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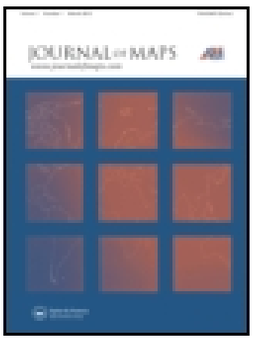

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Geology of the late Pleistocene Tres Vírgenes Volcanic Complex, Baja California Sur (México)

Denis Ramón Avellán[a], José Luis Macías[b], José Luis Arce[c], Ricardo Saucedo-Girón[d], Víctor Hugo Garduño-Monroy[e], Adrian Jiménez-Haro[e], Giovanni Sosa-Ceballos[b], Guillermo Cisneros[b], Juan Pablo Bernal[f], Paul W. Layer[g], Laura García-Sánchez[h], Gabriela Reyes-Agustín[b], Elizabeth Rangel[h], José Antonio Navarrete[i] and Héctor López-Loera[j]

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ABSTRACT

The geological map of the Tres Vírgenes Volcanic Complex (TVVC) Baja California Sur, México consists of three northeast-southwest aligned stratovolcanoes named from older to younger, El Viejo, El Azufre, and La Virgen. The map (scale 1:20,000) comprises an area of 856 km^2 edited on an ArcMap data set. The map compiles previous studies combined with new mapping and stratigraphy supported by 5 new ^{230}Th/U geochronology in zircons. The TVVC sits on top of Cretaceous granite, Cenozoic volcaniclastics, the Esperanza basalt (7.64 Ma), and the Aguajito ignimbrite (1.17 Ma). The TVVC commenced its activity around 300 ka by constructing El Viejo volcano, followed by El Azufre volcano (~173–128 ka), la Virgen scoria cones (~128–112 ka), and La Virgen stratovolcano (~112–22 ka). The La Virgen volcano emplaced the La Virgen rhyolitic tephra (~31 ka), and the Upper Andesite lavas (~22 ka).

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1. Introduction

The Tres Vírgenes Volcanic Complex (27°28′ N, 112°35′ W) is located about 36 km northwest of the town of Santa Rosalía in the northeastern part of the State of Baja California Sur, México (Figure 1(A,B)). The TVVC consists of three main northeast-southwest aligned late Pleistocene stratovolcanoes, which are from the northeast El Viejo, El Azufre, and La Virgen to the southwest. The TVVC is the youngest (ca. <0.3 Ma) of three volcanic systems in the region, which includes Aguajito and Reforma calderas, that are 1.18 and 1.2 Ma, respectively (Schmitt, Stockli, Niedermann, Lovera, & Hausback, 2010) (Figure 1(C)). The complex is the site of an active geothermal field operated by the National Power Company (Comisión Federal de Electricidad = CFE). Its exploration began in 1983 with several geological and geophysical studies (e.g. Lira, González, & Arellano, 1997) followed by the first drilling well in 1986, and its exploitation in 2001. During the same decade in which CFE studies began, other authors studied petrological aspects of the TVVC effusive products (Sawlan & Smith, 1984, 1986, 1991; Demant, 1981). Afterwards, a new surge of geological studies began with descriptions of an explosive rhyolitic eruption of La Virgen volcano (Hausback & Sawlan, 1995; Hausback & Abrams, 1996; Capra, Macías, Espíndola, & Siebe, 1998) followed by diverse geophysical studies (Campos-Enríquez, 1992; Romo, Wong, Flores, & Vázques, 2000; Wong & Munguía, 2006; Peredo-Soto & Lorenzo-Pulido, 2012; Antayhua-Vera, Lermo-Samaniego, Quintanar-Robles, & Campos-Enríquez, 2015). After the initial efforts of CFE to produce a general geological map of the TVVC a few studies presented mapped areas assisted by geochronological data (Capra et al., 1998; Schmitt, Stockli, & Hausback, 2006, 2010). A need for a new geological map was recognized by CFE which pursued a collaborative project with the Geophysics Institute of the Universidad Nacional Autónoma de México (UNAM) to prepare a new general geologic map with ^{40}Ar/^{39}Ar geochronology (Macías et al., 2012 unpublished internal report DEX-

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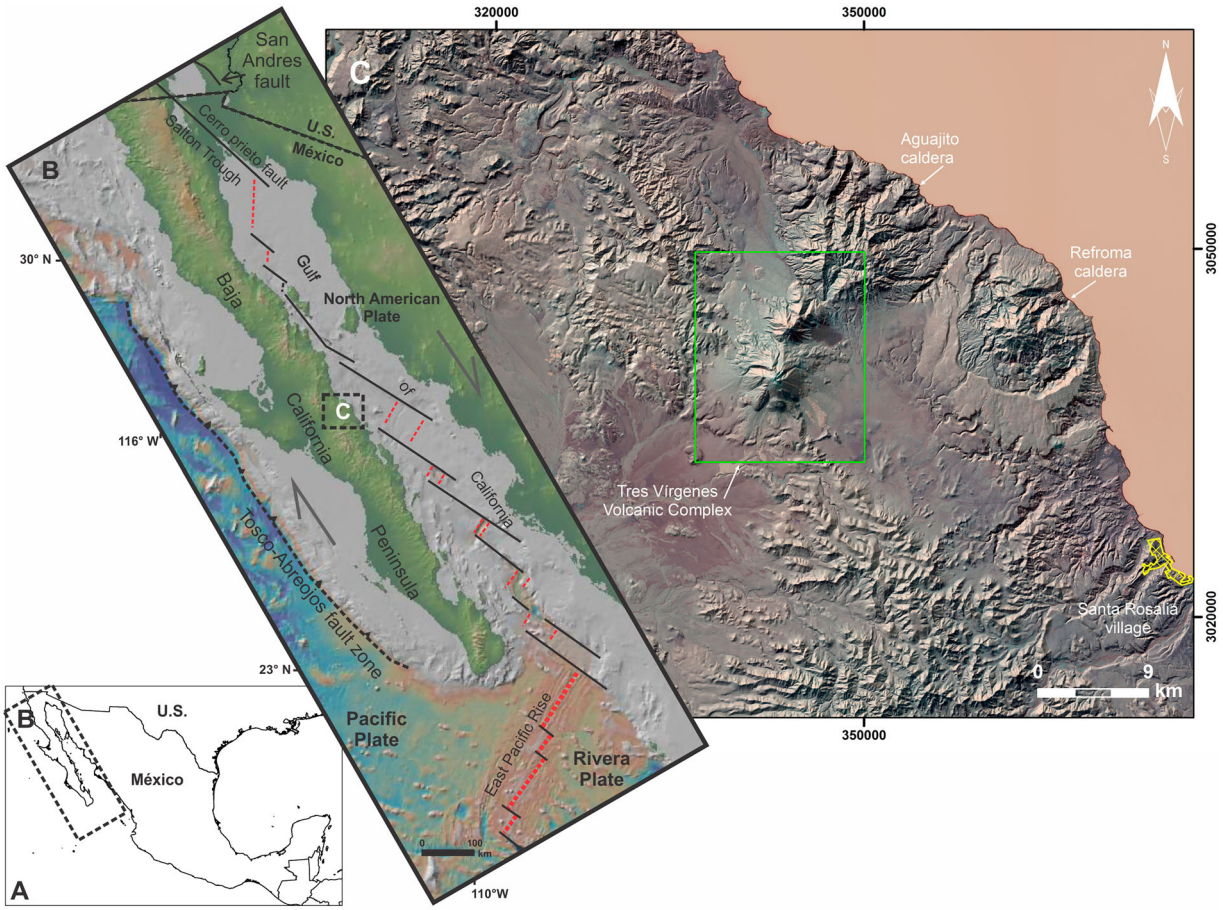

Figure 1. (A) Location of the Baja California Peninsula in Mexico; (B) Regional tectonic regime showing the active syn-rift process of the Gulf of California, subject to a transtensional stress regime with a domain of right-lateral fault systems. The boundaries of the Pacific and Rivera oceanic plates (red dashed lines) as well as the Salton Trough and Tosco-Abreojos fault zone (thick black dash line) are also indicated. Continuous black lines are transformant faults, and gray arrows indicate movement along faults. The shaded relief map and bathymetric data was acquired and modified from Ryan et al. (2009); (C) Location of the TVVC, and the Reforma and Aguajito calderas. Digital Elevation Model and shaded are based on Spot-6 satellite images (panchromatic and multispectral with 1.5 × 1.5, and 6 m of horizontal and vertical resolution, respectively.

DGL-TV-17 (contract CFE-UNAM 9400060892); Macías & Jiménez-Salgado, 2013). Unfortunately, these studies did not present a detail map and stratigraphy of the TVVC because the resolution of the $^{40}Ar/^{39}Ar$ geochronology was diminished by excess argon in the rocks. Avellán et al. (2018) presented a simplified geologic map and evolution of the area assisted by seven new $^{230}Th/U$ dates, and one $^{206}Pb/^{238}U$ in zircons dates. In this work, we present a new detailed geological map aided by geomorphological descriptions, a revised stratigraphy, and 5 new $^{230}Th/U$ zircon dates. The new map and stratigraphy show the evolution of the complex through time, setting the basis for future specialized volcanological and petrological studies.

2. Methodology

New geological data together with the revision of previously published geological information were combined to obtain a new geological map of the TVVC at a scale of 1:20,000. This geological information was represented on a 3D surface constructed using a combination of digital topography, a Digital Elevation Model (DEM) with *x*–*y*–*z* coordinates and satellite imagery processed and edited in ArcMap 9.3 and Ilwis 3.3 commercial programs. The map is georeferenced with respect to the WGS-1984-UTM-Zone-12N coordinate system. To prepare the map, we applied a georeferencing correction between the topographic maps scale 1:20,000 (10-m contour intervals) and the orthophotomap scale 1:20,000 provided by CFE. To construct thematic maps of the area (DEM-shaded relief, slopes, dissection, and altitude) we interpolated points with a 16-m^2-resolution in ArcMap 9.3. Then the topographic data was imported in Ilwis 3.3 to construct a 5-m^2-resolution DEM with *x*–*y*–*z* coordinates. The DEM data, DEM-shaded relief, and the orthophotomap were imported in Ilwis 3.3 to generate anaglyph images to visualize surface morphological features, color, texture and vegetation in 3D. We used all this information to perform the geomorphological analysis. This analysis consisted in delineating the different types of morphological features such as volcanic landforms, lithological contacts, volcanic units,

erosion zones and faults. Subsequently, we carried out extensive geological fieldwork, structural analysis, and sampling of volcanic units. The elaboration of the volcanic stratigraphy of the study area included the identification and characterization of 98 representative locations, 30 detailed stratigraphic sections, and CFE borehole data. A total of 41 rocks (1–2 kg from each) were described in hand specimens and sampled for thin sections. Five selected rocks were dated with the ^{230}Th/U method in zircons performed at the Laboratorio de Estudios Isotópicos of the Centro de Geociencias, UNAM, Campus Juriquilla (Supplementl material).

3. Volcanic Stratigraphy

The TVVC geological map is based on 99 stratigraphic sections and five ^{230}Th/U ages in zircons (Tables 1 and 2). Based on the North American Stratigraphic Code (2005) and recent description of Marti, Groppelli, and Silveira (2018), we next described the basement and 19 volcanic units (geologic map and Figure 2).

3.1. Basement

The TVVC sits on top of granodiorites of the Peninsular Ranges Batholith (Gastil, Phillips, & Allison, 1975) dated at 91.2 ± 2.1 Ma (Schmidt, 1975) and, 99.1 ± 0.8 Ma (^{40}Ar/^{39}Ar whole-rock, Macías et al., 2012). The batholith is not exposed in the area but was reached at 1129 m below the surface in drill-hole LV-2 of CFE (Garduño-Monroy, Vargas-Ledezma, & Campos-Enriquez, 1993). The batholith is covered by a 364 m thick succession of pyroclastic deposits of the Santa Lucia unit (*SL*) that represents the upper part of the Comondú Formation (Martín, Fletcher, López-Martínez, & Mendoza-Borunda, 2000). The *SL* rocks are exposed to the south-southeast of the TVVC covering a surface of ca. 29 km^2 with thicknesses varying from 140 to 360 m. A rock of this unit was dated at 21.59 ± 0.29 Ma from ^{206}Pb/^{238}U in zircons (Avellán et al., 2018). On top of the Santa Lucia unit crops out the Esperanza Basalt (*EB*) that was originally described as tholeiitic basalts by Sawlan and Smith (1984). *EB* crops southwest and south of La Virgen volcano forming eroded flat-surfaced mesas. *EB* has an age between 12.5 and 6 Ma (Calmus et al., 2003), and south of La Virgen of 7.64 ± 1.2 Ma (^{40}Ar/^{39}Ar whole-rock, Macías et al., 2012). These rocks are unconformably covered by the 1.17 ± 0.07 Ma Aguajito ignimbrite (*Ag*) (Schmitt et al., 2006) that is exposed to the northern part of the area.

3.2. Tres Vírgenes Volcanic Complex

3.2.1. El Viejo Volcano

The Lower Viejo dacite lava dome (*LVdld*) is restricted to the northern part of the complex outcropping at the base of the volcano. It directly overlies the Aguajito ignimbrite (*Ai*) and it is overlain by the Puerta dacite lava dome. This unit is characterized by a 0.1-km thick lobe-like lava that covers an area of ca. 0.73 km^2. It consists of a light-gray lava with a mottled structure due to abundant enclaves (section 83). The dacite lava has phenocrysts of alkali feldspar, amphibole and quartz. Enclaves are dark-gray aphanitic with different shapes.

The Puerta dacite lava dome (*Pdld*) is well exposed on the northern flank of the El Viejo volcano between the Lower and Upper Viejo dacite lava dome (Figure 3 (A)). To the northeast of El Viejo volcano, the *Pdld* directly overlies the *Ag*. It is characterized by a blocky lava surface and a crumble breccia at the base (Section 91). The *Pdld* is ~0.19 km thick and covers an area of 3.9 km^2. This lava contains subrounded 10 cm-sized enclaves. The dacite lava is light-gray with phenocrysts of alkali feldspar, quartz and pyroxene. Enclaves are light-gray with aphanitic textures.

The Upper Viejo dacite lava dome (*UVdld*) is the youngest volcanic unit of El Viejo volcano (Figure 3 (B)). It is asymmetrically distributed with a hogback-dome morphology elongated in an NE–SW direction. It is exposed on the northeastern part of the El Viejo volcano overlying the *Pdld* unit. To the southwest of the El Viejo volcano, *UVdld* crops out on the lower hillside of the Azufre volcano. It has an average thickness of 0.26 km and covers a minimum area of 4.4 km^2. The lava has a blocky surface (Section 75) and contains

Table 1. Summary of ^{230}Th/U zircon model-ages of samples analyzed in this study (see Supplemental material).

Sample	Location		Lithostratigraphic unit	^{230}Th age model (years)	+	–
	North	West				
TV1125	3041095	339951	LPal	110,632	43,218	30,869
TV1109	3037934	344624	Vdlc	102,247	30,547	23,836
TV1150	3040794	343911	LVal	89,822	9584	8810
TV1127	3040681	340453	Pdl	89,623	11,863	10,698

Table 2. ^{230}Th/U zircons date for Mezquital dacite lava domes unit (see Supplemental material).

Sample	Location		Lithostratigraphic unit	^{230}Th/U age sphenochron (ka)	^{230}Th/^{238}U	^{234}U/^{238}U
	North	West				
TV1116	3035902	342408	Mdld	46 + 3.2/−2.7	0.345 ± 0.017	1 ± 0

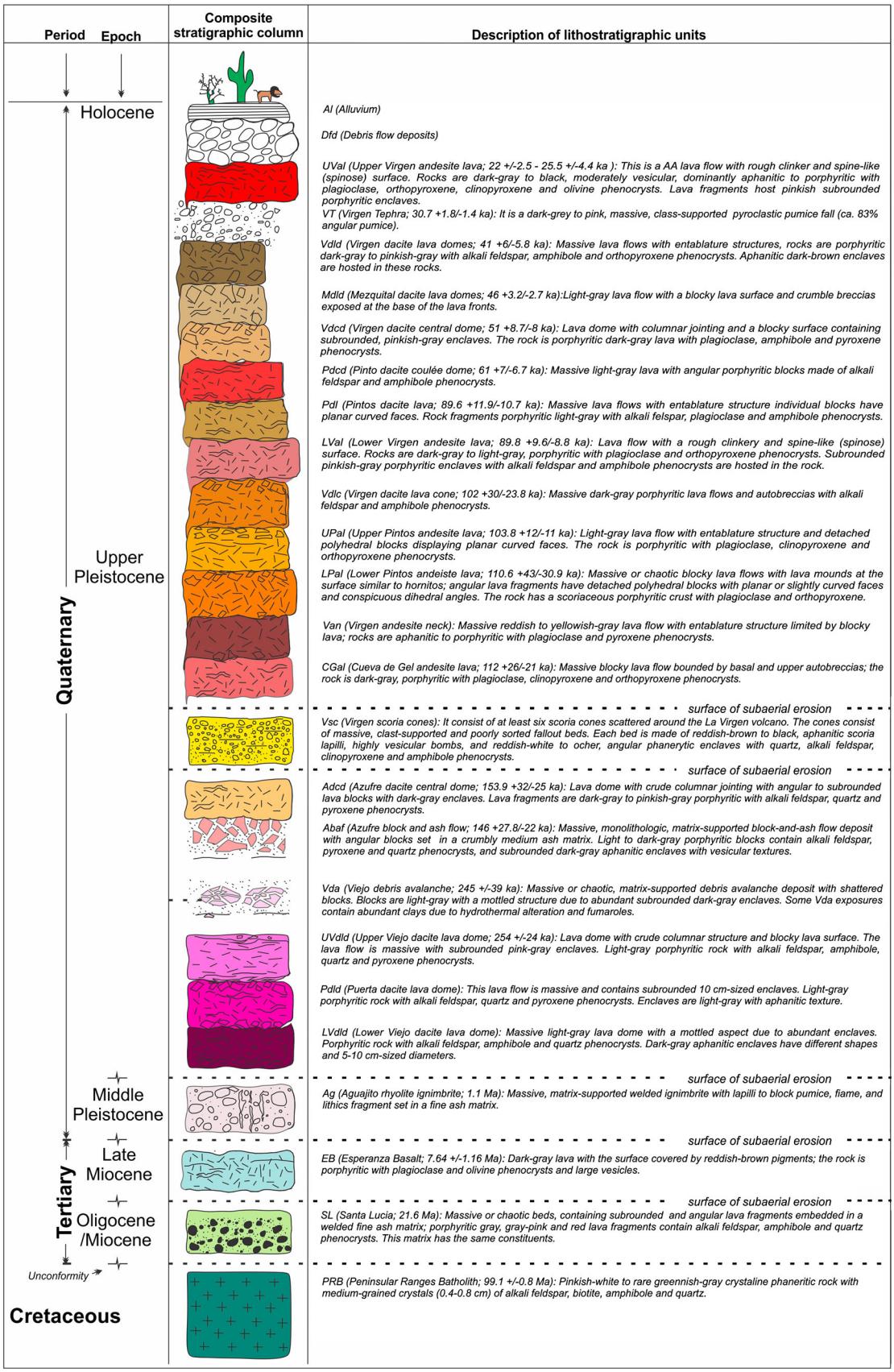

Figure 2. Composite stratigraphic column after Avellán et al. (2018) of the basement rocks, volcaniclastic formations and the TVVC units as displayed in the geological map.

subrounded enclaves. The dacite lava is light-gray with phenocrysts of alkali feldspar, amphibole, quartz and pyroxene. Enclaves are pink-gray, poorly vesicular and have aphanitic textures. The $^{40}Ar/^{39}Ar$ plateau age of this dacite lava dome is 254 ± 24 ka (Macías et al., 2012) (Table 1).

Figure 3. Photographs of the Tres Vírgenes Volcanic Complex: (A) Panoramic view from the east of the complex showing the stratigraphic relationship between the El Viejo and Azufre volcanoes; (B) Aspect of the stratigraphic relationships between Azufre volcano and the *UVdld* (Upper Viejo dacite lava dome) that is overlain by scoria cones, taken from the top of La Virgen volcano; (C) Northern flank of La Virgen volcano and the stratigraphic relationships between units as observed from the summit of El Azufre volcano; (D) Panoramic view from the southwest of the Tres Vírgenes Volcanic Complex showing the stratigraphic relationship between different units of La Virgen volcano. Key: EB, Esperanza Basalt; Ag, Aguajito ignimbrite; *Pdld*, Puerta dacite lava dome; *UVdld*, Upper Viejo dacite lava dome; *Abaf*, Azufre block-and-ash flow deposit; Adcd, Azufre dacite central dome; *Vsc*, Virgen scoria cones; *CGal*, Cueva de Gel andesite lava; Van, Virgen andesite neck; *LPal*, Lower Pintos andesite lava; *UPal*, Upper Pintos andesite lava; *Vdlc*, Virgen dacite lava cone; *LVal*, Lower Virgen andesite lava; *Pdl*, Pintos dacite lava; *Pdcd*, Pinto dacite coulée dome; *Mdld*, Mezquital dacite lava domes; *Vdld*, Virgen dacite lava domes; *UVal*, Upper Virgen andesite lava.

The Viejo debris avalanche deposit (*Vda*) crops out at the northern lower hillside of El Viejo volcano (Figure 2). This unit unconformably overlies the Aguajito ignimbrite and in some sections, it is directly overlain by fluviatile deposits. It has a minimum thickness of 0.13 km and covers an area of 0.47 km^2. The *Vda* has a hummocky morphology, at outcrop scale, it appears as massive or chaotic beds, matrix-supported with lava blocks of La Puerta dacite dome some of which have jigsaw puzzle structures. Lava blocks are

light-gray to pink-gray with a mottled structure due to the presence of subrounded dark-gray enclaves. At Section 82, *Vda* has a clay-rich matrix due to hydrothermal manifestations and fumaroles.

3.2.2. El Azufre Volcano

The Azufre block-and-ash flow (*Abaf*) constitutes the flanks of the El Azufre volcano (Figure 3(A,B)). It has a pyroclastic-fan morphology distributed to the northwest and southeast of the volcano. These pyroclastic fans, are entirely dissected by a radial drainage and at the fan toe is limited by volcaniclastic deposits (*Dfd*). On the northwest, northeast and southwest of the Azufre volcano, *Abaf* overlies the Upper Viejo dacite lava dome and at the southern part of El Azufre volcano underlies the Azufre scoria cones. The *Abaf* has an average thickness of 0.1 km and covers an area of 7.5 km^2. This unit is massive, matrix-supported and monolithologic with angular light to dark-gray lava blocks embedded in a crumbly medium ash matrix (Section 1). The rock has phenocrysts of alkali feldspar, pyroxene and quartz; and subrounded dark-gray enclaves with aphanitic and vesicular textures.

The Azufre dacite central dome (*Adcd*) is located atop the El Azufre volcano (Figure 3(A,B)). It cuts discordantly the Upper Viejo dacite lava dome and is radially bounded by the apex of the *Abaf* pyroclastic fans. *Adcd* consists of a central dome with steep eroded flanks. It has a height of 0.3 km and an exposed area of 0.78 km^2. The dome shows crude columnar jointing that consists of angular to subrounded lava blocks with dark-gray enclaves. The dacite lava is porphyritic varying from dark-gray to pinkish-gray with alkali feldspar, quartz and pyroxene phenocrysts (Section 3).

3.2.3. Scoria Cones

The Virgen scoria cones (*Vsc*) are represented by at least six scoria cones distributed around the La Virgen volcano. Three of these cones are located on the southern flank of El Azufre volcano where they lie unconformably above the Upper Viejo dacite lava dome and Azufre block and ash flow and directly underlie the Upper Virgen andesite lava (Figure 3 (C)). The cones have elongated and coalesced shapes and are crudely aligned in an N–S direction. These scoria cones cover an area of 0.46 km^2 and have an average height of 0.06 km with respect to their surrounding surface. The fourth scoria cone lies northeast of the La Virgen volcano overlying the *Ai* and partially underlying the western flank of the Cueva de Gel andesite lava, and volcaniclastics of the Azufre volcano. This scoria cone is highly eroded with an open crater toward the northwest. It covers an area of 0.4 km^2 with a maximum height of 0.06 km. The last two scoria cones are located at the southern-southwestern flanks of the La Virgen volcano (Figure 3(D)). These unconformably overlie the Esperanza basalt and underlie the Virgen dacite lava domes. These scoria cones are partially covered by younger deposits, such as La Virgen Tephra and volcaniclastic deposits of the same volcano. The southwestern scoria cone has an exposed area of 0.54 km^2 and a maximum height of 0.16 km, while, the southern scoria cone has a visible area of 0.14 km^2 and a height of 0.16 km. The *Vsc* consist of massive, grain-supported, poorly sorted fallout beds. These beds are made of reddish-brown to black, aphanitic scoria lapilli and vesicular bombs. Some beds contain angular reddish-white to ocher phaneritic enclaves (section 77) composed of quartz, alkali feldspar, clinopyroxene and amphibole phenocrysts.

3.2.4. La Virgen Volcano

The Cueva de Gel andesite lava (*CGal*) is exposed on the northeastern lower hillside of La Virgen volcano (Figure 3(A)). It has a tongue-lobate morphology extending 4.3 km to the east with angular blocks on its surface. It covers an area of 3.7 km^2 and has an approximate thickness of 0.06 km. At the lava front, the *CGal* overlies the Aguajito ignimbrite and covers partially one of the scoria cones. *CGal* is partially surrounded and covered by the Lower Virgen andesite lava and Upper Virgen andesite lava units. At section 51, *CGal* overlies a pyroclastic flow deposit, rich in pumice and obsidian-perlite fragments. CGal is a blocky lava underlain and overlain by autobreccias; hand specimens are dark-gray, porphyritic with plagioclase, clinopyroxene and orthopyroxene phenocrysts (section 92).

The Virgen andesite neck (*Van*) represents a feeding vent of La Virgen volcano (Figure 3(C,D)). It is covered almost entirely by younger deposits of La Virgen volcano (Lower Pintos andesite lava, Lower Virgen andesite lava, Virgen dacite lava cone, and Upper Virgen andesite lava). It is exposed on the northwestern upper flank of La Virgen volcano. On the western flanks of La Virgen volcano, it is covered by remobilized scoria fall beds. *Van* is an intrusion with entablature structure; the rock is reddish to yellowish-gray, with aphanitic to porphyritic textures made of plagioclase and pyroxene phenocrysts.

The Lower Pintos andesite lava (*LPal*) is well exposed on the northwestern flanks of La Virgen volcano (Figure 3(C)). This unit overlies the Virgen andesite neck and the Upper Pintos andesite lava and it is covered by La Virgen Tephra. The *LPal* lavas spread out 2.7 km to the west and 2.7 km to the northwest of La Virgen volcano. It has a tongue-lobate morphology covering ca. 10.4 km^2 with an average thickness of 0.08 km. The longest lavas are partially covered by volcaniclastic deposits of El Azufre volcano. *LPal* has a blocky surface with mounds similar to block hornitos (section 26); lava blocks have detached polyhedral blocks with planar or slightly curved faces and conspicuous dihedral angles. Most lavas have a

scoriaceous crust, porphyritic texture with plagioclase and orthopyroxene phenocrysts. LPal was dated with the ^{230}Th/U-zircon method yielding a model age of 110 + 43/−31 ka (Table 1, sample TV1125; Figure 4 (A)).

The Upper Pintos andesite lava (*UPal*) is located on the northwestern lower flank of La Virgen volcano overlying the Lower Pintos andesite lava (Figure 3(C,D)). *UPal* consists of two lava flows that are ca. 4.8 km long, 0.08 km thick, and cover an area of 4.8 km^2. It has a tongue-lobate morphology consisting of angular blocky lavas with planar surfaces. These lavas have an entablature structure (section 23); lava blocks are light-gray to dark-gray, detached polyhedral blocks with planar curved faces. The rock is porphyritic with plagioclase, clinopyroxene and orthopyroxene phenocrysts.

The Virgen dacite lava cone (*Vdlc*) represents the main structure of La Virgen stratocone (Figure 3(D)). It overlies the Virgen andesite neck and it is covered by the Lower Virgen andesite lava and Upper Virgen

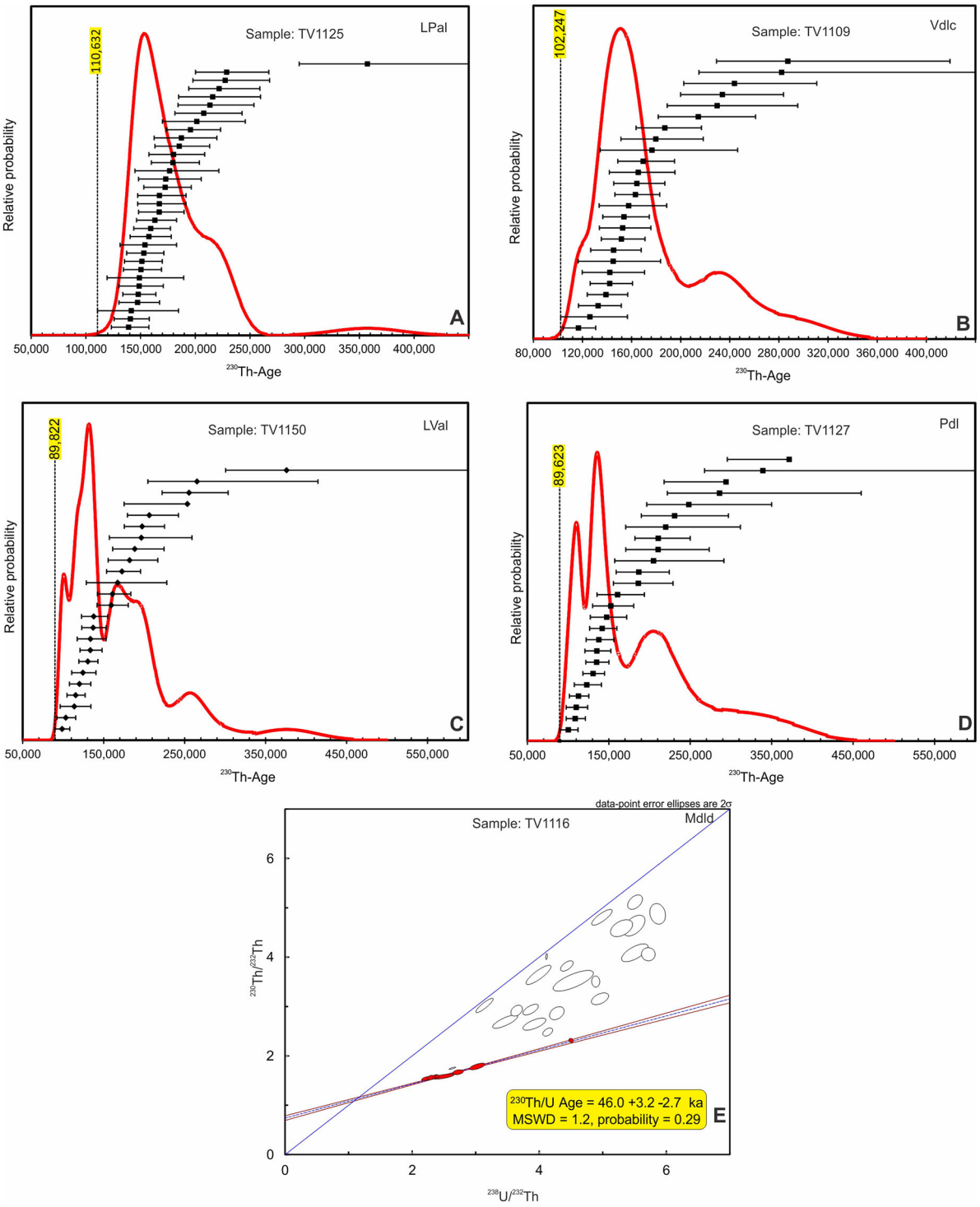

Figure 4. Diagrams of zircon modeled ages of selected samples of this study (A) TV1125, (B) TV1109, (C) TV1150, (D) TV1127, and an isochron of figure E for sample TV1116.

andesite lava. It is locally exposed on the southeastern lower flank of La Virgen volcano where it consists of lavas and autobreccias. The rock is porphyritic with alkali feldspar and amphibole phenocrysts (section 9). One sample of this unit yielded a model age of 102 + 30/−24 ka obtained by ^{230}Th/U zircon geochronology (Table 1, sample TV1109; Figure 4(B)).

The Lower Virgen andesite lava (*LVal*) outcrops on the northern hillside of La Virgen volcano. It surrounds and partially overlies the Cueva de Gel andesite lava, and is partially masked and unconformably overlain by the *UVal* unit (Figure 3(C)). *LVal* is ca. 5.5 km long, covers a visible area of 2.5 km^2 with an average thickness of 0.04 km. This unit has a lobate morphology with rough clinkery and spinose surfaces (section 51) with subrounded pinkish-gray porphyritic enclaves made of alkali feldspar and amphibole phenocrysts. Hand specimens are dark-gray to light-gray porphyritic rocks with plagioclase and orthopyroxene phenocrysts. A rock sample of this unit yielded a model ^{230}Th/U zircon age of 89.8 + 9.6/−8.8 ka (Table 1, sample TV1150; Figure 4(C)).

The Pintos dacite lava (*Pdl*) is restricted to the northwestern lower flank of La Virgen volcano. It overlies the Lower Pintos andesite lava and is mantled by the younger La Virgen Tephra (Figure 3(D)). *Pdl* is characterized by a blocky lava surface covering 1 km^2 with 0.05 km of thickness. This unit is highly dissected and eroded in its southern part forming the Los Pintos Blancos gully. Here, *Pdl* is lava with entablature structure (section 29) with angular lava blocks and planar curved faces. Hand specimens are light-gray to pinkish-gray porphyritic with alkali feldspar, plagioclase and amphibole phenocrysts. This unit was dated at 89.6 + 11.9/−10.7 ka with the ^{230}Th/U-zircon method (Table 1, sample TV1127; Figure 4(D)).

The Pinto dacite coulée dome (*Pdcd*) is the most prominent volcanic structure located on the southwestern hillside of La Virgen volcano (Figure 3(C)). This unit overlies the Esperanza Basalt and the Virgen dacite lava cone. It is a typical coulée flow with steep levées that covers an area of 2.5 km^2 with a thickness of 0.28 km. It is constituted by angular light-gray porphyritic blocks with alkali feldspar and amphibole phenocrysts (section 21).

The Virgen dacite central dome (*Vdcd*) caps the La Virgen stratovolcano. This dome is partially covered by the Upper Virgen andesite lava. It has an asymmetric morphology with a relatively very low relief eroded on the northeastern flank. It protrudes 0.12 km of the surrounding surface exposing an area of 0.5 km^2. The dome shows a crude columnar jointing with a blocky lava surface containing subrounded pinkish-gray enclaves (section 47). *Vdcd* rocks are dark-gray porphyritic with plagioclase, amphibole and pyroxene phenocryst.

The Mezquital dacite lava domes (*Mdld*) consist of at least two restricted lavas, located on the southern apron of the La Virgen volcano. One of them is located at the base of the volcano flank lying unconformably over the *EB* (Figure 3(D)). The other lava lies at 3 km to the south of La Virgen volcano base, directly on top of the Santa Lucia unit. In plain view, both lavas are lobe-like in shape with a relatively flat surface. This unit has a blocky surface and autobreccias exposed at the base of their lava fronts (sections 16 and 58). In accordance with the geomorphological analysis and their stratigraphic position, we suggest that these lavas are coeval with the fissural Tres Tortugas lavas located at circa 10 km south of La Virgen volcano. A rock sample from *Mdld* gave a ^{230}Th/U sphenochron age of 46 + 3.2/−2.7 ka (Table 2, sample TV1116, Figure 4(E)), close to the age of 42.5 ± 3.8 ka obtained for the Tres Tortugas lavas (Schmitt et al., 2010).

The Virgen dacite lava domes (*Vdld*) comprise at least four lavas confined on the southwestern-southeastern lower flanks of La Virgen volcano (Figure 3 (D)). The *Vdld* covers an area of 2.2 km^2 and have an average height of 0.15 km with respect to their surrounding surface. Three of them are situated on the southern and eastern flanks of the volcano. The *Vdld* unit is surrounded and partially covered by the Upper Virgen andesite lava and unconformably covers the Esperanza Basalt, the Virgen dacite lava cone, and a scoria cone. The uppermost lava of *Vdld* is located on the southwestern lower flank of La Virgen volcano unconformably overlying a scoria cone at the foot of the Pintos dacite coulée dome. This dome is partially covered by volcaniclastic deposits of La Virgen volcano. These domes have asymmetric lobate morphology with entablature structures. Lava blocks (section 18) are dark-gray to pinkish-gray in color and contain subrounded enclaves of dark-brown and aphanitic texture. The *Vdld* rock has phenocrysts of alkali feldspar, amphibole and orthopyroxene.

La Virgen Tephra (*VT*) is a good stratigraphic marker in the area. It was recognized by Capra et al. (1998) as the La Virgen plinian fall deposit. These authors concluded that this tephra originated at a site on the southwest flank of the La Virgen volcano. The *VT* unit is widely exposed to the south and southwest sectors of the studied area, mantling several units (*SL*, *EB*, *Vsc*, *Van*, *LPal* and *Vdld*) (geologic map). Near to La Virgen volcano, volcaniclastic deposits cover la Virgen Tephra (Figure 2). According to their distribution and stratigraphy *VT* covers ca. 500 km^2, and has a minimum volume of 1.14 km^3. The *VT* unit preceded a Vulcanian-type eruption that produced pyroclastic surge and fallout deposits named El Mezquital deposit (Capra et al., 1998). Capra et al. (1998) reported a C-14 age of 6.5 ka BP of a charcoal found at the base of the deposit. Later, Schmitt et al. (2010) combined U-Th and (U-Th)/He zircon dating of a pumice sample obtaining an age of 30.7 + 1.8/−1.4 ka. This age

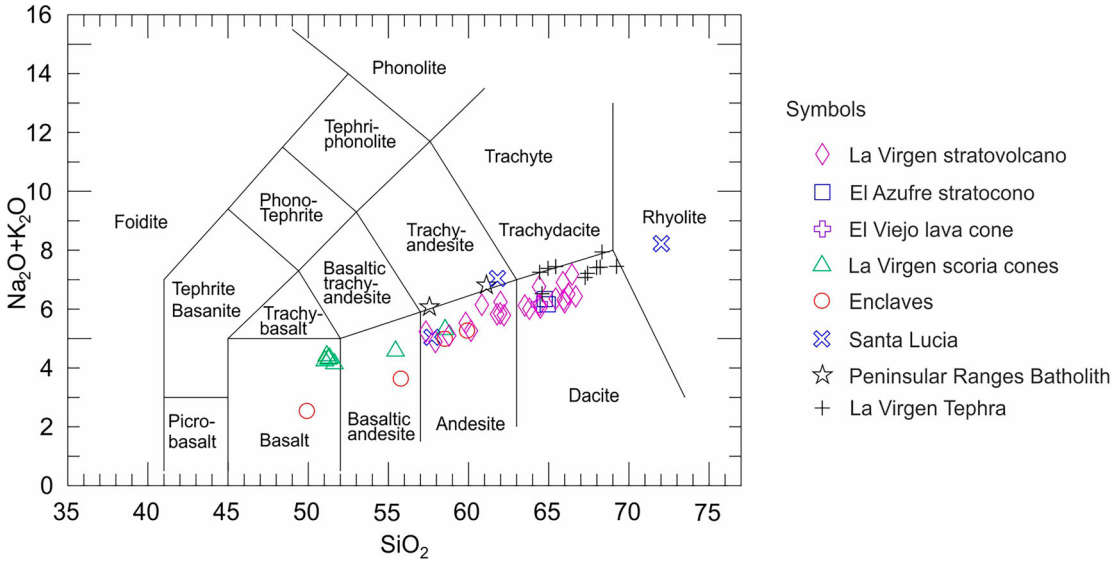

Figure 5. TAS diagram (LeBas, Le Maitre, Streckeisen, & Zanettin, 1986) of the TVVC, Santa Lucia Formation, the Peninsular Ranges Batholith and enclave rocks.

discrepancy resulted in a discussion of the timing of the Plinian event (Capra, Siebe, Macías, & Espíndola, 2007; Schmitt et al., 2006). Our new stratigraphy indicates that the age obtained by Schmitt et al. (2010) may be closer to the expected age of the tephra fall and the age obtained for the Upper Virgen andesite lava.

The Upper Virgen andesite lava (*UVal*) is the youngest effusive event of the La Virgen volcano. This lava was erupted from the summit of La Virgen volcano, it has a radial distribution from the summit and overlies most of the La Virgen units. On the north-northeast flank of La Virgen volcano, *UVal* overlies the scoria cones, the Cueva de Gel andesite lava and the Lower Virgen andesite lava. Herein, *UVal* has a restricted length of ca. 4.8 km (Figure 3(C)). East of La Virgen volcano, *UVal* is unconformably underlain by the Virgen dacite lava cone and the Virgen dacite lava reaching a length of ca. 5.6 km. At the southwestern hillside of La Virgen volcano, *UVal* overlies the Virgen dacite lava domes and the Mezquital dacite lava domes. At the volcano's apron *UVal* overlies the Esperanza Basalt, the Virgen Tephra and the Santa Lucia unit. These 9.5 km long lavas are covered and partially masked by volcaniclastic deposits sourced at La Virgen volcano. The lavas covered an area of 19.1 km^2 with a tongue-like morphology delimited by 3–10 m levées. *UVal* has a rough clinker and spine-like (spinose) surface (section 13). Rock fragments are dark-gray to black, moderately vesicular, aphanitic to porphyritic with plagioclase, orthopyroxene, clinopyroxene and olivine phenocrysts. The lava has subrounded enclaves of pinkish color and porphyritic texture. Schmitt et al. (2010) combined U-Th and (U-Th)/He zircon dating of two lava fragments from *UVal* obtaining an age between 22 ± 2.5 and 25.5 ± 4.4 ka, which is consistent with all the stratigraphic succession (Figure 5).

4. Summary and Concluding Remarks

The new map and stratigraphy of the study area show that the Aguajito caldera is transected by the N–S Cimarron left-lateral fault whose southward continuity is related to the construction of the TVVC. The TVVC rocks are calk-alkaline and range from high-silica basalts to dacites (49.9–66.7 SiO_2 wt.%), with andesites and dacites as the dominant rock (Avellán et al., 2008). The construction of this complex began ~300 ka with effusive eruptions that constructed El Viejo cone. Between 254 and 173 ka, the El Viejo activity ended and was followed by erosion of the volcano. After a repose period of a few hundred or thousand years, the volcanic activity recommenced 1 km to the southwest. It centered at the current location of the El Azufre stratocone (ca. 173 ka) that lasted until 128 ka. A series of scoria cones (La Virgen scoria cones) were emplaced around and on the flank of these volcanoes between 128 and 112 ka. Finally, after a hiatus of ≥16 ka, magmatism along the Cimarron fissure recommenced some 112 ka ago to build the La Virgen stratovolcano whose activity lasted until 22 ka ago with the emission of the Upper Virgen andesite lava flow. During La Virgen activity a major Plinian rhyolitic eruption occurred at ~31 ka (Schmitt et al., 2010).

Software

This map was produced by using ArcMap 9.3 and Ilwis 3.3 programs.

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Disclosure statement

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