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CONTRIBUTION TO PETROLOGICAL AND STRATIGRAPHICAL UNDERSTANDING OF THE CORDILLERA DE GUANACASTE LAVA FLOWS, COSTA RICA

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ABSTRACT: Geochemical data are presented for lavas from four pair Quaternary stratovolcanoes (Cordillera de Guanacaste), small basic outcrops trenchward of the volcanic front (VF), and paleovolcanic units (Pliocene-Pleistocene age) of northern Costa Rica. The more evolved lavas of the calc-alkaline series are from Rincón de la Vieja and Miravalles andesitic volcanoes, and from Cañas Dulces (dacite/rhyolite) and Bijagua (andesite) domes-field. They usually have high Zr, Ba and Rb contents. The Quaternary volcanoes grew over a regional basaltic to dacitic basement (Pliocene-Pleistocene), called Pre-Neovolcanic lavas (PNL). The Intra-ignimbrite lava flows (IIL, Pliocene age) have a clearly different trend with respect to the volcanoes, especially in their high TiO_2 and P_2O_5 content. Both old lava units show a tholeiitic tendency, transitional to calc-alkaline series. The less evolved lavas correspond to Orosí, Cacao, and Tenorio (Parcelas cone) volcanoes and also to small isolated basic lavas and cinder cones (IBL) located 20-26 km in front of the VF. These rocks are high-alumina tholeiitic basalts/basaltic andesites or transitional to alkalic basalts. Crystal fractionation is the dominant mechanism involved in generating the range of magmatic compositions. The geochemistry suggests that Guanacaste lavas are cogenetic but some source heterogeneites are required to explain the observed petrological features.

RESUMEN: Se presentan datos geoquímicos de las lavas de cuatro pares de estratovolcanes Cuaternarios (Cordillera de Guanacaste), de pequeños afloramientos de lavas básicas en el frente de arco volcánico (VF) y de unidades paleovolcánicas (edad Pliocena-Pleistocena) localizadas en el norte de Costa Rica. Las lavas más evolucionadas de la serie calcoalcalina están presentes en los volcanes andesíticos Rincón de la Vieja y Miravalles y en los domos de Cañas Dulces (dacitas-riolitas) y de Bijagua (andesitas) , usualmente con altos contenidos en Zr, Ba y Rb. Todos estos volcanes se desarrollaron sobre un basamento regional constituido por lavas (Plioceno-Pleistoceno) de composición basáltica hasta dacítica, denominadas lavas Pre-Neovolcánicas (PNL). Las lavas intraignimbritas (IIL, Plioceno) poseen claramente una tendencia diferente con respecto a los volcanes, en especial en los altos contenidos de TiO_2 y P_2O_5. Ambas unidades antiguas muestran una tendencia toleítica transicional hacia la calcoalcalina. La cristalización fraccionada es el mecanismo dominante en la generación del amplio ámbito de composicíon magmática observada. Las lavas menos evolucionadas corresponden con las de los volcanes Orosí, Cacao y el cono Las Parcelas (volcán Tenorio) y también con una serie de pequeños y aislados afloramientos de lavas y escorias básicas (IBL) localizados 20-26 km al frente del arco volcánico. Estas rocas corresponden con basaltos y andesitas basálticas toleíticas, ricas en alúmina, o transicionales a basaltos alcalinos. La geoquímica de las lavas de Guanacaste sugiere que éstas son cogenéticas, pero se requiere de cierta heterogeneidad en la fuente para poder explicar varios de los aspectos petrológicos tratados.

INTRODUCTION

The Cordillera de Guanacaste is located on the northern Costa Rican segment of the Central American volcanic front (Carr 1984), an active continental margin (Alvarado, 1984; Wilson, 1989). There is a well-defined Benioff zone in northern Costa Rica with a maximum depth to the seismic zone of about 200 km, and a subduction rate of 9 cm/year with an angle of 50° (Minster & Jordan, 1978; Barquero, 1990). In the northern part of Costa Rica, the under-thrusted Cocos Plate, located beneath the VF, is older than in the southern part (Figs. 1 and 2). This is based on the magnetic anomaly interpretation of Lonsdale & Klitgord (1978) and a constant spreading rate. The Benioff plane lies about 150 km beneath the stratovolcanoes. Matumoto et al (1977) have determined a crustal thickness of 43 ± 7 km for northern of Costa Rica (north of Arenal volcano).

Geologically, the Cordillera de Guanacaste comprises a 80 km series of composite basaltic andesite/andesite volcanoes trending NW-SE. These volcanoes overly Terciary basament and are parallel to the middle American trench. The oldest volcanic rocks exposed in this area are upper Miocene to Pliocene ignimbrites and lava flows (Alvarado et al., 1993; Gillot et al., 1994).

Scientists and naturalists (Karl von Seebach, Henri Pittier and Alexander von Frantzius) of the last century studied the general aspect of volcanoes in this region. Subsequently, many geoscientists have studied in more detail the geomorphology, petrography and eruptive and/or residual activity of these volcanoes (Dengo, 1962; Hearly, 1969; Mainieri, 1975; Santana, 1977; Fernández, 1984). Nevertheless, few works related to the general geochemical aspects of these volcanoes have been published (Kussmaul et al., 1982; Alvarado, 1985; Tournon, 1983; Carr et al., 1986).

Although a considerable amount of geological data and major and trace element compositions have been accumulated for these stratovolcanoes, very little has been published in the English literature. This study examines the general stratigraphical and petrological aspects of the lavas in four pairs of Quaternary stratovolcanoes, domes, cinder cones, and lava flows in the Cordillera de Guanacaste and other Pliocene lava flows associated in northern Costa Rica.

METHODOLOGY

Intensive field work was done for several weeks in 1986, 1988, and 1989, taking more than 250 samples in the Cordillera de Guanacaste and surrounding areas. The samples are stratigraphically or morphochronologically related and they display a variety of lithologies. These samples were studied under the petrographic microscope at the Instituto Costarricense de Electicidad (ICE) and chemical analyses were made in the Università di Milano (Italy), British Geological Survey (BGS), and Open University (England), using x-ray florescence and atomic absorption for major and trace elements, and electron-microprobe for mineral analyses. Some neoformation minerals were studied by x-ray diffractometer. The geochemical data base consists of over 178 whole rock analyses, that reveals a more complex evolution than previous works indicated. The data base compiled for this study includes principally the chemical analyses published by Tournon (1984), ICE-ENEL (1989, 1990), Zanchi (1989) and Pecchio (1990). All samples are more or less stratigraphical and petrographical representative of the volcanic units and we used unalterated rocks in the diagrams. The complete data set is available from the first author. For minerals compositions we used the data from Tournon (1984), ICE-ENEL (1990), Pecchio (1990) and Malavassi (1991).

STRATOVOLCANOES AND LAVAS FIELD

Four Quaternary groups of complex cones, Orosí-Cacao, Rincón de la Vieja-Santa María, Miravalles-Zapote and Tenorio-Montezuma, 1500-2000 meters high, are found along the Cordillera de Guanacaste within an extensive dacite-rhyolite ignimbritic plateau. Together, the four groups of composite volcanoes and old lavas represent a volume of over 450 km^3 and most of the recent lava flows are basalts to andesites. Between the volcanoes there are valleys approximately 400-500 m above sea level. The Rincón de la Vieja is the only volcano which is still active. We present the summary of general characteristics of the volcanoes and others lava units below.

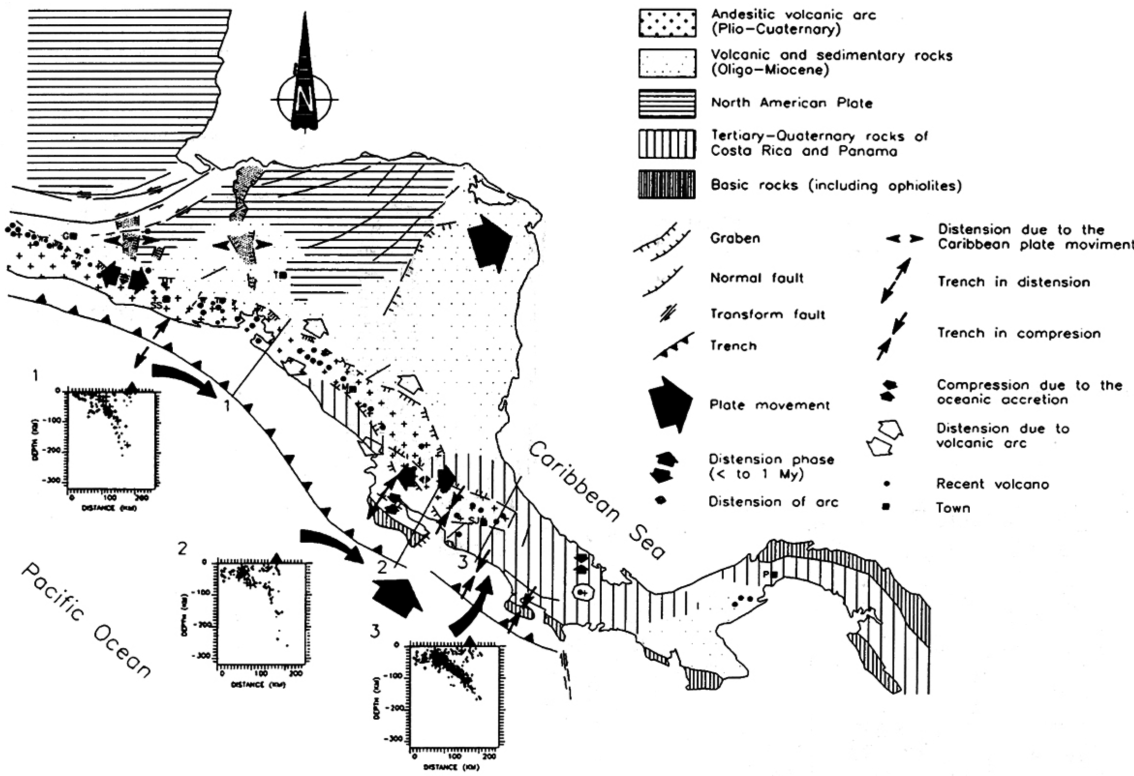

Fig. 1: Tectonic setting of Central América (after Antoninetti et al 1992).

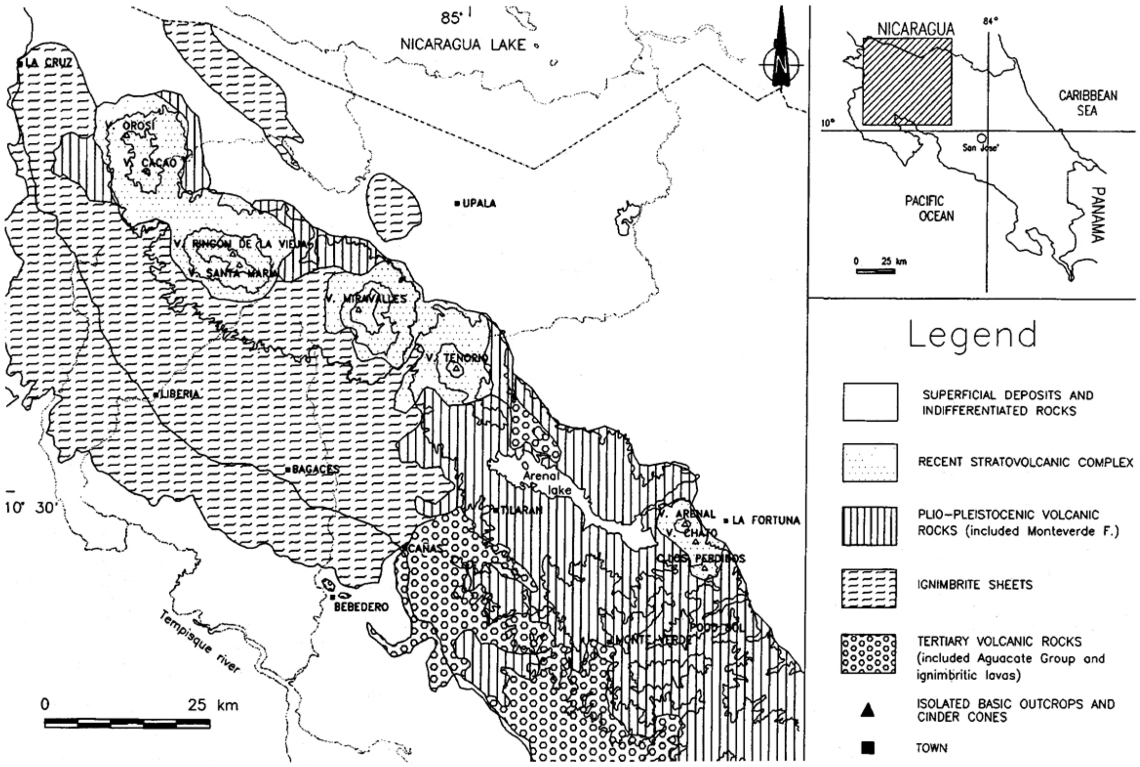

Fig. 2: General geologic features of Guanacaste region.

Intra-ignimbrite lava flows (IIL): In the rivers or in the plain between Liberia and Bebedero town (west of the Interamericana road) and surrouding area, basaltic andesite, andesite and dacite lava flows (54-64 % wt SiO_2) are interlayed with the oldest ignimbrites of Guanacaste. These lava flows may corresponding to Pliocene fissural volcanism in front of the volcanic arc. The IIL have a clearly different composition with respect to the volcanoes´ lavas, especially in their high K_2O, TiO_2, P_2O_5, FeO* contents and low MgO and Al_2O_3 contents.

Pre-Neovolcanic lavas (PNL): They consist of old volcanoes, surrounding the recent volcanoes of the Pliocene (?)-Pleistocene age. PNL have two trends: one with medium-K basaltic andesitic to dacites (only two are low-K), and the other is medium-K through high-K andesitic to dacitic lavas, similar to IIL from Tempisque area.

Orosí-Cacao Complex: They are a group of N30°W trending stratovolcanoes, each exhibiting a horseshoe shaped crater (Orosí 1440 m, Orosilito 1200 m, Cacao 1453 m). Orosí lavas are little differenciated basalts to basaltic andesites (51-54 % wt. SiO_2), while those from Cacao cone are andesites (54-56 % wt. SiO_2). One exception is a recent Mata Redonda lateral basaltic lava flow with different petrochemical and mineralogical characteristics (Tournon, 1984). The blocks of the southern debris avalanche from Cacao volcano are andesites. This volcanic complex is built upon an older andesitic lava plateau (57-61 % wt. SiO_2).

Rincón de la Vieja-Santa María Complex: It is the largest volcanic center in the Guanacaste range and it has a volume of about 250 km^3 (Carr, 1984). This center has in the summit region nine coalescing pyroclastic cones that have grown 300 meters above the volcanic center. The elevations of this cones vary within a narrow range between 1100 and 1550 m, trending N60°W and N14°E. Since the cones are spread over an 8 km long axis, from a distance the volcano appears as a long ridge. Most Holocene and historic eruptions of the Rincón de la Vieja active crater are phreatic to phreatomagmatic eruptions. The recent bombs from the Rincón de la Vieja have one of the highest SiO_2 content (55-60 % wt) of the Guanacaste volcanoes. Rincón de la Vieja has grown over an old lava unit more differenciated (basaltic andesites, and medium-K to high-K andesites).

Cañas Dulces domes field: They are located 10 km south of Rincón de la Vieja volcano. The volcanic field consists of 10 domes and lava-domes (655 m, 60 km^2) with dacite to rhyolite medium to high-K content, and Pliocene/Pleistocene age (Bellon & Tournon, 1978; Alvarado et al., 1993). Proximal pyroclastic flows, breccias, and lacustrine deposits are present.

Miravalles-Guayabo Complex: It is a medium-K andesitic stratovolcanic complex (2014 m), including the subsidence of Guayabo caldera (Santana ,1977; ICE-ELC, 1983; Fernández, 1984). There are at least 1000 meters of breccias, lava flows, tuffs, lahars, debris flows and lake sediments inside the caldera according to the deep-drills of the Geothermal Miravalles Project of ICE. Recent summit pit craters and small cones have developed towards the southwest. At least one recent lateral explosion (debris avalanche) deposit is exposed in the Guayabo-Miravalles caldera. The Guayabo composite caldera rim (15 km diameter) has a wider range of variations (basalts to dacites) than Miravalles and Cabro Muco lavas, and at the same SiO_2 content, the K_20 is lower than in the first group.

Tenorio-Montezuma Complex: Stratovolcanic complex comprising pyroclastic cones and craters, orientated at N25°W, and Bijagua andesitic dome (59-61 % wt SiO_2) field (in the north flank) that grew over a relatively old volcanic center. Many of these lava flows have a typical radial pattern. The volcanic vents are divided into two clear petrographic groups: one, the most common in the literature, and similar to Rincón de la Vieja lavas, consists of intermediate lavas (56-61 % wt SiO_2); the other group are basic volcanic rocks (50-53 % wt SiO_2) present in the Parcelas cinder cone. Similar to the rest of Guanacaste volcanoes, the Tenorio-Montezuma complex has at its base an old andesitic to basaltic andesitic plain (53-63 % wt SiO_2) with two different trends in the Al_2O_3, TiO_2 and K_2O contents.

Recent isolated basaltic cinder cones and lava flows (IBL): At least two basaltic cinder cones (Upper Quaternary) and two isolated (dikes?) exposure of basaltic andesite lavas are observed 20-26 km in front the Cordillera de Guanacaste with a NW-SE trend. The Chopo cinder cone, also called Anunciacion cone, the most known of these (Mora, 1977), has lava flows and scorias with reverse grading (49-50 % wt SiO_2; 0.67 % wt K_20) and large variability in the MgO content according to the literature range between 5-8%. The other is an alkaline basalt from Corobicí cinder cone (Pecchio, 1990).

PETROGRAPHY

Guanacaste lavas are basalts to rhyolites. Modal analyses are given in Table 1. Phenocryst chemical compositions (Tables 2, 3, 4, and 5) are briefly discussed below.

Basalts contain plagioclase (An_{95-36}), clinopyroxene ($Wo_{41-28}Fs_{30-4}En_{54-35}$), olivine ($Fo_{86-53}$), rare orthopyroxene ($En_{75-63}$) and magnetite phenocrysts in an intergranular to intersertal groundmass of plagioclase microlites (An_{62-58}), clinopyroxene ($Wo_{35-32}Fs_{21-17}En_{50-44}$), opaques, rare orthopyroxene (En_{50-44}), and rhyolitic to andesitic glass and apatite. The plagioclase phenocrysts exhibit strong normal or reverse zoning (An_{47-95}). Olivine phenocrysts are normal (Fo_{86-60}) or reversely zoned (Fo_{65-68}); partially altered to iddingsite, chlorite or serpentine, with xenomorphic corroded forms and Cr-spinel inclusions. Chromian diopside is found in the core of some augite, such as pigeonite (coronae in olivines or as microlites) in some basaltic lava flows (see Tournon, 1984; Malavassi, 1991).

Basaltic andesites have phenocrysts of normal zoned plagioclase (An_{90-43}), some with complex zoning ($An_{55-58-52}$), pyroxenes, olivine, magnetite and apatite microphenocrysts. The olivine phenocrysts (Fo_{90-72}) are automorphic to xenomorphic with spinel inclusions. The orthopyroxenes (En_{77-60}) are usually found with a rim of clinopyroxene ($Wo_{42-30}Fs_{19-10}En_{49-42}$). The groundmass ranges between intergranular and intersertal with plagioclase, pyroxene, Fe-Ti oxides, olivine, apatite, brown glass and tridimite or cristobalite.

Andesites are phyritic, seriate and glomerophyritic clusters. The most abundant phenocrysts are plagioclase (An_{90-43}), clinopyroxene ($Wo_{42-34}Fs_{22-9}En_{46-37}$), ortopyroxene ($En_{68-62}$) usually have contiguous augite rim, magnetite. Olivine (Fo_{80}) is rare (less 0.2 %), partially altered to iddingsite with spinel inclusions. Hornblende with opacitic rims is also rare. The matrix is of intersertal, intergranular or pilotaxitic texture (rare hyaline) with the same mineralogical phases as phenocrysts, and occasionally with apatite, tridimite and very rarely zircon. The plagioclase phenocrysts exhibit seriate texture with a gradual transition to microlites with glass-mineral inclusions and rich cores. These microlites (andesine-labradorite) show platy, elongated prismatic, and needle-like crystal form. Phenocrysts of intermediate size are usually normally or complex zoned (e.g. $An_{85-77-70}$; $An_{60-70-65}$). Diverse generations of plagioclase phenocrysts are according to their size, compositions, degree of preservation and abundance of inclusions are present. These reflect the genetic sequence and depth of plagioclase crystallization.

Table 1

Modal analyses of Guanacaste lavas (Vol%)

Section	MIR	IBL	TEN	IIL	CACAO	OROSI	PNL
Plagioclase	35.37	47.45	40.36	61.90	58.52	38.42	49.00
Clinopyroxene	16.33	27.74	14.76	–	12.79	24.64	25.33
Ortopyroxene	3.06	0.00	4.52	–	3.49	3.21	–
Pyroxenes Tot.	19.39	27.74	19.28	18.32	16.28	27.85	Tr
Oxides	5.44	6.57	8.13	19.78	10.85	10.36	17.64
Hornblende	0.00	2.19	Tr	0.00	11.24	0.00	0.00
Olivine	1.02	7.30	0.00	0.00	3.10	0.00	0.00
Groundmass	38.78	8.76	35.24	0.00	0.00	9.46	7.33

Key: Tr, traces; MIR, Miravalles volcano; IBL, isolated basaltic lavas; TEN, Tenorio volcano, IIL, intraignimbritic lavas; CACAO, Cacao volcano; OROSI, Orosí volcano; PNL, pre-neovolcanic lavas.

Table 2

Microprobe analyses of plagioclase from Cordillera de Guanacaste

Formula based on 8 Oxygens:

			Orosí volcano				Cacao volcano				Miravalles volcano		
SiO2	53.75	53.01	44.39	44.30	51.41	50.32	53.30	57.82	51.64	51.20	51.55	51.00	52.79
TiO2	0.01	0.08	0.00	0.01	0.06	0.00	0.00	0.00	0.03	0.02	0.02	0.02	0.00
Al2O3	28.90	28.43	35.37	35.14	29.95	31.14	29.44	26.37	30.21	30.03	30.57	30.76	29.88
FeO	0.84	0.87	0.45	0.53	0.70	0.65	0.46	0.31	0.55	0.82	0.68	0.71	0.71
MgO	0.10	0.10	0.02	0.02	0.16	0.10	0.04	0.05	0.07	0.14	0.07	0.07	0.12
CaO	11.85	11.85	19.24	18.90	13.36	15.00	12.50	8.82	13.28	13.82	13.55	14.07	13.04
Na2O	4.72	4.72	0.56	0.60	4.00	2.72	4.05	6.42	4.12	3.55	3.44	3.16	3.80
K2O	0.19	0.19	0.02	0.02	0.11	0.18	0.17	0.40	0.10	0.16	0.14	0.12	0.20
Total	100.36	99.04	100.05	99.52	99.75	100.08	99.97	100.09	100.00	99.74	100.02	99.91	100.54

			Tenorio volcano				Intraignimbritic lavas				Pre-neovolcanic lavas	
SiO2	49.52	55.54	47.00	47.00	48.52	48.68	49.29	55.54	48.44	55.37	49.35	48.28
TiO2	0.01	0.02	0.03	0.03	0.04	0.05	0.03	0.09	0.08	0.02	0.01	0.02
Al2O3	30.36	26.69	32.62	32,62	32.62	32.35	31.91	27.11	32.41	28.18	32.05	33.25
FeO	0.76	1.19	0.80	0.80	0.85	0.83	0.91	1.33	0.98	0.46	0.82	0.79
MgO	0.11	0.10	0.08	0.08	0-.14	0.12	0.07	0.12	0.05	0.07	0.09	0.11
CaO	14.31	10.07	16.87	16.87	15.69	15.88	15.55	10.33	15.64	10.31	16.11	15.96
Na2O	3.38	5.38	1.71	1.71	2.35	2.31	2.39	5.02	2.31	5.29	2.09	2.11
K2O	0.08	0.39	0.08	0.08	0.09	0.09	0.11	0.40	0.12	0.53	0.12	0.12
Total	98.53	99.38	99.19	99.19	100.30	100.31	100.26	99.98	100.03	100.23	100.07	100.13

Table 3

Microprobe anayses of pyroxenes from Cordillera de Guanacaste

Formula based on 6 Oxygens:

	Orosí volcano					Miravalles volcano			Tenorio volcano			
SiO_2	52.90	53.48	53.61	51.47	52.94	51.69	49.70	53.10	51.48	49.26	52.33	52.30
TiO_2	0.16	0.18	0.17	0.33	0.21	0.40	0.62	0.14	0.45	0.81	0.13	0.18
Al_2O_3	1.33	1.81	1.05	2.22	1.97	2.46	4.73	0.87	2.38	4.37	0.74	0.72
Cr_2O_3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FeO	17.69	16.86	17.80	10.29	17.37	7.56	8.70	19.01	9.10	9.63	20.50	20.52
MnO	0.62	0.42	0.67	0.32	0.42	0.28	0.21	0.72	0.23	0.26	0.77	0.81
MgO	25.57	25.75	25.12	14.93	25.45	15.72	14.83	25.29	15.65	15.06	24.61	24.38
CaO	1.48	1.55	1.64	19.52	1.76	20.89	20.81	1.22	20.80	20.22	1.10	1.04
Na_2O	0.06	0.00	0.04	0.34	0.05	0.19	0.22	0.00	0.30	0.31	0.03	0.02
K2O	0.00	0.02	0.01	0.00	0.04	0.03	0.01	0.00	0.02	0.01	0.00	0.01
Total	99.81	100.07	100.11	99.42	100.21	100.22	99.83	100.35	100.41	99.93	100.21	99.98

	Pre-Neovolcanic lavas			
SiO_2	48.07	51.15	51.72	51.47
TiO_2	0.03	0.46	0.40	0.41
Al_2O_3	33.27	2.34	1.23	1.98
Cr_2O_3	0.02	0.00	0.07	0.02
FeO	0.84	10.34	12.62	10.03
MnO	0.01	0.29	0.59	0.38
MgO	0.01	16.06	13.89	16.24
CaO	16.29	19.54	19.44	18.89
Na_2O	2.19	0.31	0.24	0.28
K_2O	0.13	0.00	0.00	0.00
Total	100.86	100.49	100.20	99.70

Table 4

Microprobe analyses of amphibole and olivine from Cordillera de Guanacaste

	Formula based on 24 Oxygens:				Formula based on 4 Oxygens:						
	Amphibole				Olivine						
	Cacao volcano				Miravalles volcano			Isolated basaltic lavas			
SiO2	47.72	45.17	43.81	46.38	40.39	40.37	40.51	38.13	38.30	38.70	38.40
TiO2	1.52	1.70	2.31	1.73	0.00	0.00	0.03	0.00	0.08	0.00	0.02
Al2O3	7.95	8.87	9.29	7.69	0.04	0.03	0.04	0.02	0.23	0.03	0.03
Cr2O3	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00
FeO	12.66	13.99	16.38	13.46	19.14	18.90	19.01	19.10	25.85	17.26	17.84
MnO	0.27	0.30	0.30	0.23	0.31	0.33	0.26	0.29	0.44	0.23	0.32
NiO					0.00	0.00	0.00	0.00	0.00	0.00	0.00
MgO	14.32	14.81	13.87	15.45	43.82	44.10	44.34	42.46	35.22	43.18	42.58
CaO	12.32	11.04	10.35	11.54	0.15	0.13	0.15	0.12	0.30	0.17	0.20
Na2O	1.83	1.86	1.97	1.77							
K2O	0.58	0,.38	0.41	0.37							
Total	99.17	98.12	98.69	98.62	103.85	103.86	104.37	100.12	100.42	99.57	99.39

Table 5

Microprobe analyses of spinel from Cordillera de Guanacaste

Formula based on 4 Oxygens:

	Cacao volcano				Miravalles volcano			TV	IIL
SiO_2	0.45	1.01	1.43	0.51	1.05	0.66	0.46	12.79	19.81
TiO_2	8.06	7.76	7.76	9.10	9.59	7.32	8.88	6.69	14.17
Al_2O_3	2.06	2.92	2.57	3.74	3.06	4.16	2.29	3.43	8.24
FeO	85.24	83.94	84.73	79.76	80.61	79.71	80.87	67.86	47.04
MnO	0.36	0.27	0.44	0.41	0.48	0.43	0.34	0.31	0.53
ZnO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NiO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MgO	1.04	1.26	1.25	1.55	1.99	2.03	2.10	5.00	0.84
CaO	0.04	0.05	0.05	0.10	0.05	0.04	0.04	3.63	3.01
Total	97.25	97.24	96.18	96.87	94.56	94.56	95.98	99.71	93.69

Key; TV. Tenorio volcano; IIL, intraignimbritic lava flows.

Dacites/rhyolites: There are two different types, the first present in the Cañas Dulces lava-dome field (Cañas Dulces, Fortuna, Gorgona, San Roque hills) consist of green to black lavas. The phenocrysts consist of plagioclase with strong zoning and corrosion rims, clinopyroxene, ortopyroxene (rare actinolite corrosion rims), green to brown hornblende and Fe-oxides with glomeroporphyritic clusters (hb+plag) and hornblende-andesites autolites. The groundmass is intersertal, hyalopilitic, spherulitic to perlitic with microlites of plagioclase, magnetite, clinopyroxene, glass, cristobalite and crystalites or within microlites. A magnesio-hornblende bearing dacite lava with plag (An_{80-55})+hb+opx (En_{70-68})+ox are also interbeded in pumice-ash flow deposits (Guayabo Formation) at Río Blanco and surrounding the Guayabo caldera rim. The second type of dacites/rhyolites corresponds to lava flows without hornblende (Atravesado and Las Mesas lava field, part of Cañas Dulces lava-domes field and rare samples of stratovolcanoes). These rocks are phyritic with megacrysts of plagioclase and rare microphenocrysts of clinopyroxene, ortopyroxene, opaque within a intersertal matrix with the same phenocrysts assembly or hyaline with crystalites of feldspar, cpx, opx, opaques, tridimite or cristobalite.

MAJOR AND TRACE ELEMENT COMPOSITION

Guanacaste lavas show extensive and regular major element variation from high-Al basalts to rhyolite compositions (Figs. 3, 4, 5, 6, and 7). Major and trace elements are give in Table 6 with chrondrite normalized values plotted in Fig. 6. Two pyroxenes basaltic andesites and andesites are the dominant rock type, whereas aluminous basalts, dacites, and rhyolites lava flows are subordinate. The basic lava flows (< 53 % wt SiO_2) include high-Al, low- and medium-Mg, and all medium-K content (Fig 3). Olivine phenocrysts are present in the basalts and basaltic andesites. All of these rocks have quartz and hyperstene the CIPW norm, and only the basaltic bombs (Chopo cone) have normative olivine (olivine tholeiites).

CaO, MgO, TiO_2, FeO*, and Al_2O_3 decrease with increasing SiO_2 (except to Cañas Dulces lavas with anomalous Al-content), while Na_2O and K_2O increase (Fig 5). Orosí-Cacao lavas are similar to IIL, also Rincón de la Vieja, Miravalles and Tenorio lavas are similar to several PNL; but the Cañas Dulces lavas formed a different group. For the older volcanic rocks (IIL and PNL) the aluminum contents variability is greater (13.6 to 21.6 wt % Al_2O_3), but the basalt andesite compositional spectrum of Quaternary VF centers

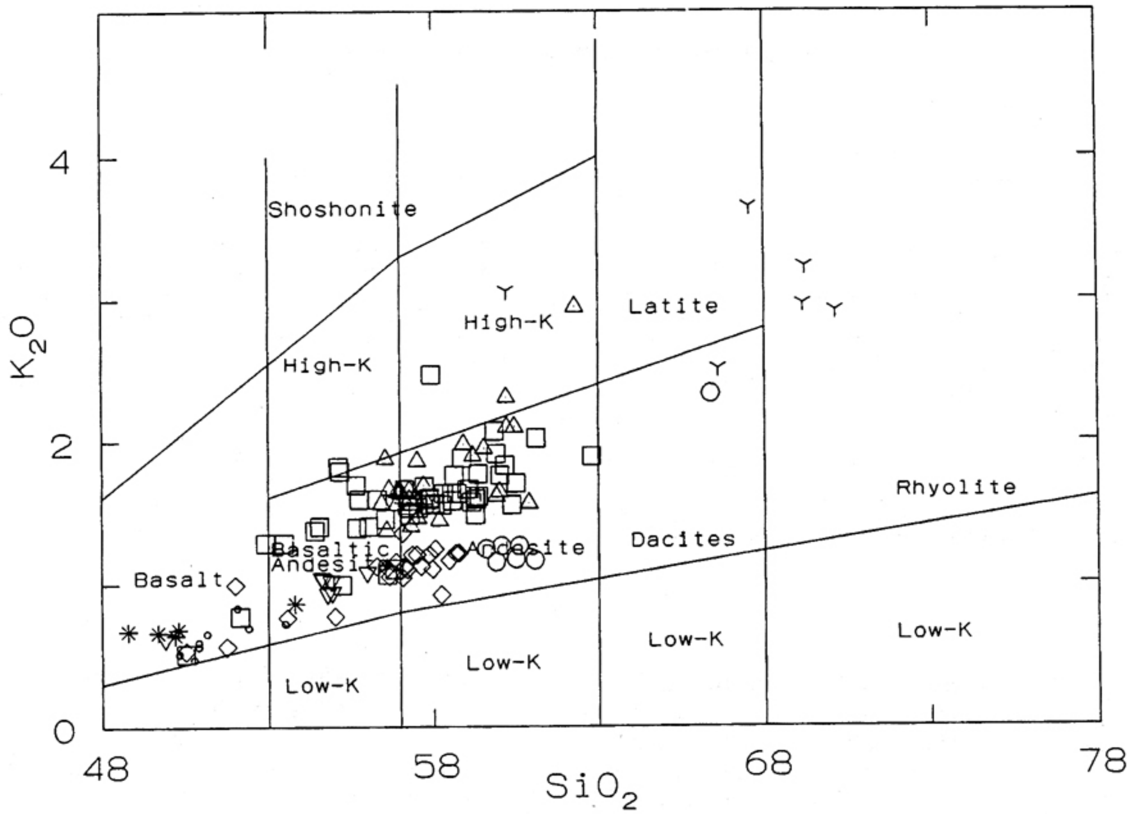

Fig. 3a: Relationship between SiO_2 and K_2O content. Line on the K_2O and lavas (basaltic to rhyolitic) divisions marks the boundary between: Low-K series, medium-K series, and high-K series (Gill 1981). Inverted triangle = Cacao; triangle = Rincón de la Vieja; diamond = Tenorio; squares = Miravalles; ∘ = Orosi; Y = Cañas Dulces Domes; o = Bijagua domes; * = IBL; x = PNL; + =

have characteristically high-alumina contents (15.4-20.5 wt % Al_2O_3). Differences in the abundance of TiO_2, Al_2O_3, Na_2O, K_2O, P_2O_5 and sometimes FeO* between IIL, Orosí-Cacao volcanoes and Cañas Dulces domes appear to reflect differences in the degree of plagioclase, opaques and apatite crystalization and/or accumulation. In fact, some samples of Miravalles volcanic complex and Orosí volcano are abnormally rich in Al_2O_3 and CaO, and they have low FeO* content relative to other rocks of the suite. Those lavas may be thought of as being liquids from the normal liquid line(s) of descend to which plagioclase has been added. They are thus typical examples of rocks termed cumulus-enriched. However, futher consideration of the mechanism by which such magmas might be formed shows that there are a number of the other posibilities. In this case, both Al_2O_3 and CaO decrease from basalt to rhyolite. This suggests that plagioclase appears early as a phenocryst phase. The petrographical data supports this petrochemical observation. Thus, major-element variation largely reflects phenocryst content, with most labradorite and labradotite-pyroxene andesites being chemically "normal" and most pyroxene and olivine andesites chemically "low Si" or basaltic andesites. Decreasing FeO* and MgO content from basalt to rhyolite is consistent with the fractionation of ol+px. The crystalization of olivine and pyroxene should be the cause of FeO* /MgO anomalous ratio (10.0-18.5) observed in several rocks form Cañas Dulces domes.

Trace element values generally correlate with major element contents and variations between samples reflect variations in phenocryst contents. V, Cr, Ni and Sr contents vary in both andesites and basalts, reflecting variations in the modal content of Ti-Fe oxides, pyroxene, olivine

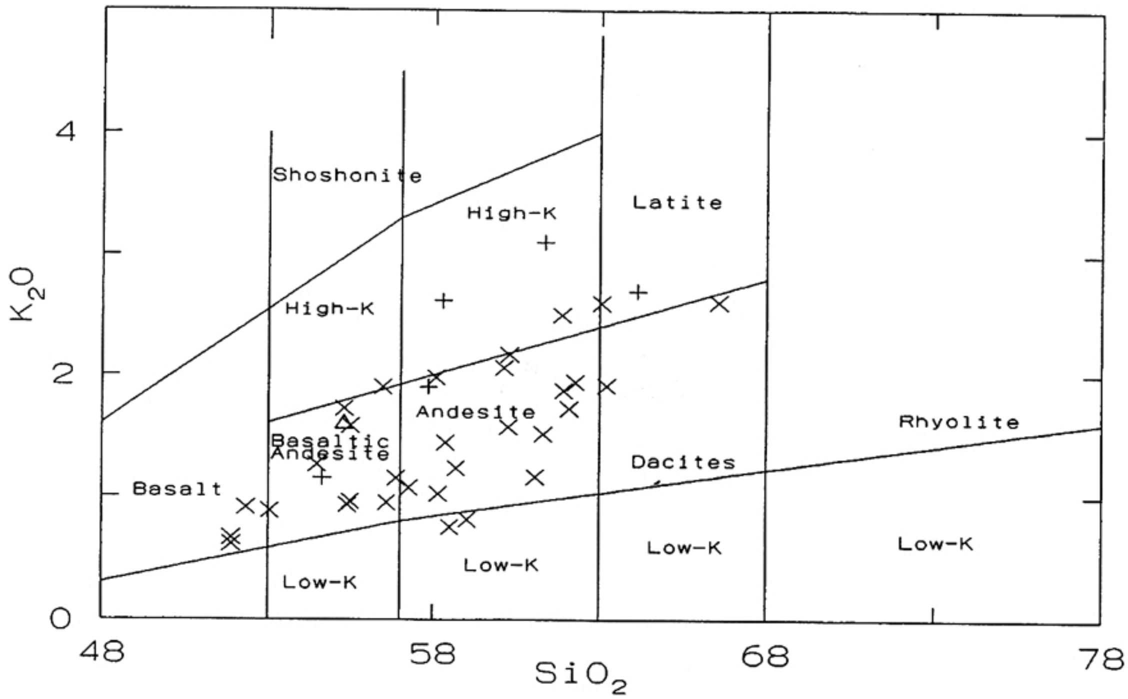

Fig. 3b: Classification of Guanacaste lavas (+ = IIL; X= PNL).

and calcic plagioclase. The less evolved lavas corresponding to Orosí, Cacao, Parcelas cone and IBL usually have lower K_2O, Rb, Sr, and Cr contents and higher Al_2O_3 and CaO contents than Rincón de la Vieja and Miravalles volcanoes, IIL, Bijagua domes and PNL. These more evolved lavas usually contain larger amounts of Zr, Ba and Rb than the first group (Fig. 7).

DISCUSSION

The importance of fractional crystallization as a major modifier of the chemistry of the lavas chemistry has been documented for several convergent margins and in Central American VF (Carr, 1984). Several lines of evidence suggest its importance in the rocks from northern Costa Rica. Within the lavas, the major phenocrysts phases are plag, cpx, opx, Fe-Ti oxides and ol. Fractional crystallization of these phases may be responsible for the transition from basalt to basaltic andesite to andesite and dacite. The relatively good, positive correlation between Rb-Ba and Zr-Rb, are consistent with the interpretation of chemical variations as a result of the fractional crystallization (Fig. 7).

For the high-Al basalts (HAB) of Guanacaste, the high alumina (18-20.5%) content together with low Cr, Ni, Co, and low MgO/FeO* are generally interpreted as originating from partial melting of mantle peridotite followed by considerable fractional crystallization of olivine and pyroxenes (e.g. Rose et al., 1980; Thorpe et al., 1982). The relatively high modal abundance of plagioclase in many lavas (20-50%), the unexpected enrichment of Sr (in several samples) and Ba, and the increased Al_2O_3 as fractionating proceeds are all arguments for the possibility that they could be enhanced at "higher" pressure, as the liquid is more compressable than feldspar (Fujii & Kushiro, 1977). The large Al_2O_3/TiO_2 ratios support this idea.

In addition, plagioclase fractionation is suggested by correlations such as Rb/Sr vs SiO_2 and CaO vs K_2O (Figs. 8 and 9). The CaO/Al_2O_3 ratio show sharphly negative correlation with silica, however. This means that a CaO-rich but

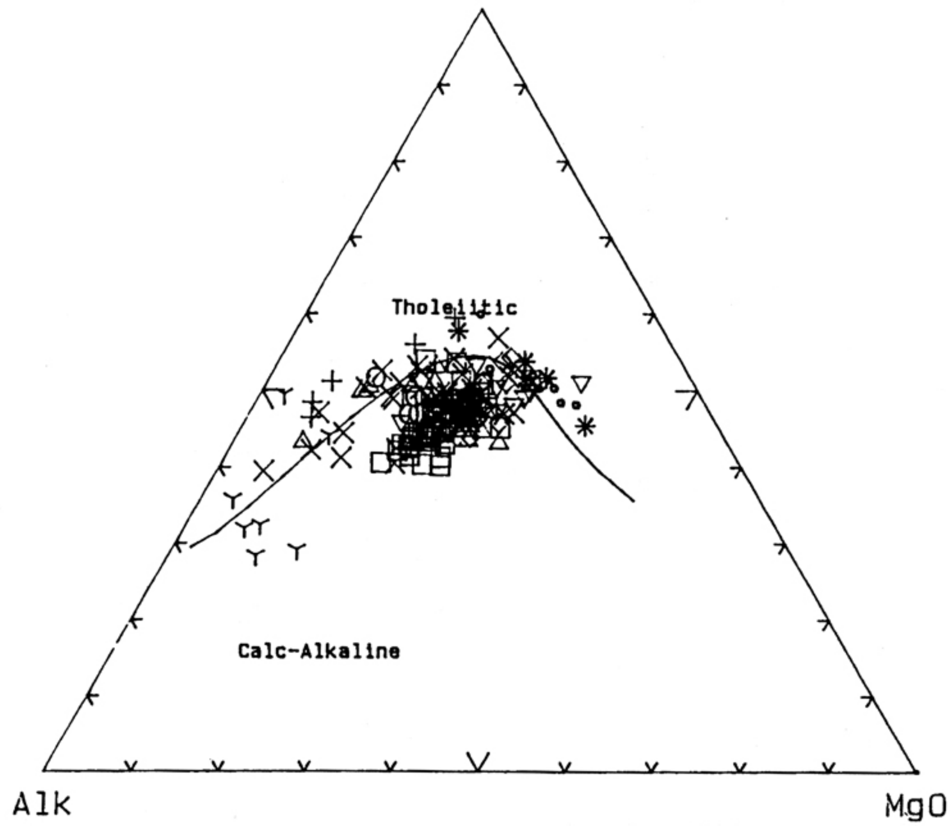

Fig. 4: AFM diagram, tholeiitic vs. calc-alkaline (Irvine & Baragar, 1971).

Al_2O_3-poor mineral may have also been fractionated (e.g. CaO-Cpx; Fig 10). Therefore, for a basaltic magma simultaneously crystallizing plagioclase, clinopyroxene and olivine, may result in the selective fractionation/removal of mafic minerals and the preferential relation of low density plagioclase crystal along the margins of a convecting magma chamber in a primitive mantle derived calc-alkaline basalt intrusion. This represents a possible mechanism for generating the plagioclase-phyric magmas of HAB composition (see Marsh & Maxey, 1985; Brophy, 1989) from Guanacaste lavas discussed above under the heading of Geochemistry.

Chemical data for Guanacaste lavas show a decrease in V concentration with SiO_2 content (Fig. 11). This trend suggests that magnetite may also be fractionated, but the high content in vanadium in some samples, suggest a relative slow fractionation of opaque minerals. The occurrence of magnetite phenocysts and especially the existence of magnetite inclusions in plagioclase phenocrysts shows that magnetite is in equilibrium with the Guanacaste parental magma.

Incompatible trace elements suggest that lavas are cogenetic (Fig. 12) but small scale source heterogeneites are required, specially in several of the more evolved lavas (Rincón de la Vieja, Miravalles, Cañas Dulces domes, IIL and PNL). Aditionally, there are several pieces of evidence that indicate magma mixing (see Sakuyama, 1984) in the Guanacaste lavas. Extreme reversed or complex zoning in plagioclase (from An_{65} to An_{80}) or some olivine (Fo_{65-80}) and other petrographic and mineralogical aspects (e.g. olivine with pigeonite rim, olivine with Cr-spinel inclusions in andesites) suggest that basaltic and andesitic magma mixed to form the stock.

The volcanic rocks of the Guanacaste volcanic zone include the widespread ignimbrite

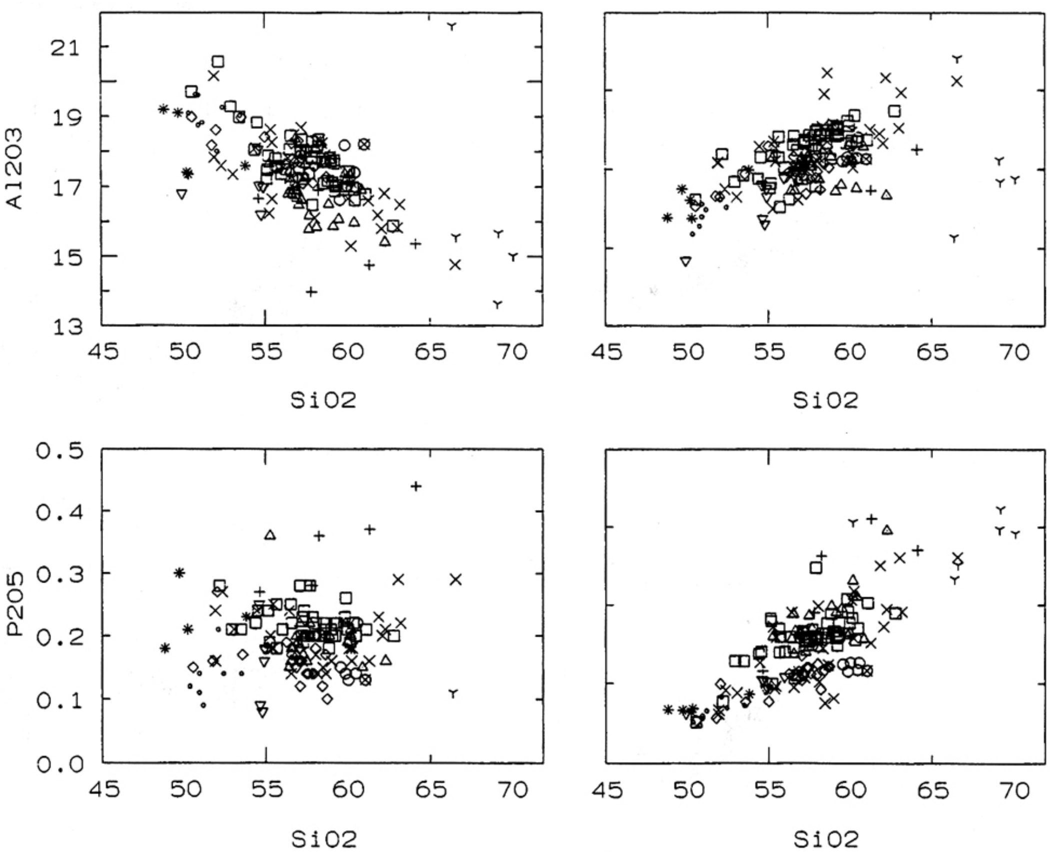

Fig. 5: Harker variation diagram for Guanacaste lavas.

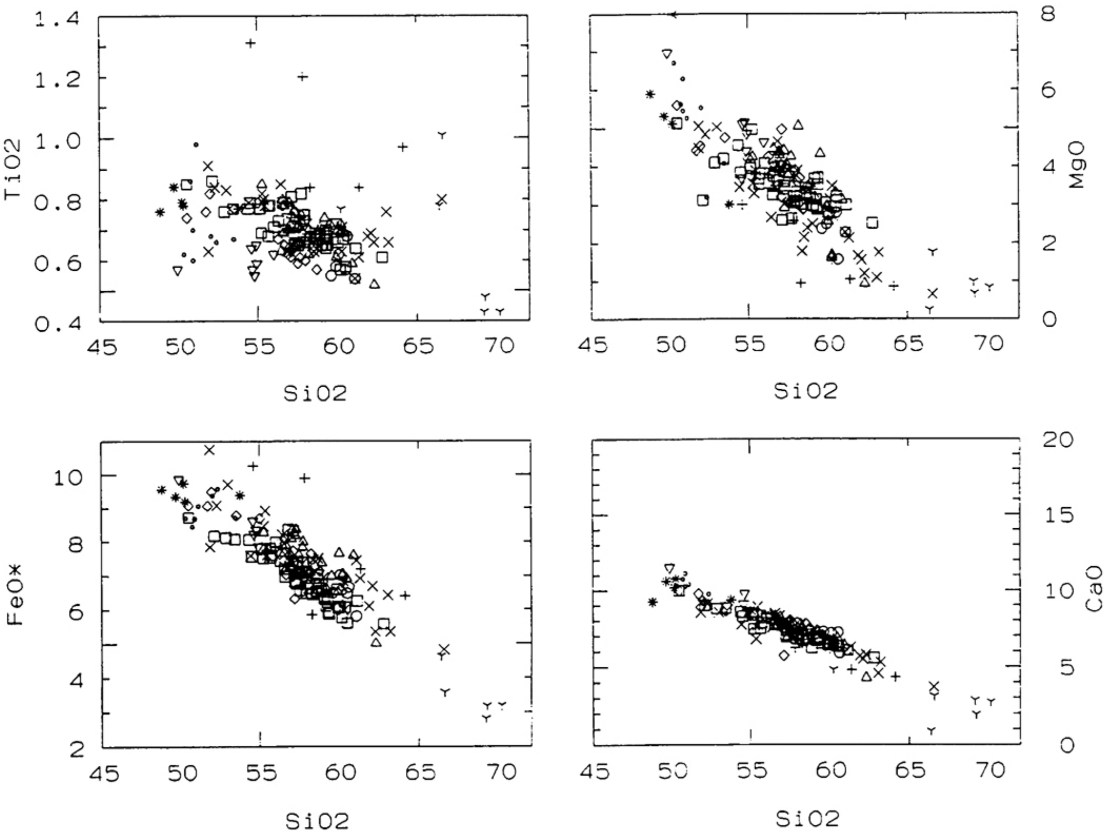

Fig. 5: Harker variation diagram for Guanacaste lavas.

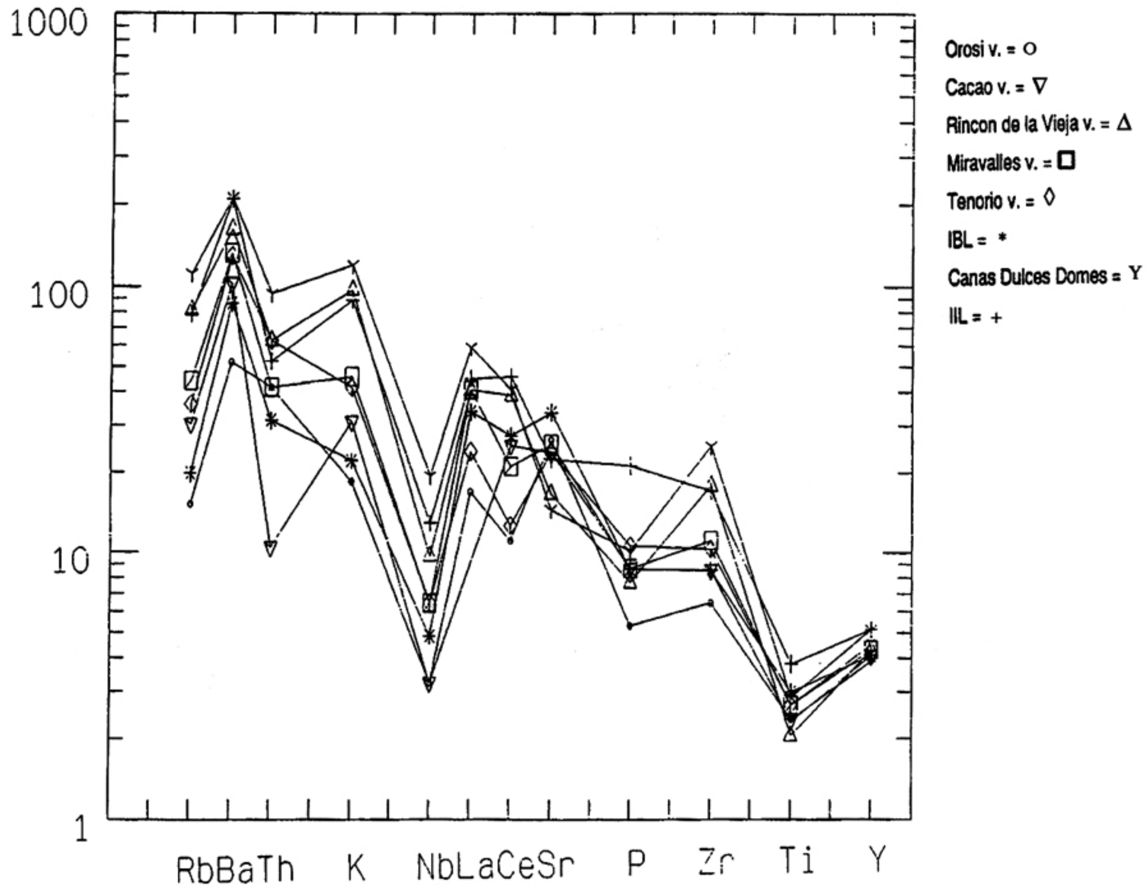

Fig. 6: MORB-normalized plot for sample of Guanacaste lavas. The normalising values are taken from Wood et al (1979).

sheets of dacite-rhyolite compositions which overlap the andesite/basaltic andesite lavas in both space and time, and both groups show intergradation of mineralogical and petrological features (Kussmaul et al., 1982; Tournon, 1984; in this work). The occurrence of many different phases of caldera collapse in Guanacaste between 8 and 0.6 M.a. (Chiesa et al., 1992; Gillot et al.,1994) strongly suggests the presence of shallow magma chambers. In these chambers crystal fractionation and *in situ* crystallization processes may have operated during periods of quescence or normal eruptive activity.

Some lavas from Guanacaste have corundum-normative, specially the Cañas Dulces Domes (*c* normative 0.11-14.26), suggesting: a) some crustal contamination, b) the fractionation of pyroxene and/or amphibole without plagioclase or, c) analytical inaccuracy. Nevertheless, contamination possibly have a significant effect on K abundances (e.g. Cañas Dulces domes) but not on Ti and P (Thompson et al., 1982; Cox, 1983; Hodder, 1985). The F/F+M ratio is high (>0.775, see Wilson, 1989) in all samples from IIL and many rocks from Cañas Dulces domes, some PNL and Rincón de la Vieja, and only one sample from Bijagua domes. It may be a reflect of an assimilation of crustal volcanic and sedimentary Terciary rocks. The Cañas Dulces lavas are chemically and genetically associated to ignimbrite events and therefore, possibly they are to some extend contaminated. The elevated K, Rb, Ba, Th, Zr and La

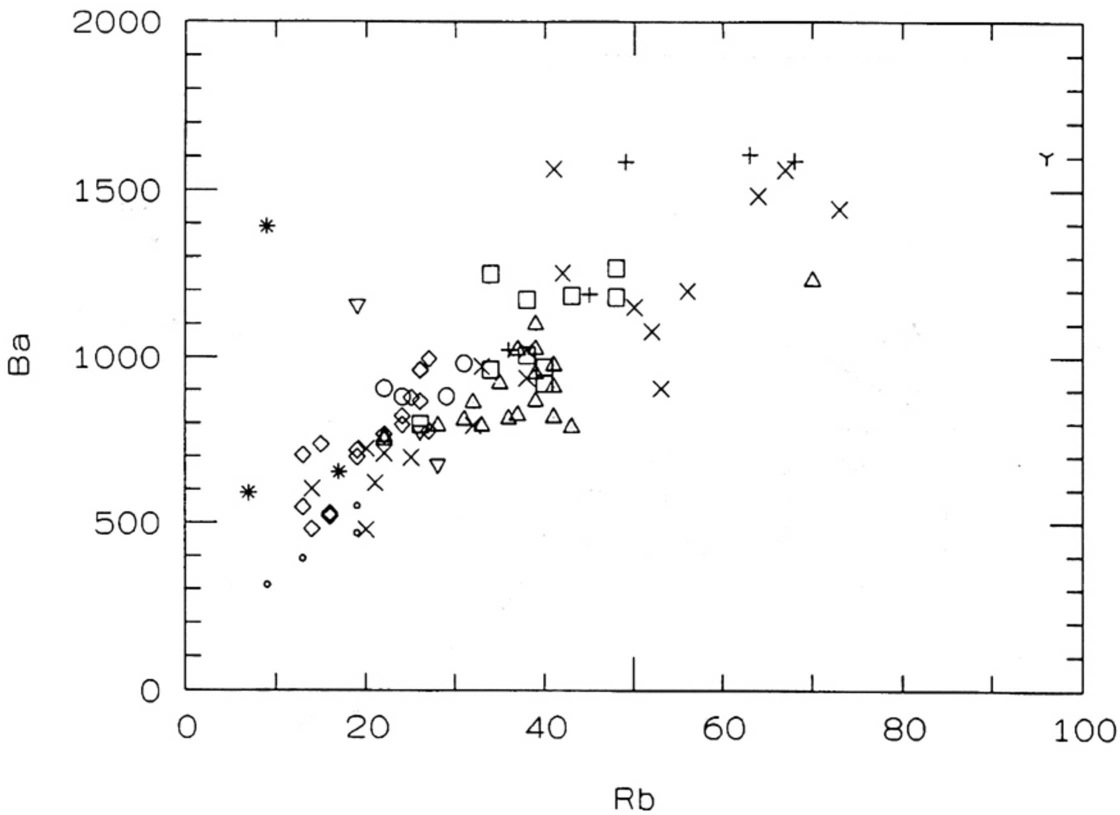

Fig. 7a: Rb vs Ba; Rb vs Zr for Guanacaste lavas.

values could also indicate that mantle-derived magmas could become contamined by terrygenous sediments *in situ* in the base of the continental crust.

In an AFM and FeO*/MgO vs SiO_2 diagrams (not include) the rocks of Guanacaste are a calc-alkaline suite leading towards the tholeiitic series (Fig. 4). Several lavas show little or no Fe-anrichment, similar to the calc-alkaline trend observed in other island arc and orogenic suites. The chemical similarity of these rocks with other island arc and active continental enrivoments is reflected in their petrographic characteristics, geochemistry and in the spider diagram (i.e. Nb anomaly, Figs. 3, 4, 5 and 6). Several rocks from Orosí, Cacao and Tenorio volcanoes, IIL, IBL and PNL, however, are located in the field of liquid produced by the tholeiitic trend of crystal fractionation. But, of these rocks only some lavas from Orosí, Cacao, IBL and PNL have at the same time K/Rb> 500 and Na_2O/K_2O >33, characteristics of island-arc tholeiitic suites (e.g. Coulon & Thorpe, 1981). These basic rocks have also similar P_2O_5 abundances, TiO_2 less than 1%, MgO less than about 6% and Al_2O_3 usually greater than 16%, typical of island arc tholeiites (Mullen, 1983). In fact, Malavassi (1991) argues about that a basalt from Orosí and another from Mata Redonda lava flows are medium-K arc tholeiites with pigeonite in the groundmass, early crystallization of orthopyroxene, nearly constant Zr/Y ratios, and Fe-Ti-Y enrichment trends.

CONCLUSIONS

1) Althrough fractional crystallization is the predominant petrogenetic process governing the major element evolution of the magmas from Guanacaste, additional magmatic processes could

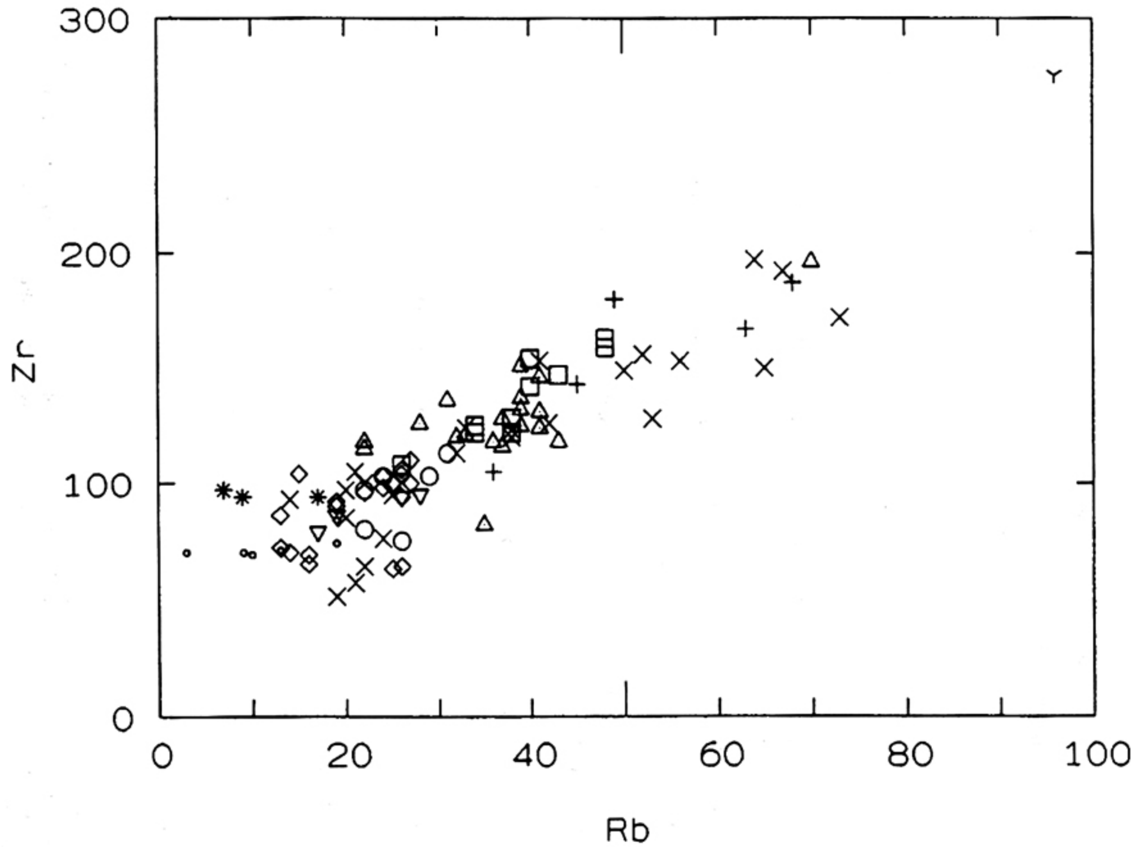

Fig. 7b: Rb vs Ba; Rb vs Zr for Guanacaste lavas.

have opperated in the magma chambers underlying the volcanoes; for example, assimilation of Tertiary crustal rocks, magma mixing and *in situ* crystallization.

2) The Guanacaste lavas vary from 48 to 70 wt % SiO_2: basalts to rhyolites with intermediates andesites and basaltic andesites dominating. They are represented in five distinct volcano types:

a) Large calc-alkaline stratovolcanoes with several and complex periods of activity (e.g. Rincón de la Vieja and Miravalles volcanoes). Old basaltic to andesitic cones are overlain by young eruptive lavas with diverse compositions ranging from basaltic andesites to andesites.

b) Stratovolcanoes of basaltic to pyroxene-andesitic lava flows, forming conical slopes, but coalescent cones with complex evolution and recent basic volcanic products (e.g. Cacao-Orosí and Tenorio-Montezuma volcanoes).

c) Old lava flows (Pliocene-Pleistocene age), including basaltic andesites to dacites from Pliocene-IIL and the PNL transitional between tholeiitic to calc-alkaline suites.

d) Dacite to rhyolitic dome-clusters of Cañas Dulces hills and andesitic dome-clusters of Bijagua hills.

e) Upper Quaternary isolated basalts/basaltic andesites cinder cones and isolated lava outcrops (quarz-tholeiites and olivine-tholeiites transitionals to mildly alkaline basalts) are located 20-26 km in front of the VF.

3) Spatial/temporal coexistence of tholeiitic high-Al and low-Mg lavas typically calc-alkaline lavas during Pliocene-Quaternary time. An extensive volcanism with tholeiitic tendency (transitional to calc-alkaline) developed in the Pliocene-Lower Pleistocene in Guanacaste (IIL and PNL) in the same place of the actual Cordillera de

Table 6

Average whole rock wet chemical analyses of Guanacaste lavas

Sample		SiO_2	TiO_2	Al_2O	FeO*	MnO	HgO	CaO	Ha_2O	K_2O	P_2O_5	V	Cr	Co	Ni	Cu	Rb	Sr	V	Zr	Hb	Ba	La	Ce	Th
Orosi	Heah	51.50	0.72	19.03	8.91	0.14	5.27	10.03	2.51	0.63	0.12														
Volcano (1)	V. Max.	53.49	0.98	19.63	9.58	0.21	6.70	11.11	3.01	0.83	0.21	250	46	29	24	42	15	80	19	75	1	431	10	27	4
	V. Min.	50.32	0.60	18.01	8.46	0.07	3.20	8.47	2.18	0.47	0.09														
Cacao	Mean	55.19	0.59	17.01	8.18	0.18	4.66	8.85	2.62	1.04	0.15	221	39	26	18	28	23	511	20	89	2	870	7	51	1
Volcano (2)	V. Max.	61.77	0.65	18.06	9.86	0.19	6.97	11.51	3.36	1.64	0.251														
	V. Min.	49.90	0.54	16.20	6.37	0.16	2.50	6.26	1.84	0.62	0.08														
Rincón de la	Mean	58.21	0.70	16.81	7.38	0.13	3.56	7.27	3.00	1.75	0.16														
Vieja	V. Max.	62.29	0.80	18.37	8.37	0.18	5.05	8.29	3.40	2.95	0.22	185	33	23	16	26	45	491	22	139	5	1044	28	63	4
volcano (3)	V. Min.	56.43	0.52	15.41	4.99	0.08	0.93	4.29	2.59	1.37	0.15														
Miravalles	Mean	57.48	0.71	17.75	6.96	0.15	3.43	7.30	3.26	1.57	0.21														
volcano (4)	V. Max	62.79	0.86	20.57	8.73	0.21	5.13	10.01	3.74	2.47	0.28	170	58	47	11	46	37	591	24	125	6	1143	29	40	3
	V. Min.	50.51	0.57	15.89	5.57	0.13	2.52	5.59	2.52	0.51	0.14														
Tenorio	Mean	56.48	0.68	17.88	7.53	0.16	3.90	7.98	2.96	1.06	0.16														
volcano (5)	V. Max.	58.77	0.82	18.98	9.50	0.19	5.60	9.98	3.29	1.35	0.27	218	35	25	17	21	23	580	20	94	2	802	13	32	3
	V. Min.	50.52	0.57	17.09	6.31	0.13	2.90	5.72	2.53	0.53	0.10														
Bijagua lava	Mean	60.29	0.59	17.40	6.41	0.15	2.38	6.71	3.20	1.21	0.15														
dones (6)	V. Max.	61.07	0.68	18.21	7.01	0.16	2.80	7.28	3.40	1.26	0.22	181	23	22	15	18	26	505	20	95	3	912	13	31	4
	V. Min.	59.60	0.54	16.62	5.80	0.14	1.57	5.90	3.10	1.15	0.13														
Cañas Dulces	Mean	66.95	0.63	16.76	4.02	0.13	0.89	2.93	3.24	2.83	0.16														
Lava	V. Max.	70.14	1.01	21.62	6.41	0.19	1.77	4.84	4.41	3.65	0.23	63	1	12	8	10	96	333	25	276	12	1605	42	78	9
domes (7)	V. Min.	60.22	0.40	13.64	2.81	0.09	0.25	0.87	2.14	2.21	0.09														
Basaltic	Mean	49.59	0.79	18.55	9.37	0.18	6.40	10.20	2.51	0.67	0.24														
isolated	V. Max.	50.29	0.84	19.20	9.56	0.18	7.99	10.76	2.75	0.68	0.30	233	151	32	41	62	17	773	20	94	3	653	24	52	3
lavas (8)	V. Min.	48.79	0.76	17.35	9.20	0.18	5.31	9.25	2.38	0.66	0.18														
Intra-ichimbrite	Mean	59.24	1.03	15.53	7.92	0.16	1.68	6.02	3.07	2.29	0.34														
lava flows (9)	V. Max.	64.13	1.31	16.90	10.26	0.23	3.00	8.20	3.31	3.10	0.44	192	10	25	13	28	47	486	24	145	6	1245	36	86	2
	V. Min.	54.62	0.84	13.98	5.85	0.05	0.86	4.34	2.73	1.15	0.27														
Pre-	Mean	58.30	0.71	17.25	7.25	0.16	2.96	7.02	3.30	1.47	0.19														
Neovolcnic	V. Max.	66.59	0.91	20.16	10.76	0.21	5.06	9.25	4.22	2.61	0.29	194	33	24	16	31	40	531	22	124	5	982	23	54	4
lavas (10)	V. Min.	51.90	0.54	14.77	4.81	0.12	0.66	3.70	2.50	0.61	0.13														

(1)=average of 8 major and 6 trace elements of basaltic andesites; (2)= average of 8 major and 4 trace elements of andesites, (3)= average of 32 major and 22 trace elements of dacites and andesites; (4)= average of 53 major and 45 trace elements of andesites; (5)= average of 24 major and 20 trace elements of andesites; (6)= average of 6 major and trace elements of andesites and dacites; (7)= average of 7 major and 6 trace element analyses of dacite and rhyolite; (8)= average of 5 analyses of basaltic lavas; (9)= average of 5 major and 4 trace elements; (10)= average of 41 major and 25 trace elements of andesitic and dcitic lavas.

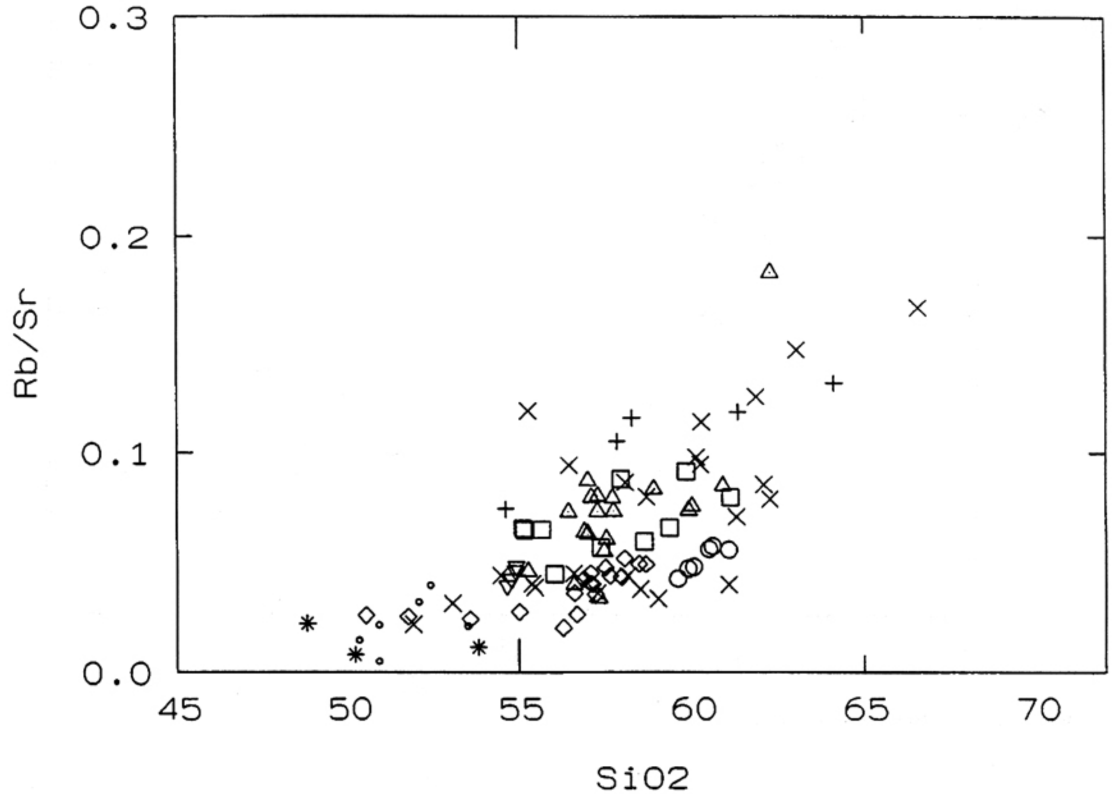

Fig. 8: SiO_2 vs Rb/Sr for Guanacaste lavas.

Guanacaste and in the Tempisque Intrabasin. The neovolcanism of Cordillera de Guanacaste began in the Middle Quaternary age and continuous to the present. The main rocks are calc-alkaline but the basic members show tholeiitic characteristics. Other, like Corobicí cinder cone, show alkaline tendency, that can be explained by the Carr et al. (1990) mixing model through a possibly regional fault parallel to the VF.

4) Gill (1981) suggests that where shallow magma chambers exists (<20 km deep) they usually underlie volcanoes with historic eruptions of andesites or dacites. In contrast magma reservoirs extending into the upper mantle normaly underlie volcanoes whose most recent eruptions are basalts or basaltic andesites. In the case of Cordillera de Guanacaste, the most recent andesitic eruptions (prehistoric lava flows and tephras) are in the Rincón de la Vieja, Tenorio, Miravalles volcanoes and several historical andesitic phreatomagmatic eruption at Rincón de la Vieja volcano. Basaltic prehistoric eruptions (Upper Pleistocene) are in the case of Mata Redonda lava flows (Orosí complex), Chopo and Corobicí pyroclastic cones (Fig.2 and 13). In effect, the Lower-Middle Pleistocene pumice-flow deposits have their posssible source near the old volcano tectonic structures between Rincón de la Vieja and Tenorio volcanoes. Civelli (1990) and Chiesa et al. (1992) support the idea of the presence of a high level magma chambers, as discussed above, for these andesitic volcanoes.

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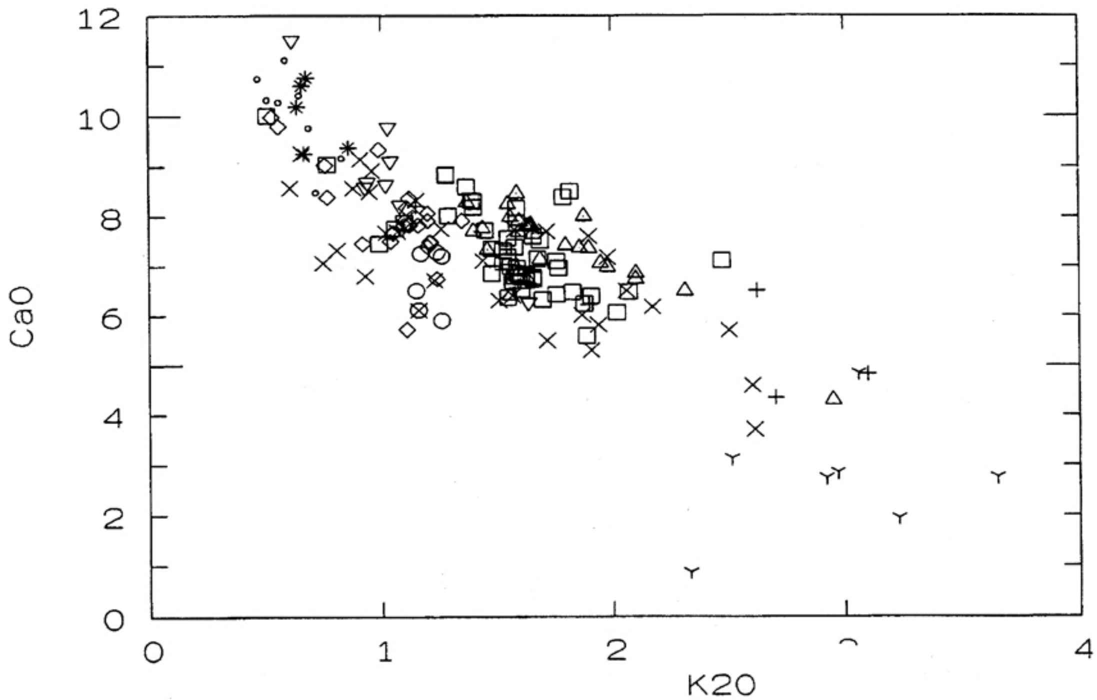

Fig. 9: K_2O vs CaO for Guanacaste lavas.

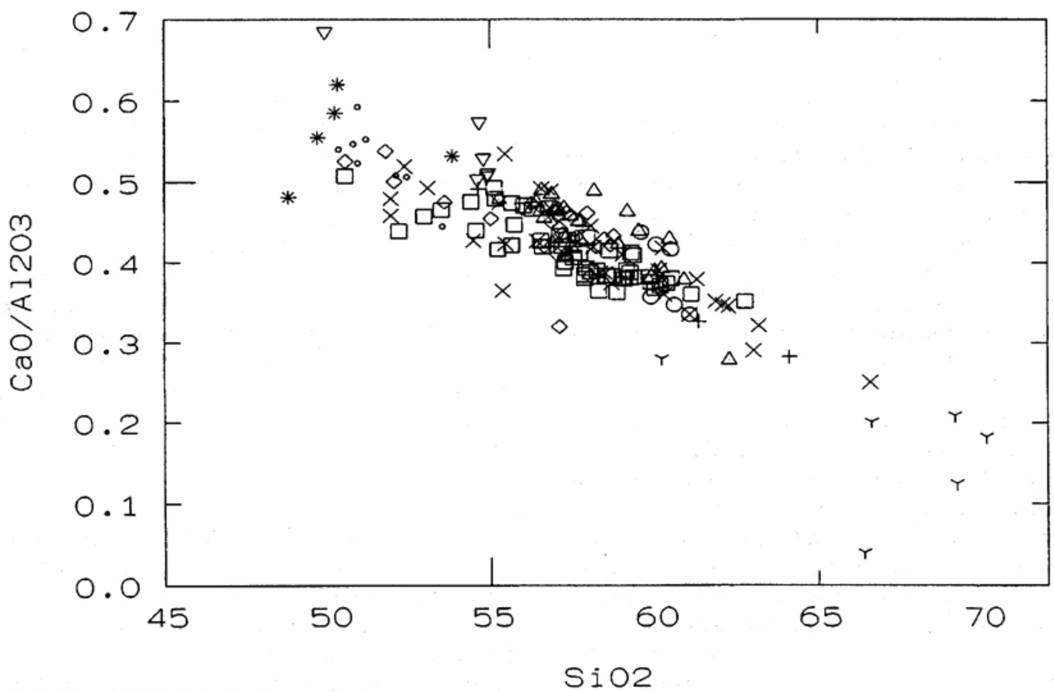

Fig. 10: SiO_2 vs CaO/Al_2O_3 for Guanacaste lavas.

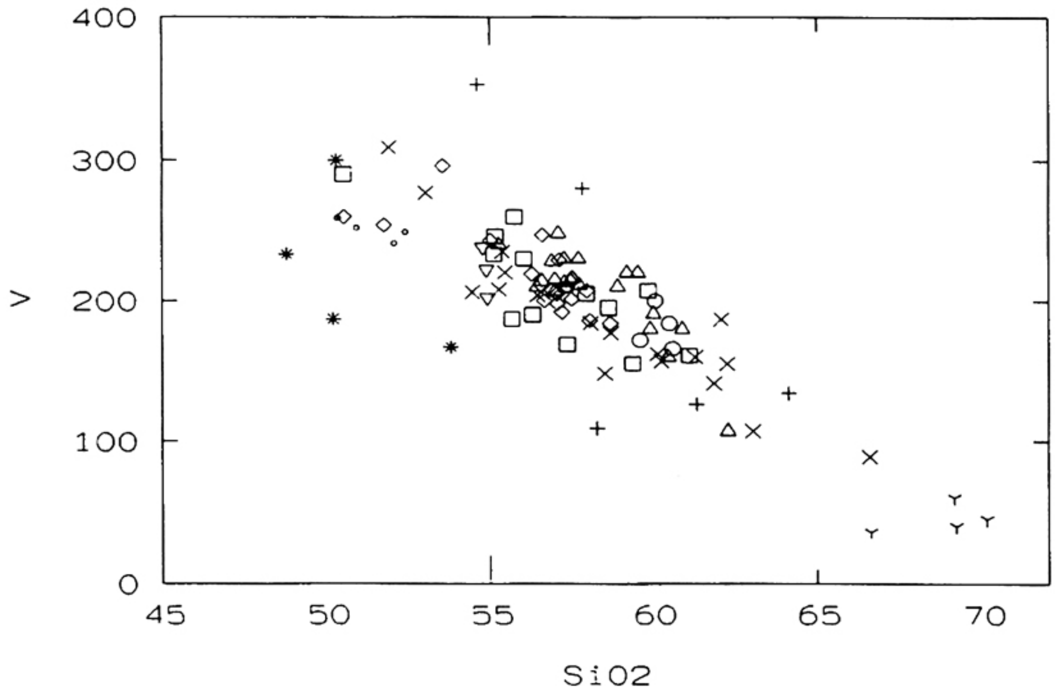

Fig. 11: SiO_2 vs V for Guanacaste lavas.

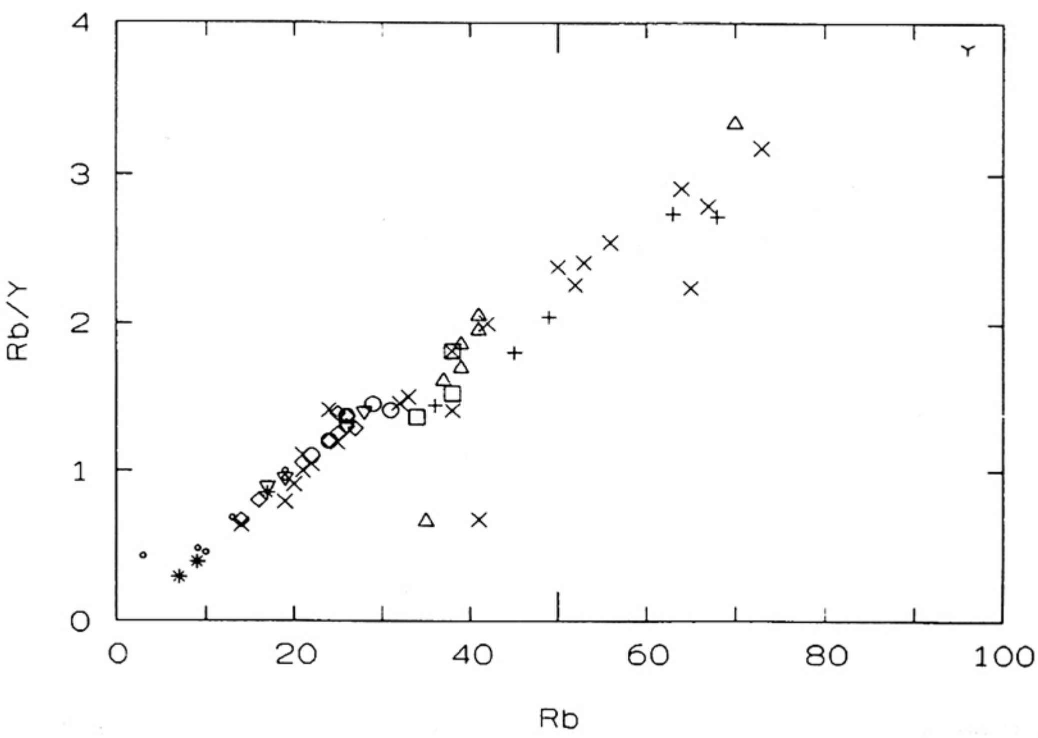

Fig. 12a: Rb vs Rb/Y and Rb vs Rb/Sr for Guanacaste lavas.

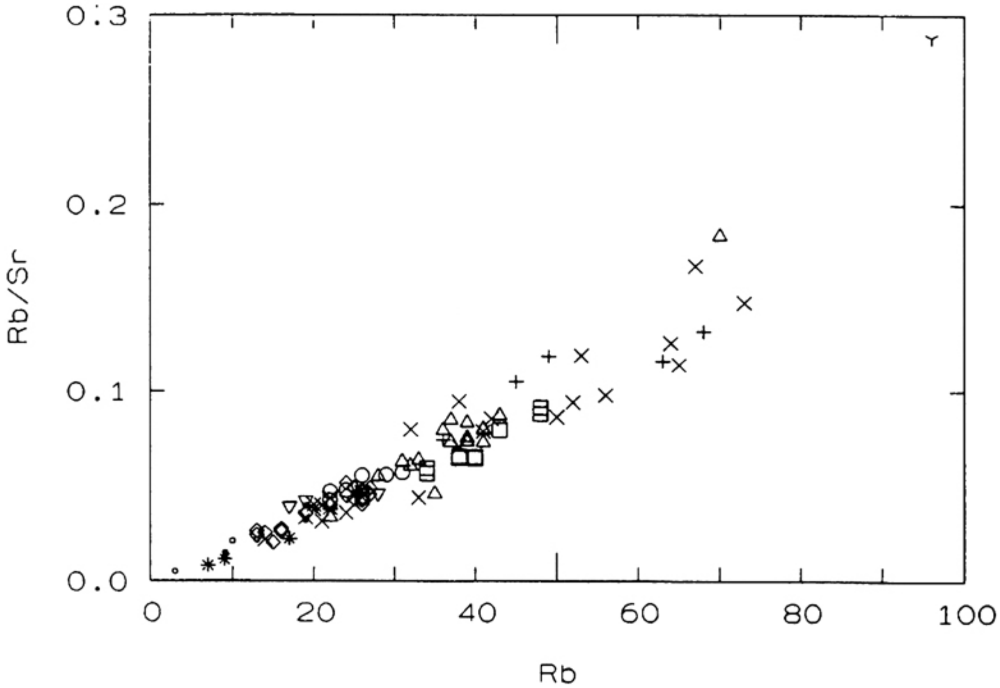

Fig. 12b: Rb vs Rb/Y for Guanacaste lavas

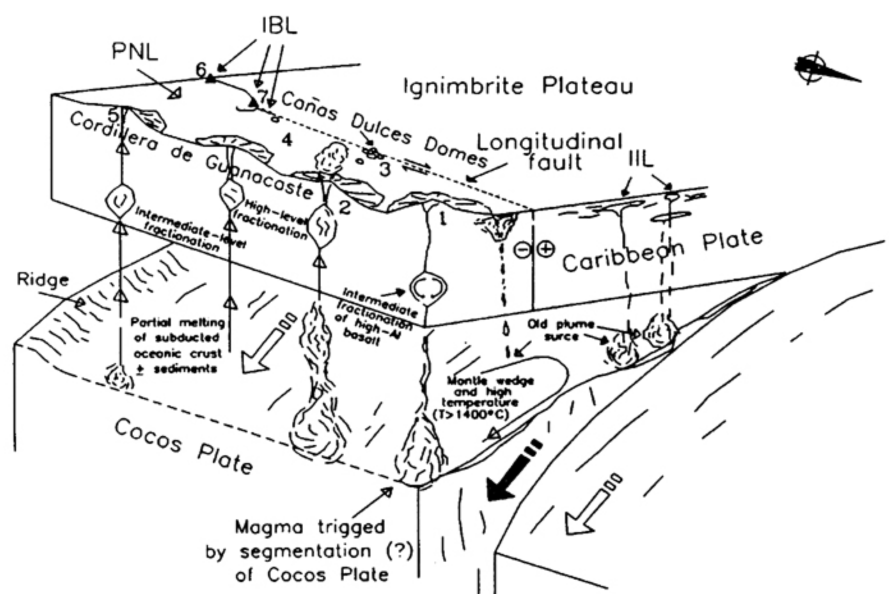

Fig. 13: General model for magma generation in the Cordillera de Guanacaste. 1. Orosí-Cacao volcanoes, 2. Rincón de la Vieja-Santa María, 3. Cañas Dulces domes, 4. Miravalles-Guayabo volcanic complex, 5. Tenorio-Montezuma volcanoes, 6. Chopo and 7. Corobicí cinder cones and other basic (basalts and basaltic andesites) outcrops.

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