

Ruby Xenocrystals in Dacite from Central Mexico

Luis Enrique Ortiz Hernández^{1,2}  and José C. Escamilla-Casas^{1*} 

Abstract

The occurrence of 1-2 cm in diameter, anhedral xenocrystals of red corundum (ruby) in a dacitic lava-flow from central Mexico -in the state of Hidalgo- has been recorded. Geochemically, this dacite nearly resembles adakitic rock ($\text{SiO}_2=63.73$ 66.64 wt %), with low alumina contents ($\text{Al}_2\text{O}_3=14.38$ 14.93 wt %), sodium ($\text{Na}_2\text{O}=3.29$ 3.57 wt %) and titanium ($\text{TiO}_2=0.55$ 0.60 wt %), slightly peraluminous ($A/\text{CNK}=1.04$ 1.17) and moderately potassic ($\text{K}_2\text{O}=1.90$ -2.04 wt %; $\text{K}_2\text{O}/\text{Na}_2\text{O}=0.53$ -0.62), with rare earth spectra enriched in light-rare earth elements ($(\text{La}/\text{Yb})_N=9.71$ 10.98). The origin of the dacite is linked to the early geological evolution of the eastern sector of the Trans-Mexican Volcanic Belt (TMVB) during the Miocene, and its provenance could be a melt of a basaltic and pelitic-sediments slab and magmatic differentiation that generated adakitic magma. The gem-type corundum could have resulted after the addition of refractory products disaggregated from the Precambrian basement, carried, and transported to the surface by ascending magma.

Key words: Ruby, corundum, dacite, xenocrystals, Mexico, state of Hidalgo.

Resumen

Se consigna la ocurrencia de xenocristales anhedrales de corindón rojo (rubí) de 1-2 cm de diámetro, en un derrame lávico dacítico del centro de México (estado de Hidalgo). Geoquímicamente, la dacita presenta algunos rasgos de roca adakítica ($\text{SiO}_2=63.73$ 66.64 wt %), con bajo contenido en alúmina ($\text{Al}_2\text{O}_3=14.38$ 14.93 wt %), sodio ($\text{Na}_2\text{O}=3.29$ 3.57 wt %) y titanio ($\text{TiO}_2=0.55$ 0.60 wt %), ligeramente peraluminosa ($A/\text{CNK}=1.04$ 1.17) y medianamente potásica ($\text{K}_2\text{O}=1.90$ 2.04 wt %; $\text{K}_2\text{O}/\text{Na}_2\text{O}=0.53$ 0.62), con espectros de tierras raras enriquecidos en tierras raras ligeras ($(\text{La}/\text{Yb})_N=9.71$ 10.98). El origen de la dacita está ligada a la evolución geológica temprana del sector oriental de la Faja Volcánica Transmexicana, durante el Mioceno, y podría provenir de la fusión de losa basáltica-sedimentos pelíticos y diferenciación magmática para constituir una lava adakítica. El corindón variedad gema sería el resultado de la incorporación de productos refractarios disgregados de basamento precámbrico, acarreados y transportados a la superficie por la lava en ascenso.

Palabras clave: Rubí, corindón, dacita, xenocristales, México, estado de Hidalgo.

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1. Introduction

Corundum is a relatively scarce mineral on our planet. Its gem varieties -sapphires and rubies- are much scarcer because they are formed at 10-40 km terrestrial depth (Stern *et al.*, 2013) from where they are transported to the surface as xenocrystals or xenoliths in alumina-rich, silica-poor igneous rocks (Giuliani *et al.*, 2014; Giuliani *et al.*, 2020). Also, the occurrence of corundum is in metamorphic rocks (Wilson, 1974; Baumgartner *et al.*, 2001) and some placer deposits (Simonet *et al.*, 2008).

While iron, titanium, and nickel trace contents in sapphires result in a wide range of colors -yellow, green, blue, orange, black and pink- ruby chromophores derive from trace chromium (Al_3 substituted by Cr_3+ in the crystalline structure) (García-Lastra *et al.*, 2005) and are less common than rubies with traces of vanadium or iron (Dubinski *et al.*, 2020) which result in rubies ranging in color from orange-red to purplish-red. In Mexico, the presence of sapphire xenocrystals has been documented in an Oligocene andesitic dike ($\text{K}/\text{Ar} = 29.20 \pm 0.30$ 30.50 ± 0.60 Ma; Ortega-Gutiérrez *et al.*, 2011). However, up until now, the occurrence of rubies has not been reported in the Mexican territory (e. g. Cruz-Ocampo *et al.*, 2007).

The aim of this work is to document, for the very first time, their occurrence and discuss the possible origin of gem-type red corundum (ruby) in Mexico, particularly in the eastern sector of the Trans-Mexican Volcanic Belt (TMVB) which crosses the middle of the state of Hidalgo (central Mexico) from east to west.

1.1. Analytical Methods

Due to their scarcity, fieldwork was carried out seeking rock samples containing xenocrystals, which were later prepared for petrographic analysis. Although fresh samples lack xenocrystals, they can be found in altered rocks. Thin sections were cut along different orientations to determine the texture and any dacite constituents; subsequently, samples were studied and photographed under a Leitz BA310 polarizing microscope at the Laboratory of Petrography at the Universidad Autónoma del Estado de Hidalgo (UAEH).

Three rock samples (PT-1, PT-2 and PT3) were selected for whole-rock geochemical analysis. These samples were pulverized for analysis preparation -major and trace elements- with a 200-mesh using an agate mortar at the Servicio Geológico Mexicano. The analyses were conducted with 95% confidence on a Phillips MagixPRO X-Ray fluorescence spectrometer and a Palma Quad-3 being, induced coupled plasma mass spectrometer (ICPMS).

1.2. Regional geology and outcrop description

In central Mexico, the southern portion of the state of Hidalgo

is geologically dominated by the TMVB (Figure 1), which is a relatively young geological province (Miocene-Quaternary) with its eastern sector characterized by discrete volcanic fields, and predominance of andesitic lava and dacitic flows, domes, pyroclastic flows, cineritic cones, and calderas. Among them, the most important are Apan-Tezontepec volcanic field (García-Palomo *et al.*, 2002), Apan- Tecocomulco (García-Tovar *et al.*, 2015), Xihuingo-La Paila (Valadez-Cabrera, 2012), Chichicuaullta-Tecocomulco (Juárez-López, 2015), Epazoyucan-Singuilucan (Aparicio-Canales & Contreras-Cruz, 2016), San Vicente (Ramírez-Ramírez, 2016) and Las Navajas (Núñez-Velázquez, 2018). These volcanic fields engulf, in variable proportion, Early to Medium-Late Miocene rocks, forming pyroclastic deposits, lava flows, domes and, eventually, calderas. After a magmatic ~7 Ma hiatus during the Pliocene, coupled with bimodal vulcanism occurred the emplacement of lava spills, pyroclastic flows, and cineritic cones (García-Tovar *et al.*, 2015).

For a portion of the Sierra de Pachuca, Martínez-González (2018) recently proposed the existence of three volcanic events: the lower formed by Oligocene to early Miocene dacitic and andesitic lava flows and domes; a middle event formed by early to mid-Miocene rhyolitic ignimbrites and pyroclastic deposits; and an upper event formed by mid-Miocene andesitic lava flows and domes. Very likely, the country rock that hosts ruby xenocrystals belongs to the first volcanic event proposed by Martínez-González (2018) and in this case, it will be placed between 23.70 21.60 Ma, equivalent to the K/Ar radiometric age reported by Geyne *et al.* (1990) for the rocks in the local stratigraphic column corresponding to the Santa Gertrudis-Zumate formations.

The area of the outcrop is about 4 km² and constitutes a 10 m column of pseudostratified dacitic lava spill, slightly tilted to the SE. The rock is tan, gray to cream, occasionally red due to sericitic alteration and oxidation; also affected by NW-SE and NE-SW trending normal faults and abundant joints. Xenocrystals are anhedral, 1-2 cm in diameter, are scarce, and occupy 1 % of the rock (Figure 2). This dacite discordantly overlaps andesitic flows, domes, and breccias of the Pachuca Group (Geyne *et al.*, 1963) and it is overlaid by lapilli tuff.

2. Petrography and Geochemistry

The lava host rock contains the typical dacitic mineralogy with subhedral plagioclase phenocrystals of medium to sodic composition and partial sericitic alteration; hornblende and biotite are accessory minerals embedded in a microlithic matrix of sanidine, interstitial glass, seldom quartz, and disseminated iron-titanium oxides. Amphiboles altered to opaques and/or hematite at the rim, and biotite is altered to chlorite. Ruby xe-

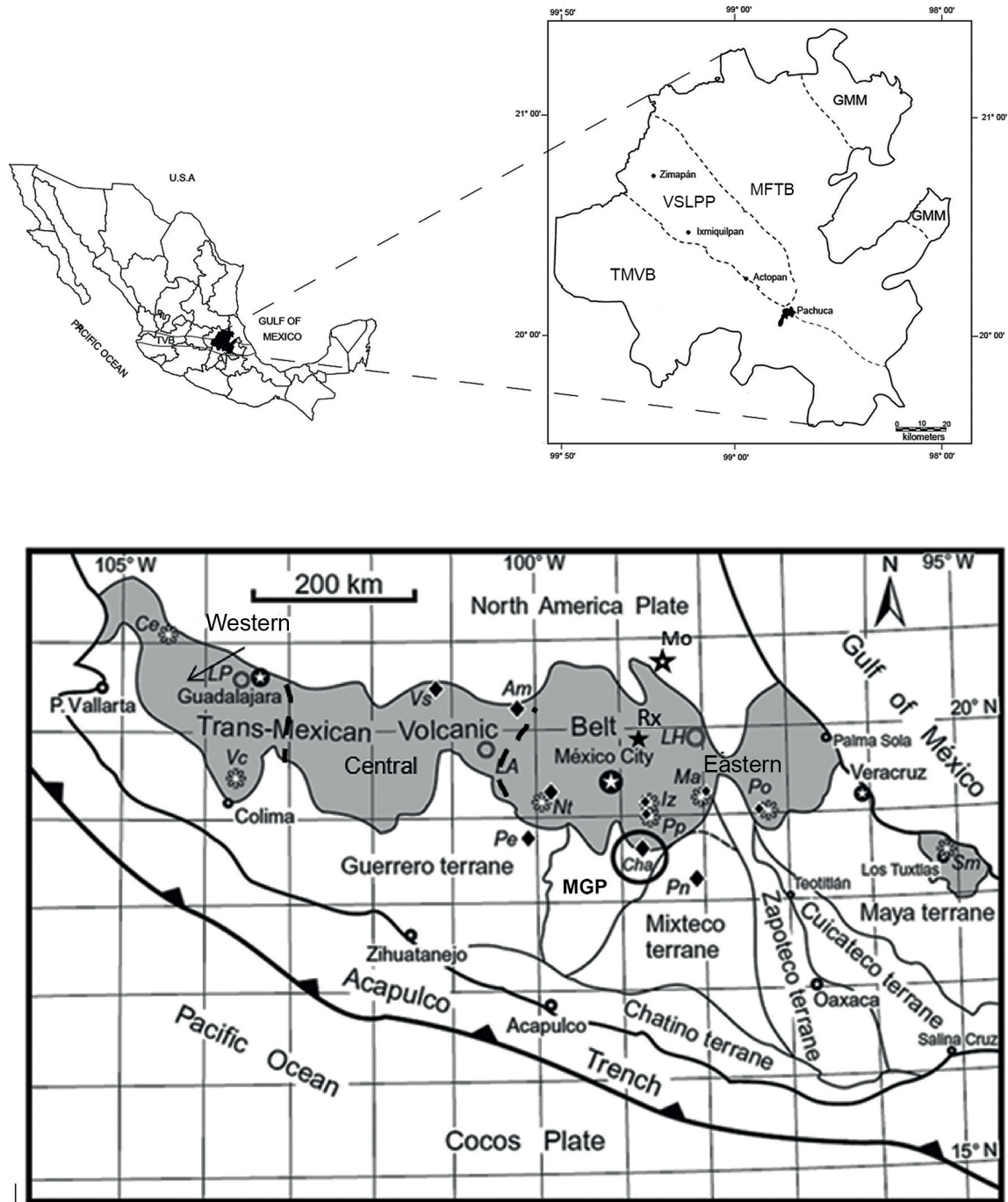


Figure 1. Location map of the state of Hidalgo and geologic provinces (TMVB = Trans-Mexican Volcanic Belt, VSLPP= Valles-San Luis Platform, MFTB=Mexican Folds and Thrust Belt, GMM=Gulf of Mexico Miogeoclinal). In the inset a map of central Mexico shows the subdivision of the TMVB in three sectors (western, central, and eastern), geologic provinces and adjacent tectonostratigraphic terranes (Sedlock *et al.*, 1993); MGP = Morelos-Guerrero Platform. Location of the principal volcanoes are indicated by asterisks: San Martín (Sm), Pico de Orizaba (Po), La Malinche (Ma), Iztaccíhuatl (Iz), Popocatepetl (Pp), Nevado de Colima (Vc), and Ceboruco (Ce). Circles indicate the active calderas: Los Hornos (LH), Los Azufres (LA), and La Primavera (LP). Localities of lower-crust xenoliths represented by small solid diamonds are in Pico de Orizaba, Iztaccíhuatl, Popocatepetl, and La Malinche (Ortega-Gutiérrez *et al.*, 2008). Large solid diamonds indicate the localities where xenoliths have been found in granulite facies rocks: Puente Negro (Pn), Chalcatzingo (Cha), Pepechuca (Pe), Amealco (Am), and Valle de Santiago (Vs) (Ortega-Gutiérrez *et al.*, 2011). A black solid star with the Rx label indicates the locality in the eastern sector of the TMVB where the dacite containing ruby xenocrysts have been found. An open star with a Mo label indicates the locality, to the north, where the Precambrian basement crops out.

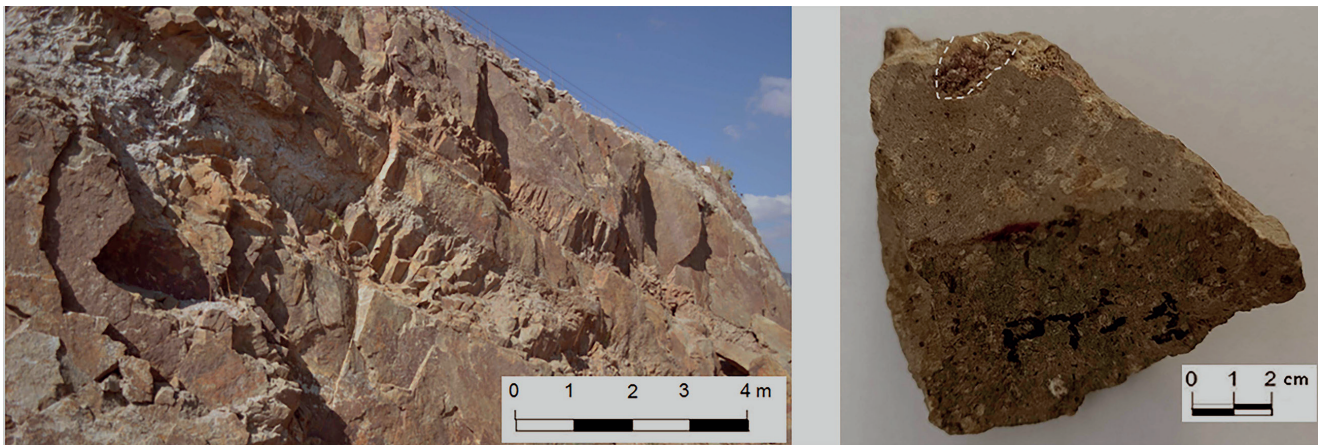


Figure 2. Photographs showing the outcropping dacitic lava host rock and a rock sample of centimeter scale ruby xenocrysts (Dotted half circle). The lava flow is pseudostratified, altered, and jointed.

nocrystals are anhedral, fractured, and scarce; present high relief, low birefringence, with abundant undetermined inclusions and an incipient diaspora alteration (Figure 3) suggesting corundum hydration. The rock is classified as hornblende-biotite dacite.

From the geochemical perspective, the three samples analyzed for major, and some trace elements (Table 1) exhibit typical dacite features, with SiO_2 contents between 63.73–66.64 wt % (Figure 4a) with low alumina contents (14.38 wt % $\leq \text{Al}_2\text{O}_3 \leq 14.93$ wt %), sodium (3.29 wt % $\leq \text{Na}_2\text{O} \leq 3.57$ wt %) and titanium (0.55% $\leq \text{TiO}_2 \leq 0.60$ wt %). It is a slightly peraluminous rock (1.04 $\leq \text{A/CNK} \leq 1.17$) (Figure 4b), moderately potassic (1.90 wt % $\leq \text{K}_2\text{O} \leq 2.04$ wt %), trondhjemitic (0.53 $\leq \text{K}_2\text{O}/\text{Na}_2\text{O} \leq 0.62$) and differentiated (43 $\leq \# \text{Mg} \leq 47$).

CIPW analysis (not shown) presents as normative minerals, quartz, plagioclase, orthoclase, hypersthene, and corundum (1.00–2.82 wt %).

Some geochemical characteristics of the studied dacite resemble adakitic rock (Zhang *et al.*, 2019), for example $\text{SiO}_2 > 56$ wt %, $\text{MgO} < 3$ wt %, $\text{TiO}_2 < 0.60$ wt %, $\text{Y} < 18$ ppm, $\text{Yb} < 1.80$ ppm (Defant & Drummond, 1990; Drummond & Defant, 1990; Drummond *et al.*, 1996; Martin *et al.*, 2005; Sun *et al.*, 2012) and the ratios $\text{Y}/\text{Yb} \sim 10$ y Dy/Yb (1.79–1.84), suggesting residual amphibole and garnet. Rare earth total sum varies between 91.50–100.90 ppm, with $(\text{La}/\text{Yb})_N = 9.71$ –10.98 ratio (normalization values of Sun & McDonough, 1989).

Light rare earth values (La, Ce, Nd, Sm, and Gd) are closer to the earth crust total values (17.60–20.90 ppm vs 20 ppm, 39.40–41.60 ppm vs 43.73 ppm, 15.40–18.30 ppm vs 19.81 ppm, 3.00–3.30 ppm vs 3.93 ppm and 3.30–3.70 ppm vs 3.83 ppm, respectively (Rudnick & Gao, 2003), as well as the ratio $\text{U}/\text{Th} = 0.22$ –0.24 vs 0.25 (Rudnick & Fountain, 1995). While the $\text{Sm}/\text{Nd} = 0.18$ –0.19 ratio is very close to mid continental crust ($\text{Sm}/\text{Nd} = 0.18$; Rudnick & Fountain, 1995).

Dacitic flow Gd/Yb ratio is higher than 1 (2.54–2.69) suggesting a source involving garnet. The Yb/Lu coefficient varies between 6.50–7.00 which is higher than silica rich adakites ($\text{HSA} \sim 5$; Moyen, 2009). La/Yb ratio varies between 13.53–15.31 falling in the range of modern continental margin adakites ($\text{La}/\text{Yb} < 50$; Sun *et al.*, 2012) but it is lower than silica rich adakites ($\text{La}/\text{Yb} > 20$; Moyen, 2009). $\text{Sm}/\text{Yb} = 2.31$ –2.46 and $\text{La}/\text{Sm} = 5.80$ –6.30 fall in the range of adakites ($\text{Sm}/\text{Yb} = 3$ –7 and $\text{La}/\text{Sm} \sim 2$ –10; Dimalanta & Yumul, 2008).

The Europium anomaly is not so evident ($\text{Eu}/\text{Eu}^* = 1.1$ –1.16), while the Cerium anomaly ($\text{Ce}/\text{Ce}^* = 0.91$ –1.05), which is close to 1, is common in rocks associated with subduction. This value of Ce/Ce^* suggests the contribution of pelagic clay sediments (Elliot *et al.*, 1997; Hastie *et al.*, 2010; Bellot *et al.*, 2018). Furthermore, present island arcs with significant volume of subducted sediments typically show $\text{Th}/\text{Yb} \geq 2$ ratios (Nebel *et al.*, 2007; Woodhead *et al.*, 2001;). In support of the later, this ratio in the studied samples varies between 3.30–3.40.

On a $(\text{La}/\text{Yb})_N$ vs Yb_N diagram, the studied dacite falls in the non-discriminant field between “normal” calc-alkaline arc rocks and adakites (Figure 4c). In other binary diagrams (not shown) like Th/Ce vs Th , the studied dacite falls in the field of Cenozoic slab derived adakite; La/Th diagram vs Yb/Gd strongly points to a magmatic arc setting (Ueki *et al.* 2022), while the $(\text{Na}_2\text{O} + \text{K}_2\text{O})/(\text{FeO} + \text{MgO} + \text{TiO}_2)$ vs $\text{Na}_2\text{O} + \text{K}_2\text{O} + \text{FeO} + \text{MgO} + \text{TiO}_2$ diagram suggests that this dacite comes from partial melt amphibolite.

On a Th vs SiO_2 diagram (Wang *et al.*, 2006), this dacite is associated with the field of adakites derived from subducted oceanic crust (Figure 4d). This fact is also corroborated on the $\text{K}_2\text{O}/\text{Na}_2\text{O}$ vs Al_2O_3 diagram (Figure 4e).

Finally, the rare earth elements diagram normalized with respect to chondrites (normalization values of Sun & McDonough, 1989; Figure 4f) shows light rare earth enrichment

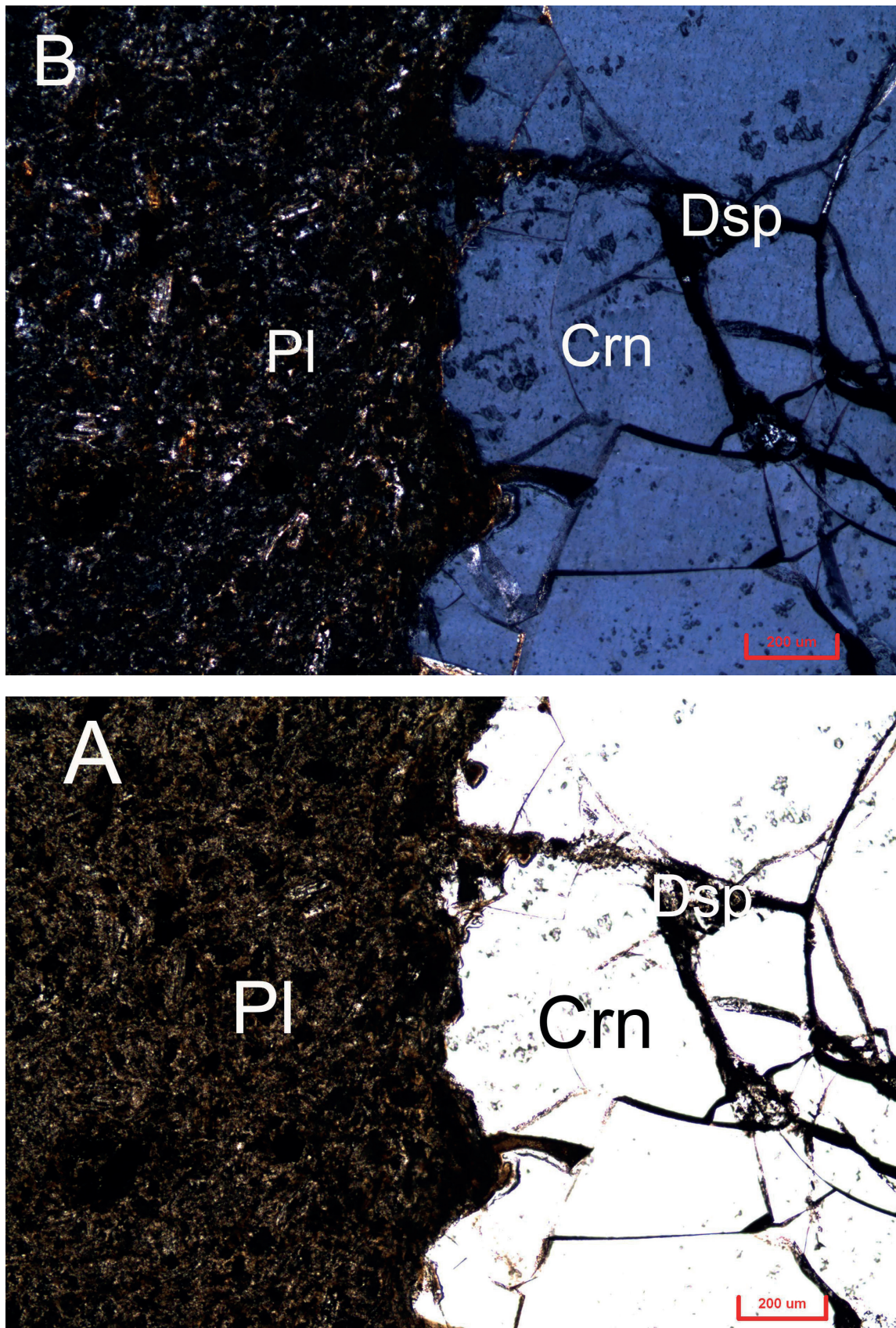


Figure 3. Photomicrographs showing the petrographic characteristics of the studied dacite and ruby xenocrysts, 5X; A = PPL; B = XPL. Plagioclase phenocrystals (PI), are observed with partially vitreous microlithic matrix and fractured anhedronal ruby phenocrysts (Crn) with incipient alteration to diaspore (Dsp).

Table 1. Whole rock chemical analysis (wt %) and some trace elements (ppm) of three dacite rock samples.

Sample	PT-1	PT-2	PT-3	Sample	PT-1	PT-2	PT-3
SiO ₂	63.73	66.00	66.64	Th	4.50	4.40	4.60
Al ₂ O ₃	14.93	14.56	14.38	U	1.10	1.00	1.00
Fe ₂ O ₃	3.4	3.46	3.09	Y	13.00	13.20	13.80
MgO	1.64	1.36	1.26	La	17.60	19.90	20.90
CaO	3.54	2.70	2.66	Ce	40.30	39.40	41.60
Na ₂ O	3.57	3.29	3.33	Pr	4.20	4.70	5.00
K ₂ O	1.90	2.04	2.04	Nd	15.40	17.40	18.30
TiO ₂	0.60	0.58	0.55	Sm	3.00	3.20	3.30
P ₂ O ₅	0.17	0.18	0.17	Eu	1.20	1.20	1.30
MnO	0.07	0.09	0.05	Gd	3.30	3.50	3.70
LOI	5.15	5.21	5.10	Tb	0.50	0.50	0.50
Total	98.70	99.47	99.27	Dy	2.40	2.40	2.50
				Ho	0.50	0.50	0.50
				Er	1.4	1.4	1.5
				Tm	0.20	0.20	0.20
				Yb	1.30	1.30	1.40
				Lu	0.20	0.20	0.20

and a negative slope from La to Lu, indicating heavy rare earth depletion with respect to light rare earth elements, a common geochemical feature of subduction associated rocks (Pearce, 1983, Rollinson, 1993).

3. Formation conditions

Despite lacking quantitative mineralogical data of glass or mineral composition in the dacite, formation conditions of the studied rock were determined based on whole rock chemical composition. As such, a temperature range of 829 877 °C was obtained for the liquidus with Norm4 (Hollocher, 2004), while the thermometer proposed by Jung & Pfander (2007) based in the Al₂O₃/TiO₂ ratio, yielded a temperature range between 925 928°C. The former range of temperature (829 877 °C) is considered more reliable for dacite formation. Additionally, other parameters were established using Norm4 (Hollocher, 2004), the magma density (2.74 2.75 g/cm3) and magma water contents (3 3.50 wt %).

Based on the geochemistry of some trace elements, mohometric methods were applied to establish the crustal depth of formation of the dacite such as the La/Yb ratio. This is because Dimalanta & Yumul (2008) proposed that the La/Yb ratios in adakitic rocks can be applied as an approach to investigate crustal thicknesses, so that a La/Yb=10 ratio represents 30-35 km

thickness and a La/Yb=10 20 ratio a crustal thickness greater than 42 km. In our study, La/Yb ratio is in the 13.80 15.30 range, consequently a crust thickness greater than 42 km is considered.

Furthermore, using the La/Yb ratio and applying the equation proposed by Sundell *et al.* (2021) after Profeta *et al.* (2015), where H represents the crustal depth ($H = 17.0 \times \ln (La/Yb) + 6.9$), a value of crustal thickness of 26-27 km is obtained. On the other hand, the calculated depth using Ce/Y ratio and the equation proposed by Mantle & Collins (2008) ($H= 18.0505 \times \ln (Ce/Y) + 21.5587$) a range of 30-30.4 km is obtained. The above-mentioned depths are concordant with the crustal thickness of 45-50 km determined for the eastern sector of the TMVB (Ferrari *et al.*, 2012; Urrutia-Fucugauchi & Flores-Ruiz, 1996).

4. Discussion

According to Stern *et al.* (2013) ruby deposits are good petrogenetic markers, indicative of continental collision, formed at amphibolitic or granulitic facies or from fusion of Al rich and silica poor protoliths, between 10 to 40 km crustal depth. Due to these facts, many ruby and sapphire deposits are found close to ancient continental margins and subduction zones (Wong & Verdel, 2017). Several geologic settings propitiate the occurrence of rubies, such as: 1) amphibole or granulite facies metamorphic belts (Dahanayake & Ranasinghe, 1981; Kriegsman &

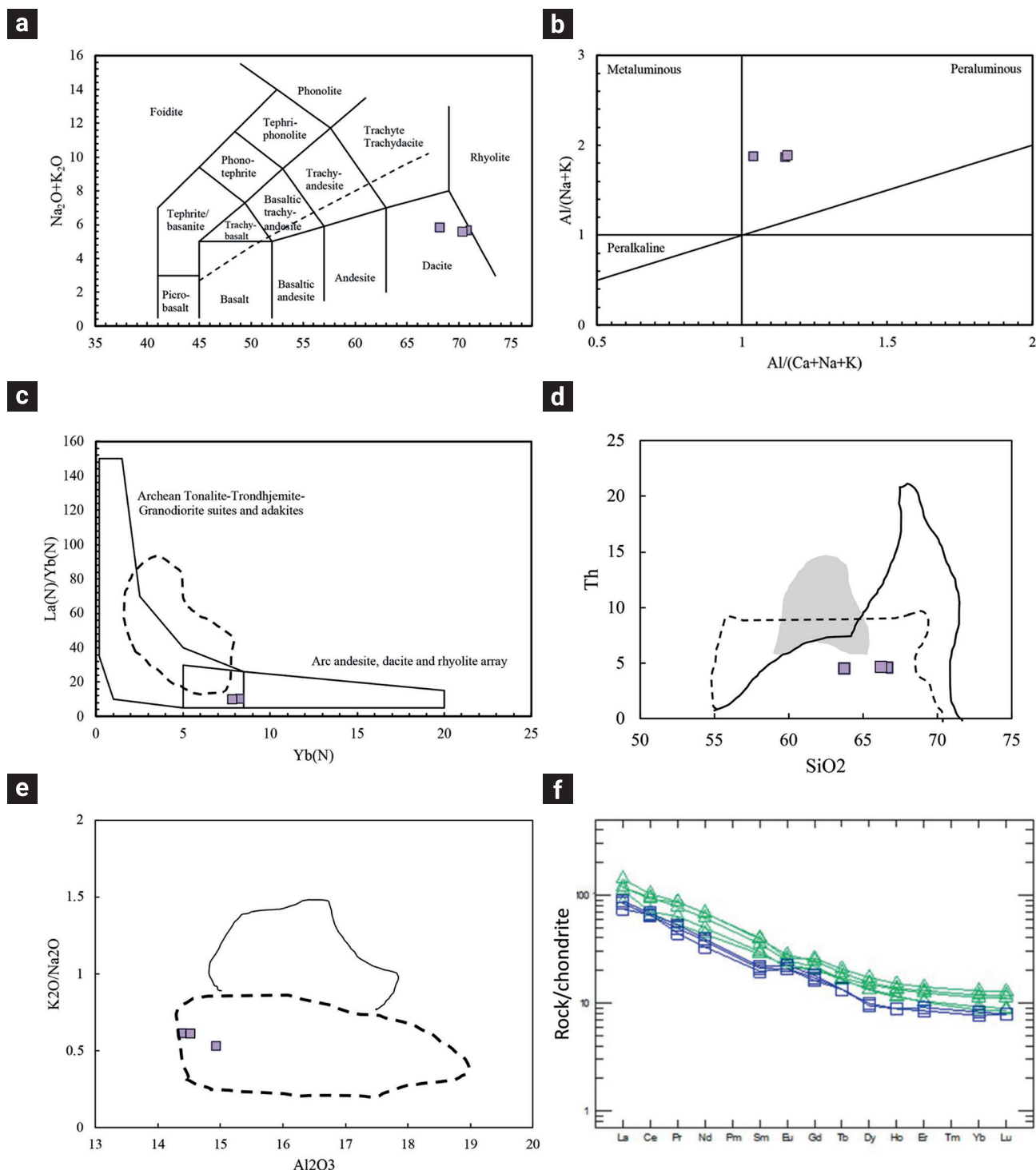


Figure 4. a) SiO_2 vs $\text{Na}_2\text{O}+\text{K}_2\text{O}$ diagram showing the host rock classification, b) its peraluminous character according to the CAN/K vs ANK diagram, and c) the non-discriminant field between arc calc-alkaline rocks and adakites (dotted line shows the field of metabasaltic rock after experimental studies in equilibrium with eclogitic residuals; Rapp *et al.*, 2003), d) Th vs SiO_2 diagram (Wang *et al.*, 2006) showing that the studied rock samples belong to adakite derived from subducted oceanic crust (dotted line), differing from adakite derived from lower delaminated crust (dark field) and from adakite derived from thick oceanic crust (continuous line). e) $\text{K}_2\text{O}/\text{Na}_2\text{O}$ vs Al_2O_3 diagram showing the classification of the dacite as adakite derived from subducted oceanic crust (dotted line; Kamei *et al.*, 2009) which is different from adakite derived from thick oceanic crust (continuous line; Liu *et al.*, 2010). f) rare earth elements normalized diagram with respect to chondrites (normalization values of Sun & McDonough, 1989) showing enrichment in light rare earth elements, typical of subduction associated rocks. Also shown, for comparison purposes, the spectrum of rare earth elements of the Sierra de Pachuca lower volcanic event (triangles, Martínez-González, 2018) with similar spectra, but enriched in rare earth elements ($(\text{La}/\text{Yb})_{\text{N}}=7.47-12.90$).

Schumacher, 1999), 2) settings of alkali basalt associated with subduction zones, involving oceanic and continental plates (Levinson & Cook, 1995), 3) continental rift zones related to alkali basalt volcanism (Giuliani *et al.*, 2020), and 4) placer deposits associated with sedimentation (Dill, 2018).

For the studied ruby, the formation setting is interpreted as, firstly, to be associated with the early geologic history of the TMVB during the Miocene -considered as the age of formation for the host rock- and secondly, that constitutes the basement of the eastern sector of the TMVB.

As stated by Ortega-Gutiérrez *et al.* (2008) the lower crust of the TMVB and surrounding setting to the south, must be at granulite facies, with a minimum temperature between 700 800 °C, a crustal thickness about 40 45 km, and with the presence of garnet at the deepest levels. Nonetheless, higher temperatures for the granulite facies (950 112 °C) have been proposed for central Mexico (Hayob *et al.*, 1989) and 990 1100 °C for southern Mexico (Ortega-Gutiérrez *et al.*, 2011).

It is accepted that the occurrence of granulitic outcrops and xenoliths coming from the lower crust have been reported in Mexico (Hayob *et al.*, 1989; Roberts & Ruiz, 1989; Ruiz *et al.*, 1988). In central Mexico (TMVB and surroundings) in five localities, granulite facies xenoliths have been thoroughly studied even though they can be present in several other places (e.g., Pico de Orizaba, Carrasco-Núñez *et al.*, 2005). Two of the localities are in the central portion of the TMVB (e.g., Valle de Santiago, see Gutiérrez *et al.*, 2014; Urrutia-Fucugauchi & Uribe-Cifuentes, 1999; and Amealco, see Aguirre-Díaz *et al.* 2002) which

are basic granulites. The remaining three localities are found in adjacent areas to the south (forearc): Pepechuca (Elías-Herrera & Ortega-Gutiérrez, 1997), Puente Negro (Ortega-Gutiérrez *et al.*, 2011) and Chalcatzingo (Ortega-Gutiérrez *et al.*, 2012), which are pelitic granulites constituted by pyrope rich garnet, sillimanite, rutile, spinel, corundum, cordierite, orthopyroxene, and Fe-Ti oxides with less common quartz and feldspar.

On these occurring granulitic xenoliths localities, it has been proposed the existence of Precambrian basement of which a nearby outcrop is documented in Molango, Hidalgo -Huiznopala gneiss- at ~75 km far from the eastern sector of the TMVB (Figure 1) and characterized by the presence of ortho- and para-gneiss, and a gabbro-anorthosite complex (Lawlor *et al.*, 1999).

According to Ortega-Gutiérrez *et al.* (2008), the eastern sector of the TMVB could be underlain by Grenvillian basement rocks (~1Ga), belonging to the Oaxaquia micro-continent (Ortega-Gutiérrez *et al.*, 1995), and constituted by metapelites, quartzofeldspathic gneisses, calc-silicates, amphibolites, and marbles intruded by anorthosites, charnokites, and garnetiferous mafic gneisses. The whole lithologic sequence is metamorphosed to granulite facies and locally re-equilibrated to amphibolite facies.

As stated by Ortega-Gutiérrez *et al.* (2008), the reported granulites might be representative of the upper part (25 30 km depth) of the lower Precambrian crust, affected by Cenozoic thermal processes including the emplacement of contemporaneous mafic magma (underplating), metamorphic granulite facies, partial melting, and magma mixing. This fact is concordant with

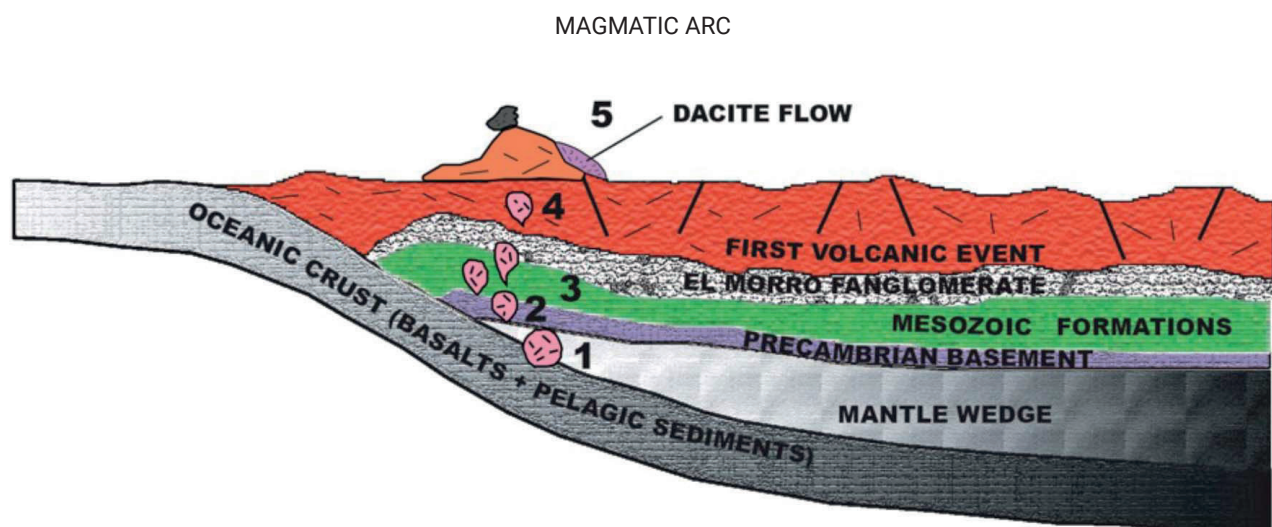


Figure 5. Schematic simplified model explaining the origin of ruby crystals: 1) formation of basaltic magma emplaced at the mantle wedge, 2) diapiric ascension of adakitic magma, 3) magmatic differentiation and assimilation of Precambrian rock xenocrystals, 4) constant ascension reaching shallow levels of the crustal arc, and 5) spill of the dacite lava containing ruby xenocrystals.

the mohometric results based on La/Yb and Ce/Y (26-27 km and 30-30.40 km, respectively).

Under these conditions, the dacite could have originated after partial melting of the basaltic lava and pelagic clay sediments -giving the rock a peraluminous character, the Ce/Ce* $\pm$ 1 anomalies, and Th/Yb $\geq$ 2 ratio- on an arc geologic setting, as it is described by Drummond & Defant (1990) and Drummond *et al.* (1996) for adakites and for silica rich adakites (Martin *et al.*, 2005; Moyen, 2009) very likely favored by a sub horizontal subduction, as it has been suggested for the eastern and central sectors of the TMVB (Gómez-Tuena *et al.*, 2003; Mori *et al.*, 2007).

Xenocrystals of red corundum (rubi), which are refractory products, may come from: a) fusion of pelagic clay sediments subducted during the formation of dacitic magma, b) from pelitic and calcareous Cretaceous formations which constitute the bedrock of the Sierra de Pachuca (e.g., El Doctor, Mexcala and Méndez formations, see Geyne *et al.*, 1963), or c) the presumable Precambrian basement of the TMVB, which could correspond to metapelitic, amphibolitic, or marble rock fragments, that were disintegrated and accidentally incorporated into the ascending dacitic magma (Figure 5). From the above-mentioned, the hypothesis involving a Precambrian basement is considered the most viable.

Fractured ruby crystals and the presence of opaques and hematite at the rim of amphibole phenocrystals in the dacite host rock, may result from sudden adiabatic decompression during quick lava ascension (Devine *et al.*, 1998), while the incipient diaspore alteration of the xenocrystals, suggests corundum hydration and disequilibrium (Voudouris *et al.*, 2009) very likely produced by hydrothermalism.

5. Conclusions

This work confirms the occurrence of red corundum xenocrystals (ruby), in an early Miocene dacitic flow with adakitic affinity in the eastern sector of the TMVB. Despite its occurrence in a small outcrop (4 km²) and the scarce presence of xenocrystals, it is highly likely that exist more outcrops of adakitic rocks with xenocrystals or xenoliths from the lower crust, which will shed light into the understanding of the bedrock and geodynamic evolution of the Sierra de Pachuca. For interpretation purposes, the source of xenocrystals found is interpreted as the Precambrian basement of the eastern sector of the TMVB.

On the other hand, this first report of the presence of ruby in rocks of the Sierra de Pachuca, strongly suggests that the rocks in this locality not only host world class metallic ore deposits but, likely, deposits of different kind.

6. References

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