Polygenetic nature of a rhyolitic dome and implications for hazard assessment: Cerro Pizarro volcano, Mexico

by G. Carrasco-Núñez and N. Riggs

ABSTRACT

Rhyolitic domes are commonly regarded as monogenetic volcanoes associated with single, brief eruptions. They are characterized by short-lived successions of pyroclastic and effusive activity associated with a series of discrete eruptive events that apparently last on the order of years to decades. Cerro Pizarro, a ~ 1.1 km^3 rhyolitic dome in the eastern Mexican Volcanic Belt, shows aspects of polygenetic volcanism including long-term repose periods (~ 50-80 ky) between eruptions, chemical variations with time, and a complex evolution of alternating explosive and effusive eruptions, a cryptodome phase, and sector collapse. This eruptive behavior provides new insights into how rhyolite domes may evolve. A protracted, complex evolution bears important implications for hazard assessment if reactivation of an apparently extinct rhyolitic dome must be seriously considered.

Keywords: monogenetic volcanism, polygenetic volcanism, rhyolites, dome growth, volcanic hazards, Mexican Volcanic Belt

INTRODUCTION

Monogenetic volcanoes comprise a wide spectrum of relatively small volcanic structures (generally less than a few km^3 erupted material) that show a commonly simple evolution (one eruption, or a few clearly related eruptions), short life span (commonly years to decades for mafic volcanoes, but possibly as much as a few centuries for rhyolitic domes), and minor chemical composition changes. Monogenetic volcanoes are, in general, either basalt or rhyolite, while polygenetic volcanoes, which erupt repeatedly and have a large and persistent magma storage chamber, are commonly andesitic or dacitic in composition. Although the most common monogenetic volcanoes are cinder cones, tuff cones and rings, and maar volcanoes of basaltic composition, most rhyolite domes also fit the criteria of monogenetic volcanoes. Mafic monogenetic volcanoes are common in small and large volcanic fields (e.g., Springerville Volcanic Field, Condit and Connor, 1996; Michoacán-Guanajuato volcanic field, Mexico, Hasenaka and Carmichael, 1985). Rhyolitic domes occur either as isolated individual volcanoes (e.g. Las Derrumbadas, Mexico; Siebe et al., 1995; Cerro Pizarro, Riggs and Carrasco-Nuñez, 2004), as part of dome fields (e.g. Taylor Creek, New Mexico; Duffield et al., 1995) or on the flanks of or within larger volcanoes (e.g., Mono-Inyo field-Long Valley caldera; Miller, 1985; South Sister volcano, Oregon; Scott, 1987; Novarupta dome, Valley of Ten Thousand Smokes; Hildreth and Fierstein, 2000). A "typical" rhyolitic dome, as modeled by Duffield et al. (1995) for the Taylor Creek field, evolves from vent-clearing pyroclastic eruptions to dome extrusion over a short time span perhaps only a few years in duration. No rhyolite domes have been observed forming, and estimates of lifespans range from a few to several years (Mono-Inyo field, Miller, 1985; Novarupta, Hildreth and Fierstein, 2000) to a maximum of a few centuries (e.g. Taylor Creek Rhyolite, Duffield et al., 1995). Individual rhyolite domes or related groups of domes do not have significant major-element compositional variations over their growth stages (Scott, 1987; Duffield et al., 1995). Because of this relatively simple common evolutionary path, rhyolite domes are not generally considered very hazardous, similar to monogenetic basaltic systems.

Cerro Pizarro rhyolitic dome, located in the eastern Trans-Mexican Volcanic Belt (Fig. 1), evolved through periods of effusive and highly explosive activity that were separated by cryptodome intrusion, edifice sector-collapse, and prolonged erosional episodes (Riggs and Carrasco-Nuñez, 2004). Chemistry of the eruptive products also changed over time. This evolution, in addition to the ~ 50-80 ka repose period between the main eruptive episodes, indicates that a model of short-lived, monogenetic activity does not characterize all rhyolite domes. The purpose of this paper is to describe the polygenetic nature of Cerro Pizarro dome in terms of timing, chemical variation, and eruptive behavior. These new insights have important implications for hazard assessment of some young silicic domes that otherwise may be considered extinct volcanoes.

REGIONAL SETTING

Cerro Pizarro is located within the Serdán-Oriental basin in the easternmost Mexican Volcanic Belt (Fig. 1). The Serdán–Oriental is a broad, intermontane, relatively flat lacustrine/playa closed basin characterized by Pleistocene isolated small basaltic scoria cones, and tuff rings and maar volcanoes of basaltic and rhyolitic composition, and somewhat larger rhyolitic domes such as Cerro Pizarro (Riggs and Carrasco-Núñez, 2004), Cerro Pinto, and Las Derrumbadas (Siebe et al., 1995). The regional basement comprises locally exposed Cretaceous limestone and small Miocene intrusive rocks.

Volcanic deposits within the Serdán-Oriental basin are dominated by pyroclastic material derived from Los Humeros caldera, located about 16 km north of Cerro Pizarro. Activity at Los Humeros began with the emplacement of the ~115-km^3 Xáltipan ignimbrite at ~460 ka (Ferriz and Mahood, 1985). A highly explosive event occurred at about 100 ka, producing the 15-km^3 Zaragoza ignimbrite (Ferriz and Mahood, 1984; Carrasco-Núñez and Branney, 2005).

EVOLUTION OF CERRO PIZARRO

The evolution of Cerro Pizarro took place in four main stages (after Riggs and Carrasco-Núñez, 20004; Fig. 2). In the first stage, vent-clearing explosions incorporated xenoliths of basement rocks including vesicular basalts from a nearby scoria cone, Cretaceous limestone, and Xáltipan ignimbrite (Ferriz and Mahood, 1985). Subsequent eruptions produced surge and fallout layers followed by passive, effusive dome growth. Oversteepened flanks of the dome collapsed at times to produce block-and ash-flow deposits and, slightly later, an external vitrophiric carapace developed (Fig. 2A). This early stage corresponds well to the model proposed by Duffield et al. (1995).

During the second stage, a new pulse of magma caused the emplacement of a cryptodome, which inflated the volcano and strongly deformed the vitrophyric carapace as well as the older parts of the dome, producing subvertical orientations of the overlying pre-dome units. Disintegration of this cryptodome caused a debris avalanche as the western flank of the volcano collapsed (Fig. 2B) (cf. Mount St. Helens, 1980, Voight et al., 1981; Soufrière Hills, Voight et al., 2002).

The third stage (Fig. 2C) was characterized by a prolonged period of erosion of the dome and passive magma intrusion. Erosion cut canyons as much as 30 m deep and produced heterolithic debris- and hyperconcentrated-flow deposits by reworking the debris-avalanche deposit deposited during Stage II. At approximately 116 ka (see below) magma intrusion caused the collapse crater to fill and the present-day conical shape of the volcano was formed. No evidence exists for pyroclastic or collapse-related deposits associated with this dome growth.

The fourth and final stage (Fig. 2D) includes both hiatus activity following dome growth at 116 ka and the final eruptions of Cerro Pizarro. Several pyroclastic successions were emplaced, including the ~100-ka Zaragoza ignimbrite (Carrasco-Núñez and Branney, 2005), which overlies the volcaniclastic deposits derived from the sector collapse of Cerro Pizarro (unit B in Fig. 3A). Stage IV surge and fall deposits are widely dispersed on the apron around the volcano (Fig. 4). The sequence includes two distinctive marker beds (Fig. 3B): the lower one ("a") is pumice rich whereas the upper one ("c"), which has abundant lithic clasts.

CHEMISTRY OF THE CERRO PIZARRO PRODUCTS

XRF analysis of 14 samples shows that Cerro Pizarro eruptive products are high-silica rhyolite, in contrast to products of the surrounding volcanoes, which are dacitic or andesitic in composition. Rocks from Stages I, II, and III are very similar in major and trace element chemistry, and vary from Stage IV only being slightly higher in TiO_2 and Fe_2O_3,and lower in MnO and Na_2O. More consistent variations are observed for trace elements: Rb, Y, Nb, Ni, Zn are higher for the Stage IV pyroclastic rocks, and Sr, Ba, and Zr are lower than the rest of the Cerro Pizarro rocks. Detailed discussion of the geochemistry will be presented elsewhere.

Even though marked inter-dome compositional variations are observed in rhyolitic fields, individual domes generally show a more homogeneous composition (e.g. Taylor Creek rhyolite, Duffield et al., 1995; Inyo volcanic chain, Sampson, 1987; rhyodacite of South Sister volcano, Scott, 1987) (Fig. 5). The relatively large trace-elements changes between Stages I, II, and III and Stage IV deposits of Cerro Pizarro (Fig. 5) may be due to differentiation processes such as crystal fractionation occurring over the long hiatus in eruptive activity.

LIFESPAN OF CERRO PIZARRO DOME

We have dated four samples of Cerro Pizarro rhyolite and one of underlying basalt by the $^{40}Ar/^{39}Ar$ method (Table 1). Stratigraphic relations preserved on the dome (Riggs and Carrasco-Núñez, 2004) indicate that the basalt scoria cone was unconsolidated at the time of cryptodome emplacement. This observation, combined with the ages of the basalt (190 ± 20 ka) and lavas of the first two stages (220 ± 60 ka and 180 ± 50 ka) strongly suggests that the three eruptive events occurred in short succession without any significant interruption; we consider that all three occurred at ~200 ka. The near-contemporaneity of the two rhyolitic eruptive events is also supported by the homogeneous composition that all the associated eruptive products exhibit in both major and trace elements.

Rebuilding of the dome (Stage III) occurred at 116 ± 12 ka. By analogy with the current growth of the dome in Mount St. Helens, the cone may have been re-established quickly, once magma began to be emplaced. The cone material falls well within the geochemical range of the older dome material. Following a substantial hiatus that lasted, within errors, between 29 and 73 ky, a final explosive event occurred at 65 ± 10 ka (Stage IV) to produce the final pyroclastic sequence.

CERRO PIZARRO DOME: MONOGENETIC OR POLYGENETIC MAGMATIC SYSTEM

Felsic domes comprise compositions from high-silica andesite and dacite to high-silica rhyolite. Composition may play an important role in controlling dome growth styles: while rhyolitic domes tend to be simpler and form through endogenous growth, dacitic and andesitic bodies more commonly have mixed endogenous and exogenous activity (Duffield et al., 1995). Andesitic-dacitic domes are often associated with larger volcanic systems, either large central composite volcanoes (e.g. Santiaguito: Harris et al., 2003; Showa-Shinzan: Mimatsu, 1995; Mount St. Helens:, Swanson et al., 1987) or Pelean-type volcanoes (e.g. Merapi: Newhall et al., 2000; Mount Pelée: Lacroix, 1904; Soufrière Hills: Sparks and Young, 2002), and therefore are associated with multiple effusive events that last for longer periods of time. These volcanoes and volcanic systems are polygenetic, involving larger amounts of magma, variations in eruptive activity, and longer life spans (Table 2).

The volume of Cerro Pizarro compares closely with other monogenetic volcanoes (~ 1.1 km^3). The complexity of its eruptive activity, however, more closely resembles that of a stratovolcano than an individual rhyolitic dome. For example, although cryptodomes are common in the literature, they are generally confined to large magmatic systems. Likewise, collapse of a major sector of the volcanic edifice is generally associated with stratovolcanoes like Mount St. Helens (Voight et al., 1981) or Pelean-type volcanoes such as Soufrière Hills volcano (Voight et al., 2002). Although Cerro Pizarro is rhyolitic and therefore more likely to have behaved as a monogenetic system, by virtue of chemistry, activity, and lifespan it should be classified as polygenetic. To the extent, however, that complex domes like Soufrière Hills or

Unzen Volcano are erupting as multiple-vent systems, with distinguishable, if undramatic changes in chemistry, clearly the designation of polygenetic is likely for many silicic domes. Cerro Pizarro can therefore be considered hybrid in terms of its magmatic activity, both in chemistry, in eruptive style, and in lifespan, between monogenetic rhyolitic domes, which erupt quickly in a predictable way, and polygenetic andesitic-dacitic domes, which often follow a far-more complex evolutionary path.

IMPLICATIONS FOR HAZARD ASSESSMENTS

Reactivation of a rhyolitic dome after a long period of repose has not been previously reported. Reactivation of a seemingly extinct volcano carries very important implications for assessment of volcanic hazards, particularly considering that renewed activity might be explosive or involve sector collapse of the volcanic edifice. Regardless of whether a dome like Cerro Pizarro should be considered polygenetic or monogenetic, the combined stratigraphic, geochemical, and geochronologic evidence from the volcano shows that a rhyolite dome has the potential for renewed activity after a long hiatus. Future eruptions in the Mexican Volcanic Belt, or any district where rhyolitic domes seem to erupt in isolation from other, larger systems, will serve as an excellent test to assess the apparent severe hazards associated with these small volcanoes.

ACKNOWLEDGMENTS

Funding was provided by PAPIIT grant No. IN 104401 and logistical support by Centro de Geociencias, UNAM. R. Lozano performed the chemical analyses at LUGIS (UNAM). S. Medina provided useful references. W. McIntosh and L. Peters performed the isotopic dating at New Mexico Geochronological Laboratory and helped us resolve complex age data. Fruitful discussions with W.A. Duffield, W.E. Scott, and C, Newhall are gratefully acknowledged. W.A Duffield and B. Zimmer read an earlier version of the manuscript and provided comments that strongly helped us improve the text.

REFERENCES CITED

Carrasco-Núñez G., and Branney, M. J., 2005, Progressive assembly of a massive layer of ignimbrite with a normal-to-inverse compositional zoning: the Zaragoza ignimbrite of central Mexico: Bulletin of Volcanology, v. 68, p. 3-20.

Condit, C. D., and Connor, C. B., 1996, Recurrence rates of volcanism in basaltic volcanic fields; an example from the Springerville volcanic field, Arizona: Geological Society of America Bulletin, v. 108, p.1225-1241.

Duffield, W. A., Richter, D. H., and Priest, S. S., 1995, Physical volcanology of silicic lava domes as exemplified by the Taylor Creek rhyolite, Catron and Sierra counties, New Mexico: US Geological Survey Map I-2399, 1:50,000.

Duffield, W.A., and Ruiz, J., 1992, Compositional gradients in large reservoirs of silicic magma as evidenced by ignimbrites versus Taylor Creek rhyolite lava domes: Contributions to Mineralogy and Petrology, v. 110, p. 192-210.

Ferriz, H., and Mahood, G., 1985, Eruption rates and compositional trends at Los Humeros Volcanic Center, Puebla, Mexico: Journal of Geophysical Research, v. 89, p.8511-8524.

Harris, A., Rose, W. I., and Flynn, L., 2003, Temporal trends in lava dome extrusion at Santiaguito 1922-2000: Bulletin of Volcanology, v. 65, p. 77-89.

Hasenaka, T., and Carmichael, I. S. E., 1985, The cinder cones of Michoacán-Guanajuato, central Mexico: their age, volume and distribution, and magma discharge rate: Journal of Volcanology and Geothermal Research, v. 25, p. 105-124.

Hildreth, W., and Fierstein, J, 2000, Katmai volcanic cluster and the great eruption of 1912: Geol. Soc. Am. Bulletin, v. 112, p. 1594-1620.

Luhr, J. T., and Simkin, T., 1993, Parícutin: the volcano born in a Mexican cornfield: Phoenix Geoscience Press, pp. 427.

Miller, C. D., 1985, Holocene eruptions at the Inyo volcanic chain, California: implications for possible eruptions in the Long Valley caldera: Geology, v. 13, p. 14-17.

Mimatsu, M., 1995, Showa-Shinzan diary (English translation). Executive committee 50th anniversary of Showa-Shinzan, Hokkaido, Japan, pp.179.

Newhall, C. G., Bronto, S., Alloway, B., Banks N. G., Bahar, I., del Marmol, M. A., Hadisantono, R. D., Holcomb, R.T., McGeehin, J. et al., 2000, 10,000 Years of explosive eruptions of Merapi Volcano, Central Java: archaeological and modern implications: Journal of Volcanology and Geothermal Research, v. 100, p. 9–50.

Riggs, N. F., and Carrasco-Núñez, G., 2004, Evolution of a complex, isolated dome system, Cerro Pizarro, central México: Bulletin of Volcanology, v. 66, p. 322-335.

Sampson, D. E., 1987, Textural heterogeneities and vent area structures in the 600-year-old lavas of the Inyo volcanic chain, eastern California, *in* Fink, J.H., ed., The Emplacement of silicic domes and lava flows: Geological Society of America Special Paper 212, p. 89-102.

Sampson, D. E., and Cameron, K. L., 1987, The geochemistry of the Inyo volcanic chain: multiple magma systems in the Long Valley region, eastern California. Journal of Geophysical Research, v. 92, p. 10403-10421.

Scott, W. E., 1987, Holocene rhyodacite eruptions on the flanks of South Sister volcano, Oregon, *in* Fink, J.H., ed., The Emplacement of silicic domes and lava flows: Geological Society of America Special Paper 212, p. 35-45.

Siebe, C., Macías, J. L., Abrams, M., Rodríguez, S., Castro, R., and Delgado, H., 1995, Quaternary explosive volcanism and pyroclastic deposits in east central Mexico: implications for future hazards: Geological Society of America Field Guide, p. 1-47.

Sparks, R. S. J., and Young, S. R., 2002, The eruption of Soufrière Hills volcano, Monserrat (1995-199): overview of scientific results, *in* Druitt, T. and Kokelaar, B. P., eds., The eruption of Soufrière Hills volcano, Monserrat (1995-199): Geological Society, London, Memoirs, v. 21, p. 45-69.

Swanson, D. A., Dzurisin, D., Holcomb, R. T., Iwatsubo, E.Y., Chadwick, W. W., Casadevall, T. J., Ewert, J. W., and Heliker, C. C., 1987, Growth of the lava dome at Mount St. Helens, Washington (USA), 1981-1983, *in* Fink, J.H., ed., The Emplacement of silicic domes and lava flows: Geological Society of America Special Paper 212, p. 1-16.

Voight, B., Glicken, H., Janda, R. J., and Douglass, P. M., 1981, The rockslide avalanche of May 18, *in* Lipman, P. W., Mullineax, D. R., eds., The 1980 eruptions Mount St. Helens, Washington: US Geological Survey Special Paper 1250, p. 347-377.

Voight, B., Komorowski, J. C., Norton, G. E., Belousov, A., B., Belousova, M., Boudon, G., Francis, P. W., Franz, W., Heinrich, P., Sparks, R. S. J., and Young, S. R., 2002, The 26 December (Boxing Day) 1997 sector collapse and debris avalanche at Soufrière Hills Volcano, Monserrat, *in*, Druit, T. H., Kokelaar, B. P., eds., The eruption of Soufrière Hills Volcano, Monserrat, from 1995-1999: Geological Society of London Memoir, v. 21, p. 363-407.

FIGURE CAPTIONS

Fig. 1. Geologic map of Cerro Pizarro (modified from Riggs and Carrasco-Núñez, 2004) Units are grouped into four main stages of evolution of the volcano. Inset map shows location of C. Pizarro within the Mexican Volcanic Belt.

Fig. 2. Summary of Cerro Pizarro evolution (modified from Riggs and Carrasco-Núñez, 2004). A) Stage I, initial open-vent explosions and the growth of a rhyolitic dome with a glassy carapace; B) Stage II, intrusion of a cryptodome and subsequent destabilization of the volcanic edifice, causing sector collapse (note that the ages of Stages I and II are well within errors and may have occurred within a few tens of years); C) Stage III, quiescence with intense erosion and consequent reworking products, and intrusion of dome at ~116 ka; D) Stage IV, explosive eruptions at ~65 ka producing a sequence of surge and fallout layers.

Fig. 3. Stratigraphic relations of Stage IV Cerro Pizarro deposits with other pyroclastic deposits. A) Reworked debris-avalanche deposit (A) overlain by ~100 ka Zaragoza Ignimbrite (B) and a pumice-fall deposit (C) from an unknown source. This succession is overlain by ~65-ka fallout and surge deposits (D) from C. Pizarro, with a soil horizon at the top (E). Photo taken ~2 km west of C. Pizarro. B) Layers "a" and "c" (see Fig. 4) separated by a thin, finely laminated surge sequence. Units overlie Zaragoza Ignimbrite. Photo taken ~3 km northeast of C. Pizarro.

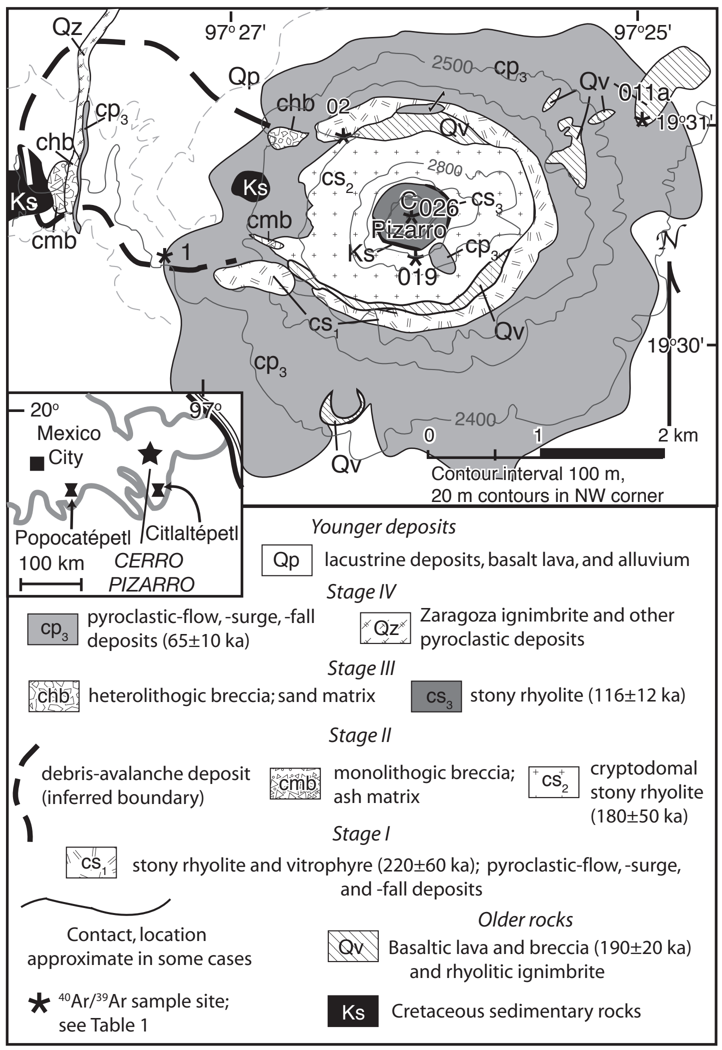
Fig. 4. Isopach maps of Stage IV fallout deposits (see Fig. 3). Layer "a"- dashes, layer "c" - dots (see Fig. 3); thickness in cm. Different orientation of dispersal axes indicates changes in wind direction during eruptions.

Fig. 5. Plots showing geochemical variations for the early (~ 200 - 100 ka) and late (~ 65 ka) stages of Cerro Pizarro rocks in comparison with other rhyolitic domes. A) Rb/Sr versus Rb. B) Nb versus Rb. Taylor Creek data from Duffield and Ruiz (1995), Inyo volcanic field from Sampson and Cameron (1987).

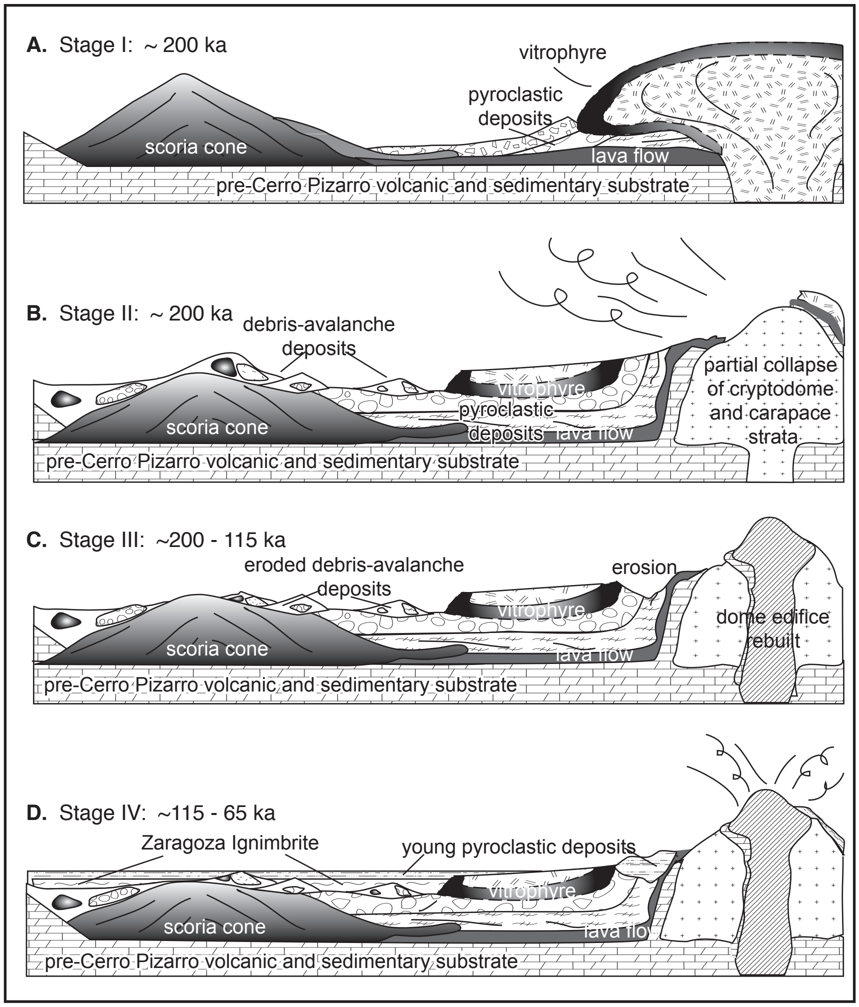
TABLES

1. $^{40}Ar/^{39}Ar$ isotopic ages of rocks and pyroclastic deposits of Cerro Pizarro and underlying basalt

2. Comparison of volcanic domes.



Carrasco-Nuñez and Riggs, Fig. 1



Carrasco-Núñez and Riggs, Fig. 2

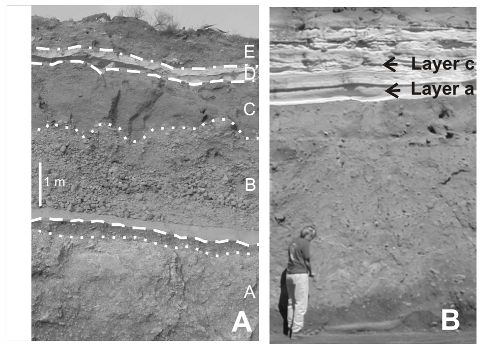


Fig. 3. Carrasco-Núñez and Riggs (2005) *.cdr

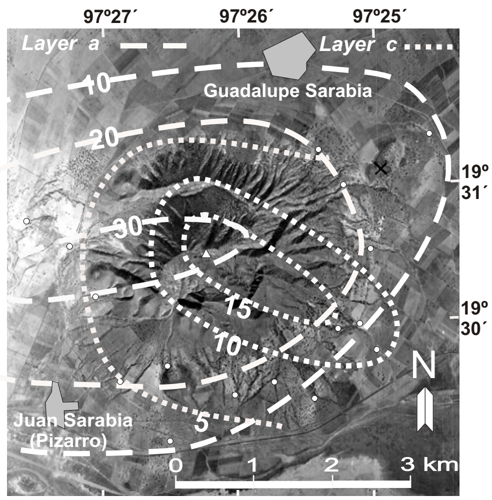


Fig. 4. Carrasco-Núñez and Riggs (2005) *.cdr

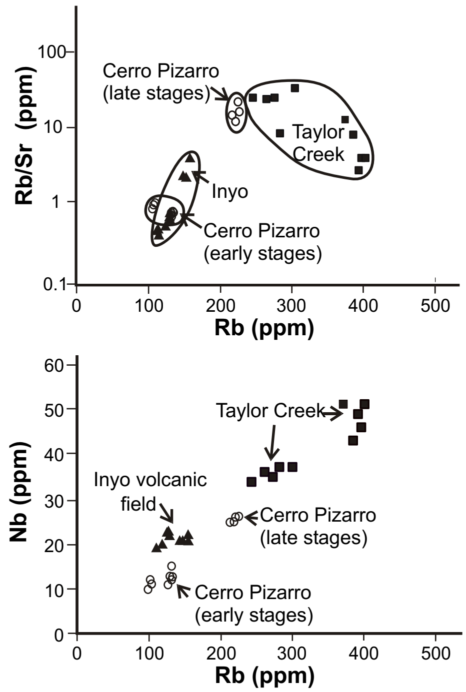


Fig. 5. Carrasco-Núñez and Riggs (2005) *.cdr

TABLE 1. $^{40}Ar/^{39}Ar$ AGES OF ROCKS AND DEPOSITS OF CERRO PIZARRO†

Sample	Stage	Dated material	Rock type	Age analysis	Geographic coordinates Latitude	Longitude	K/Ca	# steps/ crystals	Age (ka)	error 2 σ
01	IV	sanidine¥	pumice	wt mean	19º 30.45´	97º 27.3´	200.1	14	65	10
26	III	sanidine¥	rhyolite lava	plateau	19º30.31'	97º 25.3'	12.2	9	116	12
019	II	biotite§	rhyolite lava	plateau	19º 30.4´	97º 26.2´	101.2	5	180	50
02	I	sanidine¥	rhyolite vitrophyre	wt mean	19º 30.95´	97º 26.6´	49.2	11	220	60
011a		gm conc.§	basaltic lava	plateau	19º 31.05´	97º 25.0´	0.9	7	190	20

†$^{40}Ar/^{39}Ar$ dating performed at New Mexico Geochronological Laboratory using a MAP 215-50 mass spectrometer.
¥Ages for sanidine crystals were determined by total laser fusion, age analysis was obtained by weighted mean (wt mean).
§Ages for biotite or groundmass concentrate (gm conc.) by furnace step-heating.

TABLE 2: COMPARISON OF VOLCANIC DOMES†

Name	Composition	Eruptive activity	Volume	Life span	Ref.¥
Merapi, Indonesia	Andesite	Lava flow, block-and-ash flow	~20 km^3 (total volume)	~2000 yrs to present	1
Santiaguito, Guatemala	Dacite	Pyroclastic flow, lava flow	1.1 – 1.3 km^3	1920 to present	2
Novarupta, caldera related, USA	Rhyolite	Magma effusion	0.13 km^3	<4 years	3
Taylor Creek, dome field, USA	Rhyolite	Near-vent surge and fall; magma effusion	<1 km^3~10km^3; total 100 km^3	20 domes within ~2 ky	4
Cerro Pizarro, isolated dome, Mexico	Rhyolite	Pyroclastic flow, fall, surge, debris avalanche; magma effusion	~1.1 km^3	~100 ka	5
Parícutin, Mexico	Basalt	Scoria cone, lava flow	~1.1 km^3	9 years	6

† Merapi, and Santiaguito not considered monogenetic, based on their compositional variations and life spans. Parícutin provided as example of monogenetic basaltic volcano for comparison.

¥References: 1: Newhall et al. (2000); Newhall, pers. comm. (2005); 2: Harris et al. (2003); 3: Hildreth and Fierstein (2000); Hildreth, pers. comm. (2005); 4: Duffield et al. (1995); 5: Riggs and Carrasco-Nuñez (2004); this study; 6: Luhr and Simkin (1993)