Geofísica Internacional (2006), Vol. 45, Num. 4, pp. 243-253

The pyroclastic dikes of the Tertiary San Luis Potosí volcanic field: Implications on the emplacement of Panalillo ignimbrite

José Ramón Torres-Hernández, Guillermo Labarthe-Hernández, Alfredo Aguillón-Robles, Martín Gómez-Anguiano and José Luis Mata-Segura
Instituto de Geología, Universidad Autónoma de San Luis Potosí, San Luis Potosí, México

Received: August 10, 2004; accepted: September 5, 2006

RESUMEN

Una serie de diques piroclásticos en el Campo Volcánico de San Luis Potosí está asociada a fallas regionales que cortan y basculan a la secuencia volcánica terciaria (32-27 Ma). Estos diques muestran sus raíces en las formaciones riolita San Miguelito e ignimbrita Cantera y están expuestos en los arroyos El Juachín y Las Cabras.

Los diques tienen una inclinación casi vertical, su anchura es variable (máximo 60 cm) y están constituidos principalmente por ceniza volcánica, que consiste de vitroclastos o esquirlas de vidrio formadas por la fragmentación del material juvenil durante la erupción y de cristales fragmentados de cuarzo, sanidino y biotita. Los diques también contienen fragmentos de pómez blanca casi afírica de forma subredondeada de 1 milímetro hasta 1 centímetro de tamaño y fragmentos de riolita. El acomodo de material es de forma tabular y paralela a las paredes del conducto.

Los diques piroclásticos están asociados a las fallas normales formadas durante el Oligoceno medio, así como a los procesos volcánicos que dieron origen a la ignimbrita Panalillo.

PALABRAS CLAVE: Dique piroclástico, ignimbrita Panalillo, tectónica, volcanismo, San Luis Potosí, Terciario, México.

ABSTRACT

Pyroclastic dikes emplaced along regional NW-SE faults in the Tertiary San Luis Potosí Volcanic Field consist of vitric pumice shards, rhyolite lithics, and broken crystals of quartz, sanidine, and biotite. These clasts display a parallel orientation inside the dikes and have developed devitrification structures after emplacement.

The presence of these pyroclastic dikes associated to normal faults and their relation to the Oligocene pyroclastic sequences of the San Luis Potosí Volcanic Field suggests that they may represent the feeding conduits from which the Panalillo ignimbrite was erupted.

KEY WORDS: Pyroclastic dike, Panalillo ignimbrite, tectonics, volcanism, San Luis Potosí, Tertiary, Mexico.

INTRODUCTION

The San Luis Potosí Volcanic Field (SLPVF) is located southwest of the city of San Luis Potosí (Figure 1). It was first described by Labarthe-Hernández *et al*. (1982) as a volcanic field formed by Tertiary lavas and ignimbrites. Later studies have documented that the SLPVF is affected by regional normal faults that have tilted to the east this Oligocene (32 to 27 Ma) volcanic sequence (Figure 2) (Labarthe-Hernández and Jiménez-López, 1992; 1993; 1994; Nieto-Samaniego *et al.,* 1999). One of the most remarkable features in the SLPVF is the occurrence of pyroclastic dikes emplaced along these faults and their close association with the Panalillo ignimbrite. Torres-Hernández *et al*. (1998) showed that faulting and volcanism occurred synchronically. Pyroclastic products rest against faults and the angle of deposition of the different units comprising the ash-flow sequence decreases from the base to the top (typical syn-tectonic depositional feature). The pyroclastic dikes have long, roughly tabular shapes. Different types of pyroclastic dikes have been reported in the literature (Chalot-Prat, 1995; Wolff, 1986; Ellwood and Wolff, 1985; Milanovski and Koronovski, 1965; Almond, 1971). They are considered feeding conduits of explosive eruptions, whose fragmentation and cooling occurred at depths <2 km (Wilson *et al.,* 1980). In some areas, including the SLPVF, it is possible to correlate the mineralogical and chemical composition of the materials filling the dikes with the composition of clasts in the pyroclastic deposits on the surface (Wolff 1986). Pyroclastic dikes have been observed at the margins of deeply dissected cauldrons (Ekren and Bayers, 1976; Aramaki *et al*., 1977; Elston, 1984; Yoshida, 1984; Takahashi, 1986; Miura, 1997). In some cases they are related to strike-slip faults (Chalot-Prat, 1995). In general, pyroclastic dikes are associated to sub-volcanic structures. Therefore, they are only exposed in older volcanic

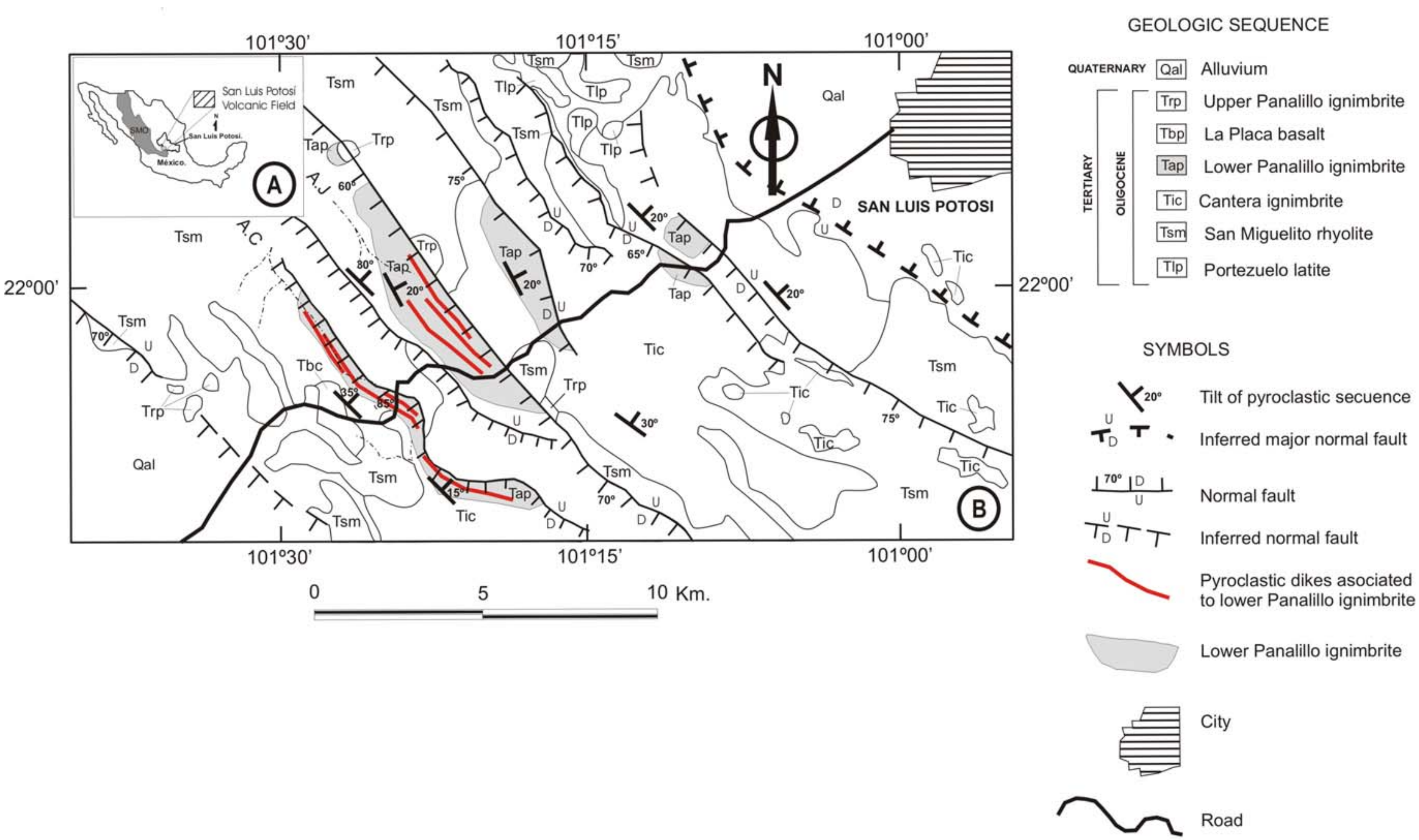

Fig. 1. A. Sierra Madre Occidental (SMO) and study area ubication. B. Geologic map of the San Luis Potosí Volcanic Field, showing the location of the arroyo El Juachín (A.J.) and arroyo Las Cabras (A.C.). The regional faults cut and tilt the entire sequence and control the stream. Pyroclastic dikes are only present in the El Juachín and Cabras areas.

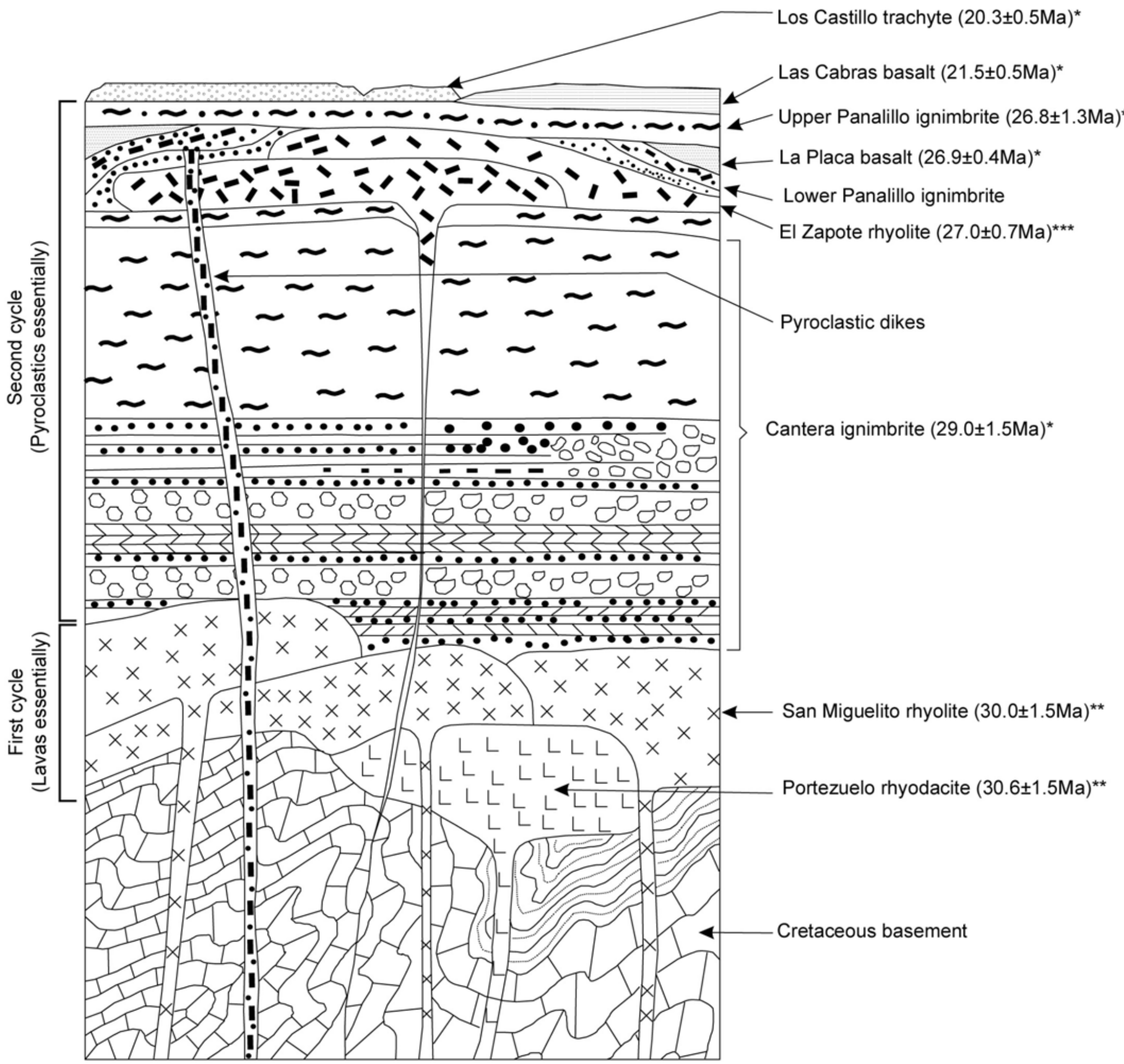

Fig. 2. Composite stratigraphic column for the San Luis Potosí Volcanic Field. K/Ar ages were reported by: *Torres-Hernández *et al*. (2001); **Labarthe-Hernández *et al*. (1982) and ***Nieto-Samaniego *et al*. (1996).

fields where exhumation and erosion has removed overlying deposits.

The study of pyroclastic dikes in the SLPVF provides new insights for the understanding of this sub-volcanic phenomenon. In this paper we describe pyroclastic dikes in Arroyo Juachín and Arroyo Las Cabras areas (Figure 2). Petrographic and chemical analyses of their components (pumice clasts and lithic fragments) and stratigraphic position of the ignimbrites in the SLPVF, provide enough information for proposing a genetic model for the dikes and their implication for emplacement of The Panalillo ignimbrite.

REGIONAL GEOLOGIC FRAMEWORK

The SLPVF is located at the southeastern edge of the Sierra Madre Occidental Magmatic Province (Figure 1). The prevolcanic basement consists of Cretaceous (Valanginian to Maastrichtian) marine limestones, lutites, and sandstones with NW-SE trending fold-axes. An Eocene conglomerate sequence with interbedded 44.1 ± 2.2 Ma old andesitic lavas of the Casita Blanca Formation (Labarthe-Hernández *et al*., 1982) overlies discordantly the Mesozoic rocks.

This sector of the SMO is mostly Oligocene in age and was emplaced in two cycle (Figure 2): During the first period (31 to 30 Ma; Labarthe *et al*., 1982) silicic lava domes including the Portezuelo latite and San Miguelito rhyolite were erupted. During the second cycle (29 to 27 Ma; Labarthe *et al*., 1982) the Cantera and Panalillo ignimbrites were emplaced. In addition, subordinate emissions of rhyolitic and basaltic lavas interbedded with the ignimbrites (El Zapote rhyolite and La Placa basalt) took place. Miocene volcanism (21 to 20 Ma; Labarthe *et al*., 1982) produced basaltic to trachytic lavas (Cabras basalt and Los Castillo trachyte) of limited distribution in the southern part of the SLPVF. Overlying deposits are represented by Miocene-Pliocene thin conglomerates (Halcones conglomerate), Pliocene-Quaternary basaltic lavas, and phreatomagmatic deposits associated to maar volcanism (Las Joyas secuence), and Quaternary alluvial deposits in the Villa de Reyes graben and other depressions.

STRATIGRAPHY

A schematic stratigraphic column showing the relative position of the dykes and related Panalillo ignimbrite is presented in Figure 2. The volcanic rocks in this field are Oligocene-Miocene (44.1 ± 2.2 to 20.3 ± 0.5 Ma) in age. The Portezuelo rhyodacite is 30.6 Ma and Los Castillo trachyte is 20.3 Ma old. Volcanism was accompanied by a complex history of mostly extensional tectonic events. The most prominent episode of volcanism occurred between 31 to 30 Ma and included two stages of dome formation. The first was rhyodacitic in composition (Portezuelo trachyte) and the second rhyolitic (San Miguelito rhyolite). Around 29 Ma, explosive volcanic activity formed the Cantera ignimbrite. A new explosive event produced a thin mantle of pyroclastic deposits followed by the emplacement of voluminous rhyolitic domes (Zapote rhyolite) around 27.0 ± 0.7 Ma (Nieto-Samaniego *et al*., 1996). The next explosive eruption produced a series of pyroclastic flows and associated pyroclastic dikes (Panalillo Inferior ignimbrite). This event occurred synchronically with normal faulting, because the pyroclastic deposits rest with an angle of 35° at the base and decrease to 10° at the top. A series of basaltic lava flows (La Placa basalt) were emplaced mainly in the southern and southeastern parts of the volcanic field. The pyroclastic activity almost ceased after the emplacement of the Upper Panalillo ignimbrite (26.8 ± 1.3 Ma; Labarthe-Hernández *et al*., 1982), an extremely hot sequence of ash flows characterized by post-emplacement rheomorphic structures. The final volcanic event produced small basaltic lava flows (Las Cabras basalt) in the south-central part of the volcanic field (21.5 ± 0.5 Ma; Torres *et al*., 1998) and trachyte lavas (Los Castillo trachyte) in the southern and southwestern parts of the volcanic field (20.3 ± 0.5 Ma; Torres *et al*., 1998).

Arroyo Juachín area

Labarthe-Hernández *et al*. (2000) were the first to mention the occurrence of pyroclastic dikes running roughly parallel to the fault plane that controls the course of the El Juachín stream. These dikes mainly consist of rhyolitic (SiO_2= 70%; Na_2O + K_2O=4.76%; CaO=1.39%; Al_2O_3=9.87%; Fe_2O_3=1.98% wt.) volcanic material of different granulometric sizes. The fine-grained material (silt-sized ash) is plastered to the dike walls, while coarser material (sand, gravel, and blocks) are concentrated in the center of the dike. Dikes have a variable width, ranging from a few cm up to a maximum of 60 cm (Figures 3A and 3B) and have a NW-SE orientation, dipping 70º - 90º to the SW. Ash in the dikes consists of vitroclasts and fragmented crystals of quartz, sanidine, and biotite. It also includes sub-rounded to sub-angular fragments of underlying volcanics rocks (San Miguelito rhyolite and Cantera ignimbrite), which are dark-gray to reddish or pinkish-brown in color due to oxidation. The long-axis of lithic fragments is parallel to the dike walls. In addition to the banded appearance of the dikes, flow-erosion surfaces are frequently observed at the contact with the intruded rocks.

Arroyo Las Cabras area

The pyroclastic deposits of the Lower Panalillo ignimbrite displayed along the Arroyo Las Cabras have different bedding angles, which notably vary from the base to the top. Above the Cantera ignimbrite the deposits dip 45° to the NE. Covering this deposit are two massive units containing abundant white pumice and lithic clasts, which are again overlain by a series of thin white pyroclastic flow deposits dipping 35º to the NE. On top is another sequence of biotite-rich pyroclastic flow deposits dipping at the base 25º to the NE and towards the top only 10º in the same direction. The uppermost pyroclastic Las Cabras deposits are interbedded with horizons of epiclastic material.

The dikes in the Las Cabras area associated to the Lower Panalillo ignimbrite have variable thicknesses, with a maximum thickness of 80 cm (Figures 4A and B). Most dykes are parallel and the smallest are only 1-3 cm-thick. The dikes have a variable shape and width. They widen, thin, branch or strangle, following a winding trajectory and, in some cases, forming anastomosed systems.

Vertical slickensides (striations) observed on the walls of some dikes, suggest slight vertical movement after emplacement and some outcrops exhibit short

Fig. 3. Photographs of the El Juachín dikes. A) Typical outcrop showing thickness of the dike. B) Close-up showing the planar character of the clastic filling (hammer for scale).

displacements of horizons of pyroclastic material on both sides of the dikes. Ash, pumice, and lithics are graded showing vertical banding (Figure 4A). In their widest part, the dikes show a complex network of fine and coarse material (> 3 cm), although as a whole the coarse material does not have a tabular distribution (Figures 4C and D). The coarse material includes mostly mm-to-cm sized sub-angular accidental lithic clasts, although some have diameters of up to 12 cm (Figure 4D). Pumice clasts range in size from a few mm to up to seven cm. Commonly the dike's fill consists of pumice and ash only. In some other parts welding is more intense near the dike's walls. Particles can also be cemented by amorphous silica.

RELATIONSHIP BETWEEN PYROCLASTIC DIKES AND PYROCLASTIC DEPOSITS

The similar composition of components (particularly of the pumice clasts) in the pyroclastic dikes and pyroclastic deposits suggests a common genesis. At Arroyo Las Cabras a pyroclastic horizon contains two types of non-collapsed pumice clasts (yellowish-white and ochre). The yellowish-white pumice is the most abundant. It is slightly fibrous and contains scarce small crystals (< 1 mm) of quartz and sanidine (ca. 10%). The clasts are sub-angular to sub-rounded. The ochre pumice is rare but larger and very fibrous. It contains quartz and sanidine crystals in similar amounts to those in the white pumice. In only one of the pyroclastic dikes the two types of pumice occur together. For this reason it is possible to establish a genetic relationship between both, the dikes and the pyroclastic deposits containing the two types of pumice clasts.

In pyroclastic deposits containing both pumice types (yellowish white and ochre), small faults displace layers of pyroclastic material, without cutting through the entire deposit. This suggests that the small-scale micro-faulting occurred shortly after the time of the eruption.

Finally, not all dikes are connected to the surface, indicating that in some cases, the injection of pyroclastic material, which induced hydrofracturing, stopped before reaching the surface. This same feature has been observed in lava dikes (Gudmundsson *et al.*, 1999).

DISCUSSION

Generation of pyroclastic dikes

Miura and Tamai (1998) pointed out that in some of the mega-blocks within the intra-cauldron ignimbrite of the Dorobu Caldera (Dorobu ash–flow A), it is possible to observe networks of small dikes filled with pumice, lithic fragments, and ash-matrix similar to that of the Dorobu ignimbrite A unit. These authors concluded that this is clear evidence for an hydraulic fracturing process caused by water–magma interaction that occurred at the beginning of a paroxysmal eruption, generating the ignimbrite and the subsequent collapse of the magmatic chamber roof that formed the cauldron structure. They also found fractures that branch out irregularly from the dikes. Inside the dikes the coarser material is concentrated at the center bracketed by finer ash stuck to the host-rock walls. The character of these fractures is similar to those formed by hydraulic fracturing and highly expanded underground water (Heiken *et al.*, 1988). Because fault-mirrors with grooves and half-moon structures in which pitches have values near 90° are present along the contact between the dike and the host walls in the Arroyo Las Cabras and the Arroyo Juachín areas, it is inferred that the faulting process initiated with the breaking of the host rock prior to the injection of pyroclastic material. It is possible that hydrofracturing and faulting occurred simultaneously.

For the case of clastic dike injection, Shrock (1948) and Potter and Pettijohn (1963) proposed that these dikes were formed by the intrusion of material contained in some substrata at a certain depth, and that this material had been injected from the bottom towards the top as a fluid. In some cases the driving mechanism might be intense quakes for which the fracture can originate coevally with the intrusion. In any case, the rupture of the rock progresses from beneath towards the top. It may initiate by pressure of accumulated gas or by hydrostatic pressure, processes that further promote the rupture through the clastic material forcing its intrusion. The force that drives this mechanism corresponds to the lithostatic load of the beds overlying the sedimentary layer that supplies the injection material (this is not the case in pyroclastic dikes of the SLPVF). The elements that indicate the forced injection of the material are: flow lines, oriented minerals (i.e. micas) or other minerals oriented parallel to the dike walls, a cutting relationship, and the dike material being older than the intruded strata.

We propose that the SLPVF dikes were formed by forced injection of juvenile material or magma as the injected fluid (pumice and volcanic ash) coming from the fragmentation zone. Pumice clasts with an eutaxitic texture were observed only in one dike displaying medium to strong welding (Figure 4A). Different degrees of welding were also observed at the arroyo Las Cabras dikes. Such textures and structures could not be formed by sedimentary particles infilling pre-existing fractures.

The complex internal structure of the dikes observed in the CVSLP is not common in other reported dike areas. For example, Chalot–Prat *et al.* (1995) mention that in the

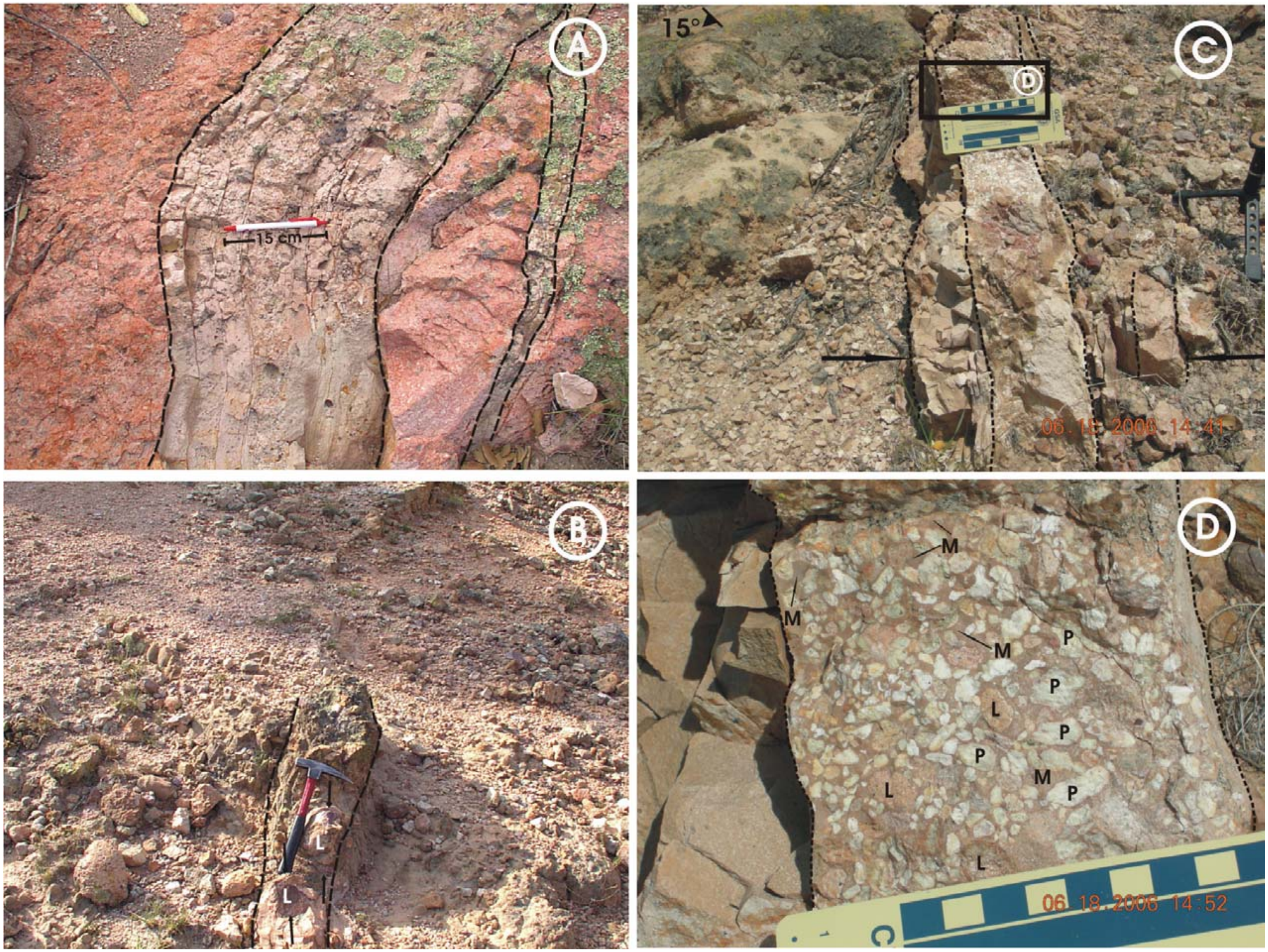

Fig. 4. Photographs of the Las Cabras dikes showing: A) Maximum thickness of the dikes (40 cm). B) Pyroclastic dike intruding the Panalillo Inferior ignimbrite sequence. C) Almost vertical dike oriented N45°W with vitrophyric material near the rim of the dike´s walls, and coarse material in the central part. D) Close-up of C showing its components: pumice (P), lithics (L), and matrix-ash (M). Scale in centimeters.

Tazekka volcanic complex east of Morocco, ignimbrite material filling the dikes is homogeneous. Chalot–Prat *et al*. (1995) also consider that deposition of the pyroclastic flows can be ascribed to a violent release of vitroclastic material from deep fractures (as in the CVSLP). Furthermore, they also infer that the active tectonics which induced the opening of the fissures is related to the volcanic activity, both being interdependent processes.

We infer that the different granulometric sizes of the material filling the dikes is the result of a particle flow in the tabular channel of the open fractures. This assumption is supported by reported experimental work. Johnson (1970) and Hui and Haff (1986) modeled the flow of granular material in a vertical channel demonstrating that the different profiles of material speed, perpendicular to the channel wall, are symmetrical, and concluded that symmetry indicates that all profiles have a cutting relationship equal to zero in the center of the channel.

The complexity of the internal structure of the dikes at arroyo Las Cabras is the result of repetitive explosive events. Each event formed one deposit until the filling was completed (or until the depressurization of the magmatic chamber was completed). The complex patterns of structures such as cut-and-fill and cross-cut in the flow deposits of the dikes were caused by erosion of material before deposition by the rising flow (because of the turbulent character of the flow in the tabular conduit), and by the rupture of the filling during the sequential opening of the fractures that lodge the dikes. Wilson *et al*. (1980) analyzed the emission of young pyroclastic material through a rectangular vertical conduit and concluded that the process results in a rather complex phenomenon than in a simple flow movement along an inclined surface. In a flow of pyroclastic material moving along the surface, gravity induces a quick down-slope movement of the grains and inter-granular fluid. The resultant deposits of pyroclastic material in a vertical tabular conduit have some differences in their arrangement.

Complex patterns of filling are not commonly reported in pyroclastic dikes, but in contrast are well documented in lava feeder dikes, in which the filling of fractures hosting dikes occurred by repeated lava emissions. For example, Walker and Eyre (1995) reported a basal lava dike complex in American Samoa, distinguishing a "composed dike facies" and an "isolated dike facies". In these dikes, the intrusion of a dike into another may occur at the center of the first dike or at the margins between the dike and the host rock. In the first case, dikes have a central vesiculated part that might correspond to the most gaseous part of the fluid, which therefore remained warmer for longer periods of time opposing minor resistance to the new dike material injected.

In the case of dikes formed by material that is introduced itself between an earlier dike and the host walls, it is assumed that the conditions in the dike are more homogeneous and therefore the new material is less resistant to injection along the margins of the structure. Although this case refers to lavas, characteristics of the pyroclastic dikes are very similar in the sense that here also, the dikes present a complex history of in-filling, where successive emissions of pyroclastic material occurred at the center of an earlier dike, or between the walls and the same body.

CONCLUSIONS

The complex history of dike filling suggests that fractures were progressively opened, and that successive flows occupied the central parts of the dike until the phenomenon ceased. In some cases renewed injections occurred at the margin of the dike.

The dikes (in a profile view as well as in a plan view) present branching which ends in points. Not all reach the surface. The geological relationships of the dikes at Arroyos El Juachín and Las Cabras suggest that several emission sources existed in order to produce the complex dike pattern. We believe that the juvenile pyroclastic material feeding the dikes was injected at high speeds undergoing a vigorous elutriation. This process of turbulent ash eruptions and spreading or opening of new lateral fractures produced a random, rather than homogeneous, distribution of juvenile material inside the fractures. On occasion it was also observed that the closing of conduits at some places occurred in such a way that the pumice material concentrically filled the last open spaces through which the pyroclastic material flowed. It is widely accepted that if the intrusion is comprised by pyroclastics, it probably formed near the surface (Shinohara, 1990). This situation is underscored if the juvenile material (pumice) filling the dikes presents no collapsing or welding. A summary of our interpretation of the dike-formation process is illustrated in Figure 5.

ACKNOWLEDGEMENTS

We thank Armando García Palomo, Claus Siebe, Renato Castro Govea and two anonymous reviewers for their comments. We also thank Ignacio Hernández and Lilia Arana for their assistance. Gratefulness to Dr. Rafael Barboza-Gudiño, Director of the Instituto de Geología from the University of San Luis Potosí for the technical support and to Ing. Lucio Gallegos-Juárez for the traslation of the first manuscript.

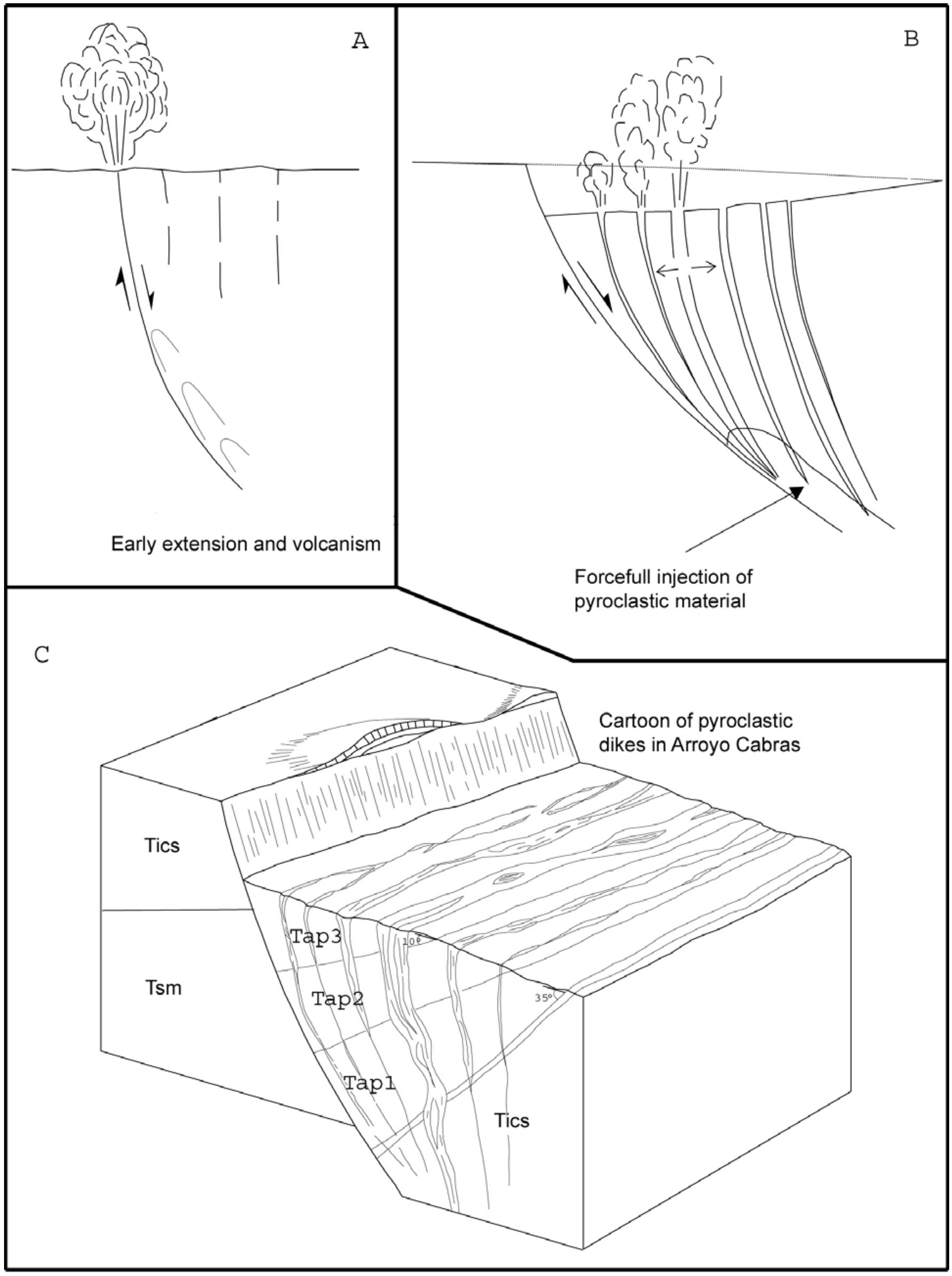

Fig. 5. Schematic model of dike emplacement. A) Pyroclastic volcanism begins along normal and listric faults (extension). B) The forceful injection of pyroclastic material induces opening of fractures and dike initiation. C) When the extension stops the complex pattern of dikes reflects the successive events of pyroclastic emission**.** From base to top the tilt of the deposits decrease.

BIBLIOGRAPHY

ALMOND, D. C., 1971. Ignimbrite vent in the Sabaloka cauldron, Sudan. *Geol. Mag.*, *108,* 159-176.

ARAMAKI, S., M. TAKAHASHI and T. OZAWA, 1977. Kumano acidic rocks and Okueyama complex: Two examples of the granitic rocks in the outer zone of southwestern Japan. *In:* Yamada, N. (Ed.), Plutonism in relation to volcanism and metamorphism. Proc. 7th Circum-Pacific Plutonism Project Meeting. Int. Geol. Correlation Program, UNESCO, Toyama, Japan, 127-147.

ARANDA-GÓMEZ, J. J., C. D. HENRY and J. F. LUHR, 2000. Evolución tectonomagmática post-paleocénica de la Sierra Madre Occidental y de la porción meridional de la provincia tectónica de Cuencas y Sierras, México. *In:* Alaniz-Álvarez, S.A., y Ferrari, L. (Eds). Número especial: Avances de la Geología Mexicana en la última década. Boletín de la Sociedad Geológica Mexicana, v. III, 59-71.

CHALOT-PRAT, F., 1995. Genesis of rhyolitic ignimbrites and lavas from distinct sources at deep crustal level: field, petrographic, chemical and isotopic (Sr, Nd) constraints in the Tazekka Volcanic Complex (Eastern Morocco). *Lithos*, *36,* 29-49.

EKREN, E. B. and F. M. BAYERS, Jr., 1976. Ash flow fissure vent in west central Nevada. *Geology, 4*, 247-251.

ELLWOOD, B. B. and J. A. WOLFF, 1985. Welded–tuff dykes: possible implications for the mechanism of explosive– effusive transition during the closing stages of pyroclastic eruptions. *EOS*, *66,* 1151.

ELSTON, W. E., 1984. Mid-Tertiary ash flow tuff cauldrons, south-western New Mexico. *J. Geophys. Res.*, *89*, 8733-8750.

GUDMUNDSSON, A., L. MAINONI and J. MARTI, 1999. Injection and arrest of dykes: Implications for volcanic hazards. *J. Volcanol. Geotherm. Res.*, *88,* 1-13.

HEIKEN, G., K. WOHLETZ and J. EICHELBERGER, 1988. Fracture filling and intrusive pyroclasts, Inyo domes, California. *J. Geophys. Res.*, *93*, 4335-4350.

HUI, K. and P. K. HAFF, 1986. Kinetic grain flow in a vertical channel: International *Journal of Multiphase Flow*, *12,* 289-298.

JOHNSON, A. M., 1970. Physical processes in geology: San Francisco, Freeman, Cooper & Co., 577p.

LABARTHE-HERNÁNDEZ, G., M. TRISTÁN-GONZÁLEZ and J. J. ARANDA-GÓMEZ, 1982. Revisión estratigráfica del Cenozoico de la parte central del estado de San Luis Potosí. Universidad Autónoma de San Luis Potosí, Instituto de Geología, Folleto Técnico 85, 208 p., with map.

LABARTHE-HERNÁNDEZ, G. and L. S. JIMÉNEZ-LÓPEZ, 1992. Características físicas y estructuras de lavas e ignimbritas riolíticas de la Sierra de San Miguelito, S. L. P. Universidad Autónoma de San Luis Potosí, Instituto de Geología, Folleto Técnico 114, 31, with map.

LABARTHE-HERNÁNDEZ, G. and L. S. JIMÉNEZ-LÓPEZ, 1993. Geología del domo Cerro Grande, Sierra de San Miguelito, S. L. P. Universidad Autónoma de San Luis Potosí, Instituto de Geología, Folleto Técnico 117, 22, with map.

LABARTHE-HERNÁNDEZ, G. and L. S. JIMÉNEZ-LÓPEZ, 1994. Geología de la porción sureste de la Sierra de San Miguelito, S. L. P. Universidad Autónoma de San Luis Potosí, Instituto de Geología, Folleto Técnico 120, 34, with 2 maps.

LABARTHE-HERNÁNDEZ, G., M. GÓMEZ-ANGUIANO, J. R. TORRES-HERNÁNDEZ and G. AGUIRRE-DÍAZ, 2000. Caracterización de un depósito de brechas co-ignimbríticas de rezago en el Arroyo El Juachín, Sierra de San Miguelito, S. L. P. México. *GEOS*, 20, p. 351.

MILANOVSKI, E. E. and N. V. KORONOVSKI, 1965. “Tuffolavas” and related formations of Central Caucasus. *Bull. Volcanol. 28,* 3-11.

MIURA, D., 1997. Coherent caldera floor in a deeply dissected caldera: evaluation of its structure in relation to caldera formation, Miocene Kumano caldera, southwest Japan. Abstr. IAVCEI, General Assembly, Puerto Vallarta, Mexico, p. 152.

MIURA, D. and TAMAI, 1998. Intracaldera structure and mega breccias at Dorobu caldera, northeastern Honshu, Japan. *J. Volcanol. Geotherm. Res. 80,* 195-215.

NIETO-SAMANIEGO, A. F., C. MACÍAS-ROMO and S. A. ALANÍZ-ÁLVAREZ, 1996. Nuevas edades isotópicas de la cubierta volcánica cenozoica de la parte meridional de la Mesa Central, México. Inst. de Geol., UNAM. *Rev. Mex. de Ciencias Geol., 13,* 117-122.

NIETO-SAMANIEGO, A. F., S. A. ALANÍZ-ÁLVAREZ and G. LABARTHE-HERNÁNDEZ, 1999. La deformación Cenozóica poslaramídica en la parte meridional de la Mesa Central, México. *Rev. Mex. de Ciencias Geol*., 14, 13-25.

NIETO-SAMANIEGO, A. F., L. FERRARI, S. A. ALANÍZ-ÁLVAREZ, G. LABARTHE-HERNÁNDEZ and J. ROSAS-ELGUERA, 1999. Variation of Cenozoic extension and volcanism across the southern Sierra Madre Occidental volcanic province, Mexico. *Geol. Soc. Am. Bull. 111*, 347-363.

POTTER, P. E. and F. J. PETTIJOHN, 1963. Paleocurrents and Basin Analysis. Springer-Verlag. 295 p.

SHINOHARA, H., 1990. Behavior of volatiles in magma. *In:* Basic Studies of Volcanology. *Bull. Volcanol. Soc. Japan*, 34, S99-S110, (in Japanese with English abstract).

SHROCK, R. R., 1948. Sequence in layered rocks: A study of features and structures useful for determining top and bottom of successions in bedded and tabular rocks bodies. Mc Graw – Hill Book Company, Inc. First Edition, 483p.

TAKAHASHI, M., 1986. Anatomy of a middle Miocene Valles-type caldera cluster: Geology of Okueyama volcano-plutonic complex, southwest Japan. *J. Volcanol. Geotherm. Res*., *29,* 33-70.

TORRES-HERNÁNDEZ, J. R., G. LABARTHE-HERNÁNDEZ, C. SIEBE and L. ALVA-VALDIVIA, 1998. Evidencias de magmatismo sin-tectónico en el Campo Volcánico de San Luis Potosí. S.L.P., México. *GEOS*, *18,* 373.

TORRES-HERNÁNDEZ, J. R., G. LABARTHE-HERNÁNDEZ, M. TRISTÁN-GONZÁLEZ, A. AGUILLÓN-ROBLES, C. SIEBE-GRABACH, J. L. MACÍAS-VÁZQUEZ, J. M. ESPÍNDOLA-CASTRO and J. J. ARANDA-GÓMEZ, 2001. Vulcanismo y extensión: la evolución de un campo volcánico en el Altiplano Central de México. ACTAS INAGEQ, 7, 1, p. 58.

WALKER, J. P. L. and P. R. EYRE, 1995. Dyke complexes in American Samoa. *J. Volcanol. Geotherm. Res*., *69,* 241-254.

WILSON, L., R. S. J. SPARKS and G. P. L. WALKER, 1980. Explosive volcanic eruptions- IV. The control of magma proprieties and conduit geometry on eruption column behavior. *Geophys. J.R. Astron. Soc*., *63*, 117-148.

WOLFF, J. A., 1986. Welded–tuff dykes, conduit closure, and lava dome growth at the end of explosive eruptions. *J. Volcanol. Geotherm. Res*., *28,* 379-384.

YOSHIDA, T., 1984. Tertiary Ishizuchi cauldron, southwestern Japan arc: formation by ring fracture subsidence. *J. Geophys. Res*., 89, 8502-8510.

José Ramón Torres-Hernández[1], Guillermo Labarthe-Hernández, Alfredo Aguillón-Robles, Martín Gómez-Anguiano and José Luis Mata-Segura

Instituto de Geología, Universidad Autónoma de San Luis Potosí, Av. Dr. Manuel Nava No. 5, Zona Universitaria, 78240 San Luis Potosí, México
[1]Author to whom correspondence should be addressed: Email: jrtorres@uaslp.mx