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CHRONOSTRATIGRAPHY OF UPPER MIOCENE-QUATERNARY VOLCANISM IN NORTHERN COSTA RICA

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ABSTRACT: The Santa Rosa ignimbritic plateau (Bagaces Formation) of Upper Miocene to Late Pliocene age (between 8 to 1.6 m.y. ago), in the north of Costa Rica, consists of a pile of pyroclastic flow deposits with minor interbedded lava flows and terrigenous sediments overlain by several pumice flow deposits (volume ca. 50 km^3 DRE): Río Liberia pumice-flow Formation (ca. 1.6 m.y. ago), Guayabo Pyroclastic Formation (between 1.5-0.6 m.y. ago), and Cañas pumice-flow deposit (< 1 m.y.), and topped by the recent volcanic centers of the Guanacaste chain (< 600 000 years ago). This succession has been sampled for K-Ar dating. Aditional rocks were collected from the region between the Arenal volcano (active since 1968) and the Monteverde andesitic plateau in the north (2-1 m.y. ago). There are also more examples of relatively recent volcanism in this region, for example the San Miguel dome (< 0.7 m.y. ago) in the fore arc, and Los Perdidos complex (caldera and domes) of Upper Quaternary age (ca. 0.1 Ma), which is overlaped by the dormant Chato volcano (38-3.5 x 10^3 years old) near the actual volcanic front. The total volume of volcanic rocks erupted during the Quaternary is equivalent to about 900 ± 150 km^3 of dense rock. The volume of basaltic andesitic magma is several times larger than the volume of silicic magma erupted during the same period. The age of silicic volcanism precedes and overlaps with the age of the Quaternary andesitic volcanic front, which is largely younger than 600 000 years. This study demonstrates that in the geodynamical evolutin of the Southern Central America Orogen Volcanism is one of alternating periods of huge volcanic activity separated by periods of relative reposal.

RESUMEN: En el norte de Costa Rica, una sequencia de flujos piroclásticos con coladas de lava intercaladas, constituye la plataforma ignimbrítica de Santa Rosa (Formación Bagaces) del Mioceno Superior al Plioceno tardío (entre 8 y 1,6 m.a.), sobreyacida por varios depósitos de flujos de pómez (volumen total de aprox. 50 km^3, roca densa equivalente, DRE): las formaciones Río Liberia (~ 1,6 m.a.), Guayabo (1,5 a 0,6 m.a.) y Cañas (≤ 1 m.a.), y cubierta parcialmente por los productos de los estratovolcanes Cuaternarios (< 600 000 años). Adicionalmente, se colectaron muestras de rocas en los alrededores del volcán Arenal y en la región de Monteverde, en donde se ubica la plataforma andesítica del mismo nombre (2-1 m.a.). En esta región se localiza un vulcanismo relativamente reciente representado por el domo San Miguel, y los domos de los cerros Los Perdidos (ca. 0,1 m.a.) que están sobreyacido por los productos del volcán Chato (38-3,5 x 10^3 años). El volumen de rocas volcánicas eruptadas en la región norte del país durante el Cuaternario es de unos 900 ± 150 km^3 en los últimos 2 m.a., en el cual el volumen de magma basáltico andesítico es varias veces mayor con respecto al volumen de magma ácido. La edad del vulcanismo ácido precede y se interdigita con la del vulcanismo del frente volcánico andesítico Cuaternario. El presente estudio demuestra que el patrón geodinámico del orógeno sur de América Central se desarrolla acorde con fases de intensa actividad volcánica separada por períodos de reposo relativo.

INTRODUCTION

The Cordillera de Guanacaste is composed of a nortwest-southeast aligned chain (80 km long) of complex stratovolcanoes: Orosí-Cacao, Rincón de la Vieja-Santa María, Miravalles-Zapote and Tenorio-Montezuma volcanoes. Of these volcanoes only Rincón de la Vieja is active. Other cones, however, show morphological features or residual activity which suggest that they were active during the Upper Quaternary (Alvarado 1989b) (Fig. 1).

The Tilarán chain is composed of Neogene orogenic volcanic rocks and intrusive

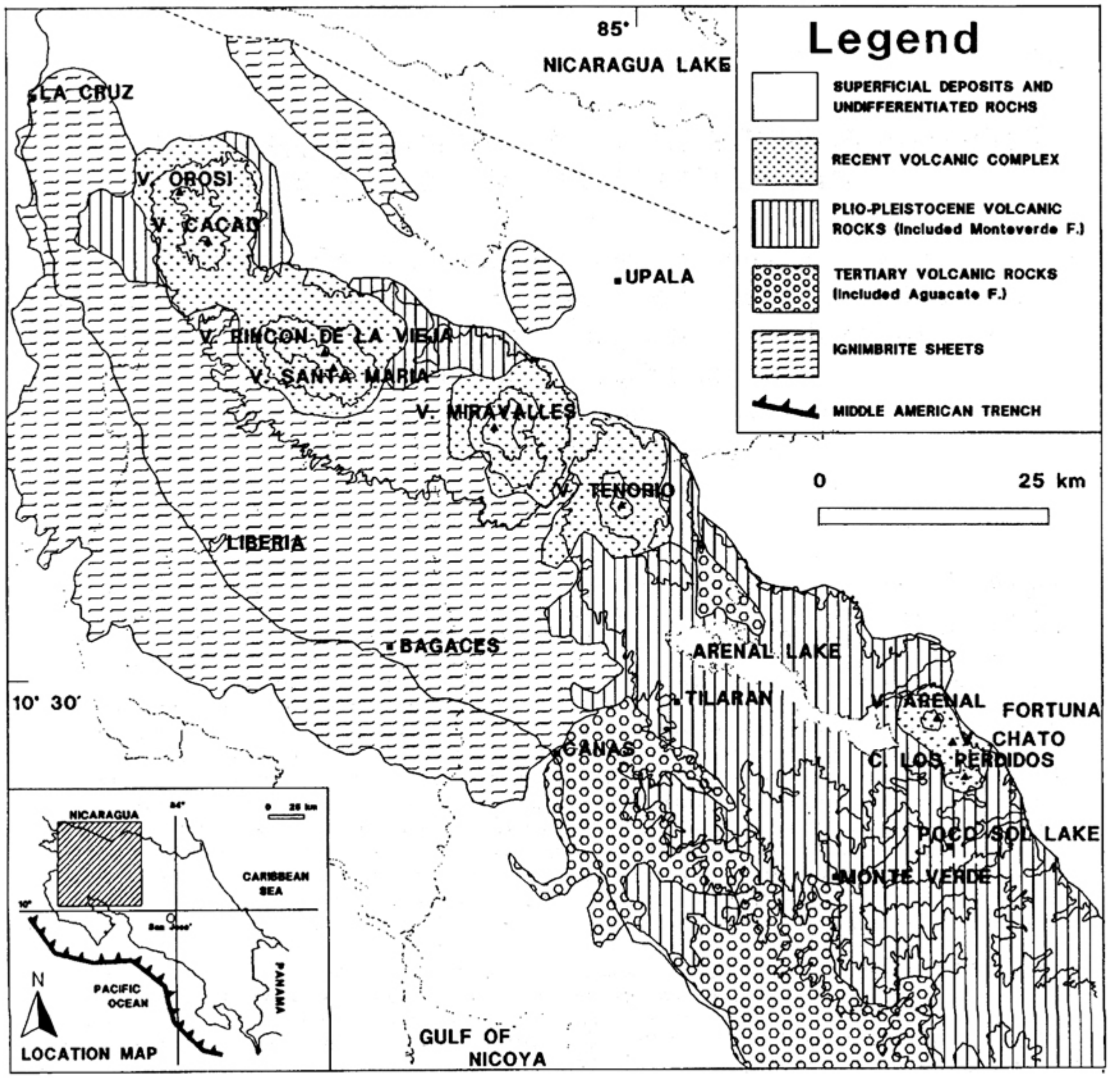

Fig. 1: General geological map of the Guanacaste region.

batholits/stocks, covered by the Quaternary Monteverde Andesitic Plateau and silicic domes (Cháves & Sáenz 1974; Schulz et al. 1987). The Monteverde formation was intruded by rhyolite-dykes (Schultz et al. 1987). The San Miguel acid volcanic dome (Alvarado, 1984) for example, on the southwestern flank of the Cordillera de Tilarán, is consequently very young (< 0.7 m.y., Appel, 1990). In general, the Costa Rican volcano-plutonic arc is the result of Cocos-Caribbean plate convergence. Volcanic rock compositions indicate that crystal fractionation was the main petrological process envolved in the development of this orogenic subalkaline chain (Table 1).

A number of recent studies have contributed to the improved understanding of the stratigraphical, structural and petrological aspects of the volcanic rocks in Guanacaste. All large-scale volcanic structures and principal geological units (Chiesa, 1991; Chiesa et al. 1987, 1992; Alvarado et al. 1993) have been established by detailed mapping. Here we present new K-Ar dating of the principal volcanic events in northern Costa Rica together with brief geological descriptions and

Table 1

Chemical composition of the analyzed volcanic rocks

Muestras	πG 49Y	πG 49Z	πG 50A	πG 50B	πG 50C	MZ 37	H 63	πG 49P	πG 49O
SiO_2	55.56	48.52	62.30	62.09	54.13	59.36	75.16	73.80	72.73
TiO_2	0.81	0.75	0.50	0.49	0.59	0.69	0.23	0.20	0.25
Al_2O_3	17.00	17.39	17.50	17.60	21.06	17.16	13.11	12.69	14.66
Fe_2O_3	3.68	2.59	2.85	2.34	0.45	2.04	0.00	1.20	1.31
FeO	3.99	6.51	3.29	3.58	6.13	4.33	1.78	0.00	0.66
MnO	0.18	0.18	0.18	0.18	0.15	0.15	0.07	0.07	0.05
MgO	3.9	6.24	1.80	1.70	2.52	2.72	0.59	0.12	0.34
CaO	7.75	10.82	5.70	6.02	9.04	6.13	1.76	1.30	2.13
Na_2O	3.26	2.34	3.40	3.70	3.60	3.58	2.80	2.55	3.68
K_2O	2.57	1.04	1.75	1.76	1.19	2.94	4.26	3.65	3.09
P_2O_5	0.26	0.14	0.16	0.16	0.19	0.22	0.02	0.03	0.02
H_2O	2.13	3.79	1.50	1.17	0.72	1.23	0.00	5.03	0.99
Total	101.09	100.31	100.93	100.79	99.77	100.55	100.00	100.64	99.91

discussion of significant events. This chronologic study of the volcanic province records activity over a long period time.

THE K-Ar METHODOLOGY

The method of K-Ar dating developed in the Centre des Faibles Radiactivités (joint laboratory CNRS-CEA) in France, corresponds to the conventional K-Ar method, in which potassium and argon are analysed (natural K is dosed by flame photometry, flame emission and atomic absorption, and argon is isotopically measured by mass spectrometry). The technique for argon analysis has been adapted for the dating of very young rocks by improving the accuracy and precision of estimated contaminant 40 argon. It consists of a direct comparison of atmospheric argon and argon extracted from the sample under rigorously controlled, identical analytical conditions, this permits the measurement of the significant proportion of radiogenic argon to as low as 0.12 %. It corresponds typically to some 10^3 years in a 1 % potassic lava and allows dating of lavas around 50 000 years old with an accuracy better than 10 %. This accuracy is partly conserved when dating old material, but over half a million years, the relative uncertainty in the dosage of the potassiun limits the accuracy to about 1.7 % of the age value. In order to profit from this high level of accuracy, it is necessary to select the material suitable for dating. In the lava flow samples, the groundmass is selected, which corresponds to the part of the magma which solidified at the moment of emplacement, under atmospheric conditions. The xenocrysts and all early crystallized minerals are eliminated as the may contain inherited radiogenic 40 argon which results in an over-estimation of the age. When possible, different mineral phases are separated and compared with an internal test of coherence for the dating. For example, in the case of the ignimbrites units (Bagaces, Liberia and Guayabo formations), diverse mineral phases have been separated and their K-Ar ratios have been compared. The glass from pumice clast, and the plagioclase and the biotite phenocrysts were selected from samples of the biotitic-pumice flow deposit. The coherence of the apparent potassium-argon ages at the level of 10^5 years is an internal checking or act as a control, confirming the age at around 1.6 Ma. Small discrepancies between the different phases are interpreted to be the result of a small amount of inherited radiogenic 40 argon in the mineral, or the effect of a slight alteration with possible migration of potasium and/or argon.

CHRONOSTRATIGRAPHY AND VOLCANO-TECTONIC EVOLUTION

One of the most fundamental aspects of the magmatic evolution of the northern part of Costa Rica in terms of the dynamic history of geotectonic-magma-volcanism, is the succession of magmatic phases in the Guanacaste and

Tilarán/Arenal region. This region has been divided into two areas:

Guanacaste Ignimbrite-Plateau

An extensive ignimbrite sequence (ca. 2 400 km^2) is present principaly in the Pacific watersheds of the Guanacaste range, flanking the stratovolcanoes and exposed in fluvial valleys. The Meseta de Santa Rosa ignimbrite plateau in Guanacaste is composed of andesitic-dacitic pyroclastic sheets, often without hydrous minerals (Tournon, 1984; Chiesa et al., 1987, 1992), with interbedded continental sedimentary deposits, lava flows and thick paleosoils (Lower Ignimbrite Sequence *sensu* Tournon, 1984, or Bagaces Formation *sensu* Dengo, 1962). The K-Ar data demostrate that huge explosive events separated by large repose phases occured over a long period of time between 8 m.y. and ca.1.6 m.y. ago (Table 2). From the distribution of the facies it appears that the vents were probably aligned as in the present volcanic front, perhaps shifted slightly to the southwest. The oldest ignimbrite in this sequence is the Carbonal pyroclastic flow deposit (dacitic-vitrophiric lava-like flow) dated in 7.8 Ma (sample 49S, Table 3 and Fig. 2). Gardner & Turin (in Alvarado et al., 1993) reported a preliminary age of 6.5 Ma. The volume of the Lower Ignimbrite Sequence is more than 150-180 km^3, which corresponds to 100 ± 40 km^3 DRE of dacitic magma (Table 2).

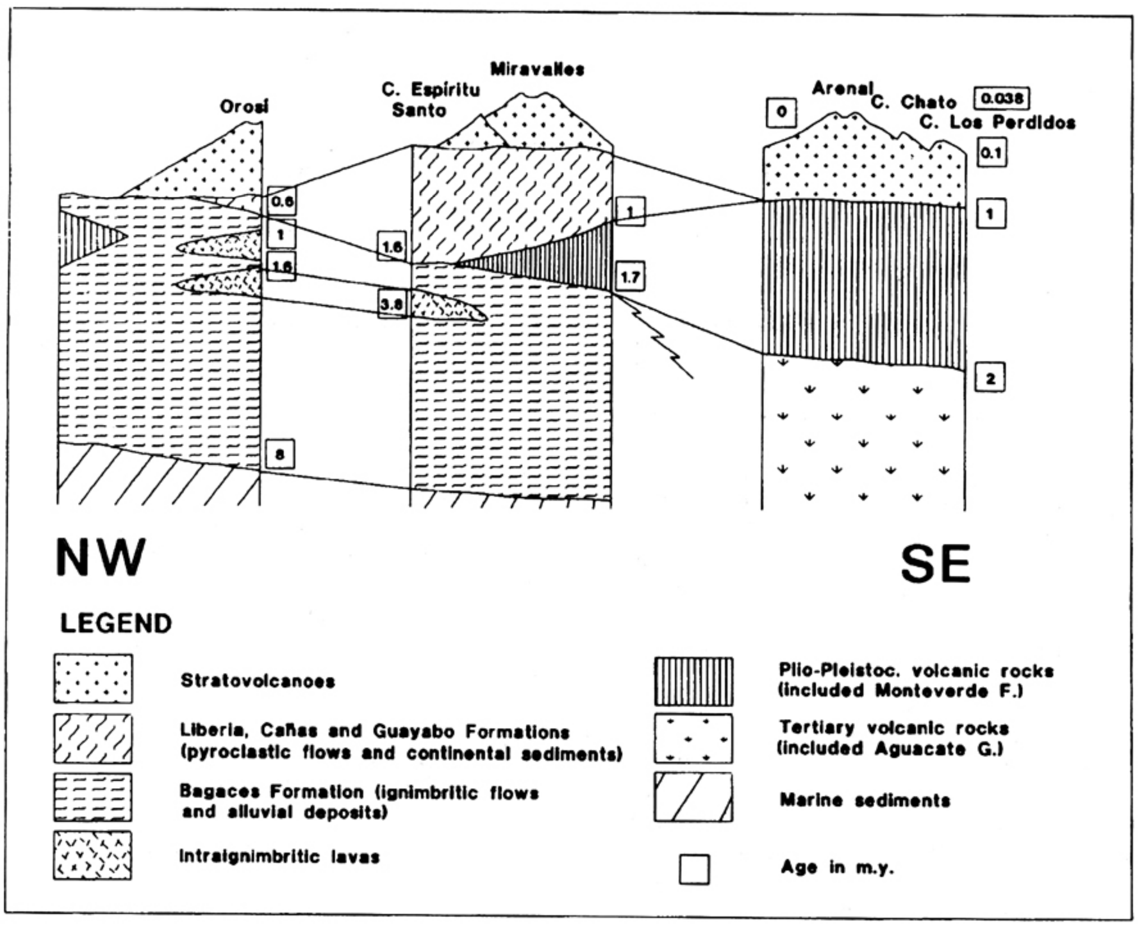

Fig. 2: Stratigraphic correlation of the Guanacaste-Arenal region.

Table 2

Age and estimated volume of different formations in Northern Costa Rica

Name Formation	Age (Ma)	Volumen (DRE, Km3)	References
Bagaces	8 - 1.6	100 ± 40	in this work
Río Liberia	ca. 1.6	25 ± 2	Chiesa (1991)
Guayabo	1.4 - 0.6	15.5 ± 5	Chiesa et al. (1992)
Monteverde	2 - 1	400 ± 100	Alvarado et al. (1993), in this work
Stratovolcanoes	0.6 - 0	460 ± 40	Alvarado et al. (1993), in this work
Total		1000 ± 187	

Table 3

Dataciones con el método K-Ar

Muestra, mineral		Tipo de roca Long., Lat., Cota	Localización 1011at.g-1		K %	40Ar* %	40Ar	Edad (Ma)
πG 50C,	masa de fondo	Andesita	461.8,271.1,	250	0.701	1.23	0.278	0.038±0.004
πG 50A,	masa de fondo	Dacite	462.2,267.4,	650	1.262	5.22	1.098	0.083±0.003
						3.68	1.101	0.084±0.003
πG 50B,	masa de fondo	Dacite	462.0,265.3,	1050	1.180	7.13	1.148	0.094±0.003
						7.18	1.214	0.099±0.003
πG 49P,	vidrio	Ignimbrita	400.5,295.0,	500	2.80	6.81	16.84	0.580±0.012
	plagioclasa				0.394	7.43	2.60	0.620±0.010
MZ 37,	masa de fondo	K-andesita	477.5,254.6,	1080	3.064	63.29	41.01	1.281±0.020
						58.76	41.49	1.301±0.020
πG 49Y,	masa de fondo	K-andesita	462.3,258.9,	830	2.305	4.14	30.87	1.282±0.040
						4.37	31.63	1.313±0.040
πG 49Z,	masa de fondo	Al-basalto	466.4,259.9,	500	0.549	0.34	6.40	1.117±0.350
						0.39	7.31	1.275±0.350
						0.39	7.47	1.303±0.350
πG 490,	vidrio	Ignimbrita	390.5,278.4,	340	3.52	40.14	51.22	1.393±0.030
						39.68	52.20	1.420±0.030
	plagioclasa				0.59	33.66	11.25	1.83 ±0.030
	biotita				4.93	4.37	82.92	1.61 ±0.060
H63,	anfibol	Ignmbrita	405.9,283.6,	200	0.342	2.53	5.20	1.456±0.036
πG 49A,	vidrio	Ignimbrita	400.0,286.3,	260	3.39	4.78	56.63	1.600±0.050
						3.41	54.92	1.551±0.060
	plagioclasa				0.53	11.51	7.04	1.270±0.030
						32.91	7.25	1.310±0.030
πG 49S,	vidrio	Dacite	356.9,295.8,	10	3.01	47.69	246.0	7.810±0.160
						43.34	250.9	7.990±0.160
	plagioclasa				0.692	31.50	21.52	7.850±0.160

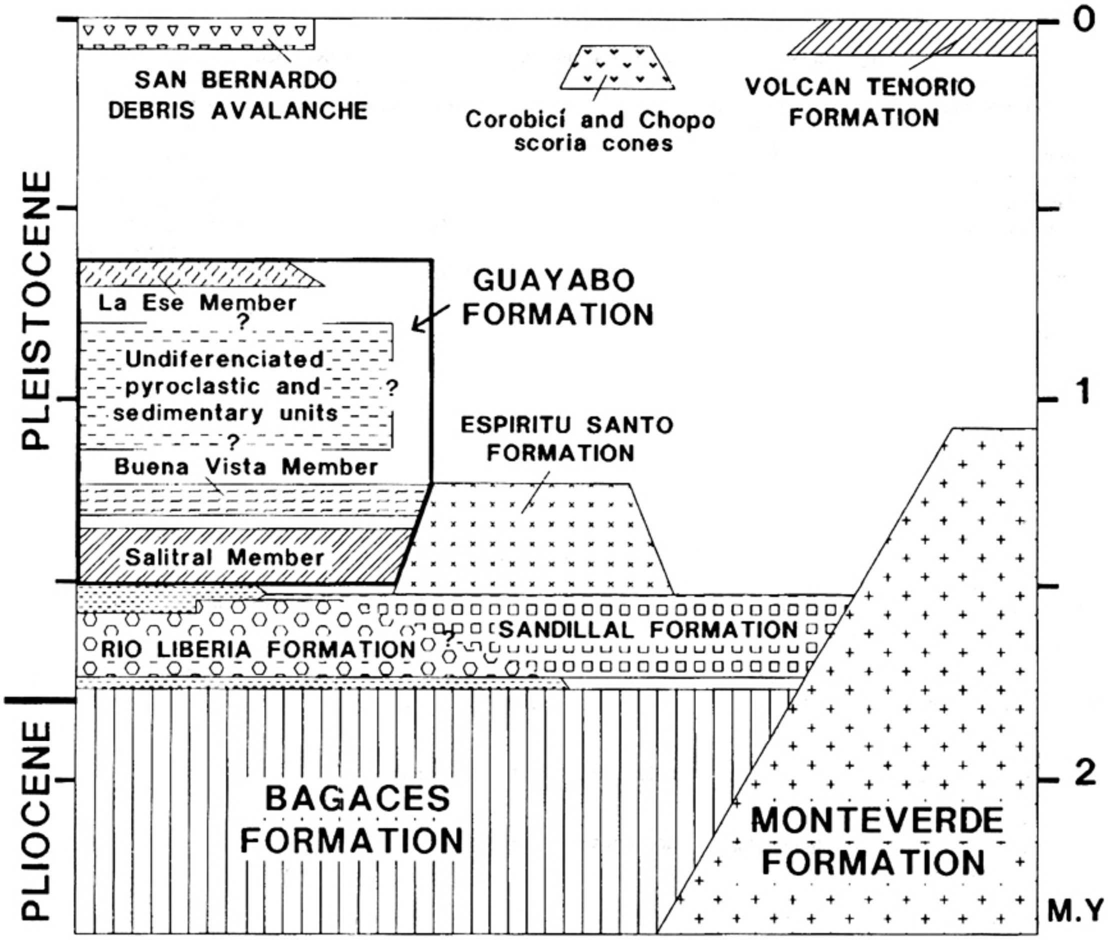

Fig. 3: Generalized stratigraphic sequence of the central sector of the Guanacaste region.

The volume of andesitic volcanism during the Upper Miocene, that corresponds to the Aguacate volcanism, was not calculated.

The Lower Ignimbrite Sequence is overlaped by pumice flow deposits (dacitic to rhyolitic composition), often with hydrous primary minerals (Río Liberia, Cañas and Guayabo Formation) of Lower to Middle Quaternary age (Table 2). One of these, is the deposit of the greatest known ignimbrite eruption in the Quaternary time at Guanacaste, the Río Liberia Biotitic-Pumice Flow deposit, which forms a marker horizon (Chiesa, 1991). It is a crystal-rich pyroclastic flow deposit (Qz-Biot-Hb-Ox-Plag An_{30-35}) covering an area of ca. 4000 km^2, which corresponds to 34 km^3 of ignimbrite erupted volume (about 25 km_3 of rhyolitic magma). The age of this flow is about 1.6 Ma, representing approximate the boundary between Pliocene and Quaternary periods (samples G49 A and O, Table 3). The stratigraphic position of the Cañas pumice flow deposit is no yet clear, but it is slightly older than 1.1-1.7 m.y. because it underlies basaltic andesite lava flows of the Monteverde Formation at Cañas (see Alvarado et al., 1993), and therefore, may be older than Río Liberia pumice flow deposit.

In the Miravalles area, above the marker horizon, there are several dacitic-rhyolitic pumice flow deposits which are associated to the Guayabo-Cabro Muco caldera system (Mora

1988; Civelli,1990, Chiesa et al. 1992). These Pleistocene pyroclastic flow deposits (ca. 1.45 to 0.6 m.y.) show a progressive decrease in volume (ca. 6.23, 5.3, and 3.7 km^3 DRE) and record a decrease eruptive energy, from the oldest to the youngest (Chiesa et al., 1992). There is a large interval of ca. 0.8 m.y. (from 1.4 to 0.6 m.y.) however, without important ignimbrite deposits from the Guayabo caldera. Nine deep drill holes exist in the Guayabo caldera from the Miravalles Geothermal Project (ICE), but, correlation between the extracaldera ignimbrites and the intracaldera pyroclastic deposits has not yet been established. In adition, the intracaldera volume may affect the total volume estimate by as much as a factor of 2 to 3 (cf. Smith, 1979).

Cordillera de Tilarán-Arenal volcano

Southeastward, in the Arenal-Monteverde sector, an important phase of effusive volcanism rapidly developed a large plateau between 2 and 1 m.y. ago (Alvarado et al., 1993; in this work). This is the largest known Lower Quaternary andesitic fissural and coalesced shield eruption in Costa Rica (principally arround 1.3 m.y.) and took place in Monteverde, Peñas Blancas, Tilarán, Poco Sol, Hacha and Montes del Aguacate area (samples MZ 37, G 49Y, and G 49Z) covering an area of 1200 km^2, corresponding to the Monteverde Formation. In some areas the Monteverde andesitic flows covered pumice flow deposits in the Cordillera de Tilarán in the boundary between the Tilarán and Central volcanic chain.

In the sample from Peñas Blancas river (G 49Z, Table 3), the analytical uncertainty is rather large because of a very high contamination level due to alteration and poor quality of the sample which was, moreover, slightly zeolitized. The radiogenic 40 argon level thus appears very low (less than 0.5 %) in comparison to the lavas of the same age. Inspite of the poor accuracy of this rock, the results obtained from other three samples from the same unit at Poco Sol lake, Monteverde (the type locality) , and Peñas Blancas river, show a similar age.

Subsequent volcanism is limited to activity along a NNW-SSE alignment. These data correspond to those of the Perdidos caldera where intracalderic andesitic and hornblende andesitic domes gave ages of ca. 100 000 years (samples G-50A and G-50B, Table 3), and an old Chato andesitic lava flow of 38 000 years (sample 50C). Borgia et al. (1988) described Chato's last activity in 3 500 years before present and the first volcanic activity of Arenal volcano, about 3 000 years ago. Morphological (Alvarado, 1984, Alvarado et al., 1988) and chronological evidences suggest that eruptive activity migrated progressively northwards from the Poco Sol phreatic-explosive crater, to Los Perdidos and then Chato volcano, and finally to the presently active Arenal volcano.

CONCLUSIONS

A general model of evolution for volcanic activity in the Guanacaste and Tilarán ranges has been compiled using field observations and chronological studies. Our K-Ar data highlight the extensive and complex volcanological history in the northern part of Costa Rica from Upper Miocene to present. The pyroclastic activity, coeval with the volcanics of the Aguacate Group (Miocene-Pliocene) which developed in the Central and southern Costa Rica, characterizes the volcanism of Guanacaste from Upper Miocene to Lower Pleistocene. According to our dates, the uplift in the northern part of Costa Rica was not significant in the last 8 m.y. as indicated by only minor variations in height and dip of the tilted ignimbrite sheets. On other hand, evidence from drill holes indicates that ignimbrites are present below the current sea level, which suggests subsidence and subsequent uplift. In the Quaternary, positive recent crustal movements in the pacific cost of Guanacaste are well constrained (Miyamura, 1975; Fischer, 1980; Madrigal & Rojas, 1980) although further study is required.

The Upper Ignimbrite Sequence ($\leq$ 1.6 m.y.) was emplaced during the same period as the Monteverde Formation (Fig. 3). The reason for the abrupt onset of effusive volcanism about 1 m.y. ago and the cause of the gap in the volcanism in the Tilarán range between 1 m.y. and < 0.7 m.y. (San Miguel and Perdidos domes) is not yet clear. Volcanological, neotectonical and seismological evidence (Alvarado, 1989a), and geological and chronological data (Alvarado et al., 1993; this work) show, however, that the Tilarán Volcano-Tectonic Horst is still active.

K-Ar dating has been used to demostrated that the geodynamical pattern of volcanism in the "Southern Central American Orogen" is one of alternating phases of hugely active periods separated by expanded periods of repose.

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