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Research article

Morphology and general stratigraphy of the maar-type San Diego volcano, NE of Caldas, Colombia

Morfología y estratigrafía general del volcán maar de San Diego, NE de Caldas, Colombia

María Luisa **Monsalve**[1], Iván Darío **Ortiz**[1], Harold **Ávila Vallejo**[1]

1. Servicio Geológico Colombiano, Bogotá, Colombia.
Corresponding author: María Luisa Monsalve, mmonsalve@sgc.gov.co

ABSTRACT

The San Diego volcano is a complex, maar-type volcanic structure located northeast Caldas region on Colombia. It marks the known northern limit of the recent volcanism (Upper Pleistocene-Holocene) of the Andes, related with subduction of the Nazca plate under South America. From the integration of morphological information and the analysis of facies in the deposits of three main units —Pueblo Nuevo, La Concha and San Diego— and dated samples, at least three periods of eruptive activity are inferred, which occurred approximately 40 000, 22 000 and 16 000 years ago. These eruptions gave rise to the current configuration of the maar, which is formed by two concatenated structures that are slightly displaced from each other in a NE–SW direction and a tuff cone located in the interior of the northeast maar (oldest). The diameter of this structure is 4 x 2.4 km. Inside the southwest maar (youngest) there is a semicircular crater lake, with a diameter of 1.5 km x 1 km and a depth of up to 50 m. The structures that comprise the San Diego maar are partially eroded due to the successive eruptive activity of the volcano. The preeruptive basement is exposed inside the crater and forms subvertical walls; on it outcrops the pyroclastic rings, with irregular thicknesses, that are distributed around the structure, reaching distances between 2 and 6.5 km from the edge of the craters. The tuff cone, called El Morro, has associated thick deposits that reach distances of up to 6 km and a dacitic-rhyolitic plug.

Keywords: phreatomagmatism, monogenetic volcanism, polygenetic volcanism, maar, tuff cone, San Diego.

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RESUMEN

El volcán de San Diego es una estructura volcánica compleja tipo maar, localizada en el nororiente del departamento de Caldas. Marca el límite norte conocido del vulcanismo reciente (Pleistoceno Superior-Holoceno) de los Andes, asociado a la subducción de la placa de Nazca, bajo Suramérica. A partir de la integración de información morfológica y el análisis de facies en los depósitos de tres unidades principales —Pueblo Nuevo, La Concha y San Diego—, y dataciones en las mismas, se infieren al menos tres periodos de actividad eruptiva, que habrían ocurrido aproximadamente hace 40000, 22000 y 16000 años AP, para dar lugar a la configuración actual del maar, que está formado por dos estructuras concatenadas que se encuentran levemente desplazadas entre sí en dirección NE-SW, y un cono de toba emplazado en el interior del maar NE (el más antiguo). El diámetro de esta estructura es de 4 ⍰ 2,4 km. En el interior del maar SW (el más reciente) se aloja un lago cratérico de forma semicircular, con un diámetro de 1,5 km ⍰ 1 km y 50 m de profundidad. Las estructuras que conforman el maar de San Diego se encuentran parcialmente erosionadas debido a la actividad eruptiva sucesiva del volcán. El basamento preeruptivo se encuentra expuesto en el interior del cráter, y forma paredes subverticales, y sobre él afloran depósitos que forman los anillos piroclásticos, con espesores irregulares que se distribuyen alrededor de la estructura, y que alcanzan distancias entre los 2 y los 6,5 km a partir del borde de los cráteres. El cono de toba, llamado El Morro, tiene asociados espesos depósitos que alcanzan distancias de hasta 6 km y un plug dacítico-riolítico.

Palabras clave: freatomagmatismo, Vulcanismo monogenético, Vulcanismo poligénetico, maar, cono de toba.

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1. INTRODUCTION

Volcanic structures called *maar diatreme*s are the second most frequently occurring type in the world (e.g., Wohletz and Heiken, 1992; Lorenz and Kurszlaukis, 2007; Lorenz et al., 201 6). They are formed by the interaction of magma with groundwater, which at a certain depth below the surface, generates explosive fragmentation and results in excavation of a volcanic crater, within which the remains of pyroclasts and basement rocks collapse. The collapse of this material gives rise to funnel-shaped breccia bodies (diatremes), which can extend for hundreds of meters to ~2 km underground (Lorenz, 1986, 1987; Houghton and Schmincke, 1986; White, 1991; White and Ross, 2011; Palladino et al., 2015; Valentine et al., 2015). Around the crater, the material released by the eruption forms a relatively low tuff ring (*ejecta rim*) (Heiken, 1971; Lorenz, 1986; White, 1991; Vespermann and Schmincke, 2000).

The formation of maars and *tuff rings* is generally associated with basaltic magmas (Vespermann and Schmincke, 2000; White and Ross, 2011; Ross et al., 2017). However, maars and tuff rings formed by more siliceous magma have also been identified, which are commonly associated with the formation of lava domes. Such structures show morphological characteristics similar to those of mafic compositions in intracontinental environments (Brooker et al., 1993; Riggs and Carrasco Núñez, 2004; Cano Cruz and Carrasco Núñez, 2008; Zimmer et al., 2010; Ross et al., 2017).

Maars are typically monogenetic volcanoes. However, some have been identified that result from multiple eruptive events, as evidenced by contrasting volcanic facies, erosional boundaries, and the presence of paleosols (Tchamabé et al., 2014). These eruptions present multiple phases or a polycyclic nature (Németh, 2010) and show changes in the fragmentation style and the lateral or vertical migration of the volcanic focus (Lorenz, 1986; Carrasco Núñez and Riggs, 2008; Valentine et al., 2017). These types of changes control the shape and architecture of the resulting volcanic structure (Németh, 2010). These maars are interpreted as polygenetic and have been poorly documented (Tchamabé et al*.,* 2016). Some examples of this type are Gölcük in Turkey, Albano and Colli Albani in Italy, Purrumbete in Australia, Hule in Costa Rica, and Barombi Mbo in Cameroon (Platevoet et al*.,* 2008, Giaccio et al*.,* 2009; Salani and Alvarado, 2010; Tchamabé et al., 2014; Tchamabé et al., 2016).

In this work describes the morphological features of the San Diego maar and associated deposits, and its inferred eruptive history spans for a period of ~25 000 years. The San Diego maar (5° 39 'N; 74° 57' W) is a volcanic structure located in the department of Caldas, on the eastern flank of the Central Cordillera of Colombia, 89 km NE of the city of Manizales and 145 km northwest of the city of Bogotá. This volcano constitutes the extreme northern point of the volcanism in the Andes and is part of a group of siliceous volcanoes, including maar-diatreme-type structures, pyroclastic rings, and domes, that are aligned outside the axis of the cordillera Central, in a SW–NE direction. This alignment is consistent with the direction of the southern Palestine fault zone (Figure 1), which hosts the northern back arc vulcanism related to the subduction of the Nazca plate, beneath a relatively stable South America.

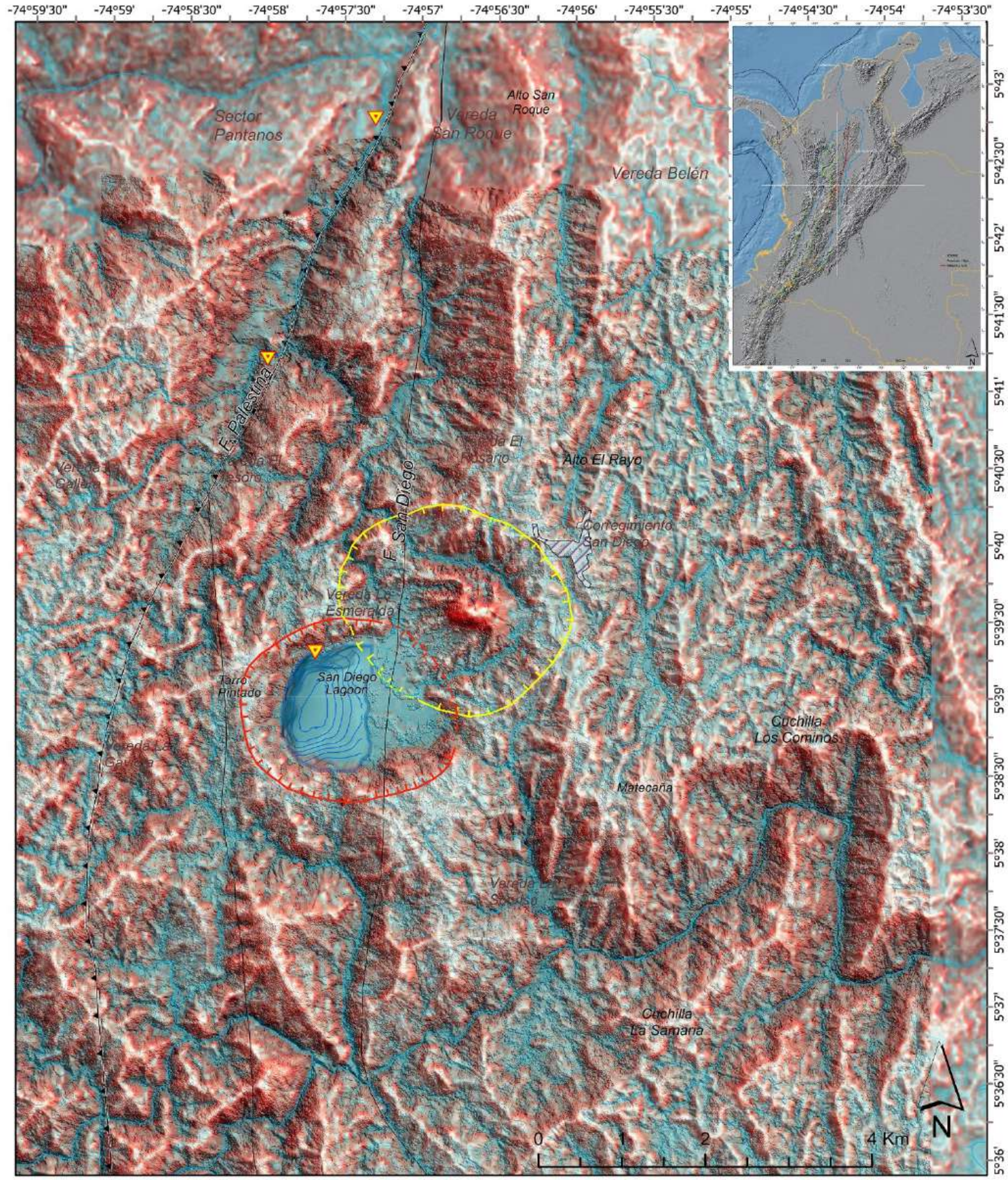


Figure 1. Location of the San Diego maar
The two concatenated craters and the main line of the Palestinian Fault stand out to the west (half-column image).

1. Method

To study the San Diego maar, satellite images, aerial photographs and digital terrain and surface models (DTM-DSM) were obtained. During field work, deposits associated with the maar were identified and mapped, and the general stratigraphy of the eruptive events was constructed. Stratigraphic column surveys were carried out, and samples were taken for laboratory analysis (component analysis, petrography, geochemistry and dating).

The dating of organic material was carried out by the carbon 14 method at the C14 Laboratory of the University of Zurich. The technique was accelerator mass spectrometry, or AMS, with the accelerator of the Ion Beam Physics Laboratory (LIP) of the Swiss Federal Institute of Technology in Zurich (ETH).

2. Geological and structural framework

The area in which the San Diego maar developed, located on the eastern flank of the Central Cordillera of Colombia, is lithologically composed of Paleozoic to Mesozoic metamorphic strips, a Cretaceous sedimentary graben, Cretaceous and Tertiary igneous intrusives, and Quaternary volcanic rocks and deposits (Figure 2). The latter are mapped as irregular patches in the northeastern area of the department of Caldas and in the southwest of Antioquia, of pyroclastic and glaciofluvial deposits (Barrero and Vesga, 1976 to; González, 1990, Gómez Tapias et al., 2015). In the San Diego area, these deposits correspond to the Matecaña Formation, defined by Flórez (1987) and named by Monsalve et al. (2014), the *Caballuna pyroclastic sequence*, or *yellow tephra*, by Borrero et al. (2016), whose age corresponds to the Upper Pleistocene, and consists of a thick sequence of pumitic fall pyroclasts, which is preliminarily associated with the El Escondido volcano 20 km SW of the San Diego maar (Monsalve et al., 2015).

The maar is built on the strips of metamorphic rocks of the Cajamarca Complex, locally composed of micaceous schists, amphibolites, gneisses, marbles and metamorphic rocks of permo-Triassic to Jurassic age (Blanco et al., 2013; Martens et al., 2014), which constitutes the basement of cordillera Central. There are also found cretaceous shales on the Berlin *Syncline* (Naranjo, 1983; Inwood et al., 2012) and granodiorites and leucogranites from the Samaná Igneous Complex, which is dated to the Early Cretaceous (Pérez, 1967; Rueda Gutiérrez, 2019).

This exhumed basement is locally faulted due to the crossing of a main regional structure, such as the Palestina fault (Feininger, 1970; Barrero and Vesga, 1976a), and faults transverse to the mountain range, both in the NE–SW direction and the NW–SE direction.

The prismatic system generated by the crossing of the transverse faults with the Palestine fault would enable the generation of distension zones for the rise of igneous material, as has been interpreted in the northern volcanic segment of Colombia by authors, such as CHEC (1983), Ortiz and Romero (2011) and Bohórquez et al. (2005).

3. Morphology of the volcanic structure of San Diego

The volcanic structure of San Diego is formed by two concatenated pyroclastic rings, which results in an irregular elliptical shape, with a greater diameter of approximately 3.7 km in the SW–NE direction. These rings originated from phreato-magmatic activity that undermined the preexisting basement, for which can be classified as a *maar-diatreme-type* volcanic structure, according to Lorenz (1973, 2003). Inside this structure, in the NE sector, there is a *tuff cone* called *El Morro*, while the SW sector is occupied by a crater lake (Figures 3 and 4).

The crater of the northeast structure has an estimated diameter of 2.4 km (Figure 4), and around it, a series of deposit outcrops that comprise the ring, which is preserved only in the north and east sectors, with observed thicknesses of up to 10 m. Within the crater, the metamorphic basement outcrops and its best exposure is found in the northeast sector of the structure. The average slope of the internal walls of the crater is 30°, while the slope toward the outside of the crater in its northeast sector ranges from 5°-10°.

The El Morro volcanic structure has a slightly eroded conical shape, and partial collapse of the volcanic edifice on its northeast flank. It has an estimated base diameter of 1.3 km and a maximum height of 450 m above the bottom of the first maar crater. The flanks of this structure are formed by layers of pyroclastic deposits that vary from massive to laminated and present an average inclination of 40°. The characteristics of this structure allow it to be classified as a tuff cone (White and Ross, 2011); erosion of the cone leaves a *plug* visible inside the canal.

The most recent volcanic structure was built in the southwest sector of the first maar and has an approximate diameter of 2.2 km; its ring is interrupted toward the northeast sector. Within this structure, there is a semicircular crater lake (Toro, 1991; Beltrán et al., 2016; PIMA, 2009).

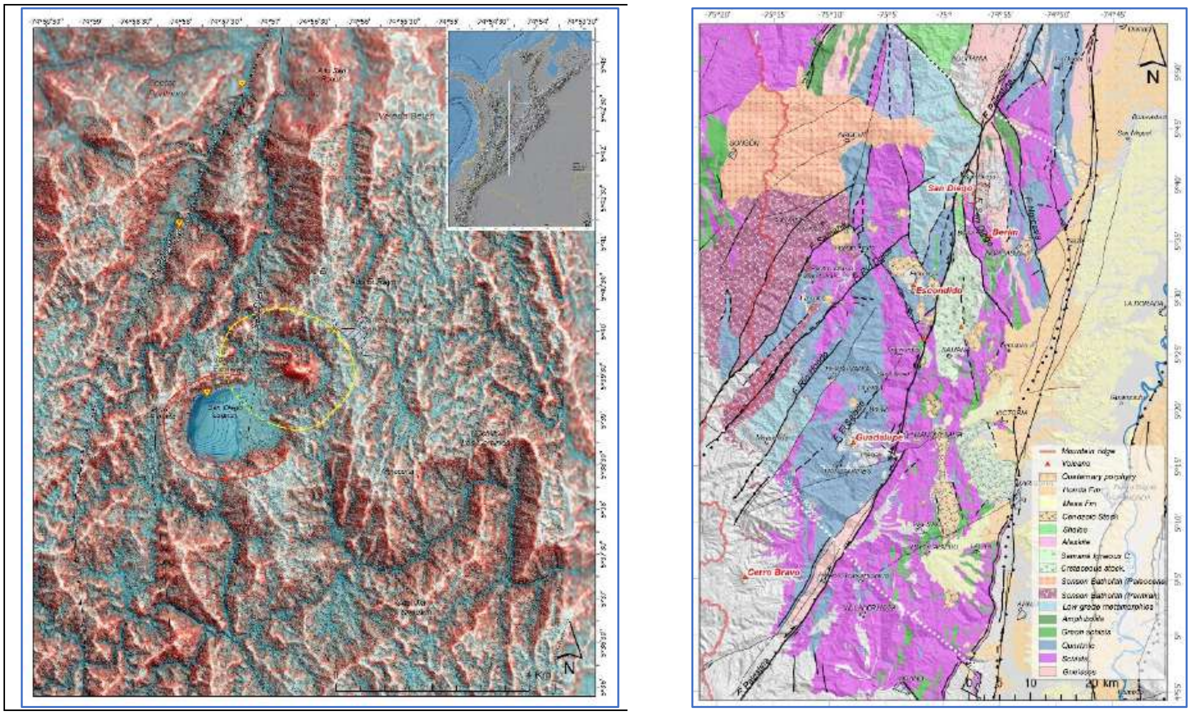


Figure 2. a) Regional map showing volcanoes and major faults. b) Regional geological map with the locations of the volcanoes. The Palestine fault is highlighted in red (map a). Geology is taken from the 1:100 000 scale plates of the SGC (Feininger et al., 1970; Barrero and Vesga, 1976a, 1976b, 1976c; González, 1980; González et al., 1980; Mosquera et al., 1998).

Figure 3. View of the volcanic structure of San Diego from the SW sector of Maar
In yellow, border of the tephra ring of the NE structure; in red, edge of the tephra ring of the SW structure. Inland, the El Morro tuff cone and a crater lagoon.

The free surface of the lake, with an approximate height of 760 masl, has a diameter of 1.6 x 1 km and a surface area of 1.33 km^2. The average temperature of the water is 28.5 °C, and a hot spring is located on the lagoon's northwestern edge, with an average temperature of 30.8 °C. The eastern margin of the lake has slopes from low to moderate (<10°), unlike the north zone, where there are slopes between moderate and high (> 30°). The bottom of the lake is generally flat and slopes slightly to the west. It has a maximum depth of 50.7 m; at the southern edge, the depth is 1.8 m, and at the northwest edge, the minimum depth is 6 m. (Beltrán et al*.,* 2016). Figure 7 shows the morphology of the lake, according to the results of the bathymetric study carried out by the SGC using an EchoBox echo sounder by Syqwest (Beltrán et al., 2016).

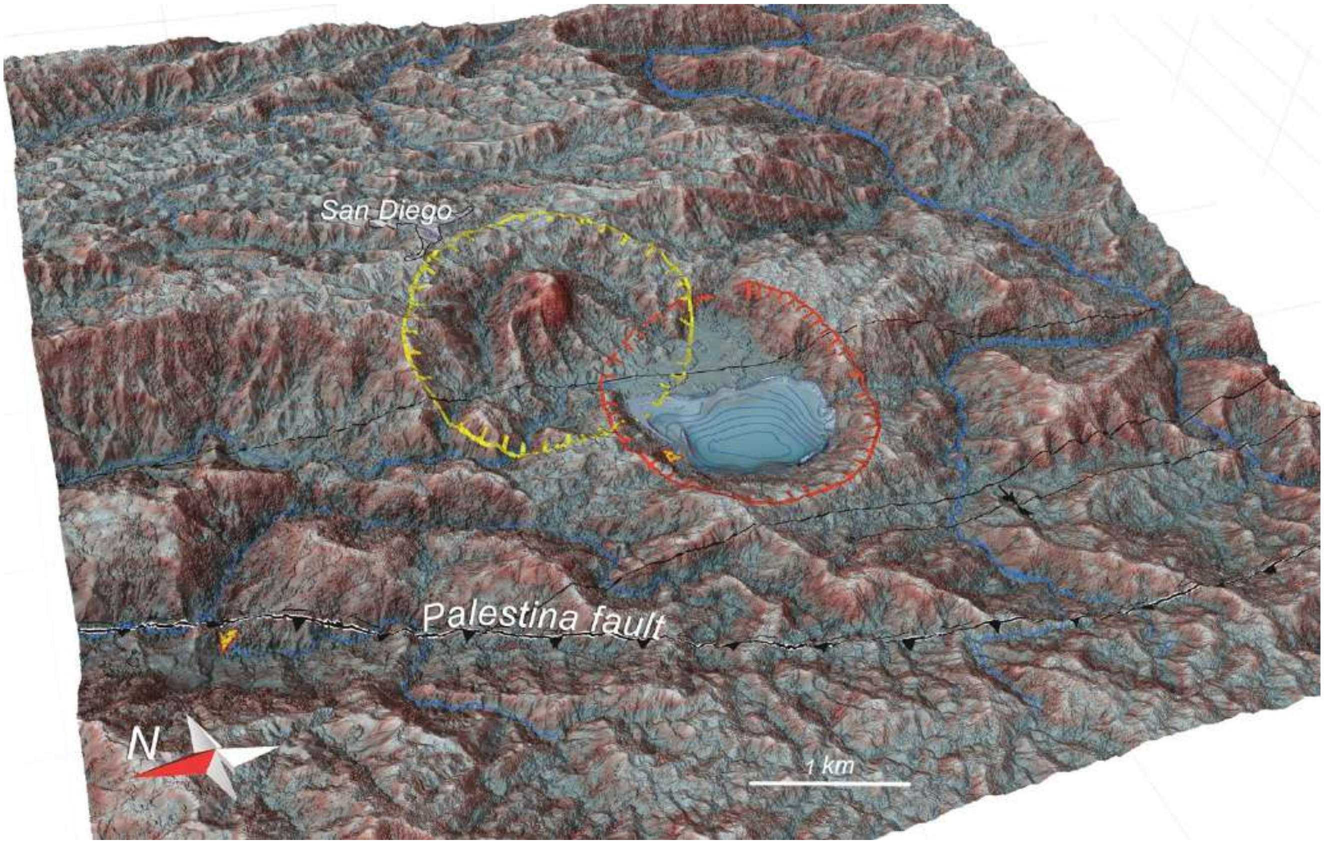


Figure 4. Structures that form the San Diego maar
The edge of the ring of the oldest maar is in yellow, and the missing edge is dashed lines. Note the El Morro tuff inside the cone. The edge of the most recent maar ring is in red; the missing edge is dotted; note the crater lake inside the cone.

Toward the east, the external morphology of the San Diego maar is undulating, while in the other sectors, the morphology is somewhat steep, typical of pyroclastic ring structures (Figure 4). For Houghton and Schmincke (1986), volcanoes with mixed characteristics are common and record variations in the predominant eruptive processes that form volcanic structures.

4. San Diego maar stratigraphy: age and related products

According to the geological record and obtained dates, three units related to the activity of the San Diego maar are defined (Figures 5 and 6):

Pueblo Nuevo Unit (PNU). Associated with the origin of the San Diego maar, corresponds to the deposits that form the remnant of the pyroclastic ring that is located in the northeast sector. Radiocarbon dating of a coal sample taken in the Matecaña sector (Figures 5 and 7a and b) yielded an age of 39 838 ± 585 BP (Monsalve et al., 2017).

La Concha Unit (LCU). Corresponds to deposits associated with the activity of the El Morro tuff cone. Dating obtained from wood within these deposits showed ages of 22 417 ± 82 BP and 20 552.8 ± 55 BP (Figures 5 and 7c). A deposit that was preliminarily associated with this structure resulted in an age of 28 521.8 ± 102 BP, which was also obtained from wood (Figure 7d).

San Diego Unit (SDU). Associated with the most recent maar (Figure 5). An age of 16 624 ± 48 BP was reported by Borrero et al. (2016) in a paleosol sample taken under a deposit that is associated with the activity of the maar in this work.

Each unit has one or more facies related to its deposits. These units are described below and summarized in Figure 6.

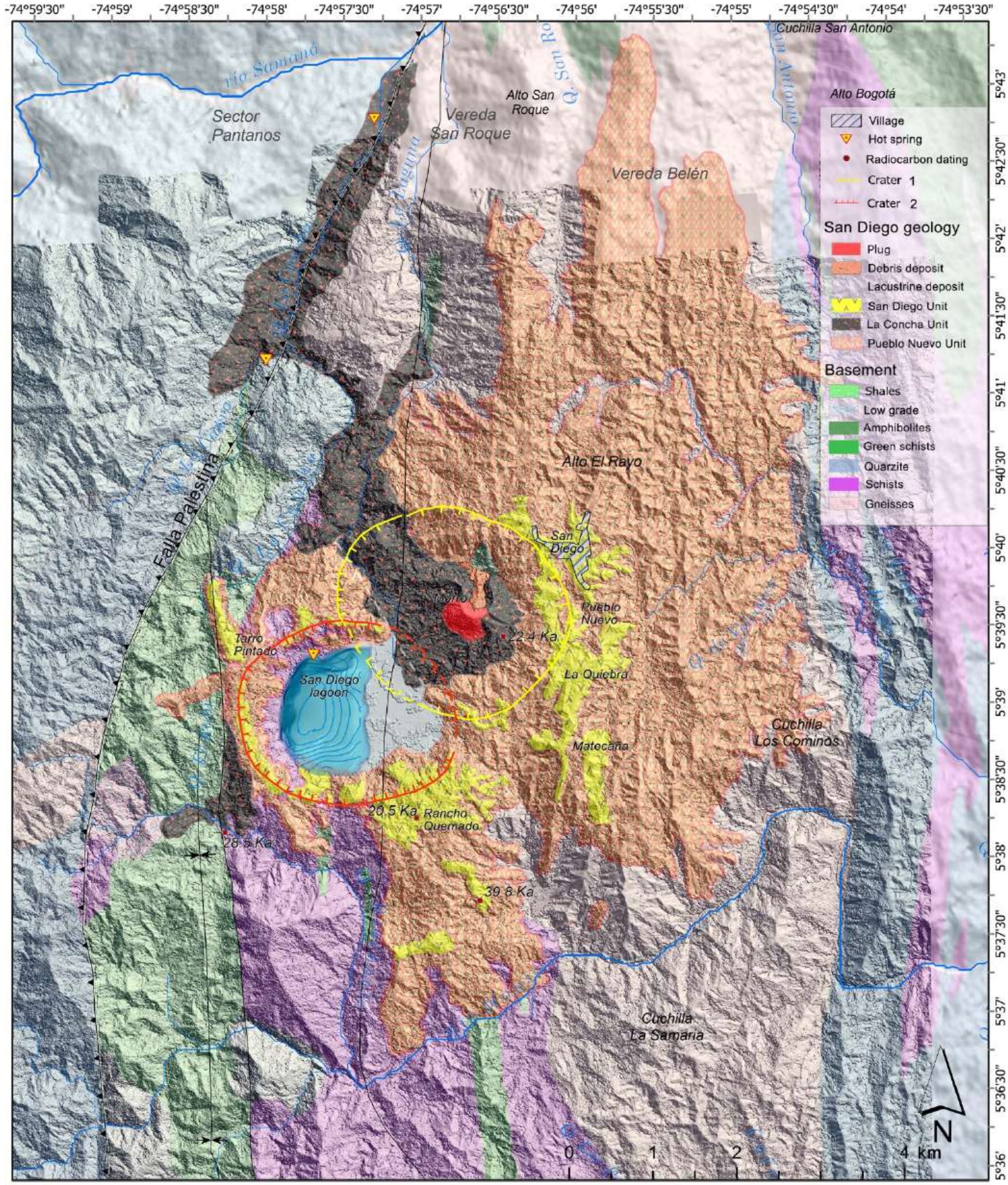
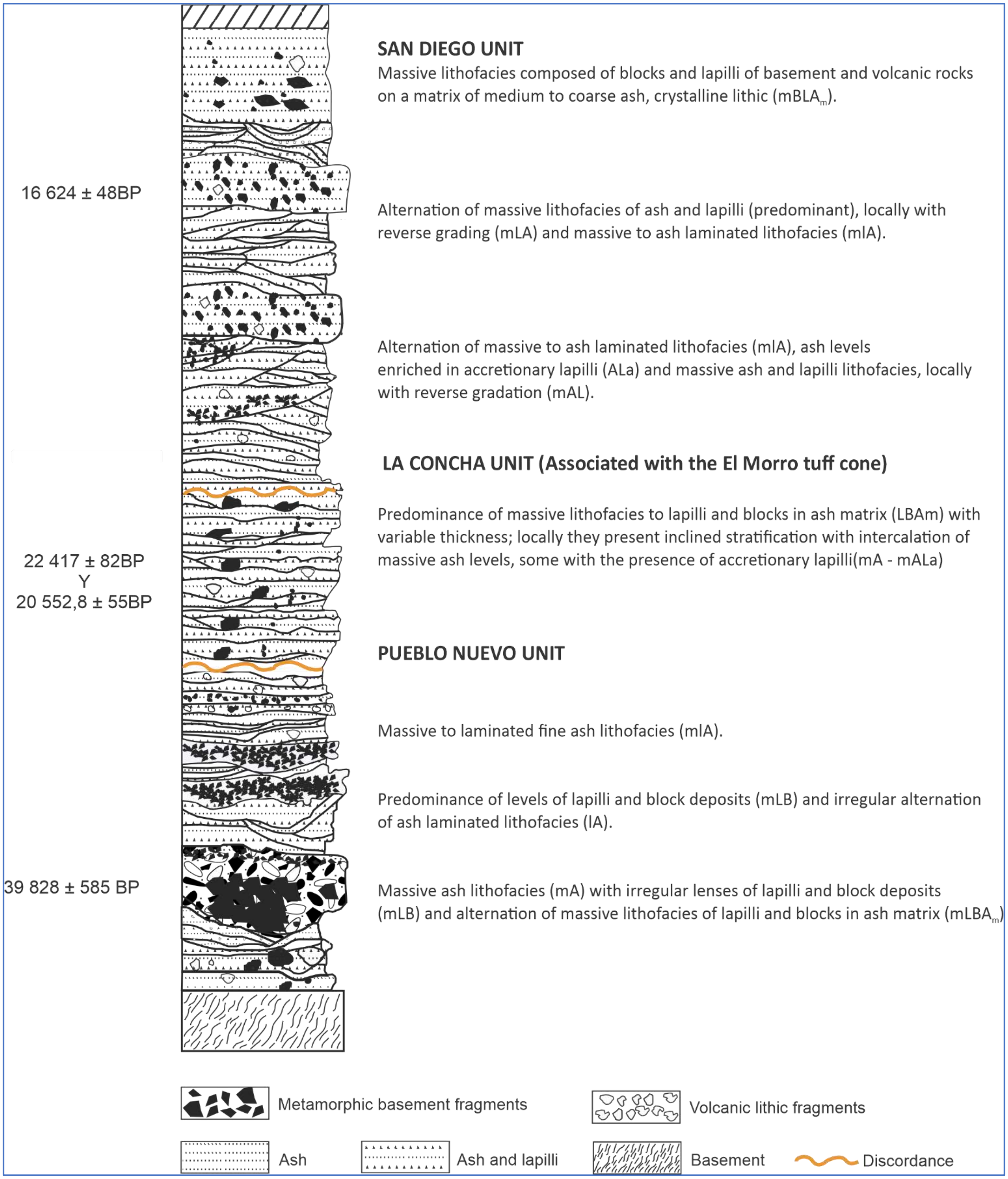


Figure 5. Geological map of the San Diego maar. Basement geology taken from Barrero and Vesga (1976a).



SAN DIEGO UNIT

Massive lithofacies composed of blocks and lapilli of basement and volcanic rocks on a matrix of medium to coarse ash, crystalline lithic ($mBLA_m$).

Alternation of massive lithofacies of ash and lapilli (predominant), locally with reverse grading (mLA) and massive to ash laminated lithofacies (mlA).

Alternation of massive to ash laminated lithofacies (mlA), ash levels enriched in accretionary lapilli (ALa) and massive ash and lapilli lithofacies, locally with reverse gradation (mAL).

LA CONCHA UNIT (Associated with the El Morro tuff cone)

Predominance of massive lithofacies to lapilli and blocks in ash matrix (LBAm) with variable thickness; locally they present inclined stratification with intercalation of massive ash levels, some with the presence of accretionary lapilli(mA - mALa)

PUEBLO NUEVO UNIT

Massive to laminated fine ash lithofacies (mlA).

Predominance of levels of lapilli and block deposits (mLB) and irregular alternation of ash laminated lithofacies (lA).

Massive ash lithofacies (mA) with irregular lenses of lapilli and block deposits (mLB) and alternation of massive lithofacies of lapilli and blocks in ash matrix ($mLBA_m$)

Figure 6. Schematic stratigraphic section showing the units that make up the complex maar of San Diego and its main facies The yellow lines mark the discrepancy between identified the stratigraphic units.

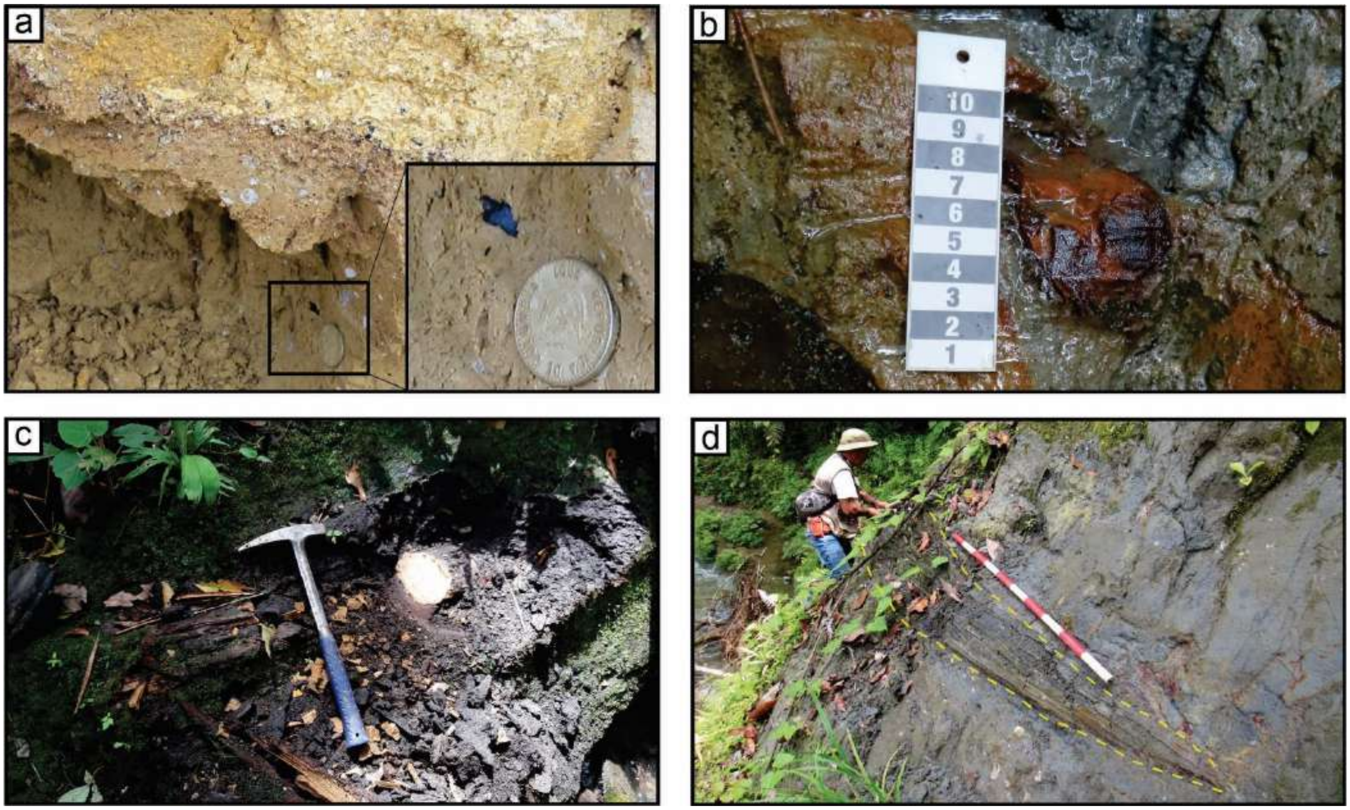


Figure 7. Samples collected for dating
a) Pueblo Nuevo Unit, Matecaña sector. The inset shows the charcoal details. b) Fragment of wood in the Rancho Quemado sector in La Concha unit deposits. c) La Cristalina stream sector, wood fragment in deposits associated with the La Concha unit. d) Quebrada Riachuelo, a fragment of wood (in yellow dashed lines) inside deposits preliminarily associated with the La Concha unit. The sampling sites are shown in Figure 5.

5. Pueblo Nuevo Unit (pnu)

The PNU has the greatest distribution in the area (Figure 5). It is composed of an irregular alternation of deposits with thicknesses that vary between 1 and 10 m (although the complete sequence was not observed at any point). These present massive ash facies (mA), massive ash with accretionary lapilli (mCLa), laminate ash (lA), laminate lapilli (lL), massive lapilli and brecciated blocks (mLB). In some of these deposits, basement fragments predominate, and in others, volcanic lithics predominate (Figures 6 and 8a).

The predominant deposit in the PNU is light yellow in color, which varies from yellowish gray and locally reddish (Figure 8b). In general, it presents massive facies of fine ash with accretion lapilli and is composed of dipyramidal quartz (Qz), plagioclase (Pg) and biotite (Bt) crystals. Occasionally, lapilli-size fragments of gray volcanic lithics, fine to medium porphyritics, metamorphic lithics (black, green and gray schists) and fragments of gray fine ash deposits are found in the deposit. It is common to find block-size metamorphic fragments, greater than one meter (Figures 9 a and b), toward the southwest and west sectors, where the deposit is interspersed irregularly with clast-supported deposits of gray color that exhibit a massive facies of lapilli and blocks (mLB) composed of fragments that vary from angular to subangular, metamorphic rocks and gneissic intrusives of the basement and to a lesser extent, volcanic fragments (Figure 9). Other sectors where deposits are enriched in basement rocks are observed to the northwest and east the interior of the maar, directly overlying the basement of the pyroclastic ring.

In addition to the intercalations of pumice levels of the Caballuna sequence with the deposits described, it is also common to observe fragments of these pumices within the deposits or overlying the PNU (Figure 9d).

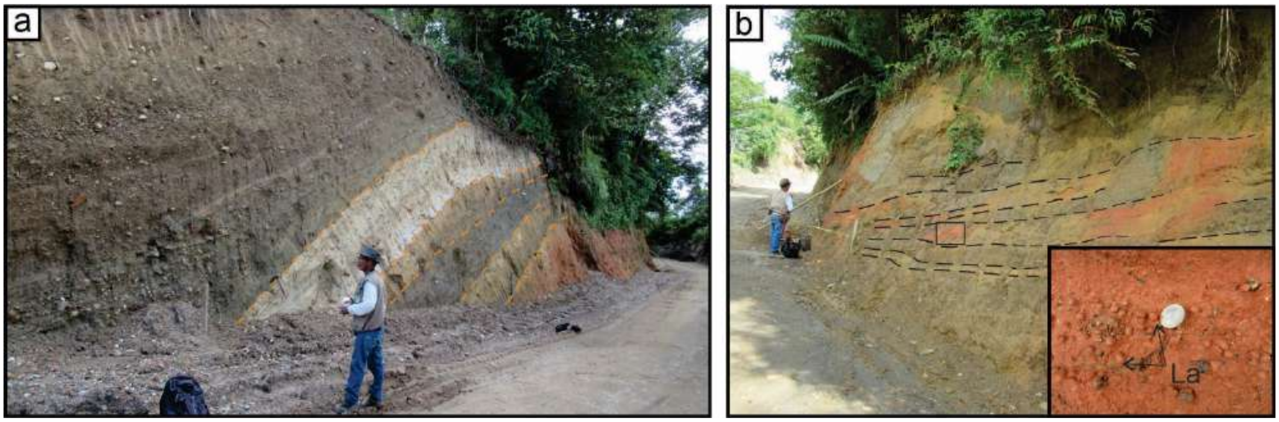


Figure 8. Pueblo Nuevo Unit in the La Quiebra sector
a) Note the alternation of deposits and their different facies. In the middle part is the Caballuna sequence. b) Level detail toward the base of the sequence; note the irregular levels mainly of the mlA facies with accretionary lapilli. The marked box corresponds to Figure 9c.

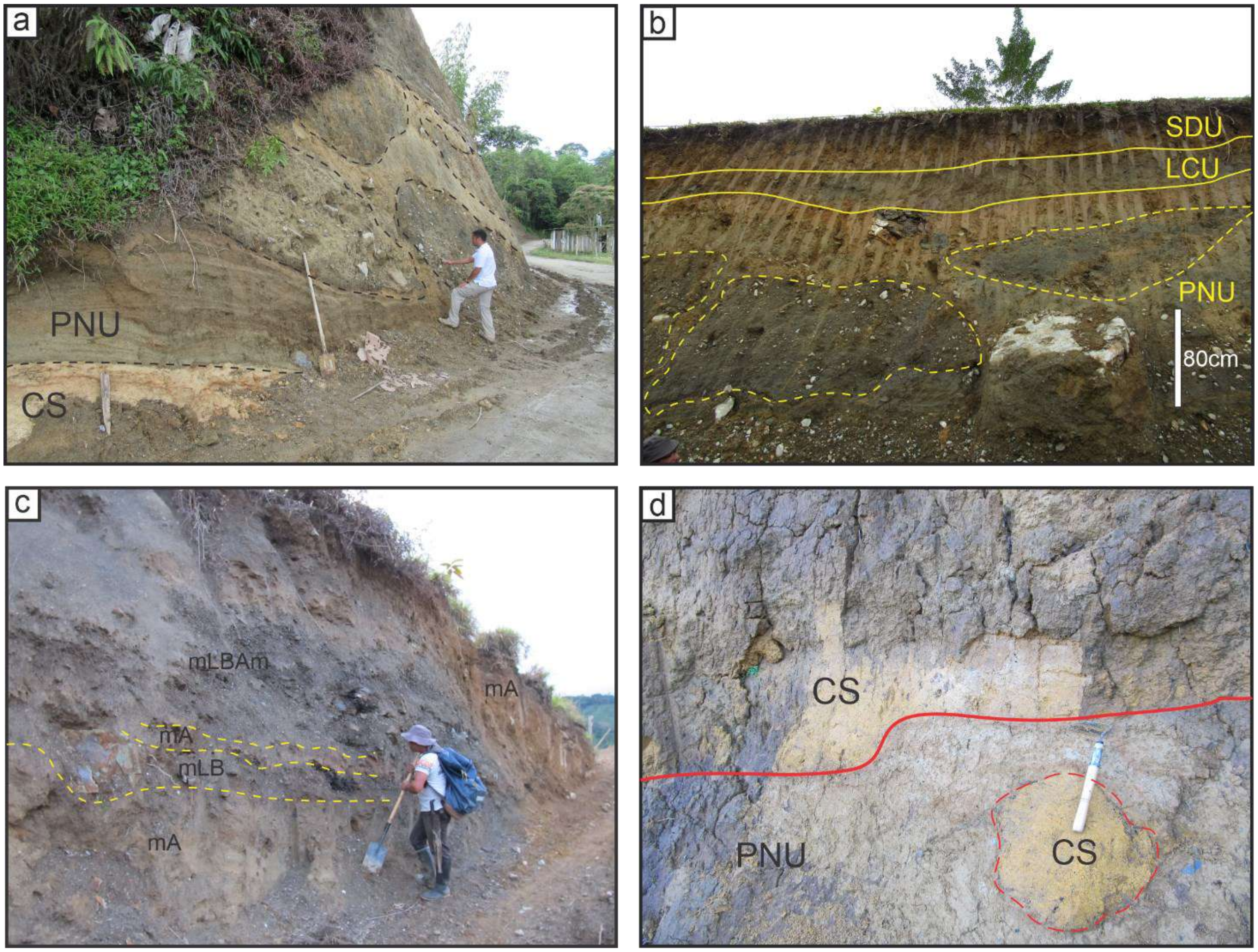


Figure 9. Deposits associated with the PNU

a and b) outcropping deposits in the Pueblo Nuevo sector, where the variation in facies in the outcrops is observed. In a), the base is a pumice layer of the Caballuna sequence (CS), underlined by a deposit of lapilli facies with lamination (lL) and laminated ash (lA). In b), irregular intercalation of the deposits of the sequence; note the basement blocks in the mA facies deposit. c) Irregular intercalation of deposits with mA, mLB and mLBA$_m$ facies. Note the occasional larger basement clasts embedded in the deposit. d) Contact between the Pueblo Nuevo Unit and deposits of the Caballuna pyroclastic sequence, which is indicated by the red line. Note the pumice fragments of this sequence embedded in the mA facies deposits with sporadic lapilli of the PNU. Matecaña sector.

The upper deposit of the PNU is gray, clast-supported and massive to pseudolaminate (mLB, lLB); locally, it presents inverse gradation and is composed mainly of fragments between subangular and subrounded volcanic rocks, sizes that vary from lapilli to block (Figures 10 a and b), among which is a thin clay film (?), the possible product of volcanic glass alteration. To a lesser extent, lithic fragments of the basement are found.

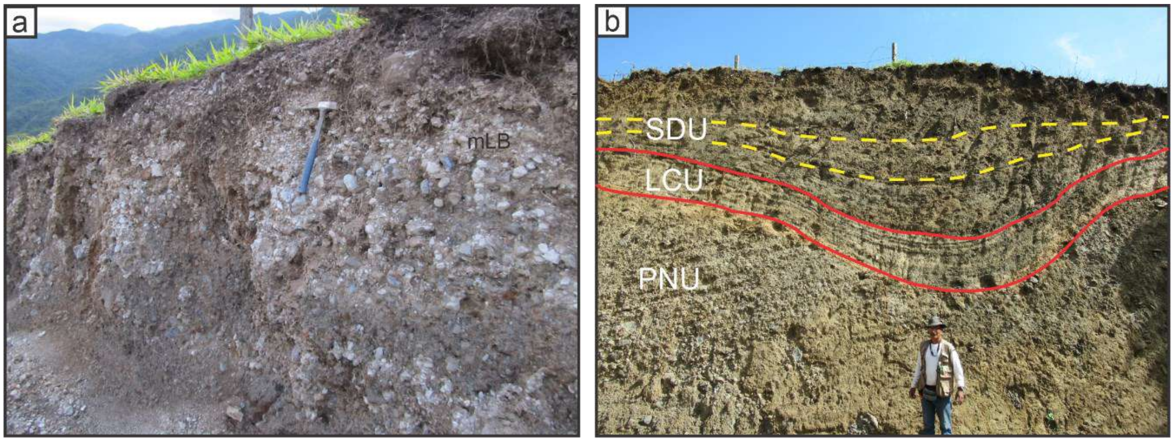


Figure 10. Deposits associated with the Pueblo Nuevo unit
a) Deposition of mLB facies, with some inverse gradation; lithics are mainly volcanic; via Laguna-Tarro Pintado. b) Units that comprise the San Diego maar (PNU, LCU, SDU); solid red lines show the erosional contact between them. At the base, the upper PNU deposit has laminated facies. New Town Sector.

Petrographically, the volcanic lithics found in the PNU have a porphyritic, hypocrystalline texture, with a micro- to cryptocrystalline matrix. The matrix presents a fluid-pylotaxitic texture, with glass and crystals of plagioclase, quartz and biotite. The phenocrysts are plagioclase, andesine-oligoclase type, with polysynthetic twins and common oscillatory zonation; oriented biotite and quartz are frequently fractured and sometimes form a glomeroporphyritic texture (Figure 11).

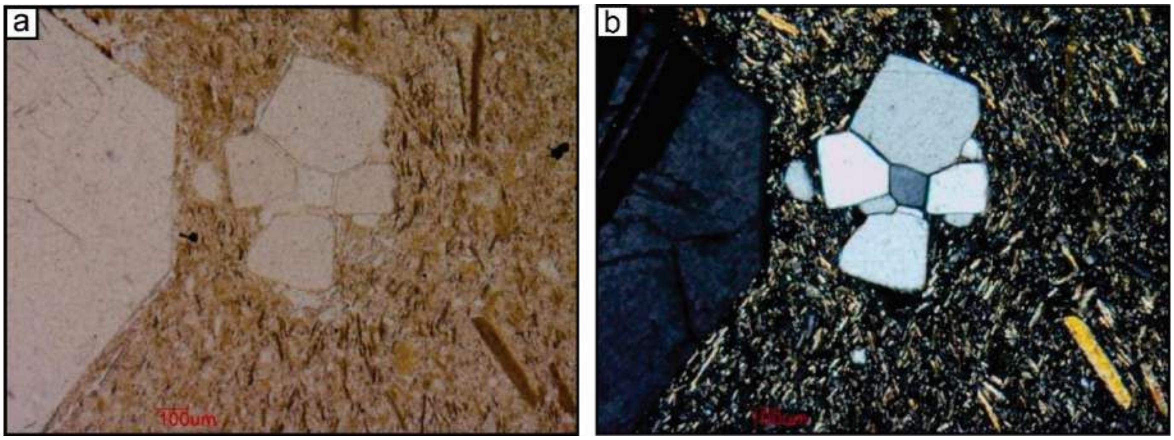


Figure 11. Volcanic lithic sample in the PNU
a) In nicoles PPL. b) In nicoles XPL (5X). General appearance of the sample, with microcrystalline plagioclase and quartz and a microcrystalline matrix. Note the fluid texture (trachytic) and the addition of quartz. Taken from Monsalve (2014).

5.1 Interpretation

The variation in the facies of the Pueblo Nuevo Unit reflects the beginning of the activity that gave rise to the San Diego maar, given by the deposits between massive and rolled ash and levels of accretion lapilli, as well as the levels with massive facies of lapilli and blocks, and a predominance of basement lithics, which indicates that the deposits are related to initial phreatic phases (Self, 1983; Lorenz, 2003, Ort et al., 2018); later, these deposits pass to a phreatomagmatic-magmatic phase, with a predominance of deposits enriched in siliceous juvenile volcanic lithics. Deposits similar to these are described by Lorenz (2003) as typical and formed in the initial phreatomagmatic phase of the Hasenberg volcano (basaltic) in the western Eifel volcanic field, which is followed by a scoriaceous magmatic phase.

In the lower part of the PNU sequence, the irregular intercalation of the deposits, as well as the presence of large sporadic basement blocks in the massive ash facies, suggest more than one initial eruptive focus acting simultaneously. The development of the maar would be controlled by the gradual collapse of the crater and the walls of the conduit, and at the same time, the emission of the collapsed fragments due to phreatomagmatic explosions, when the rising magma came into contact with the groundwater. Observations of the eruption of the Ukinrek that occurred in 1977, which formed a maar in Alaska (Kienle et al., 1980), showed that multiple foci could erupt simultaneously and have contrasting eruption styles; in this case, there was lateral migration over time.

The massive deposits rich in siliceous volcanic blocks in the upper part of the sequence, which present a limited and irregular distribution in the proximal sectors, as interpreted, have experienced rapid deposition, possibly due to the formation of ballistic curtains, as shown in the experiments carried out by Graettinger et al. (2015) and Valentine et al. (2017).

6. EL MORRO TUFF CONE. LA CONCHA UNIT

In the northeast sector of the current structure of the San Diego maar is the El Morro tuff cone at 1219 masl (Figure 12), which was formed by phreatomagmatic activity followed by a magmatic phase (*plug*) consisting of eruptive phases after the first maar formed. Toro (1988, 1989) and Borrero et al. (2016) describe this structure as a dome of rhyolitic and dacitic composition. Dating obtained in noncarbonized wood in deposits that form the cone yielded ages of 22 417 ± 82 and 20 552.8 ± 55 BP. The deposits associated with this structure are named the *La Concha Unit*.

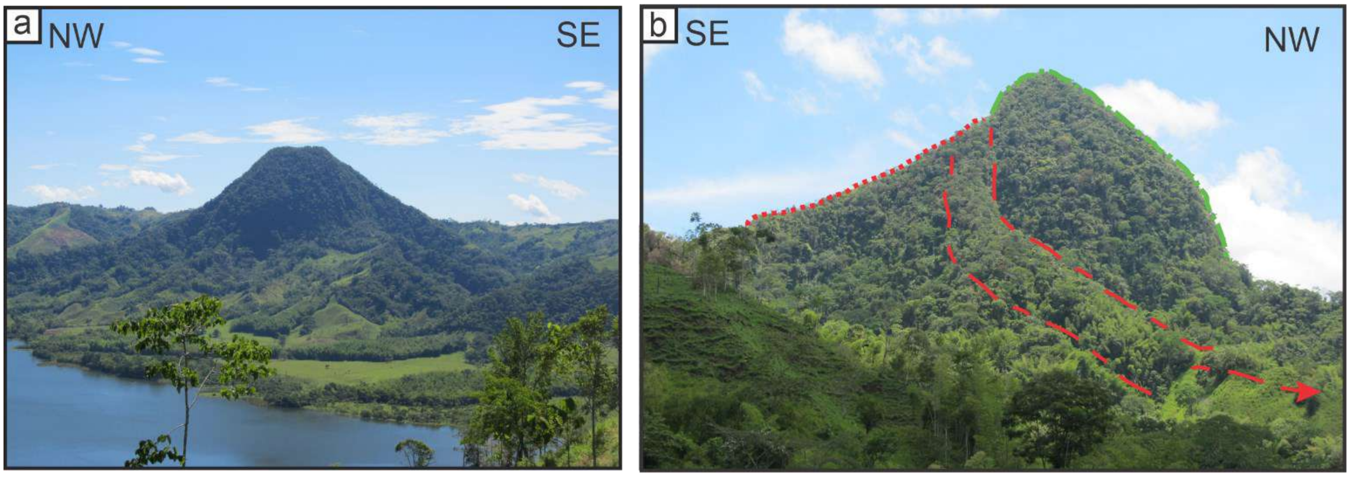


Figure 12. El Morro tuff cone
a) View from the SW. b) View from the NW. Note the morphology of the plug, with nearly vertical walls, and the relationship with the diluted and concentrated PCD deposits, indicated in red, that form the northwest flank of the tuff cone.

The La Concha Unit (LCU) comprises concentrated and diluted PCD deposits that reach distances of more than 6 km (Figure 7), with thicknesses ranging from a few meters to more than 40 m in the La Concha stream sector. The outcrops are in the vicinity of the cone and channeled in the streams Cristalina, El Morro, El Caño or La Laguna, La Concha and La Calera, and extend to the Samaná River toward the north, where the deposits are observed to be reworked.

In general, the deposits are compact, with shades ranging from dark gray to a characteristic bluish color. Toward the proximal parts, concentrated PCD deposits predominate with facies $mLBA_m$ (Figure 13) of gray color, chaotic and matrix-supported, which are composed of lithics with sizes that vary from lapilli to block: light gray volcanic, porphyritic with biotite and metamorphic in variable proportions, embedded in a matrix of medium to coarse lithic-crystalline ash (volcanic and metamorphic fragments and plagioclase, quartz and biotite crystals). In the middle and distal parts, a variation in facies is observed: massive ash (mA), ash and lapilli (mAL), massive lapilli and block in ash matrix ($mLBA_m$), and locally, massive ash enriched in accretionary lapilli (mALa) (Figures 13 a and b), forming a sequence of layers with diffuse stratification that are inclined in the La Concha stream (Figure 14).

Figure 13. a) Deposits of dilute PCD of mC facies interspersed with layers with mALa and LBAm facies. b) Detail of the levels with mA, mALa and LBAm facies. Quebrada El Morro, NE sector of El Morro.

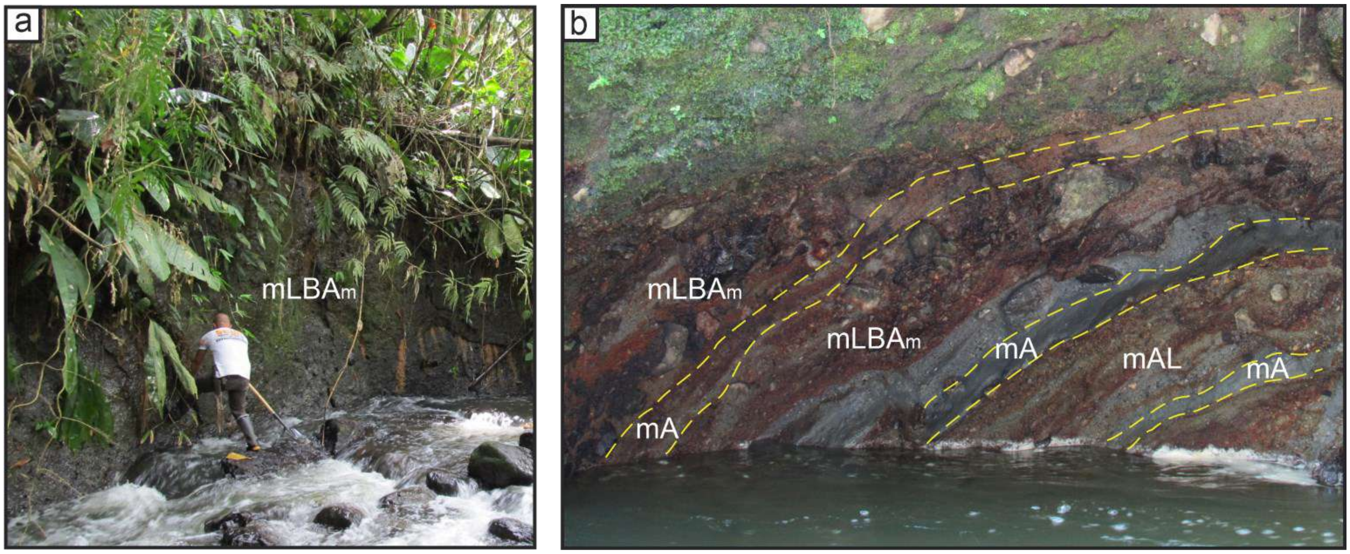


Figure1 4. a) Massive PCD deposit in the El Caño stream, W of Morro de San Diego (Figure 6). b) Inclined sequence with intercalation of mA, mAL and LBAm facies levels, exhibiting locally diffuse stratification. Quebrada La Concha.

In the erosional contact, on the deposits of the Pueblo Nuevo unit, there is a laminated deposit of fine and medium ash with the presence of accretionary lapilli (facies lA and lLa), which stratigraphically correlate with the LCU. The thickness of this deposit is less than one meter and shows little variation with distance (Figures 10d and 15).

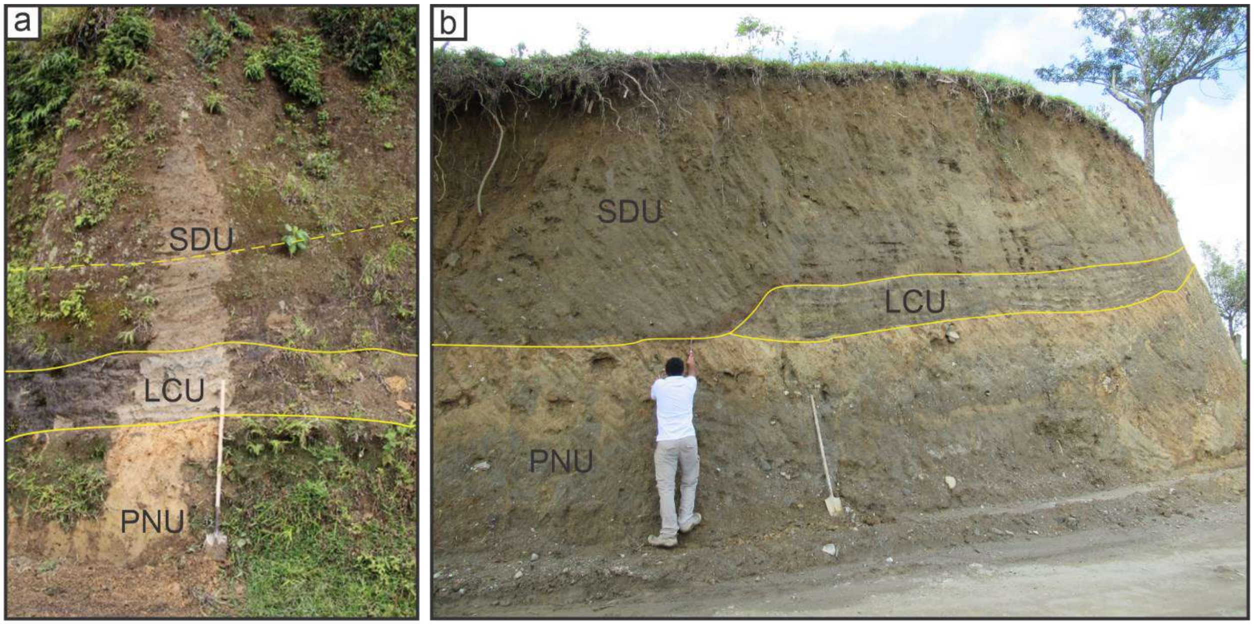


Figure 15. Eruptive sequence of the San Diego maar showing the stratigraphic position of the deposits that correlate with the LCU between the PN and SD units
a) At the entrance to San Diego. b) Pueblo Nuevo-San Diego Highway. Note the erosional contact of SDU with LCU and PNU. Note the small variation in the thickness of the deposit.

The magmatic phase after the formation of the tuff cone is represented in the *plug*. The rocks that comprise it correspond petrographically to porphyritic dacites with plagioclase microcrystals, oriented biotite and, to a lesser extent, quartz in a cryptocrystalline matrix (Monsalve, 2014; Rueda Gutiérrez, 2019) (Figure 16). This is the same mineralogical association that was observed in the rock fragments embedded in the PNU deposits and in the LCU deposits. The chemical analyses of the dome and the rock fragments correspond to the calc-alkaline series of dacitic composition up to the rhyolitic limit (SiO_2 68-70%) (Monsalve, 2014).

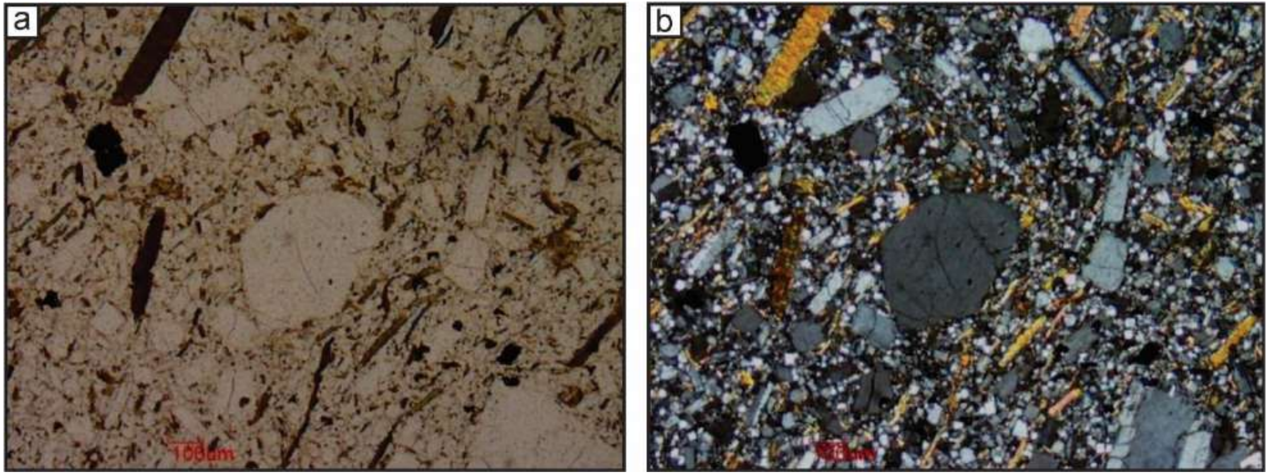


Figure 16. a) Nicole PPL. b) in nicoles XPL (5X objective)
General appearance of the sample, with plagioclase, quartz, biotite and opaque microcrystals on a microcrystalline matrix, where quartz predominates. Note the orientation of the microcrystals and biotite and plagioclase in the matrix.

Finally, deposits enriched in accretionary lapilli observed to the southwest of the lagoon, in Riachuelo Creek, were initially correlated with the LCU, but the dating obtained from 28 521.8 ± 102 BP differs from the dates obtained for this unit in other deposits. The outcrop in this creek shows thicknesses of more than 8 m of alternating layers with massive ash facies (mA) and massive ash with accretion lapilli (mALa) (Figures 17 a and b).

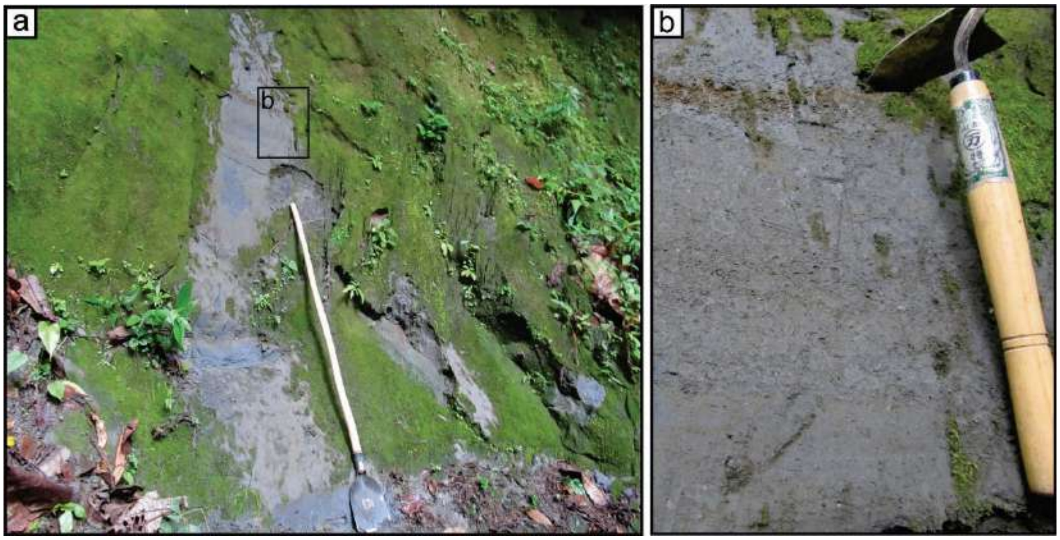


Figure 17. a) Deposits of diluted PCD of mALa facies in the Riachuelo stream. b) Detail of the levels enriched with accretional lapilli

6.1 Interpretation

Tuff cones are related to activity that varies between phreatic and phreatomagmatic (Wholetz and Heiken, 1992; Murtagh and White, 2013). The El Morro tuff cone was formed within the crater of the first maar, which was possibly occupied by a crater lake. The PCD deposits that emerge in the proximal part are associated with the beginning of cone formation in an underwater environment (below the surface of the lake) and would have given rise to massive, matrix-supported deposits with mLBA$_m$ facies), which were channeled through the valley of the La Concha stream. Underwater is a type of phreatomagmatic activity in which abundant water receives insufficient heat to evaporate and more effective fragmentation (White and Houghton, 2000). The presence of noncarbonized wood in the deposits associated with this unit indicates a relatively low temperature during deposition.

The progressive growth of the cone and the gradual depletion of water gave rise to the transition of these massive deposits at a sequence of levels with diffuse stratification, characterized by a visible difference in the size of the grains and the selection between the layers rich in ash and lapilli; this would have resulted in variation in the facies (mA, mAL, mLBA$_m$), which are interpreted as the result of unstable pyroclastic surges or multiple closely spaced events (Sulpizio et al., 2014).

The local inclination of the sequence in the canyon of the La Concha stream is interpreted as being due to the variability and topographic control exerted by the valleys of the streams through which the pyroclastic waves were channeled, as proposed by Wohletz (1998), to two-phase flows.

According to Valentine (1987), for any stratified flow that encounters an obstacle, there will be a level (streamline) above which all the fluid has enough energy to overcome the obstacle and below which the fluid stops (blocks) or simply moves around the obstacle without vertical movement.

The most dilute facies are found in the outer part of the San Diego maar craters, in a contact that varies from net to erosional on the Pueblo Nuevo unit, and they are interpreted as wave deposits left by the subaerial activity of the tuff cone. The rhyolitic *plug* that fills the El Morro conduit occurred once the water in the system was exhausted and is the result of the magmatic phase of the eruption.

Rueda Gutiérrez (2019) reported an Ar-Ar dating for the San Diego dome that registered a *plateau* age of 89 ± 4.4 ka, which differs from the age found in the deposits of approximately 22 000 years. In this work, they are associated with the formation of the tuff cone. The age of placement of the *plug* on the surface should be younger than the reported age. This may be because the Ar-Ar measurements were made on biotite phenocrysts, which must have crystallized before the eruption. Thus, the result could correspond to the age of crystallization of the biotite and not to the extrusion age of the magma (Chernyshev et al., 2006; Hora et al., 2010; Bablon et al., 2020).

Finally, the dating of 28 521.8 ± 102 BP in the deposit with characteristics similar to those of the LCU (Figures 17 a and b) could represent a unit prior to the formation of the tuff cone, although it is recommended that samples be taken at this site to verify dates or discard this age.

7. San Diego Unit

The San Diego unit crops out in contact between the net and discordant deposits that comprise the U La Concha and locally on the Caballuna volcanic sequence or on the Pueblo Nuevo unit (Figures 6 and 18). Toward the base, the unit is composed of a repetitive alternation of layers and sheets of ash with a hue that varies between *beige* and gray; it is from very fine to fine, with accretionary lapilli (facies mA, lA, mLa), and layers that vary between ash and lapilli, lithic-crystalline (plagioclase, amphibole, biotite and quartz), with good to moderate selection (mAL facies). In good exposures it is possible to identify structures additional to lamination and accretionary lapilli, such as incipient cross-stratification and megadunes (Figure 18), structures that indicate phreatomagmatic activity at their origin (Schminke et al., 1973).

Toward the top, the facies become massive (Figure 16) and is composed of lapilli and blocks (mLB) of porphyritic rocks that vary between fine and medium, with biotite; metamorphic rocks predominate. To a lesser extent, it also presents vesicular fragments of white color with a saccharide texture, possibly from altered volcanic rocks and pumice fragments of the Caballuna sequence, which is also reported by Borrero et al., (2016). Locally, it is observed in net transitional contact with the lower part of the unit and elsewhere in erosive contact (Figures 18a and 10b).

The unit has a total thickness of approximately 5 m in the vicinity of the town of San Diego and increases to > 5 m toward the southern edge of the lagoon and the Rancho Quemado sector. The laminated basal deposits are only observed toward the NE, E, SE and S of the maar, with a distribution that is restricted to the proximal parts, while the massive upper part presents a wider distribution and is observed directly on the Caballuna sequence in the sectors of Matecaña, to the SE and on the road to San Roque to the N, where Borrero et al. (2016) reported a paleosol that yielded an age of 16 624 + 48 years BP (20 056 + 93 cal years BP), which is assigned in this work to the SDU.

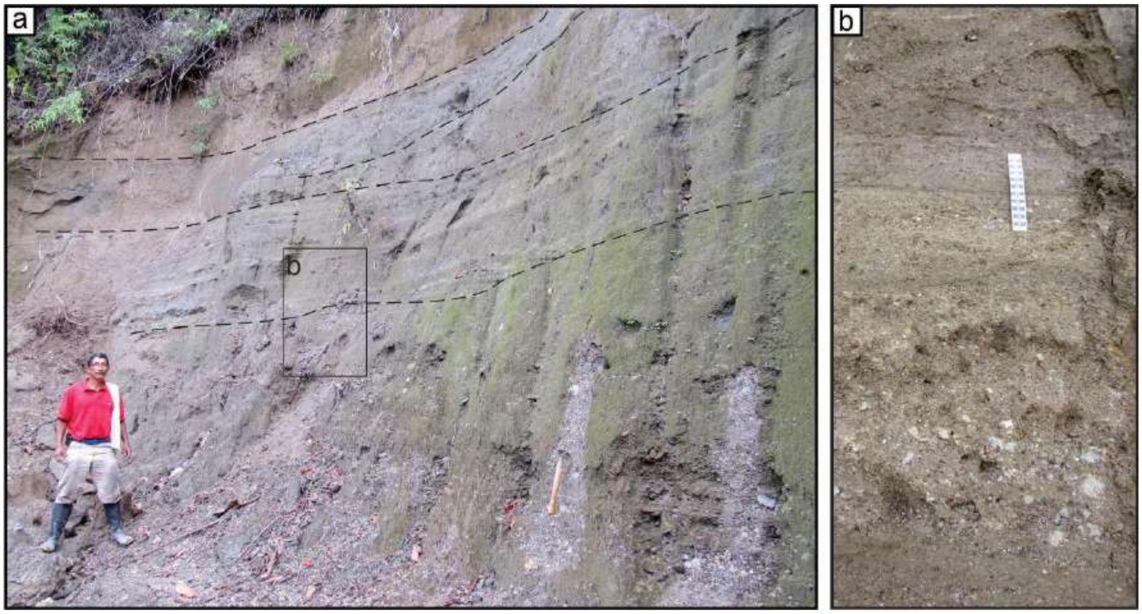


Figure 18. San Diego Unit, on the way to Tarro Pintado
a) Note the transition of facies from laminated stratified to predominantly massive at the top. b) Detail of facies variation.

7.1 Interpretation

The basal part of the SDU sequence is homogeneous, and the variation in lithofacies, both vertically and with distance, is given by variations in the thickness of the deposit, of the individual layers and in the variation in the grain size. Structures in the deposits, such as the presence of accretionary lapilli, lamination, incipient cross-stratification, sporadic impact craters and mega-dunes, lead to the interpretation that the deposit is the product of repeated phreatomagmatic explosions, which generated dilute PCDs (e.g., Schminke et al., 1973; Sheridan and Wohletz, 1983, Brown and Andrews, 2015).

The deposits of the upper part contrast with the previous deposits in their structure (massive facies), distribution and components, mainly lithic in the basement, which could indicate the deepening of the emission focus and, as suggested by Borrero et al. (2016), high-energy explosive phreatic activity.

8. Discussion

According to the Lorenz classification (1986), San Diego is a maar-type volcano because it exposes the premaar lithology, composed of metamorphic rocks, inside the crater. Maars are considered to be the second most common type of volcano on earth (Lorenz, 1986; Cas and Wright, 1987; White and Ross, 2011) and are generally associated with basic volcanism, although some are known to have a siliceous composition (Lorenz, 2003; Ross et al., 2017), as is the case with the San Diego maar.

Typical maars are generally monogenetic volcanoes (Németh, 2010; Németh and Kereszturi, 2015) with eruptions lasting from hours to several weeks (White and Ross, 2011). However, the contrasting facies presented by the deposits associated with the activity of the San Diego maar, in addition to the presence of erosional boundaries and paleosols, suggest that this structure is the result of several events separated by significant periods of rest.

The configuration of the volcanic structure, the crater and the deposits that form the rings show a complex history in its evolution, controlled by the Palestine fault, where a migration of the eruptive centers with time is suggested.

The deposits that formed the tephra ring of the initial stage, which gave rise to the first maar, show transport as currents of pyroclastic density and ballistic trajectories. The latter would have generated deposits with mLB facies from ballistic curtains (Graettinger et al., 2015; Graettinger and Valentine, 2017). On the other hand, the deposits that appear as irregular intercalations, with contrasting facies (mA and mLB), reflect simultaneous sources of material emission (Jordan et al., 2013). This irregular intercalation and simultaneous deposits of different foci and volcanic processes were evidenced in the eruption of the Unrinken maar in 1977 (Ort et al., 2018).

The characteristics of the San Diego maar and its deposits are consistent with models presented in more recent works (ex. Valentine and White, 2012; Valentine et al., 2017), which through experiments show evidence that explosions can migrate vertically and laterally as a diatreme develops, while more superficial explosions dominate the eruptive activity. The characteristics of the tephra rings and field evidence support the existence of migration in explosion sites, both vertical and lateral in the diatremes. This model complements the initial model proposed by Lorenz (1986) for the formation of maar-diatreme structures, which indicates that phreatomagmatic explosions begin at relatively shallow depths and progressively deepen as the groundwater in the aquifer is depleted.

8.1 Evidence of polygenetic activity in the San Diego maar

This maar has been considered a monogenetic structure (Toro, 1989; Borrero et al., 2014; Borrero et al., 2016). However, the contrasting volcanic facies presented by the deposits associated with their activity, in addition to the presence of erosional limits, the ages reported and obtained in the deposits and the morphology of the structure, suggest that the San Diego maar would be the result of multiple eruptive events separated by significant periods of inactivity for thousands of years. These maars are interpreted as polygenetic (Németh et al., 2012; Tchamabé et al., 2014, 2016), and this type belongs to the San Diego maar, whose eruptive history is approximately 25 000 years long.

San Diego's record of maar activity reflects a complex eruptive history in which water has played a predominant role. The initial phase of maar formation approximately 40 000 years ago, gave rise to massive irregular volcanic deposits and pyroclastic surges composed predominantly of basement lithics caused by eruptions of types varying from phreatic to phreatomagmatic.

The occurrence of abundant fragments of basement rocks shows that the explosion generated by the magma-water interaction would have been significantly energetic during this eruptive phase to fragment the metamorphic basement on which the maar was built (Cruz and Carrasco, 2008; Ort et al., 2018). This stage was related to the initial opening of the San Diego maar, which formed a crater approximately 2.4 km in diameter, after which explosions in several simultaneous foci continuously produced irregular deposits that formed the initial pyroclastic ring.

The presence of deposits toward the top of the sequence that are composed mainly of lithics of porphyritic rock would indicate a decrease in the water supply and an increase in the emission rate of a partially crystallized magma. The subrounded shapes of the components and the low vesicularity suggest that the fragmentation process was dominated by phreatomagmatic activity and that the material was emitted in the form of ballistic curtains (Graettinger et al., 2015; Graettinger and Valentine, 2017).

The possible formation of a crater lake within the initially formed structure and the hydric recharge of the system caused the rising magma to vaporize the water in the saturated area below the maar, thus favoring the phreatic and phreatomagmatic activity that gave rise to the formation of the cone of the El Morro tuff approximately 22 000 years ago; this was followed by the final rise of the magma, which gave rise to the rhyolitic *plug* that fills the cone duct. The 89 ± 4.4 ka dating reported by Rueda Gutiérrez (2019) of the San Diego dome could correspond to the crystallization of biotite (Chernyshev, 2006; Hora et al., 2010; Bablon, 2020) and not to the location of the dome or *plug*.

The migration of the activity toward the SW formed the most recent maar and gave the current configuration to the structure (Figure 3). The reactivation of phreatomagmatic activity occurred 16 624 ± 48 years ago, according to ages reported by Borrero et al. (2016). The predominant facies of the deposits indicate that the eruptive activity was initially governed by phreatomagmatic fragmentation, mainly in humid conditions: sedimentary structures, such as undulations, cross stratification, deformation of layers by impact of bombs, and abundant accretionary lapilli are observed. The new eruptive sequence reflects several phreatomagmatic explosions that involved not only the basement of the structure but also material that made up the initial pyroclastic ring and deposits of the tuff cone.

The final phase of the formation of the maar is given by high energy explosive activity, predominantly phreatic, due to the deepening of the explosion focus, which is reflected in the massive deposit with a predominance of lithics in the basement and a wide distribution that overlies all the San Diego maar stream. Figure 19 shows the evolutionary scheme of the San Diego maar.

9. Conclusions

The volcanic structure of San Diego corresponds to a maar-pyroclastic ring-type volcano with a siliceous composition. From the morphology and stratigraphy, it was possible to infer that it corresponds to a complex maar comprising several volcanic structures located in a NE–SW direction on the Palestine fault.

Field observations, crater morphology and characteristics of the deposits show a remarkable variety of eruptive styles associated with the activity of the maar. The presence of erosional contacts and dating in deposits and paleosols show long periods of rest between eruptions and suggest at least three periods in their formation, which began approximately 40 000 years ago.

The elliptical configuration of the San Diego volcano is the result of the formation of two concatenated maars, interrupted in the central part due to successive volcanic activity in approximately 25 000 years, which includes the formation of a *tuff cone*, whose remnants are found in the interior of the maar in the NE sector, while the interior SW is currently occupied by a lagoon corresponding to the crater of the SW maar.

Considering the variations in the thickness of the deposits, internal structures, relative selection in layers, unconformities and sedimentary characteristics, the deposits associated with the activity of the San Diego maar were divided into three main units, corresponding to PCD deposits and fall of pyroclasts (ballistic curtains) and associated with three main eruption types that vary from phreatic to phreatomagmatic.

The deposits present variations in thickness ranging from one meter to more than 40 m, and in the case of the La Concha Unit, they are associated with the El Morro tuff cone; the magmatic phase of the maar activity is the *plug* that fills the conduit of the tuff cone.

The variation in facies in the deposits and the evidence of long periods of rest between the stratigraphic units allow us to classify the San Diego maar as a complex, composite or polygenetic maar, which would have important implications for evaluating the level of threat in the region where this type of structure is located, which is considered mainly monogenetic.

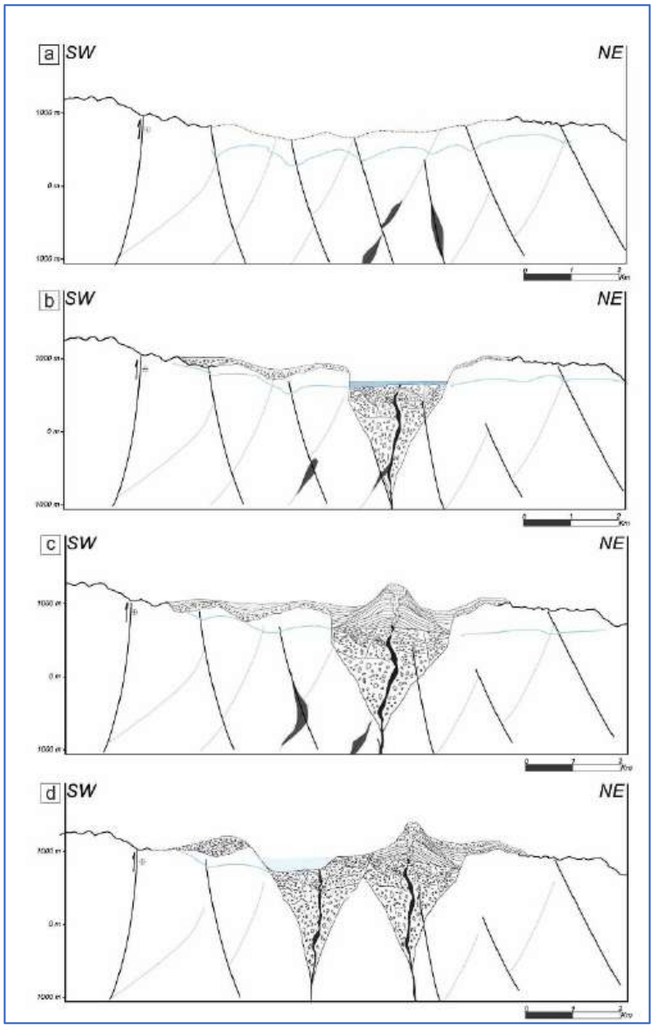


Figure 19. Schematic model of the evolution of the San Diego maar a) Preeruptive morphology of the volcano. The faults in the area (Palestine) constitute the area of weakness that favors the ascent of the magma. b) Formation of the first structure, maar-diatreme (NE), ≈ 40 000 BP, due to phreatomagmatic eruptions. c) Formation of the El Morro tuff cone and lava plug ≈ 22 000 BP. d) Migration of the eruptive focus and formation of the SW maar, ≈ 16 000 BP, which gave rise to the current configuration of the San Diego maar.

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