

New $^{40}\text{Ar}/^{39}\text{Ar}$ ages from the Central Part of the Chiapanecan Volcanic Arc, Chiapas, México

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Received: June 4, 2010; accepted: August 31, 2011; published on line: December 16, 2011

Resumen

El Arco Volcánico Chiapaneco (AVC; CVA = siglas en inglés) se localiza en la porción central del estado de Chiapas, es una cadena de estructuras volcánicas alineadas en dirección NO-SE de aproximadamente 150 km de longitud.

En su parte central el AVC está compuesto de al menos 10 estructuras volcánicas alineadas al Noreste y concentradas en fallas con rumbo NNO-SSE asociadas al Sistema de Fallas Motagua-Polochic.

Las estructuras son siete Domos Volcánicos (Huitepec, Amahuitz, La Iglesia, Mispía, La Lanza, Venustiano Carranza y Santotón), un Cráter de Explosión (Navenchauc), una Estructura de Colapso (Apas), y un Complejo de Domos Volcánico (Tzontehuitz).

En este trabajo, reportamos 13 nuevas edades $^{40}\text{Ar}/^{39}\text{Ar}$ de rocas de los siete domos que incrementan las dataciones disponibles para la actividad volcánica durante el Cuaternario, en la parte central del Arco Volcánico Chiapaneco. Con las nuevas dataciones y las reportadas en bibliografía se tiene al Complejo de Domos Tzontehuitz como la estructura más antigua 2.1 Ma y al Domo Volcánico Venustiano Carranza como el de actividad más reciente de 0.225 Ma.

Palabras clave: Arco Volcánico Chiapaneco, domos volcánicos, edades $^{40}\text{Ar}/^{39}\text{Ar}$.

Abstract

The Chiapanecan Volcanic Arc (CVA), located in the central portion of the State of Chiapas, is a 150 km long chain of volcanic structures aligned in a NW-SE direction.

The central part of the CVA is composed of an irregular northeast-trending alignment of more than 10 volcanic structures, generally centered along NNW-SSE trending faults splayed from the Motagua-Polochic Fault System. Among these structures are seven volcanic domes (Huitepec, Amahuitz, La Iglesia, Mispía, La Lanza, Venustiano Carranza, and Santotón), one explosion crater (Navenchauc), one collapse structure (Apas), and one dome complex (Tzontehuitz).

In this work, we report thirteen new $^{40}\text{Ar}/^{39}\text{Ar}$ ages of rocks from seven domes that increase the available geochronometric data on Quaternary volcanic activity in the central part of Chiapanecan Volcanic Arc. From the new and previous data, we identified the Tzontehuitz Dome Complex as the oldest volcanic center in the CVA, yielding an age of 2.1 Ma, and the Venustiano Carranza Volcanic Dome as exhibiting the most recent activity in the zone, with an age of 0.225 Ma.

Key words: Chiapanecan Volcanic Arc, volcanic domes, ages $^{40}\text{Ar}/^{39}\text{Ar}$.

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Introduction

The Chiapanecan Volcanic Arc (CVA), located in the central portion of the State of Chiapas, is a 150 km long chain of volcanoes irregularly aligned in a northwesterly direction between two more prominent volcanic features: the Trans-Mexican Volcanic Belt (TMVB) to the northwest and the Central American Volcanic Arc (CAVA) to the southeast. While both the TMVB and the CAVA have been the focus of numerous geological and geochronological studies (Demant, 1976, 1978; Nixon, 1982; Siebe *et al.*, 1995; Suter *et al.*, 1995; Aguirre *et al.*, 1998; Aguirre *et al.*, 1998; Ferrari, *et al.*, 1999; Wallace *et al.*, 1999; Aguirre and Carranza, 2000), the CVA has been relatively unmapped and poorly described until recently (Jaimes-Viera *et al.* 2004; Jaimes-Viera, 2006; Mora *et al.*, 2007). These authors have identified eight volcanic domes (Navenchauc, Huitepec, Amahuitz, La Iglesia, Mispía, La Lanza, Venustiano Carranza and Santotón), one explosion crater (Navenchauc), one collapse structure (Apas), and one dome complex (Tzontehuitz) within the CVA, and have documented changes in the eruptive style and chemical composition of the eruptive products of these volcanic centers.

The CVA lies in a tectonically complex region where three tectonic plates interact: the North American Plate, the Caribbean Plate, and the Cocos Plate (Figure 1). A zone of lateral

displacement and a zone of convergence define the boundaries between these plates. The first is characterized by a regional system of left-lateral strike-slip faults known as the Motagua-Polochic Fault System, formed by the eastward migration of the Caribbean Plate relative to the North American Plate, and the second is formed by the subduction of the Cocos plate under the North American and Caribbean Plates (Mora *et al.*, 2007).

Because of its geographic location, the CVA has a very important role in the geological evolution of the region. The purpose of this study is to demonstrate that the CVA volcanic activity is continuous from 2 Ma to the present and it is related to both the TMVB and CAVA.

Geologic setting and previous work.

The CVA was first described by Damon and Montesinos (1978) who named it "Modern Chiapanecan Volcanic Arc". These authors described it as a 150 km- long volcanic structure aligned NW-SE. Damon and Montesinos (1978) concluded that the CVA was formed as a result of a readjustment of the direction of plate motion of the Cocos Plate at 2.79 Ma; they believed it to be essentially continuous with the TMVB. Capaul (1987) renamed this arc the "Chiapanecan Volcanic Arc" (CVA), and described it as composed of Quaternary volcanoes, including El Chichón volcano, characterized by low eruptive

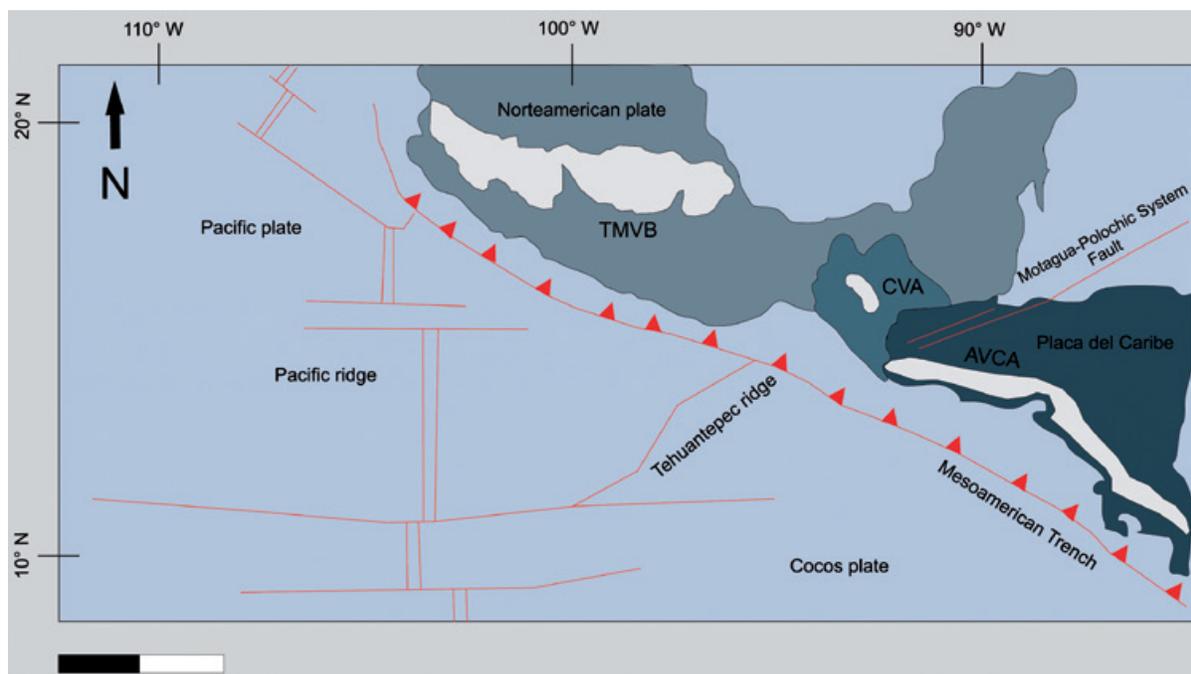


Figure 1. Location map and tectonic setting of the Chiapanecan Volcanic Arc (CVA), Trans-Mexican Volcanic Belt (TMVB) and Central American Volcanic Arc (CAVA).

volume and that were formed in a tectonically complex region of Chiapas. All eruptive products of the CVA have intermediate, calc-alkaline compositions except El Chichón which has some basic alkaline affinity (trachybasalts) (Capaul, 1987). Jaimes-Viera *et al.* (2004) conducted preliminary mapping of the central part of the CVA and showed 11 volcanic structures with deposits of pyroclastic flows and associated fall deposits (Figure 2; Damon and Montesinos, 1978; Capaul, 1987; Macias *et al.*, 2003; Jaimes-Viera, *et al.*, 2004).

The volcanic activity in the CVA was mainly effusive, accompanied by less frequent explosive and phreatomagmatic events and is characterized by volcanic domes accompanied by block-and-ash flows, ash flows with accretionary lapilli, falls, and pumice flows. The volcanic structures and deposits are calcalkaline in composition with a medium to high content of potassium. CVA volcanic rocks vary from basaltic andesite to dacite with SiO₂ between 55 and 66 wt.% (Mora *et al.*, 2007).

Jaimes-Viera (2006) and Mora *et al.* (2007) divided the study area into three groups, according with their location. The first group is represented by the Tzontehuitz Dome Complex; located at the northern part. The second group is composed of the Apas, Navenchauc, Huitepec and Amahuitz volcanic structures; they were emplaced between 2 faults: Chicoasén-Malpaso-Huixtlán to the north and Bajucú to the south. The last group consists of the Mispía, La Iglesia, Santotón and Venustiano Carranza domes. This group is characterized by a N-S alignment (Figure 2).

⁴⁰Ar/³⁹Ar geochronologic study

For ⁴⁰Ar/³⁹Ar analysis, we sampled lava domes and juvenile blocks from pyroclastic flow deposits of 9 of the 11 volcanic structures in the CVA. Thirteen crushed and sieved (to ~0.3 mm) whole-rock samples (phenocryst-free groundmass separates) were dated in the Geochronology Laboratory at University of Alaska Fairbanks (Layer, 2000). The monitor mineral

GEOLOGIC MAP OF CENTRAL PART OF CHIAPANECAN VOLCANIC ARC.

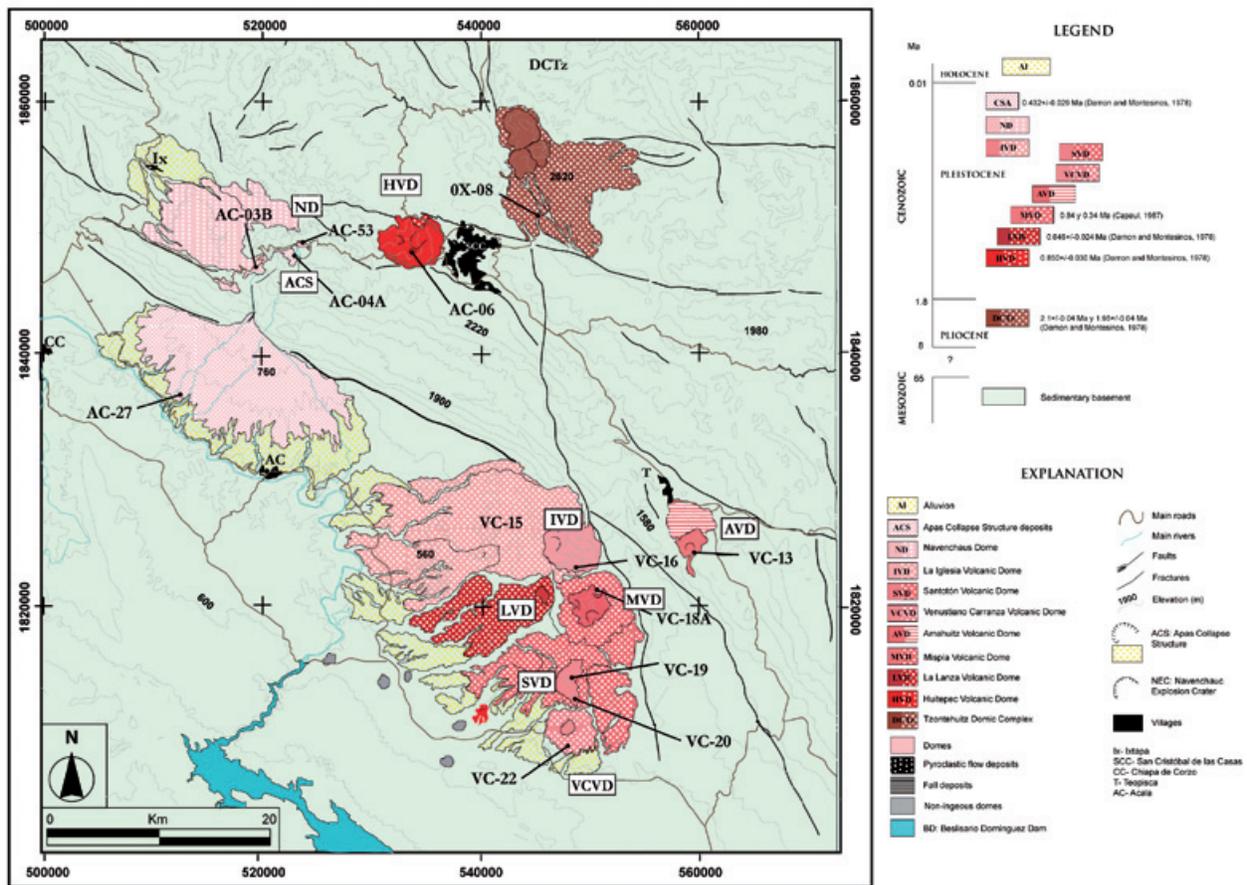


Figure 2. Geologic map of the central part of the Chiapanecan Volcanic Arc (Jaimes-Viera, 2006) showing the samples from this studio.

TCR-2 with an age of 27.87 Ma (Lanphere and Dalrymple, 2000) was used to monitor neutron flux (and calculate the irradiation parameter, J). The samples and standards were wrapped in aluminum foil and loaded into aluminum cans of 2.5 cm diameter and 6 cm height. The samples were irradiated in position 5c of the uranium-enriched research reactor of McMaster University in Hamilton, Ontario, Canada for 0.5 megawatt-hours. Two different irradiations were done in 2005 and 2006.

Upon their return from the reactor, ~10 chips of the samples and monitors were loaded into 2 mm-diameter holes in a copper tray that was then loaded in an ultra-high vacuum extraction line. The monitors were fused, and samples heated, using a 6-watt argon-ion laser following the technique described in York *et al.* (1981), Layer *et al.* (1987), and Layer (2000). Argon purification was achieved using a liquid nitrogen cold trap and a SAES Zr-Al getter at 400°C for 10 minutes. The samples were analyzed in a VG-3600 mass spectrometer. The argon isotopes measured were corrected for system blank and mass discrimination, as well as calcium, potassium and chlorine interference reactions following procedures outlined in McDougall and Harrison (1999). System blanks generally were 2×10^{-16} mol ^{40}Ar and 2×10^{-18} mol ^{36}Ar , which are 10 to 50 times smaller than fraction volumes. Mass discrimination was monitored by running both calibrated air shots and a zero-age glass sample. These measurements were made on a weekly to monthly basis to check for changes in mass discrimination. Table 1 show the ages obtained for the CVA samples along with previously published K-Ar ages from Damon and Montesinos (1978). All ages are reported at the 1-sigma level. For each run, plateau and isochron ages were calculated. For most samples, there was agreement between the two ages, and only

the plateau ages are reported (the exceptions being those samples that had significant argon loss). Criteria for a plateau are that the step heating contain three or more contiguous fractions constituting at least 50% of gas release, and the agreement in age between the fractions is significant at the 95% confidence level (as seen by an MSWD < ~2.5). All samples except VC-13C have significant plateaus. For some samples, two runs were done. Plateau ages from these samples were averaged together to get a 'best' plateau age (Table 1). Analytical data are reported in Appendix 1.

Tzontehuitz Dome Complex.

This volcanic structure was first studied by Damon and Montesinos (1978) who referred to it as "Tzontehuitz Volcano". Capaul (1987) observed that the volcanic structure is a volcanic complex. Mora *et al.* (2007) considered this structure to be composed of at least three domes (El Calvario, Tzontehuitz 1 and 2) aligned in a north-south orientation with associated pyroclastic flow deposits (Figure 2). Because it appears to be a multi-phase structure, it was described as a dome complex, rather than as a single dome. The area covered by the TzDC is approximately 16 km² (Mora *et al.*, 2007). The first geochronological data were reported by Damon and Montesinos (1978), who obtained two K-Ar whole-rock ages: 2.14 ± 0.04 , and 1.95 ± 0.04 Ma. Afterward, Capaul (1987) dated by fission-track technique three new samples and the data obtained are: (a) 1.360 ± 0.142 Ma (pumice); (b) 1.758 ± 0.190 Ma (pumice); and (c) 1.776 ± 0.168 Ma (dome). In this work, we dated one sample from Tzontehuitz 1 Dome (OX-08, Figure 2), which was classified as andesite. Our $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age for this sample is 2.132 ± 0.022 Ma (Figure 3), similar to the oldest K-Ar age.

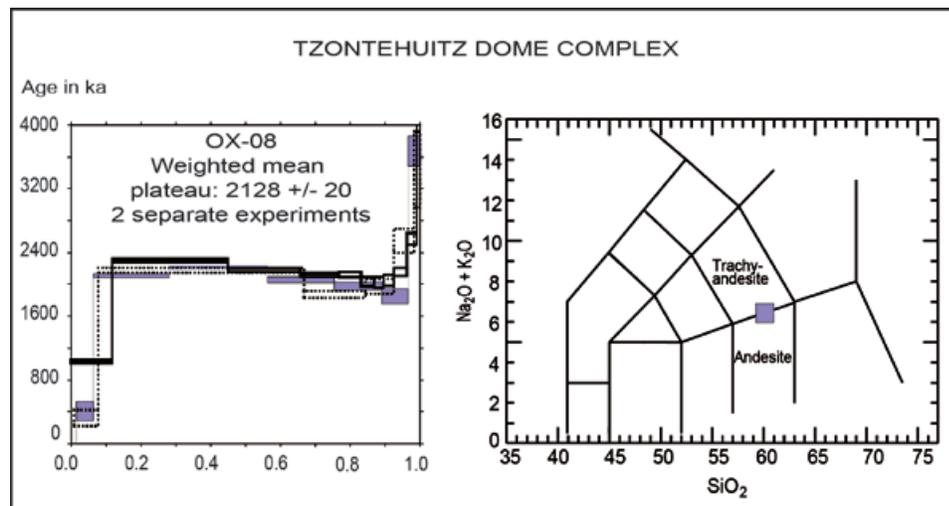


Figure 3. Age spectra plots for $^{40}\text{Ar}/^{39}\text{Ar}$ data and block chemical classification from Tzontehuitz Dome Complex.

Table 1. Summary of data on dated rocks from Chiapanecan Volcanic Arc.

Volcanic Source	Sample	% SiO ₂	Rock Type	Integrated Age (Ma)	Plateau or K-Ar Age (Ma)	Plateau Information
VCVD	VC-22	62.78	Trachydacite	0.384 ± 0.051	0.225 ± 0.030	4 fractions, 83% ³⁹ Ar release, MSWD = 0.7
ND	AC-53	63.21	Dacite	0.266 ± 0.007	0.277 ± 0.005	7 fractions, 88% ³⁹ Ar released, MSWD = 0.7
NEC	AC-03B	63.72	Dacite		0.369 ± 0.018	2-run weighted average, MSWD = 0.2
	run 1			0.391 ± 0.037	0.378 ± 0.028	5 fractions, 78% ³⁹ Ar release, MSWD = 1.4
	run 2			0.166 ± 0.059	0.363 ± 0.024	6 fractions, 87% ³⁹ Ar release, MSWD = 1.1
ACS	AC-04A	61.37	Andesite		0.316 ± 0.009	2-run weighted plateau age, MSWD = 1.2
	run 1			0.336 ± 0.029	0.344 ± 0.027	5 fractions, 99% ³⁹ Ar release, MSWD = 0.4
	run 2			0.334 ± 0.009	0.313 ± 0.009	6 fractions, 75% ³⁹ Ar release, MSWD = 1.4
ACS*	10*	---	Dacite		0.432 ± 0.029	K-Ar Hornblende
ACS	AC-27	62.54	Dacite		0.447 ± 0.011	2-run weighted plateau age MSWD = 1.3
	run 1			0.392 ± 0.030	0.423 ± 0.023	3 fractions, 92% ³⁹ Ar release, MSWD = 1.3
	run 2			0.429 ± 0.012	0.452 ± 0.010	3 fractions, 71% ³⁹ Ar release, MSWD = 0.04
IVD	VC-15	63.47	Dacite		0.676 ± 0.005	2-run weighted plateau age, MSWD = 0.6
	run 1			0.695 ± 0.019	0.689 ± 0.017	5 fractions, 99% ³⁹ Ar release, MSWD = 0.3
	run 2			0.682 ± 0.008	0.675 ± 0.005	5 fractions, 91% ³⁹ Ar release, MSWD = 1.0
IVD	VC-16	61.15	Andesite		0.689 ± 0.033	2-run weighted plateau age MSWD = 0.01
	run 1			0.598 ± 0.105	0.692 ± 0.041	4 fractions, 59% ³⁹ Ar release, MSWD = 0.4
	run 2			0.537 ± 0.103	0.685 ± 0.054	6 fractions, 96% ³⁹ Ar release, MSWD = 1.7

Table 1. Summary of data on dated rocks from Chiapanecan Volcanic Arc.

Volcanic Source	Sample	% SiO ₂	Rock Type	Integrated	Plateau or K-Ar	Plateau
AVD	VC-13C	60.80	Andesite	0.581 ± 0.058	0.739 ± 0.110	3 fractions, 77% ³⁹ Ar release, MSWD = 9.4
LVD*	9*	---	Dacite		0.846 ± 0.024	K-Ar Hornblende
HVD	AC-06	60.17	Andesite	0.295 ± 0.015	0.289 ± 0.014	6 fractions, 99% ³⁹ Ar release, MSWD = 0.2
HVD*	8*	---	Andesite		0.850 ± 0.030	K-Ar Hornblende
MVD	VC-18a	57.10	Andesite	0.982 ± 0.014	0.975 ± 0.011	5 fractions, 89% ³⁹ Ar release, MSWD = 0.7
SVD	VC-20	58.67	Andesite	1.027 ± 0.010	0.995 ± 0.009	4 fractions, 70% ³⁹ Ar release, MSWD = 1.1
SVD	VC-19	56.75	Trachyandesite	0.875 ± 0.076	1.042 ± 0.051	5 fractions, 74% ³⁹ Ar release, MSWD = 0.3
TzDC*	7*	---	Dacite		1.95 ± 0.04	K-Ar Hornblende
TzDC	OX-08	59.66	Trachyandesite	2.107 ± 0.012	2.132 ± 0.022	7 fractions, 51% ³⁹ Ar release, MSWD = 2.2
TzDC*	6*	---	Andesite		2.14 ± 0.04	K-Ar Hornblende

Ages reported at ± 1 sigma. Abbreviations: VCVD: Venustiano Carranza Volcanic Dome; ND: Navenchauc Dome; NEC: Navenchauc Explosion Crater; ACS: Apas Collapse Structure; IVD: La Iglesia Volcanic Dome; AVD: Amahuitz Volcanic Dome; LVD: La Lanza Volcanic Dome; HVD: Huitepec Volcanic Dome; MVD: Mispía Volcanic Dome; SDV: Santotón Volcanic Dome; TzDC: Tzontehuitz Dome Complex., Plateau: 3+ consecutive fractions, MSWD (mean square weighted deviates) < ~2.5, more than 50% ³⁹Ar release. Note that VC-13C age is not a true plateau age, but represents a weighted average age of three plateau-like fractions. For samples with two runs, a weighted average of the two plateau ages is reported. Bold: Best age for the sample. * K-Ar sample number, source and age data from Damon and Montesinos, 1978.

Apas collapse structure

This structure is located in the "Sierra de los Altos de Chiapas" (Jaimes-Viera, 2006; Mora *et al.*, 2007). It is 2.87 km in diameter and associated with it is a sequence of pyroclastic flows (block-and-ash flows, ash flows, and pumice flows), with two directions of emplacement: to SW and NW (Jaimes-Viera, 2006; Mora *et al.*, 2007). Damon and Montesinos (1978) reported a K-Ar age from this structure of 0.432 ± 0.029 Ma. They dated a hornblende from a dacite, which was collected from the deposit emplaced to the SW. We sampled two kinds of blocks with andesitic composition. The first sample was taken from pyroclastic

flow to the SW (AC-27, Figure 2). The second sample was taken from the contact between the basement and pyroclastic flow (AC-04A). We obtained two different plateau ages, the oldest is 0.447 ± 0.010 Ma (AC-27) and the youngest is 0.316 ± 0.009 Ma (AC-04A) (Figure 4a). The oldest age that we obtained is comparable to that from Damon and Montesinos (1978).

Navenchauc Explosion Crater (NEC).

The Navenchauc crater (approximately 1.3 km in diameter) is also located in the "Sierra de los Altos de Chiapas", close to Apas. Associated with this structure is one dome and associated

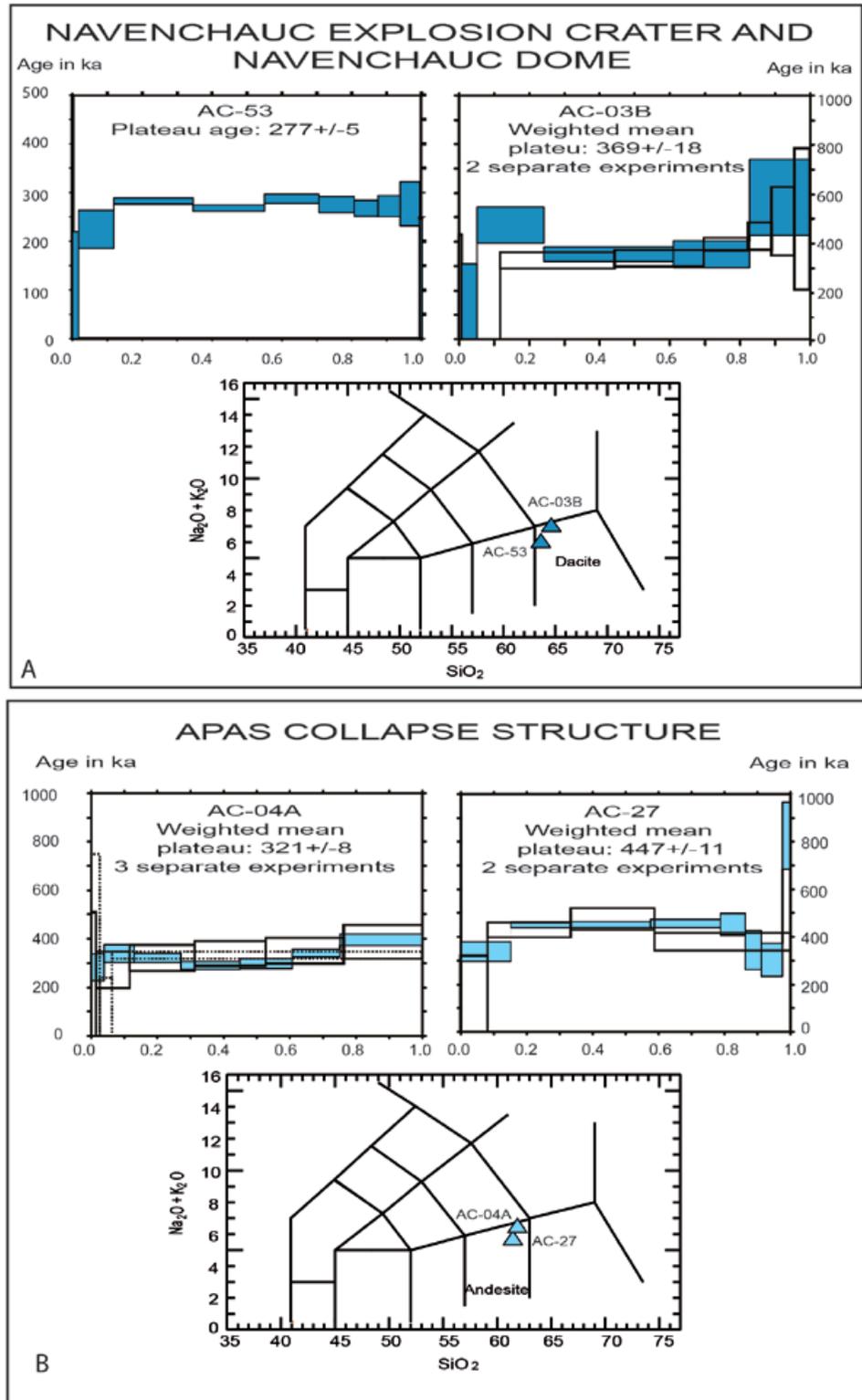


Figure 4. Age spectra plots for $^{40}\text{Ar}/^{39}\text{Ar}$ data and chemical blocks classification. (a) Navenchauc crater explosion; (b) Apas Collapse structure.

pyroclastic flow deposits. The Navenchauc Dome is found at the kilometer 64 milepost of Federal Highway 90 (Tuxtla Gutiérrez-San Cristóbal de las Casas). This dome has a maximum height of 100 m and a mean diameter of 575 m (Mora

et al., 2007). We obtained two $^{40}\text{Ar}/^{39}\text{Ar}$ ages for two samples. The first was collected from a pyroclastic flow (AC-03B, Figure 2) and its age was 0.369 ± 0.018 Ma, making it the oldest unit from this eruptive center. The second sample

dated was taken from the dome (sample AC-53, Figure 2) with an age of 0.277 ± 0.005 Ma (Figure 4b). The chemical composition of both blocks is dacitic.

Huitepec Volcanic Dome (HVD)

The Huitepec Volcanic Dome is located 1 km west of San Cristóbal de las Casas (Figure 2). It has a mean diameter at its base of 5.2 km, covers an area of ~ 21.2 km², and an approximate height of 520 m. Associated with this dome is an ash flow deposit of (Mora *et al.*, 2007). This structure has been studied by Damon and Montesinos (1978), who called it an andesitic dome; a hornblende they dated from the dome gave a K-Ar age of 0.85 ± 0.03 Ma. In this study, we analyzed an andesite sample (AC-06), which was collected from the dome. The ⁴⁰Ar/³⁹Ar whole-rock plateau age we obtained is 0.289 ± 0.014 Ma (Figure 5a), significantly younger than the previously reported K-Ar age. This could imply at least 2 eruptive periods in the formation of the structure.

Amahuitz Volcanic Dome (AVD)

According to Mora *et al.* (2007), the Amahuitz Volcanic Dome is located in the most eastern part of the study area, ~ 33 km southeast of San Cristobal de las Casas (Figure 2). This volcanic

structure is ~ 400 m in height, has a diameter of ~ 2.5 km, and covers an area of ~ 4.4 km². It consists of massive, very compact, light gray andesitic rocks with a porphyritic texture and abundant plagioclase, amphibole, and pyroxene (Mora *et al.*, 2007). Also, an avalanche deposit and an outcrop of fall deposits appear to be associated with this structure, based on their proximity (Jaimes-Viera, 2006; Mora *et al.*, 2007). We sampled a block from the avalanche deposit (VC-13, Figure 2) and we obtained an ⁴⁰Ar/³⁹Ar whole rock age of 0.739 ± 0.110 Ma (Figure 5b).

La Iglesia Volcanic Dome (IVD)

The IVD has been studied by Jaimes-Viera (2006) and Mora *et al.* (2007). It is a circular structure with a diameter of ~ 5 km and a height of 600 m, and covers an area of ~ 18.1 km² (Figure 2). It consists of massive rock and associated deposits of block-and-ash-flows that were emplaced principally to the southwest (Mora *et al.*, 2007). The samples dated were taken from the dome and we obtain two identical ages, of 0.689 ± 0.033 Ma (VC-16, Figure 2) and 0.676 ± 0.005 Ma (VC-15, Figure 6A). However, the first sample analyzed has an andesitic composition (61.15wt% SiO₂), whereas the second dated sample is dacite (63.47wt% SiO₂).

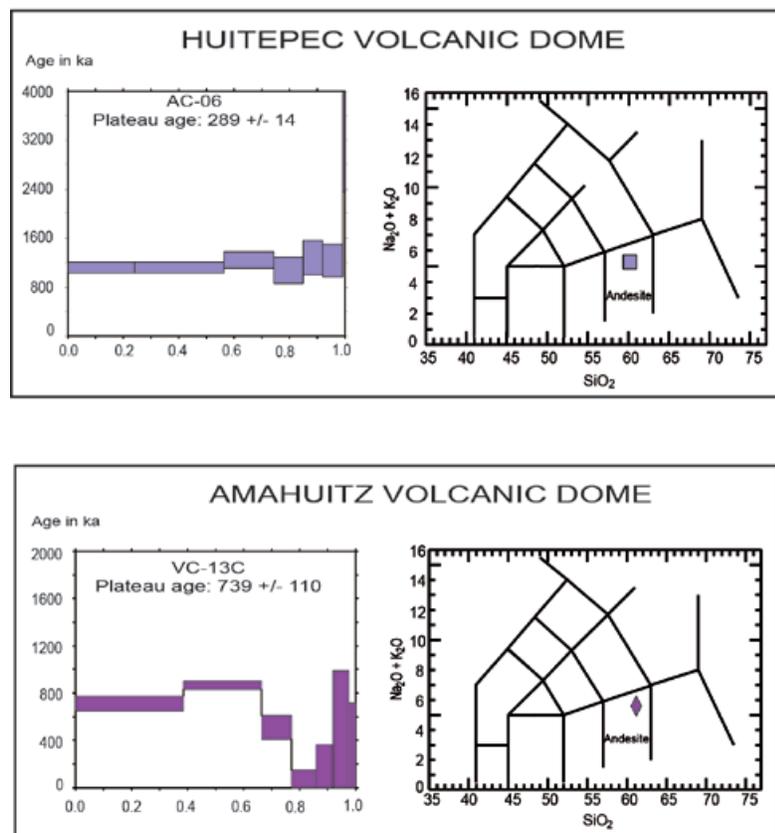


Figure 5. Age spectra plots for ⁴⁰Ar/³⁹Ar data and dome blocks chemical classification from. (a) Huitepec Volcanic Dome and (b) Amahuitz Volcanic Dome.

Mispía Volcanic Dome (MVD).

The MVD is located 5 km southeast of the IVD, has a mean diameter of ~ 3.6 km., a height of 600 m, and covers an area of ~ 8 km² (Figure 2). The rocks from this dome are basaltic andesite. Associated with this structure are some block-and-ash-flow deposits that were emplaced principally to the southeast (Mora *et al.*, 2007). This structure was identified by Capaul (1987) as Nicolás Ruiz Volcano, for which he reported fission track ages of 0.341 ± 0.044 ; 0.403 ± 0.062 and 0.670 ± 0.104 Ma. In this study, we obtained a plateau age of 0.975 ± 0.011 Ma (Figure 6B) from the dome sample VC-18A.

La Lanza Volcanic Dome (LVD).

The LVD is located 2 km east of the MVD. Damon and Montesinos (1978) described this structure as a hornblende dacite volcanic neck with vertical banded-like appearance of "pelean" type, with a K-Ar age of 0.846 ± 0.024 Ma. This volcanic dome is composed of a main spine-like structure surrounded by deposits of pyroclastic flows. The spine is semi-circular with a mean diameter of 1.5 km, covering an area of ~ 1.2 km², and a height of 140 m. Pyroclastic flow deposits have a principal direction of emplacement toward the southeast, with a maximum range of 9.5 km., a mean

thickness of 4 m, and cover an area of ~ 50 km².

Santontón Volcanic Dome (SVD).

The first studies in this dome were done by Jaimes-Viera *et al.* (2004), Jaimes-Viera (2006), and Mora *et al.* (2007). The SVD is located 4 km south of the MVD. According to these authors, it has a height of ~ 400 m, an elongated shape (major axis of 3.6 km and minor axis of 2 km), and covers an area of ~ 6.5 km². It is also surrounded by deposits of associated pyroclastic flows (Figure 2). In this structure we sampled 2 blocks from the dome, and we obtained a precise age of 0.995 ± 0.009 Ma (VC-20) and a less precise age of 1.042 ± 0.051 Ma (VC-19, Figure 2, Figure 6C). These ages are not significantly different from one another. However, these samples are chemically different, one being as andesite (VC-20; 58.67% SiO₂) and the other is a basaltic andesite (56.75% SiO₂).

Venustiano Carranza Volcanic Dome (VCVD)

This structure is an andesitic dome with block-and-ash-flow, fall and lahars deposits located 4 km to the south of the SVD (Jaimes-Viera, 2006; Mora *et al.*, 2007). Pyroclastic flow deposits are found surrounding the volcano with a mean radius of 2 km and an estimated area of 13.7 km²

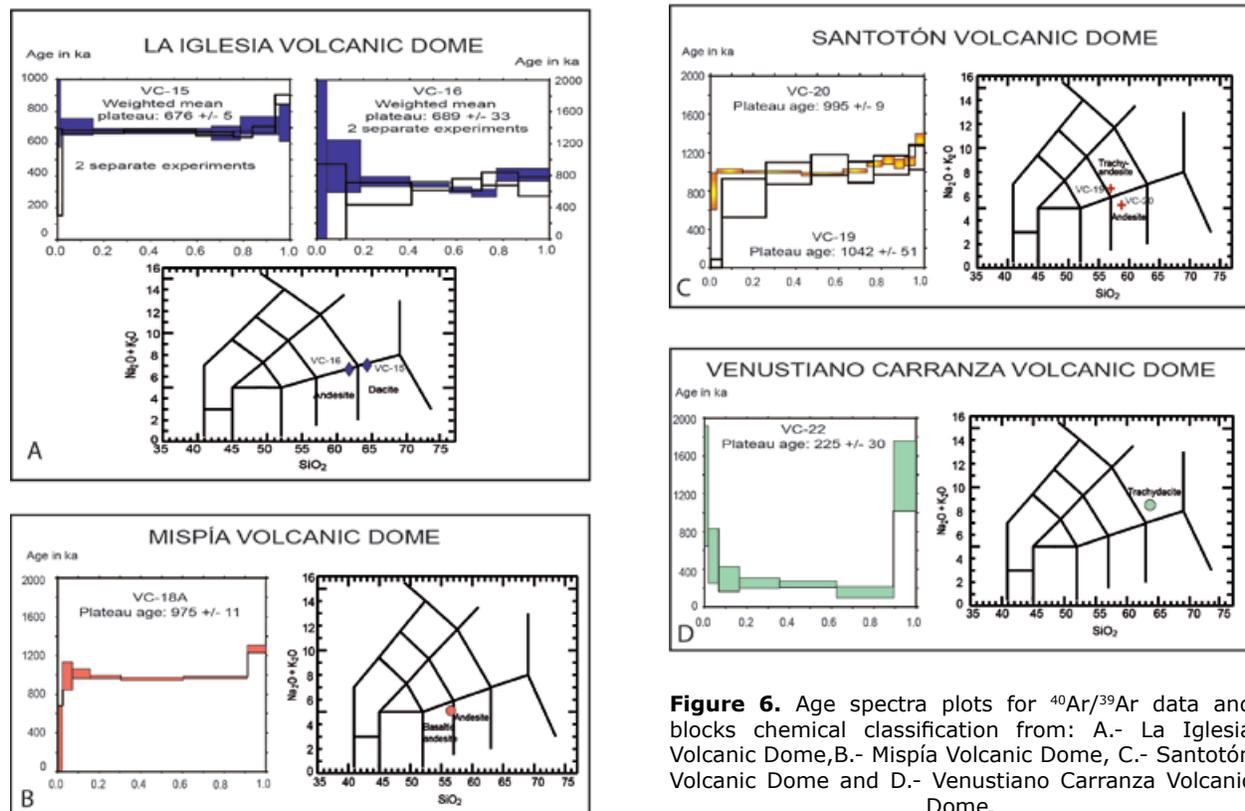


Figure 6. Age spectra plots for $^{40}\text{Ar}/^{39}\text{Ar}$ data and blocks chemical classification from: A.- La Iglesia Volcanic Dome, B.- Mispía Volcanic Dome, C.- Santotón Volcanic Dome and D.- Venustiano Carranza Volcanic Dome.

(Mora *et al.*, 2007). The sample (VC-22, Figure 2) is a juvenile block taken from the pyroclastic flow deposit, and our analysis constrains the age for its emplacement is 0.225 ± 0.030 Ma (Figure 6D).

Discussion.

According to the available data, magmatic activity began at the Tzontehuitz Dome Complex at 2.128 ± 0.020 Ma (or 2.14 Ma, reported by Damos and Montesinos, 1978). Volcanic activity at this structure reactivated at 1.95 ± 0.04 Ma (Table 1). Magmatic activity occurred to south in the Santotón structure, involving two events, one at 0.995 ± 0.009 Ma and the other at 1.042 ± 0.051 Ma. The Mispia unit recorded magmatic activity at 0.975 ± 0.011 Ma. The peak of magmatic activity apparently took place at 0.85 ± 0.03 and 0.846 ± 0.024 Ma, as represented by the Huitepec and La Lanza volcanic structures, respectively, and the Amahuitz at 0.739 ± 0.110 Ma. The Iglesia Volcánico structure manifested magmatic activity at 0.689 ± 0.033 to 0.676 ± 0.005 Ma. The Apas structure had two periods of magmatic activity, one at 0.447 ± 0.011 Ma and the other at 0.321 ± 0.008 Ma. The Navenchauc structure was formed by phreatomagmatic activity at 0.369 ± 0.018 , and an effusive dome-building episode occurred at 0.277 ± 0.005 Ma. The Huitepec structure developed around 0.289 ± 0.014 . The most recent magmatic activity of the central part of the CVA was at 0.225 ± 0.030 Ma and resulted in the Venustiano Carranza structure.

Overall, sixteen magmatic events have been recorded in eleven units. Moreover, some structures manifested more than one magmatic episode (e.g., Tzontehutz, Santotón, Huitepec, Apas, and Navenchauc). These CVA structures have elongate forms, extending up to 3.5 km in length. In the CVA, there is no evidence of large stratovolcanoes as is common in the TMBV and CAVA, probably because of the fact that the CVA was developed in a tectonic complex zone with both compression and transform processes.

Conclusions

Magmatic activity in the CVA has been characterized by the emission of volcanic products of trachyandesitic, andesitic, trachydacite and dacitic composition. These products were emplaced during different eruptive events, both effusive and explosive. A main feature of the CVA is the lack of development of large stratovolcanoes, as is common in the TMBV and CAVA. This observation can be explained by magma not being erupted for a long time via the same conduits, such that the magma arrives at the surface in different zones of weakness. This kind of activity does not permit the vertical

growth of the structures giving origin to a lateral or lineal growth, following the zone of weakness.

The oldest volcanic center is represented by Tzontehuitz Domic Complex with an age of 2.1 Ma, where as the youngest volcanic structure is Venustiano Carranza Volcanic Dome with an age of ~ 0.225 Ma. In the interval of time from ~ 1 Ma to ~ 0.7 Ma, magma sources feeding the volcanism migrated from south to north. From ~ 0.45 Ma to 0.28 Ma, the volcanic activity was concentrated in the west part of the study area. Here the manifestation was more explosive than the other parts with phreatomagmatic activity. The last volcanic activity (225 ka) in the central part of the CVA was in the south (VCVD), and the most recent volcanic activity was to the eruption sequence at El Chichón volcano (Espindola *et al.*, 2000; Layer *et al.*, 2009) in 1982.

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