex outcrops continuously along 500 m of coastal cliffs from sea level to about 50 m. It is covered by a detrital sandy formation which is directly surmounted by schistosed serpentinites, basement of the allochtonous unit. Eastward the plutonic rocks display vertical contacts with similar detrital formation.

It consists of an alternance of ultramafic rocks and gabbros. Ultramafic rocks, plagioclase-bearing peridotites and pyroxenites are heteradcumulates with olivine (Fo 85) partially serpentinized and clinopyroxene (diopside) as cumulus phases, orthopyroxene (En 82) and plagioclase (An 90-95) as intercumulus phases.

The gabbros are made of plagioclase (An 60-90, clinopyroxene and amphibole and locally display planar textures and layering. The amphiboles show a wide compositional range and very complex zoning from magnesium hornblende, titanium and chromium rich, to ferrous hornblende and actinolite (Arias, 2002). Oxides are almost totally absent and are only represented by scarce Cr-spinel inclusions in pyroxenes.

Plagiogranites occur in an islet as veinlets and pockets within gabbros and are made of plagioclase (An 50), abundant quartz and very scarce amphibole or pyroxene (hedenbergite).

The gabbros (Table 2, Fig. 4) display high Al and Mg contents ($Al_2 O_3$: 16-19 wt%; MgO: 9-10 wt%), very low Fe and Ti (TiO_2: 0.14-0.3 wt%) and strong depletion of LREE (La/Yb: 0.16-0.26) (Arias, 2002). Nb and Ta negative anomalies are noticeable; however their significance is questionable because they are close to detection limits. Plagiogranites and gabbros display similar REE patterns and are cogenetic (Fig. 4).

This plutonic complex (cumulates, gabbros and plagiogranites) is intruded by various stages of dykes with chilled margins: 1) scarce ouralitized dolerites; 2) olivine basalts; 3) aphyric basalts. The olivine basalts are very abundant. The texture is porphyric with phenocrysts of clinopyroxene and abundant totally pseudomorphozed olivine. The matrix consists of clinopyroxene, plagioclase and chlorite. The olivine basalts show high Mg, low

Ti contents and Nb Ta negative anomalies (Arias, 2002; Gazel et al., 2006).

Whole-rock $^{40}K/^{40}Ar$ datings were carried out for two gabbros, SE 9 and SE 17 (Table 1). Mean results are 127 ± 10 and 132 ± 8.5 Ma, but must be considered with caution due to their very low K contents, but a close age of 124.2 ± 4.1 Ma was provided by $^{40}Ar/^{39}Ar$ dating (Hauff et al., 2000) confirm these previous results.

B - The allochtonous unit: a massif of mantellic peridotites cut by mafic dykes

Peridotites and pyroxenites

The peridotites are partially or totally serpentinized. Serpentinization represents 50% for the best preserved peridotites (Río Seco). In the most serpentinized samples, olivine is totally replaced by serpentine and minor magnetite, orthopyroxenes are pseudomorphosed with “bastite”, clinopyroxenes recrystallized in tremolite and spinels are opacified.

The textures of the peridotites are panxenomorphic and porphyroclastic with large crystals of orthopyroxenes. Foliation weak to strong is marked by elongation of orthopyroxene crystals. The foliation planes display various directions through the massif (Fig. 2). Along the Potrero Grande valley the planes are parallel on various kilometers (N-S, with westwards dips).

Most peridotites are lherzolites or diopside bearing harzburgites (cpx: 2 to 9%) with spinel. Wehrlitic facies are exceptional (cpx: 20 %). Pargasite is scarce. Plagioclase bearing lherzolites are rather common and are spread throughout the massif. The plagioclase (An 88-95), generally totaly altered, surrounds spinel or forms intertitial polycrystalline spots. Dunites, which are quite common all over the massif, occur as pockets or centimetric “dykes” within lherzolites and harzburgites. Chromitites were rarely observed as centimetric dykes or as repeated parallel pods within totally weathered peridotites, possibly dunites. Some display “leopard facies.”

Thin pyroxenitic layers, sometimes repeated, are parallel to the foliation of the host peridotites. They are made of orthopyroxene, clinopyroxene, spinel or pentlendite.

Mafic dykes

Two generations of mafic dykes cut the peridotites and, on the contrary, are unconformable to their foliation planes: 1) pegmatitic gabbros; 2) dolerites.

1 – Pegmatitic gabbros

Pegmatitic gabbros, rather scarce, lack chilled margins. They occur as anastomozed thin dykes, more seldom as repeated parallel centimetric dykes. Their primary paragenesis, which is rarely well preserved, consists of plagioclase and orthopyroxene, generally replaced by amphibole. Well-preserved samples, with abundant fresh anorthitic plagioclases display high MgO (9-10 wt%) and low TiO_2 (0.11-0.26 wt%) contents and strong LREE depletion (La/Yb: 0.16, Table 2, Fig. 4).

2 - Doleritic dykes

All over the massif, the peridotites are crosscut by numerous doleritic dykes with chilled margins. The dykes, 0,5 to 3 meters thick, are parallel and generaly display high dip angles with N-S to NE-SW directions.

On the western coast of the massif, between Punta Morritos and Bahía Gringos, the dolerites are so abundant that they constitute a “dyke swarm” made of multiple intrusions. They display asymmetric chilled margins. Later very fine grained dykes cut microgabbros. This dyke swarm encloses metric xenoliths of serpentinized peridotites and pegmatitic gabbros. These latter rocks have geochemical patterns similar to those of the pegmatitic gabbros present in the peridotites. This dyke swarm corresponds to an exceptional density of doleritic dykes furthermore present in the entire peridotitic allochthonous unit and it does not represent a window of a “Matapalo unit” thrust by the peridotites as suggested by Beccaluva et al., (1999). The rocks of the dyke swarm suffered locally a low temperature static metamorphism and recristallized with epidote, chlorite and albite

The dolerites are made of relatively fresh plagioclase and clinopyroxene, which is rimed or generally totally replaced by green hornblende.

The mafic rocks display metamorphic recrystallizations both static and dynamic. Most doleritic dykes show preserved magmatic textures, but clinopyroxene is generaly totally replaced by zoned amphiboles: brown green hornblende (Al_2O_3: 8%), green hornblende (Al_2O_3: 5%) and light green actinolite (Al_2O_3: 2%) in rims. Some dykes show lenses made of diopside, plagioclase (An 86), and sphene, possibly resulted from calcic metasomatism processes within the amphibolite facies.

Dynamic metamorphism is obvious in narrow shear zones, which displays gneissic amphibolites. They occur all over the massif from sea level to 500 m. In the dyke swarm, from the western coast, the gneissic amphibolites are well exposed in metric bands within non-deformed amphibole dolerites. Schistosity planes with high angle dips display N110º-140º directions. Veins made of hornblende and plagioclase with microgranular texture are cutting the schistosity planes and so suggesting that igneous injections must have also occured after the deformation.

The doleritic dykes and the gneissic amphibolites have similar chemical compositions, i.e. moderate TiO_2 contents (1 wt%), slightly negative Ta and Nb anomalies and a moderate LREE depletion, as shown by La/Yb ratios of 0.5 - 0.9 (Table 2, Fig. 4).

Whole-rock and mineral $^{40}K/^{40}Ar$ ages for a set of three gneissic amphibolites (SE 10, CR 316 and CR 745) and one dolerite (SE 4) are listed in Table 1. The oldest age is for the separated metamorphic hornblendes, and the youngest for the plagioclases separated from the amphibolite SE10, perhaps enriched in potassium during fluids circulation. $^{40}K/^{40}Ar$ ages of these metamorphic events are scattered between 100 ± 3.6 and 80 ± 1.7 Ma.

Nappe emplacement and sedimentary cover

The emplacement of a large mantle nappe was a major tectonic event in southern Central America. However, its details and chronology still remain uncertain. It is convenient to consider the structural relationships between the nappe, the relative autochtonous and the sedimentary cover.

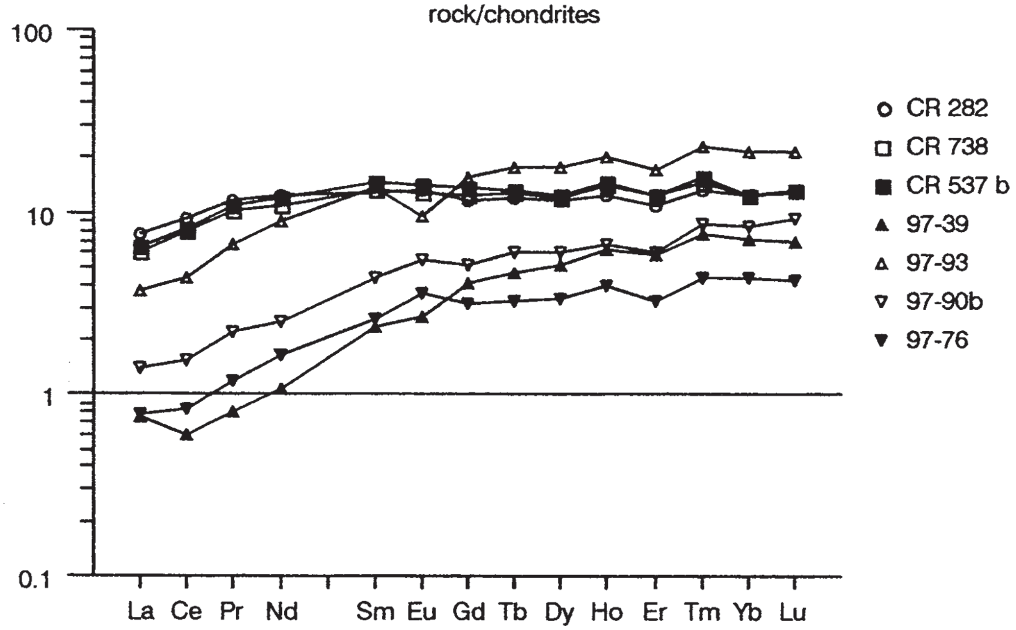
Near the contacts between the peridotitic massif and the autochtonous unit the ultramafic rocks are totally sepentinized and display schistosity planes parallel with the contacts. Horizontal fault mirrors are observed on radiolarites of the autochtonous unit, they display crenulations and N-S slicken-lines. Furthermore, on the southern coast, doleritic dykes are overfolded toward the south. These fabrics suggest that the peridotitic nappe emplaced with a southern vergence.

The northern part of the Santa Elena Peninsula is made of monoclinal series dipping towards the north. The series starts with Campanian pelagic limestones, continues with Upper Campanian marls and a thick detritic formation, Paleocene to Middle Eocene in age (Azéma et al., 1979; Di Marco, 1994). The detrital series is made of clasts derived from an andesitic volcanic source (Tournon, 1984). The contacts with the peridotites have never been observed. All authors since Dengo (1962) postulated a normal fault. However, a conformable setting of the sedimentary series onto the peridotites cannot be excluded.

In the south-eastern part of the Peninsula, sedimentary series dipping southwards are covered by a Neogene ignimbritic plateau. They consist of Paleocene detrital sediments, pelagic and reef limestones with Upper Campanian – Maastrichtian foraminiferas, rudists and corals (Azéma and Tournon, 1980). These reef limestones contain conglomeratic layers with serpentinitic pebbles. At 1.5 km off the southern coast of Playa Naranjo (Lambert coordinates: X 308.3, Y 352.2) stands Peña Bruja, an isolated reef approximately 30 m high. It is made of limestones bearing Campanian-Maastrichtian macroforaminifera (Baumgartner-Mora & Denyer, 2002). The contacts between this sedimentary "cover" and the allochtonous peridotite unit were not observed and the structural relations between these units remain unclear. A fault contact seems probable either a normal fault or a thrust. This unresolved question is essential for the tectonic history of the Santa Elena peninsula: Did the final emplacement of the ophiolitic nappe occured before or after the Campanian-Maastrichtian?

The Islas Murciélago basalts

The Islas Murciélago, located 4 km off the western Santa Elena peninsula are 10 islets and rocks aligned on a 9 km E-W trend. The islets are made of unmetamorphosed massive and pillow



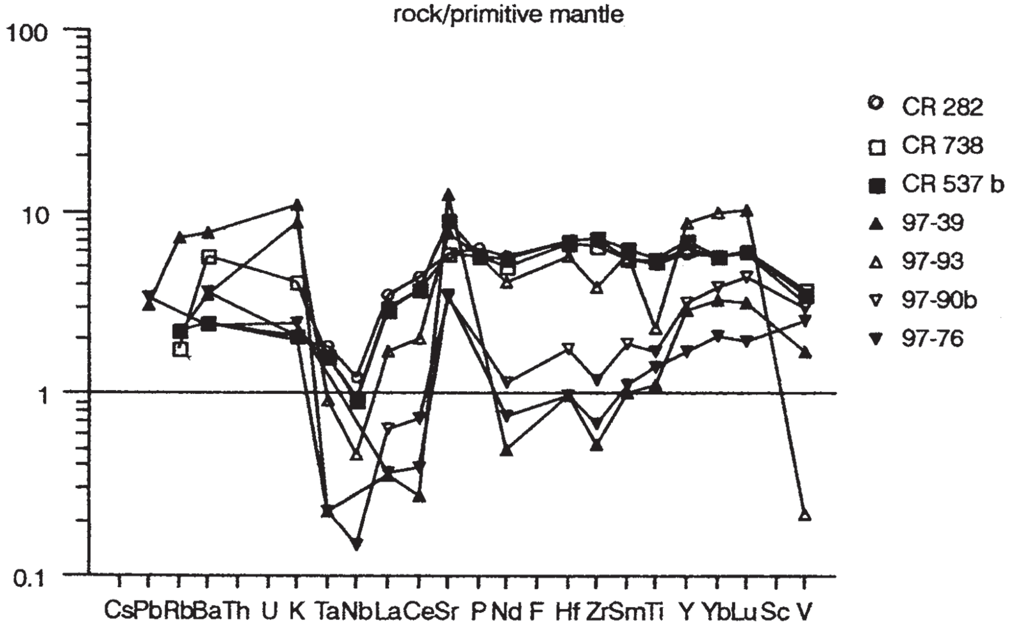


Fig. 4: Chondrite normalized REE-patterns and primitive mantle normalized spidergram for tholeiitic rocks from the Santa Elena Peninsula. Mafic dykes, doleritic dykes within peridotites: CR 282, CR 537b. Dolerite from the dyke swarm of the western coast: CR 738. Pegmatitic gabbro, dyke cutting the peridotites: 97-39. Rocks from the Bahía Nancite Block, gabbros: 97-90b and 97-76, pyroxene-bearing plagiogranite: 97-93.

flows. In Isla Catalina, the flows show northwards 60° dips. Scarce silicic sediments were observed as interpillow matrix, but not provided microfauna.

The basalts are not similar to those of the neigbouring Santa Elena coast, for they are vesicle free and display tholeiitic patterns (Desmet & Rocci, 1988). Some basalts are iron rich ($FeO+Fe_2O_3$: 16%). Negative Nb and Ta anomalies were determined by (Hauff et al., 2000) on a basalt from Isla Cocinero, for which these authors have also determined an $^{40}Ar/^{39}Ar$ age at 109 ± 2 Ma.

The significance and structural setting of this basaltic unit remains problematic because no contact with another formation was ever observed. Blocks of Paleocene fossiliferous pelagic limestones, unknown in the Santa Elena peninsula, were found on Isla Cocinero (Azéma et al., 1979), but their structural position remains unknown.

First, one can interpret the Murciélago islands as the northeast outcrop of the Nicoya Complex. The mineralogy and major elements contents look like the ferrobasalts present in Bahía Culebra, in northern Nicoya peninsula. However, some of their geochemical features, as Nb and Ta anomalies are not common on the Nicoya basalts (Hauff et al., 2000). The 9 km E-W trending of the Murciélago islands is parallel to the main structural direction of the Santa Elena peninsula. Furthermore, this basaltic archipelago seems to be rounded by both the relative autochtonous and the allochtonous units: southwards, the isla Colorada is made of peridotites and at its western side emerges a reef made of red radiolarites. Thus, the Murciélago islands may correspond to a possible tectonic slice within the Santa Elena units rather than to a northern outcrop of the Nicoya Complex.

NICOYA PENINSULA AND TEMPISQUE BASIN

In most parts of the Peninsula and locally in the Tempisque basin outcrops of basalts, intrusive rocks and pelagic sediments are exposed. These units were defined as the Nicoya Complex (Dengo, 1962). Since the last 30 years many papers were published about the Nicoya Complex. Most studies refer to the coastal outcrops where the Nicoya Complex is well exposed. On the other hand, the inland peninsula, which culminates at 1000 meters above sea level, remains poorly known.

PELAGIC SEDIMENTS

The sedimentary sequences outcrop mostly in the northern part of the Nicoya Peninsula, and consist of strongly folded red layered radiolarites (Gursky, 1988). Radiolarian associations are allocated to Callovian, Upper Jurassic, Lower Cretaceous and Santonian (Galli, 1977; Schmidt-Effing, 1979; Baumgartner, 1984). Recent revisions of biochronology argue that the deposition of the radiolarites occured from Bajocian to Albian, with a depositional gap during Upper Dogger (Denyer & Baumgartner, 2006). Manganese mineralizations occur as veins and sometimes as nodules between the radiolaritic layers (Kuijpers & Denyer, 1979; Halbach et al., 1992). Quite different are thin Coniacian-Santonian radiolaritic inercalations in the basaltic successions (Denyer & Baumgartner, 2006). The radiolarites are intruded by doleritic dykes and stocks and also occur as recrystallized metric xenoliths within massive basaltic flows. The contacts between the Jurassic-Lower Cretaceous radiolarites and the basalts are tectonic or intrusive and the possible floor of the oldest radiolarites has never been found.

Sedimentological and geochemical studies on radiolarites lead to contradictory interpretations: sedimentation near an arc (Hein et al., 1983) or in an open ocean (Gursky, 1989).

Other sedimentary facies occur in the Nicoya Complex. Massive mottled cherts were rarely observed. In Bahia Culebra, these cherts of unknown age are directly covered by a basaltic flow and intruded by an hypovolcanic stock.

Bituminous shales are apparently restricted to the southern Nicoya peninsula, in the Carmona area. At Loma Chumico, they contain an ammonite fauna: fragments of unrolled ammonites and Neokentroceras, generally allocated to Albian (Azéma et al., 1979).

BASALTS

Pillowed and massive basaltic flows constitute most of the outcrops of the Peninsula, from sea level to the top of the hills. The flows are generally thick and thickness of 100 m was observed. Contacts between flows lack sedimentary intercalation. Interpillow sediments were only observed in the south-eastern coast of the peninsula (Montezuma and Curú). Flows generally display low dip angles but some occurences are subvertical. Interpillow sedimentary matrix is only observed in the southern part of the Peninsula. The total thickness of the basaltic pile is unknown, but probably reaches up to 1 km. Textures are micro-ophitic for massive basaltic flows and vitreous with acicular crystals in pillowed ones. Parageneses consist of clinopyroxene, plagioclase, ti-magnetite and of scarce occurences of pseudomorphosed olivine. Low temperature recrystallizations often occur (pumpellyite). Some basalts, especially in the northern Nicoya Peninsula are fractionated lavas (ferrobasalts). Numerous geochemical data are available and correspond to tholeiitic compositions with EMORB patterns (Meschede & Frisch, 1994; Sinton et al., 1997; Hauff et al., 1997, 2000).

Some $^{40}K/^{40}Ar$ data for basalts yield ages between Late Cretaceous-Lower Tertiary and suggest a thermal event around 60 Ma (Appel et al., 1994). On the other hand, $^{40}Ar/^{39}Ar$ dating provided plateau ages of 92.5 ± 5.4 and 88 ± 0.7 Ma for basalts from the northen Nicoya Peninsula (Sinton et al., 1997) and of 94.7 ± 1.8 Ma for pillows from the southern Nicoya Peninsula (Hauff et al., 2000).

These ages are in accordance with the occurence of the Cenomanian-Turonian foraminifera Rugoglobigerina prehelvetica (det. J. Sigal) within calcareous matrix of a pillow flow from Playa Montezuma, southern Nicoya peninsula.

Most of the chronological data assign Cenomanian-Turonian ages for the Nicoya basalts. Otherwise, in northern Nicoya Peninsula older $^{40}Ar/^{39}Ar$ ages of 110 ± 0.9 and 137 ± 1.8 Ma were recently provided (Hoernle et al., 2004).

In the Tempisque basin, located northward of the Nicoya peninsula, some hills are made of basalts and dolerites similar to the Nicoya ones. However, at Tortugal the basalts and ultramafic lavas are cut by alkaline dykes (Alvarado et al., 1997; Alvarado & Denyer, 1998; Hauff et al., 2000). These rocks are not known in the Nicoya peninsula. The ultramafic lavas are made of large idiomorphic olivine phenocrysts, clinopyroxenes in a devitrified glassy matrix. These rocks were first interpreted as komatiites (Alvarado et al., 1997) and then as picrites resulting of accumulation processes (Hauff et al., 2000) because the textures are porphyritic rather than spinifex. However, the very high Mg content (MgO: 32%) of the altered glassy matrix argues for the ultramafic nature of these lavas. A picrite from Tortugal gave a $^{40}Ar/^{39}Ar$ age of 89 Ma (Alvarado et al., 1997), similar to those obtained for the Nicoya basalts. However, radiometric ages for the mafic lavas and alkalines dykes are not available, although mostly are pre-Campanian because underly the Barbudal Formation.

INTRUSIVE ROCKS

Dykes and stocks are rather common in the northern Nicoya Peninsula (Wildberg 1984; Tournon 1984). Dykes and sills cut radiolarites and cherts bearing Lower Cretaceous, Cenomanian and Santonian radiolaria (Galli, 1979; Schmidt-Effing, 1979; Baumgartner, 1984; Heine et al., 1983). They are high iron tholeiitic dolerites with strongly zoned pyroxenes (pigeonite, augite, ferroaugite).

In the Nicoya Peninsula and the Tempisque Basin there are unusual plagioclasic cumulates. They consist in large (5 to 7 cm) ovoid megacrysts of plagioclase (An 83-87) concentrated in the inner parts of the doleritic sills.

Besides dykes and sills are intrusive stocks rather common in northern Nicoya peninsula. The largest stocks crop out on several km2. Their contacts were not observed except for the Bahia Culebra one, which is intrusive within cherts and displays chilled margins. Textures are coarse grained, more often doleritic to subophitic.

Various stocks display differenciated rocks: anorthosites, ferrous dolerites, plagiogranites and fayalite-bearing gabbros. In some stocks (Playa Matapalito), the elongated crystals of plagioclase display planar textures and anorthositic layers parallel to the planes suggest differentiation processes in dynamic conditions.

Ferrous dolerites are made of zoned pyroxenes (augite to ferroaugite) plagioclase (An 59-36) and intersticial ores (Ti-magnetite, ilmenite and sulphide)

Plagiogranites occur as small outcrops in various stocks (Weyl, 1969; Wilberg, 1984; Sinton et al., 1997; Hauff et al., 1997; Beccaluva et al., 1999). They are made of plagioclase (An 2-13) and hedenbergite in a micropegmatitic matrix (quartz and plagioclase An 26-19).

Fayalit-bearing gabbros are made of abundant fayalite (Fo 5), hedenbergite, plagioclase (An 43-25), minor quartz and apatite, Ti-magnetite, ilmenite, sulphide (Tournon & Azéma, 1984). They are always associated to hedenbergite-bearing plagiogranites in “oil and vinegar” like breccias. The mafic rocks form coalescent centimetric to decimetric dark globules within a bright matrix made of the acidic one.These spectacular associations are well exposed in playa Ocotal and punta Cirial, and were also observed in other stocks (bahia Culebra, cabo Velas). Immiscible properties of the relative liquids are supported by the “oil and vinegar” morphology of these breccias. Thurthermore, the fayalite-bearing gabbros and the hedenbergite-bearing plagiogranites have the same liquidus at 1055°c (unpublished experimental probes).

REE patterns are close and suggest that fayalit-bearing gabbros and hedenbergite-bearing plagiogranites are highly differenciated rocks cogenetic with the dolerites of the Nicoya peninsula (Fig. 5).

Fayalite-bearing gabbros are rather rare rocks known in intracontinental tholeiitic intrusions such as the Skaergaard plutonic complex, Greenland, where hedenbergite-bearing plagiogranites also occur (Wager & Brown, 1962; McBirney & Nakamura, 1974). But to our knowledge, it is only in the Nicoya peninsula that these mafic and acidic rocks are closely associated in a same hand sample. The origin of these associations remains

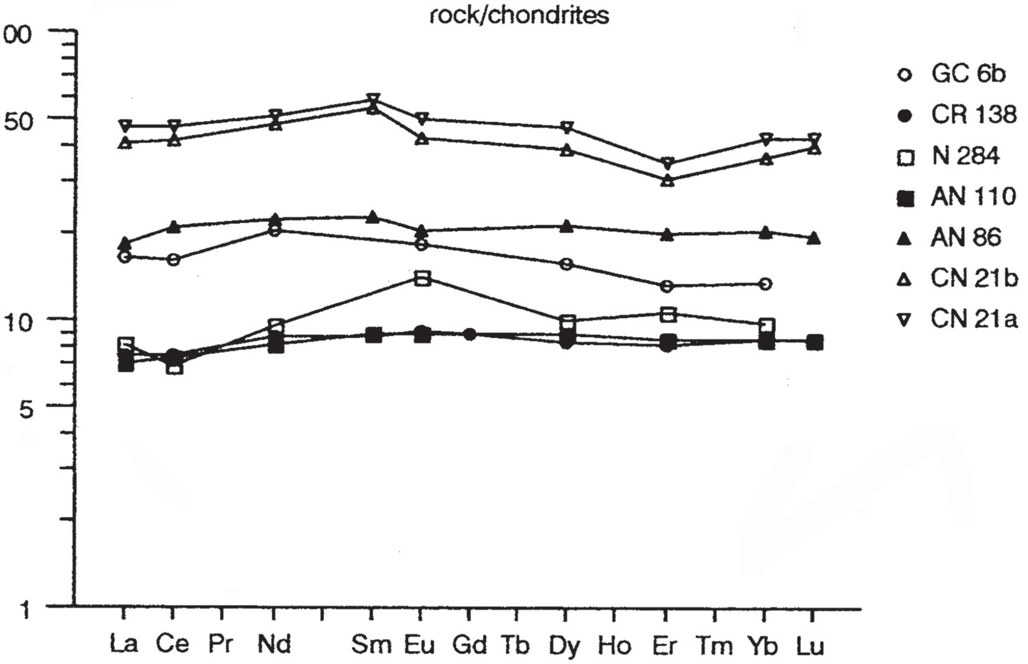


Fig. 5: Chondrite normalized REE-patterns for intrusive rocks and basalts from the Nicoya Peninsula. Ocotal stock: GC6b, dolerite; CN 21b, fayalite-bearing gabbro; CN21a, hedenbergite-bearing plagiogranite. Punta Gorda stock: N 284, gabbro; pillow basalt with Cenomano-Turonian interpillow sediments, Playa Montezuma, CR 138. An 110 and An 86: Nicoya basalts (data in Hauff et al., 1997).

unclear. One can suggests that it was the result of simultaneous injection of highly differenciated mafic and acidic immiscible magmas. An alternative process may be the in situ demixing of an iron enriched magma into two immiscible liquids.

^{40}K/^{40}Ar datings on the Ocotal stock yield 78-80 Ma ages for well-preserved fayalite gabbros, one dolerite and separated fresh plagioclase from a ferrohortonolite-bearing gabbro. The Playa Matapalito stock provides a 76 ± 2 Ma on separated plagioclase from a ferrogabbro (Table 1). Plagiogranites associated with contemporaneous fayalite gabbros in the same hand samples gave erratic ages (61 to 90 Ma). In fact, the Na plagioclases from the plagiogranites are cloudy and show K-feldspar exsolutions. On the other hand, the mafic rocks display fresh plagioclases and are convenient for ^{40}K/^{40}Ar dating.

Sinton et al. (1997) obtained non-concordant step ages on plagiogranites, but accepted reliable crystallization ages at 83.8 ± 1.1 and 83.2 ± 1.3 Ma for a gabbro and a plagiogranite, respectively. Hauff et al. (2000) provided older ^{40}Ar/^{39}Ar age at 87.5 ± 1.8 Ma for a plagiogranite from the Bahía Culebra stock. Ages ca 80 Ma were obtained for mafic rocks may be considered as reliable cooling ages of the stocks. Thus, they emplaced during Upper Cretaceous, but possibly later than the basalts (Sinton et al., 1997). These ages and the intrusive setting within sediments rule out the possibility that they represent the gabbroic member of a “Lower Nicoya Ophiolitic Complex”.

STRUCTURE AND COVER

Contrasting interpretations were proposed about the structure: juxtaposed tectonic blocks (de Boer, 1978), mélange (Galli, 1979). On the other hand, Gursky (1986) suggests that the radiolarites constitute an isoclinal series folded during Upper Cretaceous by a SW-NE compressional event. The presence of nappes within the Nicoya Complex was also proposed. Therefore, Kuijpers (1978) suggests a younger unit called the “Esperanza Unit” thrust onto an older unit called “the Matapalo Unit”. Bourgois et al. (1984) also argue for the presence of nappe within the Complex. The existence of these thrusts seems to us more a possibility, than a demonstrated fact because unquestionable vertical anomalous successions were not documented and field identification of the Esperanza and Matapalo units is problematic.

The sedimentary cover of the Nicoya Complex begins with Campano-Maestrichtian series including breccias, reef and pelagic limestones, and thick turbidites (Baumgartner et al., 1984). Some occurrences of turbidites contain both globotruncana and possible andesitic clasts such as brown amphiboles and large zoned idiomorphic plagioclases (Tournon, 1984; Lundberg, 1982). This cover rests unconformably onto the Nicoya Complex. However, in southern Nicoya Peninsula outcrop apparently anomalous successions. At the bottom of the Nosara valley outcrop globotruncana-bearing limestones apparently surmounted with pillow basalts. Similarly, on the top of the Cerro Juan de León (Cuajiniquil de Carmona) are basalts and radiolarites, whereas the base of the hill is made of strongly folded limestones with globotruncana. This setting evokes a tectonic window for the former and a klippe for the latter. Did a tangential tectonic event occurred after Late Cretaceous in the southern Nicoya peninsula ?

The predominence of basaltic outcrops with similar chemical patterns is the main feature of the “Nicoya Complex.” Although northern and southern Nicoya Peninsula display notable differences:

- northern Nicoya Peninsula: Abundance and relative thickness of radiolaritic sequences, Dogger-Cenomanian in ages; frequency of thick massive basaltic flows and plutonic stocks
- southern Nicoya Peninsula: Scarcity of radiolarites only present as thin intercalations; presence of detrital sediments, frequently bitumineous, and calcareous interpillow sediments; basaltic more often pillowed; absence or scarcity of plutonic stocks.

Thus we consider that the interpretation of the Nicoya Complex as a single structural unit is questionable.

CENTRAL COSTA RICA

In Central Costa Rica (Fig. 6), a very thick basaltic pile extends from the Pacific coast to the summits of the northwestern Talamanca Cordillera, 2000 m above sea level (Dóndoli et al., 1968; Denyer & Arias, 1991; Tournon & Alvarado, 1997; Arias, 2000). Otherwise occurrences of submarine basaltic flows and breccia were also noticed on the little known Caribbean side of the Cordillera de Talamanca (Tournon & Alvarado, 1997).

Volcanic succesions and geochemical patterns allow us to distinguish four units: The Herradura-Jacó Unit, the Turrubares Unit (Tulín Fm.), the Quepos Mélange (Quepos Block), and the Pacuare-Chirripo Unit.

The Herradura-Jacó Unit

The coastal outcrops of Herradura and Jacó are made of massive and pillow flows, which display low angle dips. Red radiolaritic intercalations are scarce. Geochemical data are rather abundant and show E MORB features (Meschede & Frisch, 1994; Sinton et al., 1997; Hauff et al., 1997).

Campanian radiolaria were noticed in scarce radiolaritic intercalations (Hein et al., 1983). Otherwise, a well preserved basalt (fresh minerals and glass) taken within a massive flow at Bahía Herradura has yielded a whole-rock $^{40}K/^{40}Ar$ age of 91 ± 5.2 Ma. The similar geochemical features of the Herradura-Jacó with the Nicoya basalts suggest that they are possible lateral equivalents.

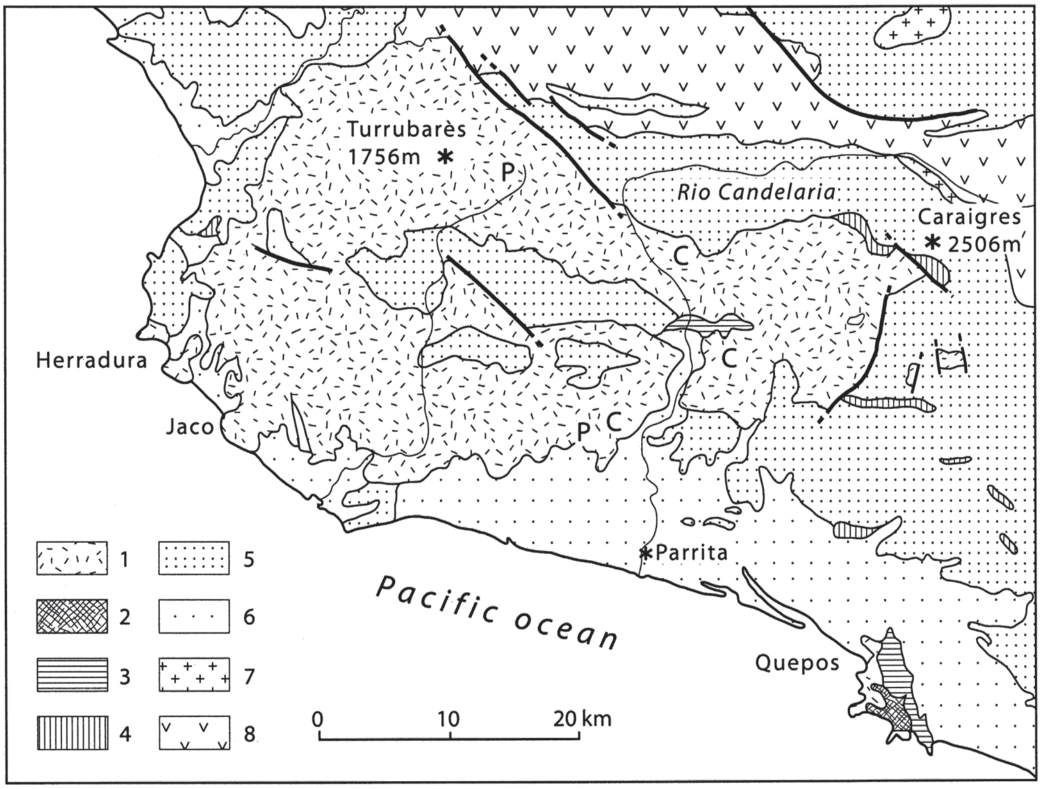


Fig. 6: Central Costa Rica: Herradura-Jaco and Turrubares units. 1: basaltic flows and pyroclastic rocks with minor sedimentary intercalations (C: Late Cretaceous; P: PaleoceneLower Eocene. 2: Paleocene. 3: Eocene. 4 Upper Eocene shelf limestones. 5: Oligocene and Neogene sediments. 6: Alluvium. 7: Neogene intrusives. 8: Neogene volcanics.

The Turrubares Unit (Tulín Fm)

Inland, a very thick pile of submarine basaltic successions, evaluated at least to 2000 m, displays quite different stratigraphical and geochemical features than the Herradura-Jacó Unit. We defined these series as the Turrubares Unit after the Cerro Turrubares, 1700 m above sea level. They mainly correspond to the Tulín Formation defined by Arias (2000). The pile is made of pillow and massive flows which display low to high angle dips. Thin sedimentary intercalations between flows and sedimentary interpillow matrix are rather common. They are white and pink pelagic limestones, sometimes red argillites. Vesicular basalts are abundant. Breccia with calcareous matrix and hyaloclastites were also observed. Lavas are aphyric basalts, picritic basalts and hyalophyric basalts with plagioclase and olivine phenocrysts. Except for clinopyoxene, primary phases i.e. olivine and plagioclase are more or less replaced by secondary minerals and the groundmass is often recristalized with phyllite minerals such as celadonite. This suggests strong alteration processes including contaminations by sea water. Thus, various analyses (Arias, 2000) show erratic mobile element contents, especially for K and Na. However, the contents of less mobile elements are coherent and display LREE enrichment characteristic of enriched tholeiites and transitional basalts (Table 3 and Fig. 7).

The chronology of the Turrubares Unit is supported by well preserved microfaunas within interflows and interpillow sediments. They are assigned to Campanian-Maastrichtian with the presence of Globotruncana calcarata, G. arca, G. stuartiformis (det. Bellier) or Paleogene (globigerinidae). More precisely, Arias (2000) noticed Upper Paleocene and Lower-Middle Eocene microfaunas.

The structural relations between the Herradura-Jaco and the Turrubares units remain unknown. This volcanic pile is covered by Upper Eocene shelf limestones (Denyer & Arias, 1991).

Quepos

The promontary of Quepos is made of Paleocene pelagic limestones and basalts covered with Middle-Upper Eocene olistostrome and detrital sequences (Baumgartner et al., 1984). Volcanics are aphyric pillow basalts, picritic basalts and breccias made of volcanic and sedimentary clasts. The succession is unconformable and these volcanics would appear to be reworked blocks within a mélange formation.

A Paleocene age is supported by the presence of microfauna in interpillow pelagic limestones (Subbotina pseudobulloides).

Basalts display an enrichment of incompatible elements, in particular of LREE (Sinton et al., 1997; Hauff et al., 1997). Their geochemical features, the presence of interpillow Paleocene pelagic limestones, and that of picrites are features quite similar to those of the Turrubares Unit.

The Talamanca Basaltic Unit

In Brazo Boyei (a right tributary of Río Chirripó) crop out breccias with calcite matrix and thin pillow flows. The basalts are strongly vesiculated with vesicles filled with calcite. The textures are porphyritic with abundant iddingsitized olivine phenocrysts in a groundmass made of clinopyroxene and altered plagioclase. Clinopyroxene is Ti-augite with low SiO_2 and high Al contents (Al_2O_3: 9 %), characteristic of alkaline basalts. A pillow flow is conformably covered by marly pelagic limestones bearing Lower-Middle Eocene microfauna (Globogerinatheka, Globigerapsis, Morovozella spinulosa, det. G. Glaçon).

Another basaltic complex made of breccias, massive and pillowed flows is exposed at the bottom of the Rio Pacuare and tributaries (Tournon & Alvarado, 1997).

In Quebrada Terciopelo, a volcanic succession made of breccias and thin pillow flows of vesicular basalts is intruded by dykes of teschenites similar

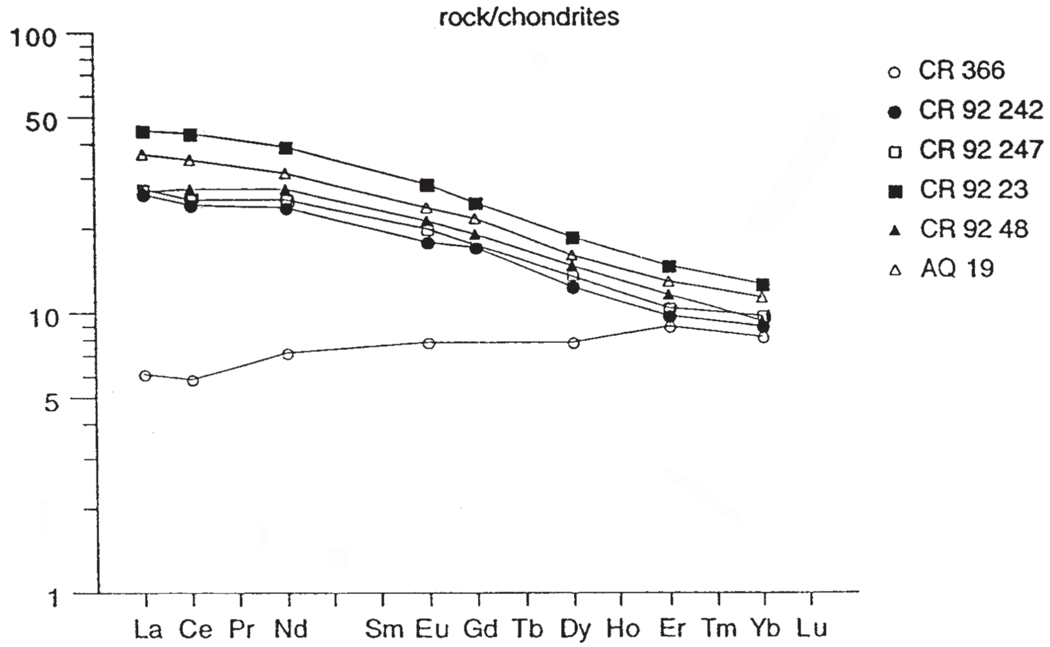


Fig. 7: Chondrite normalized REE-patterns for basalts from Central Costa Rica.
Herradura-Jacó coastal Unit: CR 366, massive basalt from Herradura, Turrubares Terrane; CR 92 242: pillow basalt with Upper Campano-Maastrichtian interpillow limestone Quebrada Roble; CR 92 247: pillow basalt, Quebrada Roble; CR 92 23: basalt associated with paleogene limestones, Quebrada La Palma; CR 48: massive basaltic flow, Río Tulín; AQ 19: basalt from Quepos (in Hauff et al., 1997).

to the Neogene intrusives, which are abundant in the area (Azambre & Tournon, 1976). Interpillow pink pelagic limestones bear small pelagic foraminiferas, possibly Paleogene in age. The pillow flows are conformably covered by shelf Miocene limestones.

In the Quebrada Grande, similar volcanic breccias of strongly vesiculated basalts are covered by shelf limestones bearing Upper Eocene macroforaminiferas. These limestones contain conglomeratic layers with andesitic pebbles.

The basalts from Quebrada Terciopelo and Grande are strongly altered and primary minerals, even pyroxene, are totally altered. Strong alteration and abundance of vesicles rule out any significance of analyses for the Talamanca basalts. However, these outcrops show the presence, along the Caribbean margin, of Paleogene alkaline volcanism that erupted below shallow water. Are these basaltic complexes traces of accreted seamounts or in situ alkaline series? On the other hand, the presence of andesitic pebbles in the calcareous “cover” suggests that an arc related volcanism occurred in central Costa Rica during Upper Eocene.

SOUTHERN COSTA RICA

Tholeiitic basaltic flows and minor gabbroic stocks are exposed extensively in the southern peninsula area of Costa Rica (Fig. 8). They were regarded as an ophiolite complex, equivalent of the “Nicoya Complex” (Berrangé & Thorpe, 1988). However, according to chronology, ages of sedimentary covers and paleomagnetic data,

Table 3

Representative geochemical analyses

Sam-ple wt%	Nicoya rocks			Central and SouthernCosta-Ricarocks							Panamá rocks		
	CR284	N226b	N226a	CR366	92-242	92-247	92-23	92-48	88-116	92-156	P113	P2	P41
SiO_2	46.20	45.50	56.30	49.00	48.50	46.80	49.00	48.50	47.30	49.25	47.80	47.30	47.25
TiO_2	2.70	2.17	2.56	0.82	1.77	2.04	2.95	2.57	1.34	0.87	1.20	1.20	1.36
Al_2O_3	12.90	9.55	10.05	14.95	14.35	14.36	13.66	13.65	14.10	14.70	14.60	15.10	15.00
Fe_2O_3	19.28	28.85	17.64	10.60	10.35	11.56	12.30	13.60	12.32	10.60	11.87	11.65	12.80
MnO	0.27	0.44	0.32	0.18	0.17	0.18	0.19	0.19	0.19	0.17	0.22	0.25	0.22
MgO	5.56	1.57	1.61	8.90	7.50	6.51	6.40	6.20	7.52	8.70	7.32	6.99	6.23
CaO	9.62	6.70	6.90	12.45	10.98	12.50	11.60	7.50	11.60	11.10	13.10	12.75	10.20
Na_2O	2.53	2.06	3.96	1.99	2.79	2.91	2.42	3.85	2.50	2.43	2.05	2.09	3.69
K_20	0.09	0.15	0.58	0.04	0.87	0.21	0.40	0.88	0.08	0.17	0.04	0.03	0.10
P_2O_5	0.12	0.86	0.44	0.09	0.16	0.20	0.29	0.20	0.11	0.08	0.12	0.13	0.14
LOI	0.74	2.18	0.29	1.05	2.72	2.89	0.55	2.96	2.15	1.87	2.54	2.45	3.88
total	100.01	100.03	100.65	100.07	100.16	100.16	99.76	100.09	99.81	99.94	100.86	100.34	100.87
ppm													
Cr	2.5	2.1	2.5	430	300	450	248	156			270	258	109
Ni	9	1	1	135	120	190	123	80			109	119	55
Co	67	39	25	45	40	39	43	42			51	47	47
Se	53	32	43	45	32	29.7	35	32.5			45	45	47
V	690		12		273	278	380	362			335	340	407
Rb					12.5	3	6.8	6.1	1.15	2.8			
Ba	16	35	153	10	205	35	67	56	43	35	8	8	30
Sr	110	105	101	77	365	310	280	217	165	154	107	107	106
Nb	3.9	13.6	14.3	3	10	10.4	17.5	13.5	4.4	3.2	4.1	3.2	3
Zr	40	96	124	39	112	120	175	92	73	46	61	61	36
Y	22	66	89	18	24	26.5	33.5	26	25	17.5	24	24.4	33
La	2.7	9.9	15.4	2	8.7	9.1	14.7	9	5	2.4	3.8	3.2	3
Ce	6	28	39	5	21	22	37.5	24	10.5	5	9	8.5	7
Nd	6	26	36	4.5	15	16	24.5	17.5	8.5	5	4.1	7	7
Eu	1.10	3.1	3.2	0.6	1.39	1.54	2.21	1.66	1.06	0.72	1	0.95	1.10
Dy	3.40	11	15.5	2.7	4.3	4.65	6.45	5.05	4.25	2.85	4	3.9	5
Er	2.40	6.5	8.5	2	2.2	2.35	3.35	2.6	2.5	1.8	2.4	2.7	4.40
Yb	2.15	6.05	7.8	1.8	1.96	2.13	2.8	2.05	2.55	1.87	2.25	2.25	3.35
La/Yb	1.25	1.36	1.97	1.11	4.44	4.27	5.25	4.39	1.21	1.28	1.69	1.42	0.89

Total iron as Fe_2O_3. ICP AES analyses by J. Cotten Université de Bretagne Occidentale, Brest.
Nicoya Peninsula, CR284: ferrogabbro, Punta Gorda stock, X 342.95, Y 280.10. N 226b and N 226a: fayalite gabbro and hedenbergite plagiogranite associated in the same hand-sample, Ocotal stock, 347.40, 281.25. Central Costa Rica, Herradura-Jaco coastal unit, CR 366: massive basalt, Bahia Herradura, 390.35, 400.35. Turrubares Unit, 92-242: pillow basalt, with calcareous interpillow matrix bearing Globotruncana, Quedrada Roble, 503.20, 189.20. 92-247: pillow basalt, Quebrada Roble, 503.20, 189.20. 92-23:

Di Marco (1994) proposed to assign them to four units: the Golfito Terrane, the Rincón Block, the Burica Terrane and the Osa Mélange.

The Golfito Terrane

It outcrops in the Golfito area and eastern Golfo Dulce. The series strarts with pillow flows with calcareous matrix and intercalations of Upper Campanian pelagic limestones (Globotruncana calcarata, G. stuartiformis, det. J.P. Bellier) and continues with pelagic limestones, detrital rocks cut by doleritic dykes and massive basaltic flows. This upper sequence is assigned to Middle Maastrichtian (Globotruncana ganserri zone; Obando, 1986; Di Marco, 1994). This volcanic and sedimentary series is covered with Paleocene turbidites and scarce limestones. The clasts from the turbidites include glass and quartz and suggest an acidic volcanic source (Di Marco, 1994).

The Rincón Block

This block is exposed in western Golfo Dulce, northern Osa Peninsula and Isla Violín. It is made of a very thick sequence of massive and pillowed tholeiitic flows with scarce sedimentary intercalations, where microfauna are Campanian-Maastrichtian, Upper Paleocene-Lower Eocene, Middle-Upper Eocene (Di Marco, 1994). Similar chronology is given by ^{40}K/^{40}Ar data on basalts (Berrangé et al., 1989).

The Burica Terrane

In the Burica Peninsula is an exposed deformed basement made of massive and pillow basaltic flows and minor gabbroic stocks. Scarce thin layered radiolarites intercalations occur between basaltic flows. Campanian radiolaria were noticed (Di Marco, 1994). This basement is covered uncomformably with Paleocene siliceous limestones, calciturbidites and reworked shelf limestones. These facies are not similar to those of the Paleocene from the Golfito Terrane (Obando, 1986; Di Marco, 1994).

Available analyses for Rincon, Golfito and Burica basalts display tholeiitic features with flat or slightly depleted REE patterns (Berrangé & Thorpe, 1988; Hauff et al., 2000; this paper table 3 and Fig. 9).

The Osa Mélange

Most of the Osa peninsula is made of thick Pliocene turbidites, which rests on a basement well exposed along the coasts (Lew, 1983). The basement displays chaotic features and is interpreted as a mélange formation defined as the Osa-Cano Mélange (Di Marco, 1994). The blocks of all sizes are sedimentary or igneous. The sedimentary blocks display a wide diversity of lithology and ages: Lower Cretaceous radiolarites (presence of Thanarla conica, det. de Wever), Campanian-Maastrichtian pelagic limestones (Di Marco, 1994), Paleocene pelagic limestones (Azéma et al., 1979), Middle Eocene radiolarites (Dictyoprora mongolfieri, D. amphora, Giraffospyris laterispina, Sethocyrtis babylonis, Siphocampe elisabethae) and Eocene shelf limestones (Azéma et al., 1983).

On the western coast (Aguras), blocks, mainly shelf limestones, are packed within a fine grained sedimentary matrix.

The igneous blocks are basalts, dolerites and gabbros. Geochemical patterns are heterogeneous with MORB, E-MORB and OIB signatures (Berrangé & Thorpe, 1988; Hauff et al., 2000). Lower Tertiary ages are noticed: the calcareous matrix of alkaline pillow basalts contains Lower Tertiary microfauna (Tournon, 1984), whereas a doleritic dyke within radiolarites displays enriched MORB patterns and

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basalt, block within calcareous breccia, Quebrada La Palma, north of Parrita, 426.25, 393.90. 92-48: massive basalt flow, Quebrada Tulin, Cerro Turrubares, 491.12, 194.10. Rincon Block, 88-116: massive basalt, 543.70, 302.60. Burica Terrane, 92-156: massive basalt, Rio Claro. Western Panama, P113: massive basalt, Playa Venado, Azuero Peninsula. Eastern Panama, Darien, P2: massive basalt, La Palma, 818.80, 930.90. P41: massive basalt, Bajo Grande, 812.10, 926.50.

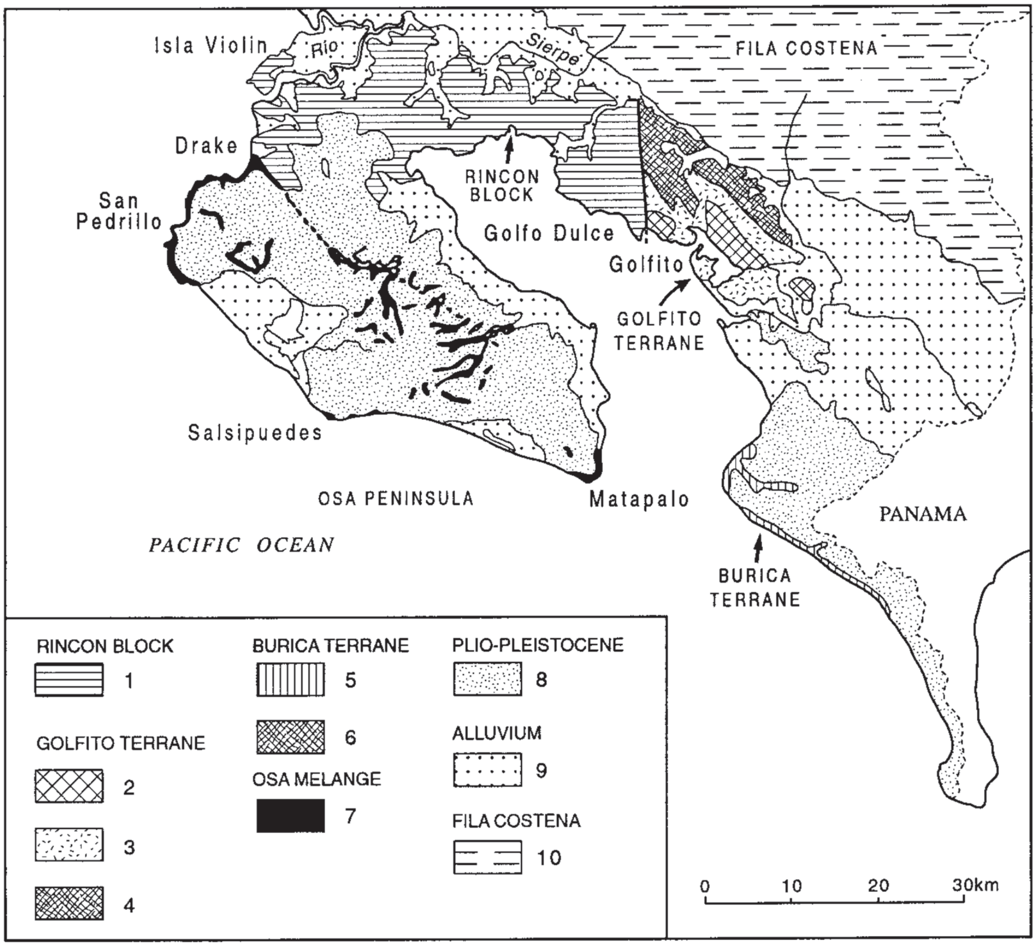

Fig. 8: Southern Costa Rica, localization of the basaltic complexes within the structural units.
Rincón Block, 1: Basalts, Golfito Terrane, 2: Basalts and minor mafic intrusives, 3: Late Cretaceous sediments, 4: Paleocene arc-derived detrital sediments. Burica Terrane, 5: Basalts, 6: Paleocene sediments, 7: Osa Mélange. 8: Plio-Pleistocene marine sediments, 9: Alluvium, 10: Fila Costena, Upper Eocene, Oligocene and Neogene formations. Modified after Di Marco, 1994.

provided a whole-rock ^{40}K/^{40}Ar age at 45.5 ± 2.5 Ma (sample 950, Table 1).

Locally, the Osa Mélange is strongly tectonized and displays deformation of blocks (Río Tigre) or even cataclastic textures (Salsipuedes). The interpretation of the Osa Mélange is subject to debates concerning mélange processes and origin of blocks. Meschede et al. (1999) proposed a tectonic origin: a lateral equivalent of the Nicoya complex suffered subduction and tectonic erosion. Vanucchi et al. (2006), after a detailed fabric analysis of the shear zones, argue also for tectonic processes: seamounts originated in the Pacific Plate undergone tectonic erosion and underthrusting to depths of several kilometers, then exhumed during Late Tertiary. On the contrary, Denyer et al. (2006) interpret the Osa Mélange as the result of sedimentary processes: blocks from an active margin and seamounts emplaced gravitationally and deposited in a trench.

WESTERN PANAMA: AZUERO AND SONA PENINSULAE

Regional metamorphic rocks

Metamorphic rocks are exposed in the Azuero and Soná peninsulas and are not known elsewhere in the Central America isthmus (Del Giudice & Recchi, 1969; Tournon et al., 1989). In the western part of the Azuero Peninsula, the Río Torio section displays schistosed amphibolites with vertical E-W schistosity planes and massive layers.

In the Soná Peninsula, the upper Río San Rafael section displays various outcrops of metabasites with E-W schistosity planes. They are basaltic and picritic in composition and are cut by unmetamorphosed doleritic dykes as observed in Azuero. The paragenesis is made of strongly zoned amphiboles, epidote, chlorite and albite. The complex zonation of amphiboles suggest that the Sona amphibolites had undergone an counterclockwise regional metamorphism progressive from the greenschist facies to the hornblende plagioclase amphibolite facies at low to medium pressure and temperature (350 to 650°c). A retromorphic episode occured in the greenschist facies (Tournon et al., 1989).

The Azuero and Sona metabasites have very low K2O contents and material suitable for isotopic datation is not available. Their contacts with the neighbouring basaltic series covered with Late Cretaceous limestones were not observed, but are probably faulted. An amphibole bearing dolerite dyke cutting the Azuero metabasites provides a $^{40}K/^{40}Ar$ whole-rock age of 40.4 ± 2.7 Ma (sample P 147, Table 1) that suggests only a minimun age for the metamorphic event.

Basaltic units

Basalts occur along the coast of Soná, in the south-western Azuero Peninsula and in the Coiba Island (Wildberg, 1984; Kolarsky et al., 1995). In Playa Venado, southern Azuero Peninsula, massive and pillow basalts with MORB compositions (Tab. 3, Fig. 9) display subhorizontal dips and lack sedimentary intercalation. The down stream section of the Rio Torio show pillow basalts and dolerites directly covered with Campano-Maastrichtian pelagic limestones (presence of Globotruncana). $^{40}Ar/^{39}Ar$ data provide for Azuero basalts a wide range of ages from 71 to 21 Ma (Hoernle et al., 2002).

Arc related magmatism

Calc-alkaline magmatism is represented in the Azuero Peninsula by quartz diorite stocks, andesitic breccias and dykes. The quartz diorite of Canafistula intrudes Campano-Maastrichthian limestones which are metamorphosed in hornfels and provided a whole-rock $^{40}K/^{40}Ar$ age of 58 Ma (P 182, Table 1). This age is quite similar with that of 62 Ma on hornblende and that of 51 Ma on feldspar provided both by $^{40}K/^{40}Ar$ dating on another Azuero quartz diorite stock (Kessler et al., 1977).

EASTERN PANAMA

Darién

In the area of the gulf of San Miguel, Darién province, are exposed siliceous sediments and volcanic rocks. Near La Palma, Bandy & Casey (1973) noticed cherts with radiolarian fauna (Dictyomitra torquata, Phaseliforma, Pseudoaulophacus). This association may occur from Turonian to Campanian (de Wever, pers. com.). The volcanic rocks are basalts and andesites, which were interpreted as a bimodal series (Goosens et al., 1977).

Massive and pillowed basalts occur near La Palma (Punta Sabana, Punta Panama) and along the south-western coast of the Gulf of San Miguel (Bajo Grande) where outcrops a succesion of massive and pillow flows with vertical dips and without sedimentary intercalation. These basalts display MORB compositions (Table 3, Fig. 9).

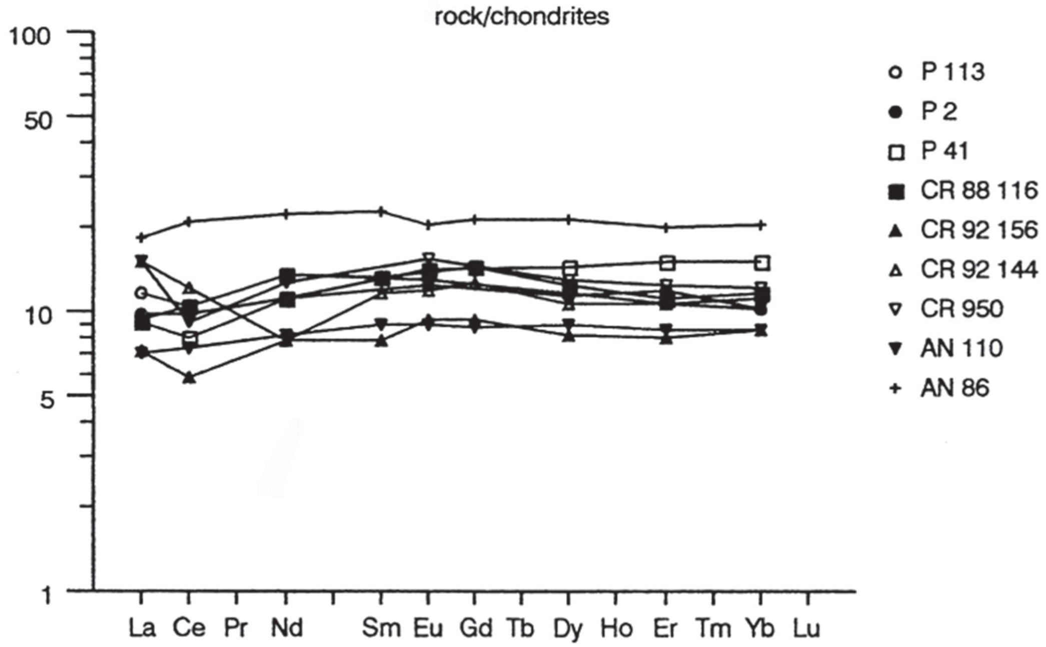

Fig. 9: Chondrite normalized REE-patterns for basalts from southern Costa Rica and Panama. Western Panama: P 113 pillow basalt, Playa Venado, Azuero Peninsula; Eastern Panama: P 2 pillow basalt, La Palma, Darién; P 41: pillow basalt, Baja Grande, Darién; Southern Costa Rica: Rincón Block CR 88 116, massive basalt; Burica Peninsula CR 92 156, pillow basalt, Banco; Golfito Terrane CR 92 144, pillow basalt with Upper Campanian interpillow limestones; Osa Mélange, CR 950 doleritic dyke cutting a radiolaritic block. AN 110 and AN 86: Nicoya basalts, data in Hauff, 1997.

Andesitic lavas also occur near La Palma and westwards in the Patino area. At Punta Hueca, a pillowed flow is made of hypersthene bearing andesite and displays calcareous matrix. The interpillow limestones bear algae and Lower Miocene macroforaminifera (Myogypsina, Amphistegina) which indicate shallow water deposition. $^{40}K/^{40}Ar$ data on the inner part of an andesitic pillow (P 49, Table 1) provides a mean age of 22.5 ± 0.5 Ma, in accordance with that of the interpillow fauna.

Thus, two volcanic episodes occured in the Gulf of San Miguel area: (i), tholeiitic basalts, possibly Upper Cretaceous in age, and (ii) Lower Miocene calc-alkaline lavas and tuffs.

San Blas

The coast of San Blas extends along the Caribbean margin, from the Canal Zone to the Colombian border. Case (1974) postulated that it is made of an oceanic basement, because the area displays positive gravity anomalies as does the Pacific margin where basalts are exposed.

In the Portobello area, 30 km east of the Canal Zone were observed basaltic andesites, scarce tholeiitic gabbros and basalts also occur.

At the coast in front of Nargana Island are exposed detrital sediments and calc-alkaline stocks. Among them the Río Azucar stock is made of quartz diorites and gabbros. A well preserved gabbro provides a $^{40}K/^{40}Ar$ whole-rock age at 63.1 ± 3.2 Ma (P 218, Table 1).

Eastwards, the Río Morti area is made of detrital sequences with clasts belonging to a calc-alkaline volcanic series including andesites, dacites and rhyolites. Their $^{40}K/^{40}Ar$ ages range from 55 to 61 Ma (Maury et al., 1995).

Thus the existence of an oceanic basement occuring along 300 km on the Caribbean margin of eastern Panama is questionable. On the other hand as in western Panama, it was the location of a Paleocene arc-related magmatism.

DISCUSSION

In most geodynamic reconstructions, the Central America isthmus is interpreted as composed of oceanic crust, where intra-oceanic subduction formed an arc since Late Cretaceous or Lower Cenozoic. Since the end of the seventies, the ultramafic, mafic and pelagic units which are extensively exposed on the Pacific margin were generally interpreted as an ophiolite complex: the Nicoya Ophiolite Complex. We show that these units display disparate features and are not cogenetic: ages of mafic rocks from Dogger to Eocene, contrasting geochemical patterns and different tectonic settings. Only the Santa Elena and Rio San Juan ultramafic massifs and some blocks from the Santa Elena Mélange correspond to an ophiolitic complex as defined since the Penrose Conference (1972).

Dynamic evolution of the "oceanic" series from Central America isthmus would be constrained by geophysical data, especially paleomagnetic and seismic ones.

Paleomagnetic studies were carried out on various Cretaceous and Lower Tertiary sedimentary and igneous rocks (Gose, 1980; Frisch & Meschede, 1992; Di Marco et al., 1995). Serpentinized peridotites and basalts have high magnetite contents but their ages and paleo-horizontal reconstitutions remain generally uncertain. In contrast, sedimentary rocks, especialy pelagic limestones are poorly magnetized but can be precisely dated with microfauna and allow tilt corrections.

Gose (1980) after data on Upper Cretaceous sediments concluded a near present latitude for southern Nicaragua, but an equatorial position for the "cover" of the northern Santa Elena peninsula. Frisch & Meschede (1992) studied magnetism of serpentinized peridotites, basalts and radiolarites from numerous sites of the Santa Elena and Nicoya Peninsula and argue for an equatorial origin.

The limestones studied by Di Marco et al. (1995) were sampled on few sites, but ages and structural setting are well documented. Disparate paleopositions are proposed and lead the authors to distinguish various "terrains":

- The "Chorotega Terrain" includes two sites in the Nicoya Peninsula and one site on the Caribbean coast of western Panama. Late Cretaceous position would be close to its present latitude.
- The "Nicoya Terrain" includes the "cover" of the northern Santa Elena Peninsula and one site in the Nicoya Peninsula. Late Cretaceous position would be close to its present latitude.
- The "Golfito Terrain" includes sites in the Golfito area and in the Azuero Peninsula, an equatorial latitude during Upper Cretaceous is suggested.
- The "Burica Terrain," the origin of the Paleocene cover is assigned slightly south of the present position.

Seismic data make conspicuous areas with thick crust. The Costa Rican Caribbean and Pacific margins display positive anomalies of gravity, whereas an axial zone with negative anomalies rests on a thick crust which is up to 40 km in northern Costa Rica (Matumoto et al., 1977; Ponce & Case, 1986; Montero et al., 1990).

Recently, detailed seismological analysis confims that the axis of Costa Rica rests on a thick crust which displays a complex deep structure (Sallares et al., 2001). The authors interpret this crustal structure as the result of arc related magmatism and underplating on a plateau basalt. This model involves that the building of a thick crust started during Late Cretaceous and occured mainly during Cenozoic. The age of the thickening of the Costa Rican crust remains an unresolved problem. Did this thickening occured before or after the obduction of the large Santa Elena - San Juan ophiolite?

An E-W ophiolitic belt

The peridotites from the Santa Elena peninsula and the San Juan area have similar textures and the same mineral compositional variations. Their locations along the same parallel suggests that these two massifs may belong to a 150 km long E-W trending ophiolitic belt, represented by its mantle section. The abundance of lherzolites and the composition of primary phases, especially diopside suggest that these mantle peridotites underwent low to moderate depletion. They correspond to the Lherzolite Ophiolite Type (LOT) as defined by Nicolas (1989). In the Santa Elena allochtonous unit, the mafic rocks are exclusively present as dykes within peridotites and the crustal section is unknown. On the other hand, the Santa Elena mélange displays possible dismenbered fragments of the ophiolitic crustal section: the Bahía Nancite Block and some components of the Playa Naranjo breccia. Furthermore, gabbros from the Bahía Nancite Block display similar chemical patterns with pegmatitic gabbroic dykes present in the peridotites of the ultramafic nappe (Fig. 4). The scarcity of gabbros may be the result of tectonic erosion or may correspond to a small development of magmatic chambers, as generally observed in LOT ophiolites (Nicolas, 1989).

The Santa Elena–Río San Juan LOT ophiolite formed possibly at a slow spreading ridge, rather in a marginal basin than in an open oceanic setting during Early Cretaceous. Although the age documented on the possible gabbroic section must be confirmed. The ophiolite was intruded by wide doleritic injections, possibly subduction related, and underwent a tectonic and metamorphic event as shown by the shear zones marked out with medium temperature gneissic amphibolites. This tectonic and metamorphic event occured around 100 Ma. The serpentinitic conglomerates within reef limestones suggest that the ophiolite was yet obducted during Upper Campanian–Maastrichtian.

A compressional tectonic event occured later than Cenomanian and strongly deformed a long lived oceanic basin forming an accretionary prism. Final emplacement of the ophiolitic nappe formed the Mélange Formation made of dismembered blocks from the ophiolite, reworked fragments of a possible accretionary prism within a detrital matrix. The chronology of this emplacement remains unclear because the stuctural relations between the nappe and the “cover” are not well established. Furthermore, the blocks made of detrital sediments (Playa Tule) are possibly the youngest elements of the mélange, but their age remains unknown.

On what margin was obducted the Santa Elena-Río San Juan Ophiolitic Belt? Most intraoceanic ophiolites, the New Caledonia ones for instance, emplaced on continental fragments (Paris et al., 1982). Thus the obduction during Upper Cretaceous of the Santa Elena-San Juan ophiolite on a yet thickened crust cannot be ruled out. The ophiolitic W-E trending belt could be the suture resulting of the N-S convergence between the Chortis Block and a possible “continental” fragment or a pre-existing mature arc presently forming the deep crust of northern Costa Rica.

This model involves that the obduction of the ophiolite occured at latitude similar to the present. However, paleomagnetic data available for Upper Cretaceous sediments from the nappe “cover” suggest that they deposited at an equatorial or 5-10° S (Gose, 1983; Di Marco et al., 1994). These paleomagnetic data involve a rather unrealistic scenario: a 1000 km northward migration of the obducted ophiolite with its Upper Cretaceous “cover.”

Fragments of oceanic basins

The radiolaritic deposits, possible witnesses of oceanic basins, are known in three structural units: 1) the Santa Elena Mélange, 2) the Osa Mélange, 3) the Nicoya Complex in the Nicoya Peninsula.

In the Osa Mélange, the radiolaritic blocks, Lower Cretaceous and Middle Eocene in ages, are possible oceanic fragments. They are associated with MORB and EMORB volcanics. Alkaline pillow lavas within calcareous matrix are possible remains of Lower Tertiary seamounts.

The Santa Elena and Nicoya radiolaritic series have rather similar chronologies: Lias-Lower Dogger to Cenomanian for the former, Bajocian to Santonian for the latter. But the sedimentary successions as the associated volcanics are not similar. In Santa Elena, large blocks from Sitio Santa Rosa display thick isoclinal successions which are unknown in Nicoya, i.e. alternance of red layered radiolarites, radiolaritic breccia and grey cherts. Three alkaline series are present in the Santa Elena Melange: 1) the Middle Jurassic lamprophyric sills intruding the Sitio Santa Rosa radiolarites, 2) the alkaline pillow basalts of unknown age, 3) the weak alkaline basalt - trachyte suite of the Respingue Block. The alkaline lamprophyres are Dogger in age and intrude the older Lias-Lower Dogger radiolarites. Such rocks are known in continental rifts but also in oceanic setting near passive continental margins (Cornen, 1982).

In contrast with the complex sedimentary succession observed in the Santa Elena mélange, the sedimentary sequence from northern Nicoya Peninsula show a rather monotonous succession of Mn radiolarites. Fine biostratigraphical data show that, except a possible gap in Bathonian, they deposited continuously from Bajocian to Cenomanian (Denyer & Baumgartner, 2006). This sedimentary succession was intruded and dismembered by basalts and later stocks with MORB patterns. This major magmatic event is not known in Santa Elena. Thus, the Santa Elena and Nicoya radiolaritic deposits are not lateral equivalents.

Fragments of Upper Cretaceous oceanic plateaus

The plutonic and basaltic rocks of the Nicoya Peninsula were also subject to contradictory interpretations. Field and chronological data lead us to propose the following succession: (i) a long lived Callovian to Cenomanian oceanic basin whose basement is unknown; (ii) a thick basaltic pile made of pillow and massive flows; and (iii) late intrusive stocks which intruded the sedimentary section and possibly the basis of the volcanic pile. Isotopic and stratigraphic data suggest that the magmatic rocks erupted between Cenomanian and Santonian. This succession rules out the possibility that the Nicoya Complex would be an ophiolite complex but argues, as suggested also by geochemical patterns, that it corresponds to fragments of an oceanic plateau.

The basalts from the Herradura-Jacó coastal unit are rather similar to the Nicoya Peninsula ones and may be Lower Campanian in age, as suggested by available isotopic and stratigraphical data. Western Panama displays thick tholeiitic flows covered with Campanian-Maastrichtian pelagic limestones as observed in Nicoya. However, a radiolaritic basement is unknown.

Geochemical and stratigraphic features suggest that the basaltic units from the Nicoya Peninsula, Herradura Jacó coast, and some from Panama are possible lateral equivalents of the Caribbean basaltic plateau.

Southern Costa Rica displays disparate basaltic units. The basalts from the Burica terrane are possibly contemporaneous with the Herradura Jacó unit. On the other hand, the Golfito basalts, Upper campanian and Maastrichtian, and the Rincón Block, result of long lived eruptive activity (Late Cretaceous to Eocene), are too young to be lateral equivalents of the Nicoya Peninsula flood basalts. It is also the case of Cenozoic basalts from western Panama (Hoernle et al., 2002).

Seamounts

The alkaline lavas from the Santa Elena Mélange are possible relics of various seamounts. But the setting of the lamprophyric rocks in a rift cannot be ruled out. The presence of alkaline pillow lavas in the Osa Mélange also suggests OIB activity (Berrangé & Thorpe, 1988; Tournon, 1984; Vanucchi et al., 2006).

The major possible seamount known in Central America isthmus appears to be the Turrubares Unit. This thick volcanic pile may correspond to seamount activity according to volcanic successions, geochemical patterns, frequency of vesiculated lavas and picritic basalts. The volcanic activity from Late Cretaceous to Middle Eocene appears rather long for a single seamount and suggests the presence of a succession of seamounts. Exotic origin for these possible seamounts is suggested by comparison with the neibouring Nicoya Peninsula, presently 30 km far off. During Late Cretaceous and Paleocene the Nicoya Peninsula received several kilometers of turbiditic sedimentation. Such detrital deposits with andesitic clasts are unknown in the Turrubares Unit. Therefore, the Turrubares Unit was not close to the Nicoya Peninsula prior to Upper Eocene.

Structural relations between the Turrubares Unit and the Herradura-Jacó Unit, possible lateral equivalence of the Nicoya basaltic pile, remain unknown. One can suggest two settings: 1) tectonic contact, 2) conformable contact, the Herradura-Jacó Unit corresponding to the floor on which erupted seamount activity. In any case the possible accretionary process took place as late as Eocene.

The Talamanca basalts erupted on shallow water sea floor during the Paleogene. Their significance remains uncertain: Eastern extension of the Turrubares Unit or in situ alkaline intraplate volcanism?

Regional metamorphic unit

The metabasites from Western Panama outcrop in the Sona and Azuero peninsulae, far off 70 km. These two occurrences are quite similar, made of mafic to ultramafic materials metamorphosed within the greenschist and amphibolite facies. Both display the same E-W direction of the shistosity planes and are the result of both thermic and tectonic events. The Soná schists suffered an inusual anticlockwise path.

One may ask if they correspond to a metamorphic basement spread through Western Panama or to fragments of accreted exotic terranes.

The significance of these regional metamorphic rocks remains enigmatic for ignorence of age of the metamorphism and the structural relations with the neighbouring formations.

CONCLUSIONS

Central America isthmus displays a disparate assemblage of oceanic units (Fig. 10). The ages of sediments and igneous rocks are from Lower Dogger to Eocene. Furthermore, the plutonic and volcanic rocks display very wide compositional fields. Thus, the origin of these oceanic units cannot be the result of a single process such as the emplacement of an ophiolitic complex or the accretion of oceanic plateau fragments.

We propose that the oceanic units present on the isthmus are the result of two major geodynamic processes:

- The closing of a northern basin.
- The accumulation of terranes originated in the Pacific Plate.

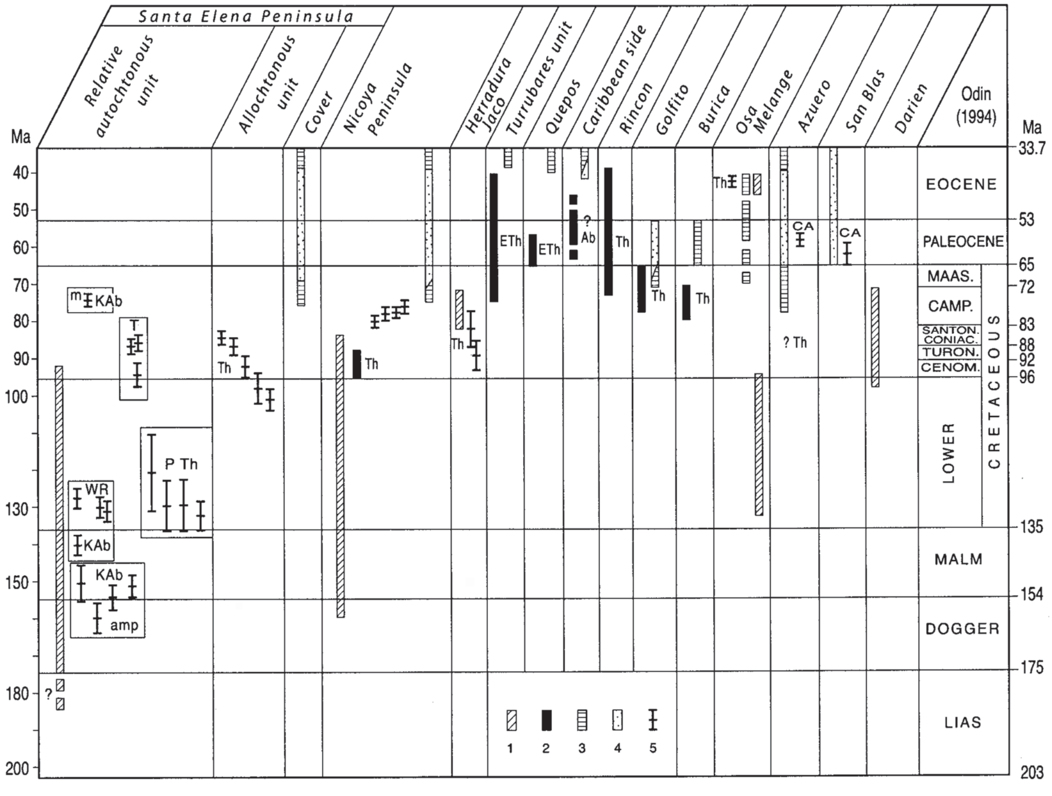

Fig. 10: Chronology of the mafic complexes, the oceanic sediments and their sedimentary covers, Costa Rica and Panama. 1: Siliceous pelagic sediments, radiolarites and cherts. 2: Ages of microfaunas within matrix of pillow basalts or sedimentary intercalations between basaltic flows. Sedimentary cover: 3 calcareous, 4 detritic. 5: ^{40}K/^{40}Ar data, Table 1, this paper; Kab: potassic alkaline basalts, amp: amphibole, wr: whole-rock, m: mesostasis; T: trachyte, Respingue.; ETh: enriched tholeiites and transitional basalts; Th: tholeiitic basalts; CA: calc-alkaline intrusives. Time scale after Odin (1994).

1 – The closing of a northern basin

A northward convergence involving a block, presently northern Costa Rica, caused the closing of a northern basin. The relics of this possible vanished basin are the San Juan peridotites, the Allochtonous Unit and most components of the Mélange of the Santa Elena Peninsula. This basin received a siliceous sedimentation from Lias-Lower Dogger to Cenomanian. Lamprophyric alcaline lavas would correspond to a first rifting and were followed by seamount activity. The age of the ophiolite, that is the age of the mafic member, remains uncertain, perhaps Lower Cretaceous. The ophiolite underwent igneous injection and both static and dynamic metamorphism around 100 Ma. Northward migration of a block, presently northern Costa Rica caused the closing of the “Northern Basin,” obduction of the ophiolite and final thrust of a 150 km long ophiolitic suture. The emplacement of such a large ophiolitic belt suggests that obduction took place onto a yet thickened crust, possibly a continental fragment, present in northern Costa Rica. Obduction took place prior to Campanian but the age of final emplacement of the nappe and mélange formation remains uncertain.

This possible geodynamic process is rather similar to that proposed for the Guatemalian ophiolites, interpreted as the result of the closing of a protocaribbean basin during Late Cretaceous (Beccaluva et al., 1995). Thus, the origin of the Sana Elena and San Juan units must be traced in a protocaribbean basin.

2 – Accumulation of terranes originated in the Pacific Plate

These events would be the result of eastward or south-eastward convergence.

The Nicoya Complex is a good candidate for a plateau basalt fragment because it consists of a very thick pile of basaltic flows erupted during Cenomanian-Turonian onto Jurassic-Lower Cretaceous oceanic sediments. The other volcanic series which display EMORB features (Herradura-Jacó, southern Costa Rica, Panama) erupted between Upper Cretaceous to Lower-Middle Eocene, are also regarded as plateau basalts originated at the Galapagos hotspot (Hauff et al., 2000). But we cannot exclude that some of them originated in other geodynamic settlement, for instance at an oceanic ridge.

On the other hand, possible accretion of seamounts, like the Turrubares Unit added large volumes of basalts to the isthmus.

In our present knowledge, precise geodynamic reconstructions for the Upper Cretaceous to Upper Eocene seem rather speculative. The chronology of these successive accretions and tectonic events is not clearly established and it remains uncertain and contradictory about the paleolatitudes of these oceanic units.

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