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ABSTRACT
The geographical map of the Tres Vírgenes Volcanic Complex (TVVC) Baja California Sur, México consists of three northeast-southwest aligned 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, which include 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 composed of three active geothermalfield operated by the National Power Company (Comisión Federal de Elec-
tricidad = 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, & Vázquez, 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de México (UNAM) to prepare a new general geologic map with $^{40}$Ar/$^{39}$Ar geochronology (Macías et al., 2012 unpublished internal report DEX-
Unfortunately, these studies did not present a detail map and stratigraphy of the TVVC because the resolution of the 40Ar/39Ar 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 230Th/U dates, and one 206Pb/238U in zircons dates. In this work, we present a new detailed geological map aided by geomorphological descriptions, a revised stratigraphy, and 5 new 230Th/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-m2-resolution in ArcMap 9.3. Then the topographic data was imported in Ilwis 3.3 to construct a 5-m2-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 \( ^{230}\text{Th}/^{238}\text{U} \) method in zircons performed at the Laboratorio de Estudios Isotópicos of the Centro de Geociencias, UNAM, Campus Juriquilla (Supplemental material).

3. Volcanic Stratigraphy

The TVVC geological map is based on 99 stratigraphic sections and five \( ^{230}\text{Th}/^{238}\text{U} \) ages in zircons (Tables 1 and 2). Based on the North American Stratigraphic Code (2005) and recent description of Martí, 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 (\(^{40}\text{Ar}/^{39}\text{Ar} \) whole-rock, Macías et al., 2012). 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 (\(^{40}\text{Ar}/^{39}\text{Ar} \) 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-Enríquez, 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 km² with thicknesses varying from 140 to 360 m. A rock of this unit was dated at 41.59 ± 0.29 Ma from \( ^{206}\text{Pb}/^{238}\text{U} \) 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 (\(^{40}\text{Ar}/^{39}\text{Ar} \) whole-rock, Macías et al., 2012). These rocks are unconformably covered by the 1.17 ± 0.07 Ma Agujaito ignimbrite (Ag) (Schmitt et al., 2006) that is exposed to the northern part of the area.

3.2. Tres Virgenes 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 Agujaito 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 km². 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 (Pdl) 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 Pdl directly overlies the Ag. It is characterized by a blocky lava surface and a crumble breccia at the base (Section 91). The Pdl is ~0.19 km thick and covers an area of 3.9 km². This lava contains surrounded 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 Pdl 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 km². The lava has a blocky surface (Section 75) and contains

<table>
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<th>North</th>
<th>West</th>
<th>Lithostratigraphic unit</th>
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<td>344624</td>
<td>Vdlc</td>
<td>102,247</td>
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<td>342408</td>
<td>Mdld</td>
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<th>( ^{230}\text{Th}/^{238}\text{U} )</th>
<th>( ^{235}\text{U}/^{238}\text{U} )</th>
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<tr>
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<td>342408</td>
<td>Mdld</td>
<td>46 + 3.2/−2.7</td>
<td>0.345 ± 0.017</td>
<td>1 ± 0</td>
</tr>
</tbody>
</table>
subrounded enclaves. The dacite lava is light-gray with phenocrysts of alkali feldspar, amphibole, quartz and pyroxene. Enclaves are pink-gray, very vesicular and have aphanitic textures. The $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age of this dacite lava dome is 254 ± 24 ka (Macías et al., 2012) (Table 1).

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.
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 km². 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

Figure 3. Photographs of the Tres Virgenes 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 Virgenes 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; Vdld, Virgen dacite lava cone; LVal, Lower Virgen andesite lava; Pdld, Pintos dacite lava; Pdcd, Pinto dacite coulée dome; Mdld, Mezquital dacite lava domes; Vdld, Virgen dacite lava domes; UVal, Upper Virgen andesite lava.
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 km². 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 km². 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 km² 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 km² 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 km² and a maximum height of 0.16 km, while, the southern scoria cone has a visible area of 0.14 km² 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 km² and has an approximate thickness of 0.06 km. At the lava front, the CGaL overlies the Aguijito ignimbrite and covers partially one of the scoria cones. CGal is partially surrounded and covered by the Lower Virgenandesite lava and Upper Virgenandesite 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 entabulation 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 km² 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 km². 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.](image-url)
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 with plagioclase and orthopyroxene phenocrysts. A rock sample of this unit yielded a sphenochron age of 46 + 3.2/-2.7 ka (Table 1, 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 volcanioclastic 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 southwestern 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, volcanioclastic 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 $^{14}$C 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
discrepancy resulted in a discussion of the timing of the Plinian event (Capra, Siebe, Macías, & Espindola, 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 km² with a tongue-like morphology delimited by 3–10 m levées. UVal has a rough cinder 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 calc-alkaline and range from high-silica basalts to dacites (49.9–66.7 SiO₂ 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 south-west. 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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**Disclosures**


