Journal of Maps

ISSN: (Print) 1744-5647 (Online) Journal homepage: https://www.tandfonline.com/loi/tjom20

Geology of La Reforma caldera complex, Baja California, Mexico

L. García Sánchez, J.L. Macías, R. Sulpizio, L.S. Osorio-Ocampo, C. Pellicioli, A. Pola, D.R. Avellan, G. Cisneros, F. García, Y.Z.E. Ocampo-Díaz, R.M. Lira-Beltran, R. Saucedo, J.M. Sánchez-Núñez, J.L. Arce, P. Corona-Chávez, G. Reyes-Agustin, M. Cardona, P.W. Layer, J. Benowitz, L. Solari & G. Groppelli

To cite this article: L. García Sánchez, J.L. Macías, R. Sulpizio, L.S. Osorio-Ocampo, C. Pellicioli, A. Pola, D.R. Avellan, G. Cisneros, F. García, Y.Z.E. Ocampo-Díaz, R.M. Lira-Beltran, R. Saucedo, J.M. Sánchez-Núñez, J.L. Arce, P. Corona-Chávez, G. Reyes-Agustin, M. Cardona, P.W. Layer, J. Benowitz, L. Solari & G. Groppelli (2019) Geology of La Reforma caldera complex, Baja California, Mexico, Journal of Maps, 15:2, 487-498, DOI: 10.1080/17445647.2019.1612287

To link to this article: https://doi.org/10.1080/17445647.2019.1612287

JOURNAL OF MAPS
2019, VOL. 15, NO. 2, 487–498
https://doi.org/10.1080/17445647.2019.1612287

Science

OPEN ACCESS Check for updates

Geology of La Reforma caldera complex, Baja California, Mexico

L. García Sánchez[a], J.L. Macías [b], R. Sulpizio[c,e], L.S. Osorio-Ocampo[a], C. Pellicioli[c,d], A. Pola[f], D.R. Avellan[g], G. Cisneros[b], F. García[b], Y.Z.E. Ocampo-Díaz[h], R.M. Lira-Beltran[a], R. Saucedo[i], J.M. Sánchez-Núñez[j], J.L. Arce[k], P. Corona-Chávez[l], G. Reyes-Agustin[b], M. Cardona[b], P.W. Layer[m], J. Benowitz[m], L. Solari[n] and G. Groppelli [c]

[a]Posgrado en Ciencias de la Tierra, Instituto de Geofísica, Universidad Nacional Autónoma de México, Ciudad de México, México; [b]Instituto de Geofísica, Universidad Nacional Autónoma de México, Morelia, México; [c]Istituto per la Dinamica dei Processi Ambientali, sezione di Milano, C.N.R., Milano, Italia; [d]Dipartimento di Scienze della Terra "Ardito Desio", Università degli Studi di Milano, Milano, Italia; [e]Dipartimento di Scienze della Terra e Geoambientali, Università degli Studi di Bari "Aldo Moro", Bari, Italia; [f]Escuela Nacional de Estudios Superiores, Unidad Morelia, Universidad Nacional Autónoma de México, Morelia, México; [g]Cátedra CONACYT – Instituto de Geofísica, Universidad Nacional Autónoma de México, Morelia, México; [h]Área de Ciencias de la Tierra, Facultad de Ingeniería, Univeridad Autónoma de San Luis Potosí, San Luis Potosí, México; [i]Instituto de Geología, Universidad Autónoma de San Luis Potosí, San Luis Potosí, México; [j]Centro Interdisciplinario de Investigaciones y Estudios sobre Medio Ambiente y Desarrollo, Instituto Politécnico Nacional, Ciudad de México, México; [k]Instituto de Geología, Universidad Nacional Autónoma de México, Ciudad de México, México; [l]Instituto de Investigaciones en Ciencias de la Tierra, Universidad Michoacana de San Nicolás de Hidalgo, Morelia, México; [m]Geophysical Institute, University of Alaska at Fairbanks, Fairbanks, USA; [n]Centro de Geociencias, Universidad Nacional Autónoma de México, Juriquilla, México

ABSTRACT

A new geological map at 1:50,000 scale of La Reforma Caldera Complex has been produced applying modern survey methodologies to volcanic areas. This map aims to represent a reliable and objective tool to understand the geological evolution of the region. La Reforma Caldera Complex is a Pleistocene nested caldera located in the central part of the Baja California peninsula, Mexico. The twelve formations defined within the Quaternary volcanic record were grouped into three phases (pre-caldera, caldera, and post-caldera). The pre-caldera phase (>1.35 Ma) is characterized by scattered eruptions, mostly occurred in submarine environment. The caldera phase (1.35–0.96 Ma) groups several distinct explosive and effusive eruptions that formed the present-day caldera depression. The post caldera phase includes scattered effusive eruptions (ended at 0.28 Ma) and resurgence, characterized by several hundred meters of uplift of the central block within the caldera depression.

ARTICLE HISTORY
Received 3 December 2018
Revised 16 April 2019
Accepted 24 April 2019

KEYWORDS
Geology; stratigraphy; caldera complex; Pleistocene volcanism; ignimbrites; geothermal resources

1. Introduction and previous studies

Geological maps have to be objective and detailed because they represent a fundamental tool to understand the geological evolution of a given area, and, when mapping is conducted at relatively high scale, they provide a sound basis for detailed studies aimed at assessment of natural hazards, and exploitation of geothermal potential and/or ore deposits. For this reason, within the project CEMIE GEO (Centro Mexicano de Innovación en Energía Geotérmica), which involves different sites in Mexican Quaternary volcanic districts, we surveyed La Refoma Caldera Complex area and produced a new geological map at 1:50,000 scale Main Map.

La Reforma Caldera Complex is located in the central part of the Baja California peninsula, 35 km to the NW of the town of Santa Rosalía (Demant, 1984). Along with the Aguajito Caldera (Garduño-Monroy, Vargas-Ledezma, & Campos-Enriquez, 1993) and the Tres Vírgenes volcanic complex (Avellán et al., 2018) La Reforma caldera complex represents a manifestation of the Quaternary volcanism in the central part of the Baja California (Figure 1). The first geological contributions in the region focused on the Plio-Pleistocene sedimentary rocks of the Santa Rosalía Basin (Ortlieb, 1978; Ortlieb & Colleta, 1984; Wilson, 1948; Wilson & Rocha, 1955) because of the exploitation of copper and manganese minerals. Wilson and Rocha (1955) provided a detail geological map of the Santa Rosalía area, but did not include La Reforma range, located to the northwest. Schmidt (1975) published the first geological map of the Sierra La Reforma that was interpreted as a complex system of uplifted tectonic blocks. One of these blocks was made of crystalline granodioritic rocks dated by the Author at 91.2 ± 2.1 Ma by K-Ar method. Demant and Ortlieb (1981) recognized the Sierra La Reforma as a resurgent caldera, and Demant (1984) presented a regional geological map of Santa Rosalía with a mineral and petrological characterization that included La Reforma caldera. In 1982, the National Power Company (Comisión Federal de Electricidad = CFE) began geological and geophysical

CONTACT G. Groppelli gianluca.groppelli@cnr.it, gianluca.groppelli@unimi.it Istituto per la Dinamica dei Processi Ambientali, sezione di Milano, C.N.R., Milano, Italia

Supplemental data for this article can be accessed https://doi.org/10.1080/17445647.2019.1612287.

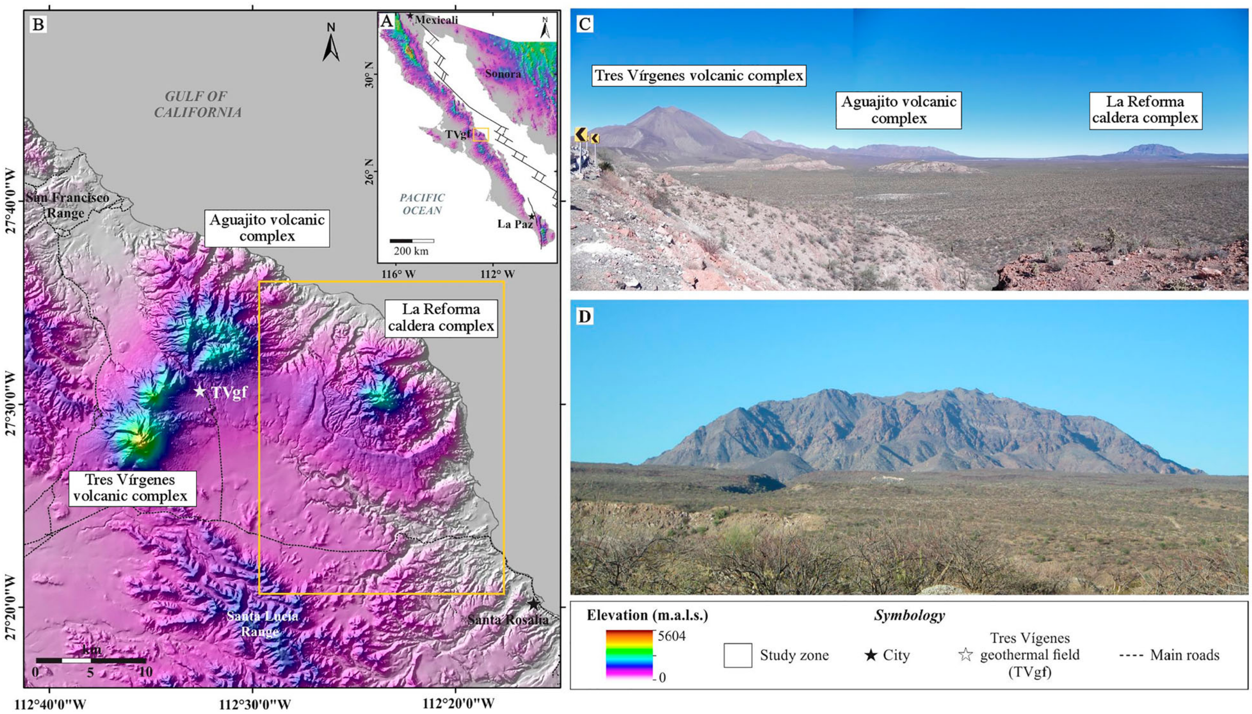

Figure 1. (A) Tectonic setting of the Gulf of California in northwestern Mexico with the location of the study area (box) and Tres Vírgenes geothermal field (TVgf). (B) Shaded relief map of the study area that displays the location of the Tres Vírgenes volcanic complex (TVVC), the Tres Vírgenes geothermal field (TVgf), the El Aguajito volcanic complex and La Reforma caldera complex, (C) Panoramic view from the south of the TVVC, El Aguajito volcanic complex and La Reforma caldera. (D) Close up view from the southwest of La Reforma caldera in the background (resurgent area) and gentle slopes formed by lava flows in the foreground.

prospecting in the Tres Vírgenes area (southwest of La Reforma) for geothermal exploration (e.g. Lira, González, & Arellano, 1997; Lira, Ramirez, Herrera, & Vargas, 1983) followed by its exploitation in 1986. The CFE survey involved other prospecting areas as El Aguajito (Garduño-Monroy et al., 1993) and set the basis for new studies of Tres Vírgenes (Capra, Macıas, Espındola, & Siebe, 1998; Sawlan et al., 1981; Schmitt, Stockli, & Hausback, 2006; Schmitt, Stockli, Niedermann, Lovera, & Hausback, 2010) with the updated geology of the Tres Vírgenes volcanic complex (Avellán et al., 2018; Macías et al., 2012). Schmitt et al. (2006) dated the age of La Reforma (1.3 Ma) and Aguajito ignimbrites (1.2 Ma) with the U-Pb method in zircon, with the aim of understanding the general evolution of the Quaternary volcanic centres northwest of Santa Rosalia.

Despite these efforts, no detailed studies of La Refoma were carried out to produce a comprehensive volcanological map and evolution of the caldera. The CEMIE GEO project, a Mexican initiative to carry out modern geothermal studies, allowed to perform new investigations of La Reforma caldera, aimed at understanding its geothermal potential.

Here, we present the first contribution of this project with the revised geology and stratigraphy of La Reforma caldera complex that was assisted by $^{40}Ar/^{39}Ar$ and U-Pb geochronology (Table 1) from previous studies and new data from the PhD work of García-Sánchez (2019). This new map will set the basis for modern studies in the area, which will be helpful to future prospecting for ore deposits and geothermal potential areas, as well as paleogeographic reconstructions of marine depositional systems and mineralization.

2. Methods

The geological map, here presented at 1:50,000 scale, has been surveyed at 1:25,000 scale in a logistically difficult area due to the absence of any roads and access feasible only by the coastline and a few mountain pathways (Figure 2).

The fieldwork was preceded by critical review of existing literature for the studied area, along with analyses of satellite images (including ESRI and Google images) and of a 25 m pixel-sized digital elevation model (DEM) and its derived morphological features (slope aspect, shaded relief, 3D visualization, etc.).

The geological survey, carried out during 5 field campaigns (from 2014 to 2017), has been realized using INEGI topographic map and iGIS® software on iPad mini equipped with Google Earth images. Geological survey was carried out on lithostratigraphic basis, which allowed for the definition of various formations. Indeed, lithostratigraphic units are the only ones easily recognizable in the field because of their lithology and stratigraphic position (Groppelli & Martì-Molist, 2013; Groppelli & Viereck-Goette, 2010; Martí, Groppelli, & da Silveira, 2018; Salvador,

Table 1. Summary of age determinations from selected samples of La Reforma caldera complex.

Sample	Coordinates		Altitude (m)	Lithostratigraphic unit	Age (Ma) error 1 σ	Method	Material dated	MSWD
	Longitude	Latitude						
RF-102	358009	3050519	612	Plutonic rocks	97.8 ± 1.5	U/Pb	zircons	–
RF-5A	360207	3046366	157	Santa Lucía formation	19.25 ± 0.08	$^{40}Ar/^{39}Ar$[2]	Whole rock	–
RF-47	367168	3037565	160	Cueva Amarilla ignimbrite	2.4 ± 1.5	U/Pb	zircons	–
RF-53F	354423	3046366	250	Carrizo ignimbrite	1.89 ± 0.27	$^{40}Ar/^{39}Ar$[2]	Whole rock	2.58
RF-26D	365319	3033781	319	Contrabando formation	1.47 ± 0.08	$^{40}Ar/^{39}Ar$[2]	Plagioclase	0.41
RF-51	369626	3037573	1	Punta Candeleros formation (pillow lavas)	1.42 ± 0.05	$^{40}Ar/^{39}Ar$[2]	Whole rock	1.35
RF-65	358751	3051407	6	Punta Candeleros formation (lava dome)	1.36 ± 0.06	$^{40}Ar/^{39}Ar$[2]	Whole rock	0.46
RF-18	355645	3036623	257	Los Balcones ignimbrite	1.35 ± 0.02	$^{40}Ar/^{39}Ar$[2]	Whole rock	0.86
RF-88	363593	3041869	719	Cerro la Reforma formation	1.27 ± 0.02	$^{40}Ar/^{39}Ar$[2]	Whole rock	0.57
RF-16A	357090	3038486	367	La Reforma ignimbrite	1.29 ± 0.02	$^{40}Ar/^{39}Ar$[2]	Whole rock	1.08
RF-12	357200	3037510	394	Mesa el Yaqui formation	1.18 ± 0.46	$^{40}Ar/^{39}Ar$[2]	Whole rock	0.16
BH00R41	–	–	–	Aguajito ignimbrite (Schmitt et al., 2006)U/Pb	1.17 ± 0.07	U/Pb	zircons	1.3
RF-122	366559	3045415	14	Punta Arena ignimbrite	0.96 ± 0.21	$^{40}Ar/^{39}Ar$[2]	Whole rock	2.6
RF-26I	365319	3033781	319	Cueva del Diablo formation	0.46 ± 0.08	$^{40}Ar/^{39}Ar$[2]	Whole rock	0.71
RF-41A	368029	3043132	33	Cueva del Diablo formation	0.28 ± 0.05	$^{40}Ar/^{39}Ar$[2]	Whole rock	0.44

The analyses were performed at: (1) Laboratory of Isotopic Studies of the Centro de Geociencias of the UNAM, Juriquilla, and (2) Geochronology Laboratory at the University of Alaska, Fairbanks. Further details on age determinations are given in García-Sánchez (2019).

1994). In addition to the stratigraphic position, we used abrupt change in lithology, presence of palaeosols, or intercalation of marine sediment to define formations.

For the pre-Quaternary basement units (Figure 3), we adopted the published regional stratigraphic framework (Bryan, Orozco-Esquivel, Ferrari, & Lopez-Martinez, 2014; Conly, Brenan, Bellon, & Scott, 2005; Ferrari, Orozco-Esquivel, Bryan, López-Martínez, & Silva-Fragoso, 2018; Hausback, 1984; Kimbrough et al., 2001; McLean, 1988; Sawlan & Smith, 1984; Schmidt, 1975; Umhoefer, Dorsey, Willsey, Mayer, & Renne, 2001). For the Quaternary volcanics, we have defined twelve formations (Table 2). The youngest one (Cueva del Diablo formation) includes lithostratigraphic units of lower rank, members, as the lithological properties allow distinguishing them from the adjacent part of the formation (Salvador, 1994). Moreover, six different lithosomes (Pasquarè et al., 1992; Wheeler & Mallory, 1953) provide additional details to the stratigraphic succession of the Cueva del Diablo formation, based on their morphology, vent location and product distribution (Table 3).

In order to summarize the volcanic succession, we have identified three main phases (pre-caldera, caldera and post-caldera) on the basis of the relationships of the deposits with the caldera evolution. Moreover, we have grouped all the pre-Quaternary rocks into a 'sedimentary and igneous basement' unit.

During field mapping, we have collected samples for petrographic and geochemical analyses and age determination of rocks. Petrographic data allowed for a better characterization of the lithostratigraphic units, whereas radiometric data allowed constraining formations and lithosomes, thus helping reconstruct the evolutionary phases of La Reforma caldera.

All the field data have been stored in a geodatabase, using iGIS software in the field and then ArcGis® platform during the preparation of the geological map.

The colour scale chosen for representation of lithostratigraphic units on the map follows the three evolutionary phases: pre- (brown shaded), syn- (red shaded) and post-(green shaded) caldera phases. A scale of light blue was used to represent the sedimentary and igneous basement units, whereas blue colour was used for the Cretaceous basement (granitoids) in order to highlight its location. This was important in order to highlight the resurgence of the central part of the caldera. Regarding symbols, we have marked crater rims, pit crater rims, caldera rim, bedding attitude, marine terraces and faults. Dykes have been marked by lines too. Insets at 1:20,000 scale highlight the detailed stratigraphic succession in two deep fluvial valleys to the west and south-west.

In addition to the legend, we have included the following elements into the map: (1) an inset showing the geographic location of the mapped area, (2) a stratigraphic scheme to illustrate the relationships among

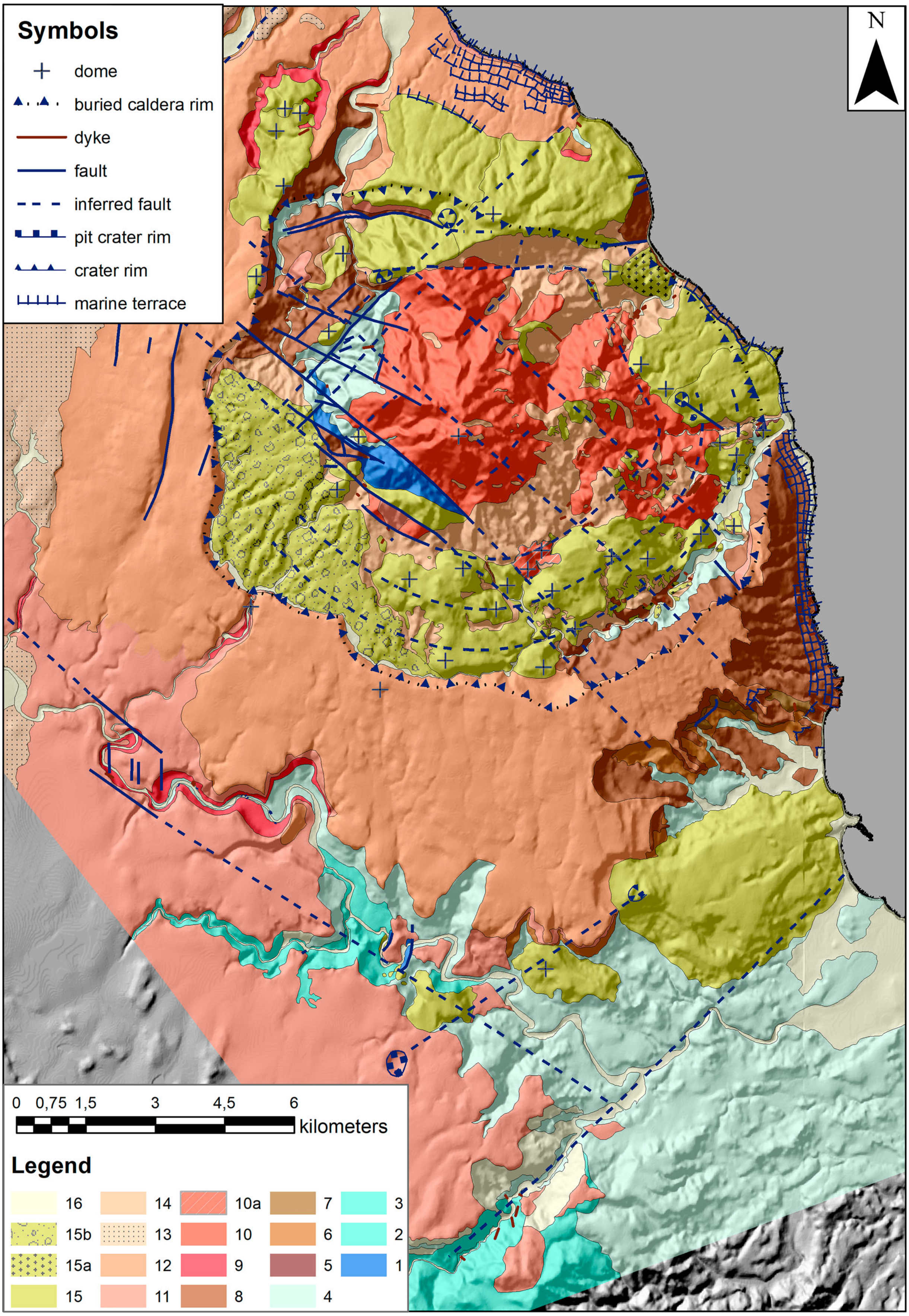

Figure 2. Geological map on a shaded topography (INEGI data). Numbers refer to the lithostratigraphic units described in Table 2, except (16) Recent alluvial deposits.

Table 2. Description of the lithostratigraphic units (group, formation and member) identified within La Reforma caldera complex.

Formation	Acronym	Description	Location	Geochemistry	Interpretation and notes
Post-caldera phase					
Cueva del Diablo formation	15	Scoria cones and domes sometimes associated with limited lava flows (Figures 4(c) and 5(c)). Lava flows are usually thin (2–5 m) and alternated to scoriae. Dikes and small sub-intrusive bodies are also present (Figure 6(a and b)). Lavas display large variability in texture (from aphyric to porphyritic, with phenocrysts of pl, px, and Fe-Ti oxides).	The formation crops out both inside and outside the caldera	Mainly basaltic-andesitic and andesitic lavas. Locally rhyolitic lavas	This formation includes all the deposits formed after the caldera phase. The volcanic activity is scattered and low volume respect the previous phase. Inside the caldera depression usually the centres are located along the ring faults. It is possible to identify several lithosomes (see Table 3).
Arroyo Grande member	15b	Sands to gravels deposits made of lavas and plutonic rocks with interbedded three thin (<1 m) white fallout deposits (Figure 6 (c)). The deposits are matrix supported, partially loose, and coarsely stratified (0.5–1 m) with parallel and lenticular shapes. The total thickness is up to 50 m.	Western side of the caldera depression		The deposits form alluvial fans within the western part of the caldera depression probably due to the dismantling of the resurgent block.
Caldera phase					
Punta Arena ignimbrite	14	White loose pyroclastic deposit, made of grey and white pumices, lava and scoria lithics (red and grey) in abundant ashy matrix. Matrix is generally whitish to yellowish in colour, but it becomes light-green when hydrothermalised (Figure 5(c and d)). It is locally fairly well-consolidated due to hydrothermal alteration. Locally abundant shells (mainly bivalves) are present, mixed into the deposit. Lag breccias made of abundant heterolithologic lithic blocks are present around Cerro la Reforma. The thickness varies from few meters to more than 200 m because of the irregular paleo-topography at the time of deposition.	This ignimbrite crops out only inside the caldera depression	White pumices are trachydacitic, while the grey ones are dacitic.	This ignimbrite represents the last event caldera-forming partially filling the paleo-depression formed during the previous caldera collapses. It was deposited in subaqueous environment and affected locally by hydrothermal circulation. Age: 0.96 ± 0.21 Ma.
Aguajito ignimbrite	13	Not welded, light-brown pyroclastic deposit with white pumice and loose crystals of pl at the bottom, overlain by light-pink to light-purple, lithic-rich ignimbrite. Welded at top, with brown fiammes, lithics (granite, lavas), ash-rich matrix, and loose crystals of pl, amph and px. The total thickness is up to 40 m.	This ignimbrite, belonging from the Aguajito Volcanic Complex, crops out only along the western sector outside La Refoma caldera depression.	Rhyolite	This ignimbrite represents one of the main volcanic events of the close Aguajito Volcanic Complex. Age: 1.17 ± 0.07 Ma (Schmitt et al., 2006).
Mesa El Yaqui formation	12	Blocky lava flow succession, dark-grey in colour, associated with few scoria layers. Aphyric to porphyritic lavas with phenocrysts of pl, ol, px and Fe-Ti oxides. The thickness varies from 3 to 20 m.	These lava flows cover most of the external slopes of the caldera depression, and locally also of its inner walls.	The lavas are basaltic-andesite in composition.	This formation represents an effusive period during the caldera-forming phase, when most of the caldera depression was already formed. Age: 1.18 ± 0.46 Ma.
La Reforma ignimbrite	11	Pyroclastic deposits consisting of basal welded, reddish bed overlain by various welded brownish to dark-grey deposits (Figure 5(b)). Welded deposits contain black fiamme pumice and accidental lithics (lavas). Loose crystals of pl and px occur in ashy matrix. The thickness is up to 40 m.	This formation crops out in limited areas inside the caldera depression and widely outside the caldera.	Rhyolite	This ignimbrite represents one of the main events caldera-forming and responsible of most present caldera morphology. Age: 1.29 ± 0.02 Ma.
Cerro La Reforma formation	10	Succession of thick lava flows (up to 10 m) associated with minor pyroclastic deposits (Figure 5(d)). The formation comprises also lava domes along caldera rims (in map n. 10a). Lavas are porphyritic with phenocrysts of pl, px and Fe-Ti oxides. Xenocrysts of qtz and sedimentary xenoliths are also present. The thickness is more than 400 m because the base is always not visible.	This formation crops out only in the central part of the caldera depression (resurgence block). The original depositional surface appears tilted to SE.	The lavas are dacitic in composition.	This formation represents the first lava flow filling of the caldera depression, later tilted during the resurgence. Age: 1.27 ± 0.02 Ma.
Los Balcones ignimbrite	9	Grey welded pyroclastic deposit made of light-grey pumice and dark grey fiamme, with abundant lithics (grey, black and white lavas) (Figures 4(c) and 5(a and b)). Abundant loose crystals of pl and minor px in greyish ash-rich matrix. The thickness is up to 30 m.	This ignimbrite crops out outside the caldera depression, mainly along deep valleys.	Rhyolite	This ignimbrite represents the first known event caldera-forming. Age: 1.35 ± 0.02 Ma.

(*Continued*)

Table 2. Continued.

Formation	Acronym	Description	Location	Geochemistry	Interpretation and notes
Pre-caldera phase					
Punta Candeleros formation	8	Hyaloclastites, pillow lavas and lava domes with columnar jointing (Figure 4(a and b)). Lava texture varies from aphyric to porphyritic with phenocrysts of pl and px.	This formation crops out widely in the NW and SE sectors of the caldera depression, both inside and outside.	Lava composition varies from basaltic-andesite to andesite with minor trachy-dacite.	The formation includes effusive episodes, mainly submarine, affecting the area immediately before the onset of the caldera phase. Age: 1.42 ± 0.05 Ma (pillow lavas); 1.36 ± 0.06 Ma (lava dome).
Contrabando formation	7	Stratified, light-yellow pyroclastic deposit made of white and grey pumices (Figure 4(a)). Loose crystals of pl and px occur in yellowish ash-rich matrix. The thickness is up to 15 m.	This formation crops out only in the SE area along the external slopes of the caldera depression.	ND	The formation represents one of the scattered explosive events affecting the area before the caldera phase. The source area is unknown due the scarce outcrops. Age: 1.47 ± 0.08 Ma.
Carrizo ignimbrite	(not mappable)	Red welded pyroclastic deposit containing yellow and grey pumices and abundant lithics (green or grey lavas and black scoriae) (Figures 4(c) and 5(a)). Abundant loose crystals of pl in reddish ash-rich matrix. The thickness is up to 10 m.	This ignimbrite crops out only in limited areas along deep valleys all around the caldera depression.	Rhyolite	The formation represents one of the scattered explosive events affecting the area before the caldera phase. The source area is unknown due the scarce outcrops. Due to the reduce thickness and few outcrops, this formation is not mappable at the present scale. Age: 1.89 ± 0.27 Ma.
Cueva Amarilla ignimbrite	6	Greenish grey pyroclastic deposit with white pumice at bottom and black scoriae at top (Figure 4(a and c)). Loose crystals of pl and px occur in greenish ash-rich matrix. The thickness is up to 30 m.	This ignimbrite crops out in the S and N sector along the external slopes of the caldera depression.	ND	The formation represents one of the scattered explosive events affecting the area before the caldera phase. The source area is unknown due the scarce outcrops. Age: 2.4 ± 1.5 Ma.
Mesa de Enmedio ignimbrite	5	Light-grey pyroclastic deposit made of pumices (10–50 cm long). Loose crystals of pl and px occur in yellow ashy matrix. The thickness is up to 5 m.	This formation crops out only close to the Punta Arena	ND	The formation represents one of the scattered explosive events affecting the area before the caldera phase. The source area is unknown due the scarce outcrops.
Sedimentary Formation of the Santa Rosalia basin	4	Siltstones, sandstones and isolated conglomerates (Figure 4(c)) with interlayered several volcanic deposits (ignimbrites, pillow lavas, hyaloclastites, and reworked volcanics, see # 5, 6, 7, and 8). Brownish siltstones (up to 30 m thick) at base, overlain by fossiliferous sandstones and conglomerates (5–20 m thick). Fossils mainly consist of bivalves (*Pectinidae*) and well-preserved oysters and sea urchins.	This formation crops out mainly along the coast and deep valleys south of the caldera depression. Inside the caldera, it crops out in the resurgent block and locally at the base of the caldera inner walls.		This formation, known also as *Formación sedimentaria de la cuenca de Santa Rosalia*, Auct. (Ortlieb & Colleta, 1984; Wilson, 1948), represents the marine sedimentation, during which coeval scattered volcanic activities happened. The Santa Rosalia basin is a tectonic depression due to the opening of the California Gulf. Age: Pliocene-Middle Pleistocene (Ortlieb & Colleta, 1984).
Sedimentary and igneous basement					
Santa Lucia formation	3	Lava flows and domes, associated with dikes. Lavas with aphyric to porphyritic texture and phenocrysts of pl and px and amph. The formation, interlayered with the Comondú Group (see n. 2), is up to 80 m thick.	This formation crops out only in the south margin of the map.	Lavas are andesitic to basaltic in composition.	Andesite-dominated arc lava suites erupted when the Gulf region was affected by oblique-subduction of the Farallon-Guadalupe plate under the North America plate along the western margin of Baja California (Conly et al., 2005). Age: 19.25 ± 0.08 Ma.
Comondú Group	2	Red sandstones, siltstones and conglomerates interlayered with lavas (Santa Lucia Formation, see n. 3) (Figure 3(b)). The thickness is up to 100 m, but the base is always not visible.	This group crops out only in the south margin of the map and some deep valleys.		Volcanic and sedimentary unit deposited in an arc-forearc context linked to the Farallon-Guadalupe and North America plates subduction, possibly extending through the Gulf early rifting phases (Ferrari et al., 2013, 2018; Umhoefer et al., 2001). Age: 30–12 Ma (Umhoefer et al., 2001).
Plutonic rocks	1	Several crystalline intrusive bodies (Figure 3(a)). Holocrystalline rock with 3–4 mm sized phenocrysts of Kfs, pl, qz, amph and bio. Some associated aplitic dikes are present. The thickness is variable (from 8 to more than 50 m) and the base is always not visible.	These rocks crop out inside the caldera depression (western margin of the resurgent block) and outside along Yaqui canyon.	The intrusive rocks are granodioritic in composition.	Also known as *Batholites Peninsulares*, (Gastil, 1975; McLean, 1988; Schmidt, 1975) these rocks represent a voluminous batholith intruded into the Early Cretaceous supra-crustal volcanic and sedimentary sequence. Intrusions occur as small sheet and diapirs or as a combination of large nested intrusive centres and smaller isolated intrusions (Kimbrough et al., 2001). Age: 97.8 ± 1.5 Ma.

Table 3. Description of the lithosomes recognized inside the Cueva del Diablo formation (Post-caldera phase).

Lithosomatic unit	Acronym	Description	Interpretation and notes
Punta Prieta scoria cones	L6	Scoria cones associated with a thin lava flow (max. 5 m thick) extending eastward up to the sea. No evidences of marine terraces.	Small scoria cones that produced limited lava flows cropping out in the eastern sector of La Reforma Caldera. These represent the most recent volcanic event of La Reforma caldera complex. Age: 0.28 ± 0.05 Ma.
Cerro Colorado scoria cone	L5	Low-volume products aligned pit craters and scoria cones, except for the easternmost lava flow that extends up to the coastline. No evidences of marine terraces. The easternmost lava flow field is a complex 'aa' morphology with superimposed flows reaching a maximum thickness of 50 m.	NE-SW striking aligned pit craters and scoria cones, cropping out outside the caldera depression (south). The easternmost cone is associated with a large lava flow extending up to the coastline. Age: 0.46 ± 0.08 Ma.
Punta El Gato stratocone	L4	Scoria cone associated with a short lava flow. The lava flow surface is smoothed by erosion. Lava flow thickness is up to 10 m.	Short lava flow cropping out outside the caldera depression (north).
Punta Gorda stratocone	L3	Eroded scoria cone associated with a lava flow extending up to the coastline. The lava flow surface is smoothed by erosion. Lava flow thickness is up to 10 m. No evidences of marine terraces.	Lava flow cropping out outside the caldera depression (north) and extending up to the coastline.
Morro de las Palmas dome	L2	Small-volume rhyolitic domes cropping out along the northern side of La Palma river. Presence of thick lava flows, with a maximum thickness of 40 m.	Rhyolitic domes cropping out outside the caldera depression (north) forming a small dome field.
Las Minitas dome	L1	Domes associated with thick (more than 20 m) tabular lava flows displaying columnar joints.	Thick tabular lava flows and domes covering the Punta Arena Ignimbrite and cropping out inside the caldera depression (north).

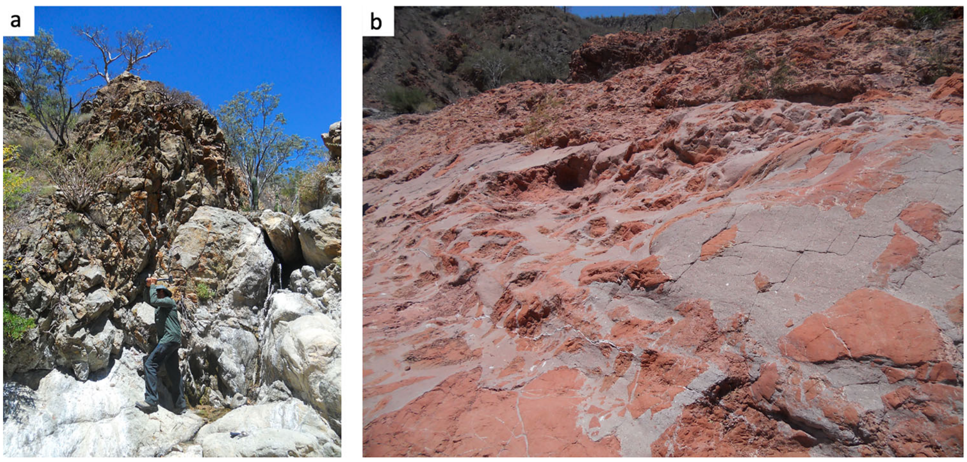

Figure 3. View of representative outcrops from the sedimentary and igneous basement of La Reforma caldera complex. (a) Granitoid basement from central part of La Reforma caldera complex; (b) Reddish fluvial conglomerate (Comondú Group).

lithostratigraphic units, fundamental to understand the volcanic succession and the evolution of the caldera complex, and (3) a 3D view of the mapped area reporting a simplified geology in order to visualize the relationships between morphology of the caldera complex, resurgence phenomena and the volcanological evolution.

3. Evolution of La Reforma caldera complex

The geological map (Figure 2) highlights how La Reforma caldera complex developed over a basement made of igneous (granitoids) rocks (Peninsular Ranges Batholith, Gastil, 1975), volcaniclastic and sedimentary rocks (Comondú Group, Bryan et al., 2014; Hausback, 1984; López, García, & Arellano, 1995; Sawlan, 1991; Sawlan & Smith, 1984; Umhoefer et al., 2001) with interbedded lava flow, ignimbrites, and domes (Santa Lucia formation, Garduño-Monroy et al., 1993).

The pre-caldera volcanic activity developed in a shallow water, marine basin, as suggested by the occurrence of siltstones and fossiliferous sandstones (Sedimentary Formation of the Santa Rosalia basin) interbedded with volcanic units. The pre-caldera activity is characterized by both explosive and effusive eruptions, with emplacement of pyroclastic density currents (PDCs; Mesa de Enmedio and Cueva Amarilla ignimbrites), volcaniclastics (Contrabando formation), pillow lavas and domes (Punta Candeleros formation). Only one subaerial ignimbrite is exposed at El Carrizo canyon, SW of the caldera rim (Carrizo ignimbrite). The pre-caldera activity probably built up a stratovolcano, whose remnants are today exposed on the SE and NE parts of the caldera complex, and along the sea cliffs in the Punta Gorda area.

The onset of La Reforma caldera started with the eruption of Los Balcones ignimbrite, nowadays not

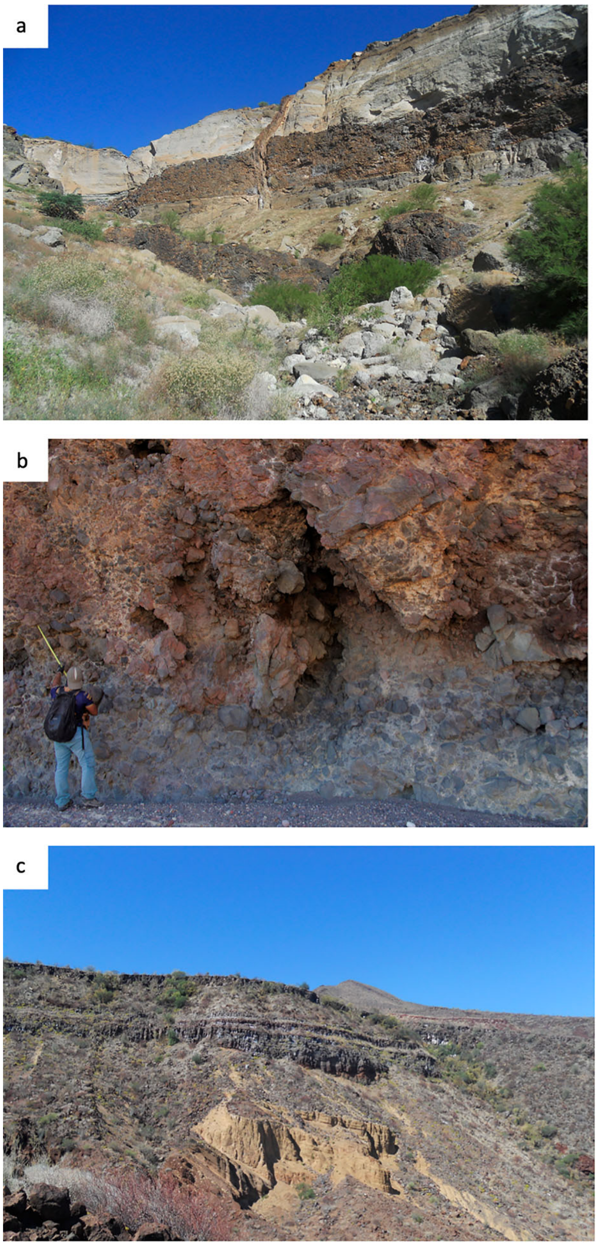

Figure 4. View of representative outcrops from the pre-caldera phase of La Reforma caldera complex. (a) Cueva Amarilla ignimbrite, Contrabando formation and Punta Candeleros formation from the Canada La Cueva Amarilla area; (b) Massive hyaloclastitic lava (≤7 m) composed of grey to red angular blocks supported by a matrix of altered yellow glass. (c) from bottom to top Sedimentary Formation of the Santa Rosalia Basin, Cueva Amarilla ignimbrite, Carrizo ignimbrite and Los Balcones ignimbrite topped by post-caldera lava flows (Cueva del Diablo formation) (Punta el Gato area).

exposed within the caldera, but only visible in the Arroyo Grande and El Carrizo canyons, to the SW of the caldera rim, and La Palma canyon to the north. The caldera depression was filled by lava flows alternating with scoriae, with a thickness of more than 400 m (Cerro La Reforma formation). La Reforma ignimbrite marks the second caldera-forming eruption, which enlarged the initial caldera depression. The deposits of La Reforma ignimbrite are extensively exposed outside the caldera rims to the S and SW, whereas they crop out sporadically within the caldera in the northern, eastern and southern parts. The eruptive activity resumed with the emplacement of widespread, thin lava flows, probably erupted along fissures parallel to the caldera-forming ring faults, and composing the Mesa El Yaqui formation. The geographical distribution of these lava flows (bordering almost all the caldera rims), suggests they were accompanied by resurgence of the central block of the caldera, which prevented most of the intrusion of feeding dykes within the caldera depression. After the emplacement of Mesa El Yaqui formation, La Reforma stratigraphic succession is characterized by the occurrence of Aguajito ignimbrite, likely deriving from the nearby Aguajito volcanic complex (Garduño-Monroy et al., 1993; Schmitt et al., 2006). The Aguajto ignimbrite deposits are well exposed to the west, but they have been never reported within La Reforma caldera. The Punta Arena ignimbrite is the last eruption of the caldera phase, and it extensively crops out only within the caldera, where it fills up topographic depressions with thickness of up to 200 m. Thin horizontal stratification and the occurrence of marine shells within the deposits testify for the subaqueous deposition of this formation.

The Cueva del Diablo formation contains the post-caldera deposits (Table 3), dominated by the evidence of effusive activity along the ring faults and faults bordering the central resurgent block (Las Minitas dome, Morro de las Palmas dome, Punta Gorda stratocone, Punta El Gato stratocone, Punta Prieta scoria cones). Only a few eruptive centres occur outside the caldera rims, and are located along NE-SW tectonic alignments (Cerro Colorado scoria cone). It is during this phase that the resurgence culminated to the present-day status, with the exposure of the plutonic rocks of the Peninsular Ranges Batholith in the SW part of the resurgent block. The uplift of the central part of the resurgent block determined the closure of the drainages to the E, with the formation of a small sedimentary basin in the western part of the caldera. This morphological barrier was likely responsible for the deposition of the volcaniclastic sediments of the Arroyo Grande member.

The magmatic driven resurgence of the central block of the caldera was accompanied by a regional uplift of the entire complex, in the order of more than 100 m, as testified by several marine terraces visible on the marine cliffs to the east (Figure 7). This regional uplift has been also responsible of the emersion of the whole caldera complex, as it is visible today.

4. Conclusions

The new geological map of La Reforma caldera complex represents an accurate and updated basis for understanding the geological evolution of this part of

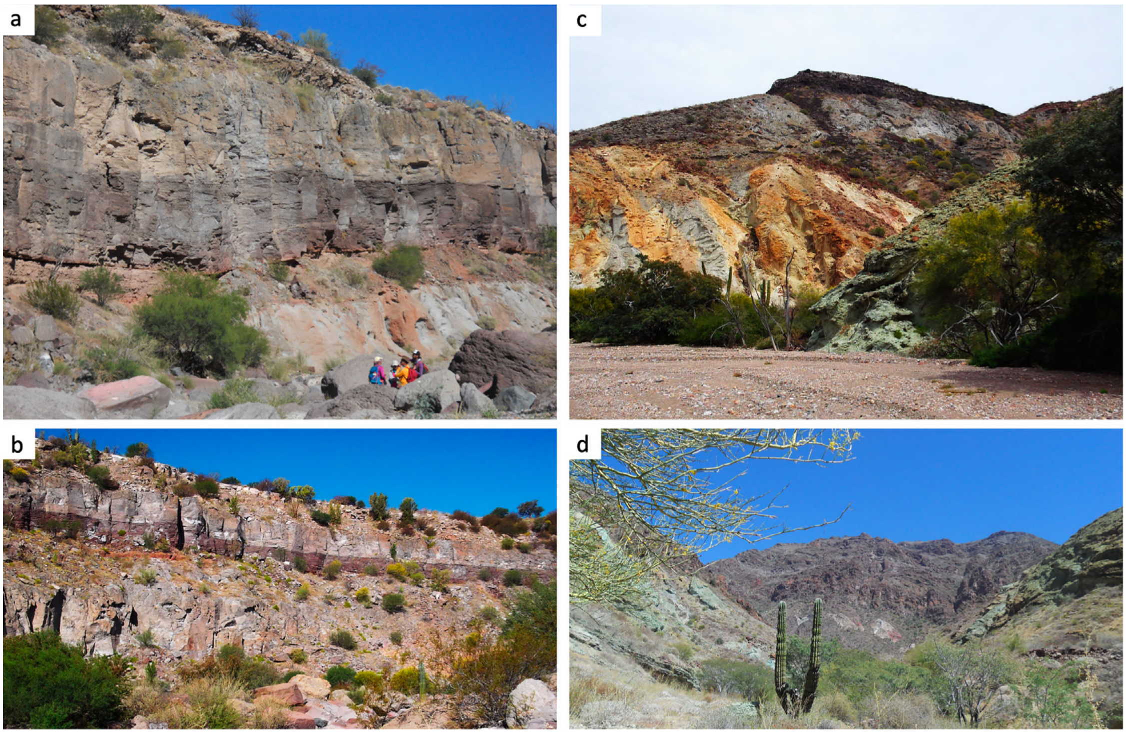

Figure 5. View of representative outcrops from the caldera phase of La Reforma caldera complex. (a) Los Balcones greyish ignimbrite on top of the Carrizo reddish ignimbrite in the Yaqui canyon area; (b) La Reforma ignimbrite (grey and red basal facies) on top of the Los Balcones ignimbrite; (c) Punta Arena ignimbrite, locally displaying yellowish and greenish hydrothermal alteration topped by post-caldera lava flows in the Cerro La Cueva del Diablo area; (d) View of Cerro La Reforma formation.

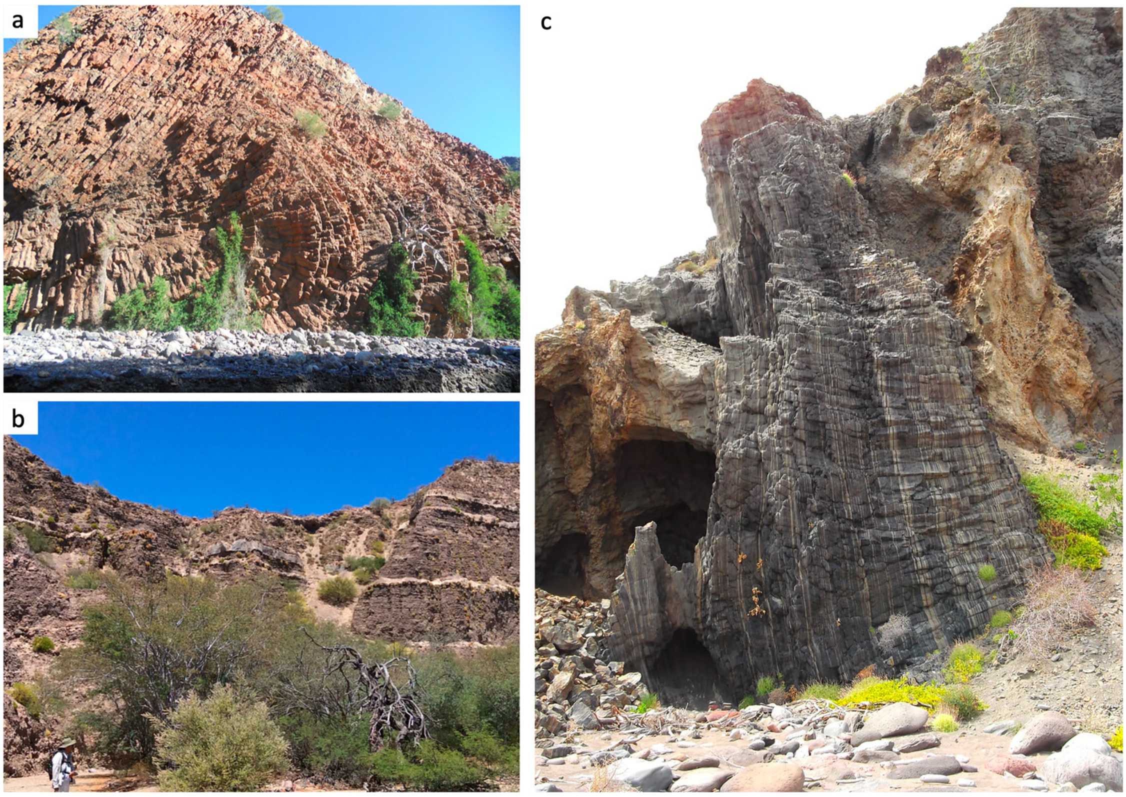

Figure 6. View of representative outcrops from the post-caldera phase of La Reforma caldera complex. (a) Intrusion with cooling joints from the Cueva Del Diablo formation; (b) View of the Arroyo Grande member in the Arroyo Grande canyon area; (c) Layered intrusion.

Figure 7. View of representative outcrops displaying Quaternary morphologies of La Reforma caldera complex. (a) Several orders of marine terraces along the coast (Punta El Contrabando and Punta Candeleros); (b) Marine terraces along the northern coast (Punta El Gato).

Baja California (Figure 2). The map has relevance for the comprehension of the Pleistocene volcanism in the area as it provides new insights into the inception of volcanism in this part of the peninsula. The content of the map includes a new stratigraphic reconstruction of La Reforma pre-caldera, syn-caldera, and post-caldera activity and their timing. This information will provide support to understand the evolution of the Santa Rosalia Basin and the interaction between marine sedimentation and submarine and subaerial volcanism. The geological map of La Reforma caldera complex also represents an invaluable contribution towards the knowledge of the territory and the exploitation of natural resources.

Software

Geological boundaries, structural features and polygons were digitized from field paper maps using ArcGIS ESRI (10.2.1 for Desktop, 10.2.1.3497 version), often with the aid of Google Earth Pro. The regional setting scheme (on the upper left corner of the map page) was constructed and edited by using CorelDraw X6. The 3D scene (on the bottom of the map page) was edited using ArcScene (ArcGIS 10.2.1). The map was produced by using ArcGIS ESRI and the final editing page was performed in Adobe Illustrator 6.0.

Acknowledgements

This study was funded by Grant 207032 of the Centro Mexicano de Innovación en Energía Geotérmica (CeMIE Geo) projects P15 to J.L. Macías. *Italgas S.p.a.* funds issued by CNR-IDPA (Milan) sponsored C. Pellicioli in her PhD research activity. We thank F. Mendiola for her technical support during the laboratory analyses of this study, and V.H. Garduño, A. Jiménez, H. Cepeda, and P. Pacheco for their observations during fieldwork in Baja. All field campaigns were made possible thanks to the kind assistance of UMA and Ecoturismo Borrego Cimarrón, Bonfil, B.C.S personnel guides, especially of F. Romero (El Borrego). Thanks for the comments made by reviewers (H. Apps, G. Giordano and M. Sacchi) and by the associated editor (A. Merschat) to the map and manuscript.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by CeMIE Geo [grant number 207032]; Consiglio Nazionale delle Ricerche - Italgas [grant number CIG 648306172D].

ORCID

J.L. Macías http://orcid.org/0000-0002-2494-9849
G. Groppelli http://orcid.org/0000-0003-4660-2288

References

Avellán, D. R., Macías, J. L., Arce, J. L., Jiménez-Haro, A., Saucedo-Girón, R., Garduño-Monroy, V. H., & Layer, P. W. (2018). Eruptive chronology and tectonic context of the late Pleistocene Tres Vírgenes volcanic complex, Baja California Sur (México). *Journal of Volcanology and Geothermal Research*. doi:10.1016/j.jvolgeores.2018.06.012

Bryan, S. E., Orozco-Esquivel, T., Ferrari, L., & Lopez-Martinez, M. (2014). Pulling apart the mid to late Cenozoic magmatic record of the Gulf of California: Is there a Comondú arc? *Geological Society, London, Special Publications*, *385*(1), 389–407.

Capra, L., Macıas, J. L., Espındola, J. M., & Siebe, C. (1998). Holocene plinian eruption of La Virgen volcano, Baja California, Mexico. *Journal of Volcanology and Geothermal Research*, *80*(3), 239–266.

Conly, A. G., Brenan, J. M., Bellon, H., & Scott, S. D. (2005). Arc to rift transitional volcanism in the Santa Rosalia region, Baja California Sur, Mexico. *Journal of Volcanology and Geothermal Research*, *142*(3), 303–341.

Demant, A. (1984). The Reforma caldera, Santa Rosalia area, Baja California. A volcanical, petrographical and mineralogical study. In V. Malpica-Cruz, S. Celis-Gutierrez, J. Guerrero-García, & L. Ortilieb (Eds.), *Neotectonics and sea level variations in the Gulf of California area, Symposium (Hermosillo, Son. April)* (pp. 21–23).

Demant, A., & Ortlieb, L. (1981). Plio-Pleistocene volcano-tectonic evolution of la Reforma caldera, Baja California, Mexico. *Tectonophysics*, *71*, p. 194.

Ferrari, L., López-Martínez, M., Orozco-Esquivel, T., Bryan, S. E., Duque-Trujillo, J., Lonsdale, P., & Solari, L. (2013). Late Oligocene to Middle Miocene rifting and synextensional magmatism in the southwestern Sierra Madre Occidental, Mexico: The beginning of the Gulf of California rift. *Geosphere*, *9*(5), 1161–1200.

Ferrari, L., Orozco-Esquivel, T., Bryan, S. E., López-Martínez, M., & Silva-Fragoso, A. (2018). Cenozoic magmatism and extension in western Mexico: Linking the Sierra Madre Occidental silicic large igneous province and the Comondú Group with the Gulf of California rift. *Earth-Science Reviews*, *183*, 115–152.

García-Sánchez, L. (2019). *Origen y evolución de la Caldera de La Reforma, Baja California Sur: Estudio vulcanológico, petrológico, geoquímico e isotópico* (UNAM, Ph Dissertation).

Garduño-Monroy, V. H., Vargas-Ledezma, H., & Campos-Enriquez, J. O. (1993). Preliminary geologic studies of Sierra El aguajito (Baja California, Mexico): A resurgent-type caldera. *Journal of Volcanology and Geothermal Research*, *59*, 47–58.

Gastil, R. G. (1975). Reconnaissance geology of the state of Baja California. The Geological Society of America, Inc. *Memoir*, *40*, 139–143.

Groppelli, G., & Martì-Molist, J. (2013). Volcanic stratigraphy-state of the art. *Ciências da Terra/Earth Sciences Journal*, *18*, 99–104.

Groppelli, G., & Viereck-Goette, L. (2010). Introduction. In G. Groppelli & L. Viereck-Goette (Eds.), *Stratigraphy and geology of volcanic areas* (Vol. 464, pp. V–VII). Boulder, CO: Geological Society of America.

Hausback, B. P. (1984). Cenozoic volcanic and tectonic evolution of Baja California Sur, Mexico. In V. A. Frizzel Jr. (Ed.), *Geology of the Baja California Peninsula* (pp. 219–236). SEPM Pacific Section, Special Publication 39.

Kimbrough, D. L., Smith, D. P., Mahoney, J. B., Moore, T. E., Grove, M., Gastil, R. G., … Fanning, C. M. (2001). Forearc-basin sedimentary response to rapid Late Cretaceous batholith emplacement in the Peninsular Ranges of southern and Baja California. *Geology*, *29*(6), 491–494. doi:10.1130/0091-7613(2001)029<0491:FBSRTR>2.0.CO;2

Lira, H. H., Ramirez, S. G., Herrera, F. J. J., & Vargas, H. (1983). Estudio geologico a semidetalle de la zona geotérmica de las Tres Vírgenes, B.C.S., Intern. Rep. 30/83, Gerencia de Proyectos Geotermoelectricos-CFE (Mexico).

Lira, H. H., González, M. L., & Arellano, F. G. (1997). Actualización del modelo conceptual del Campo Geotérmico de Tres Vírgenes, Baja California Sur. Technical Report, RE-12/97, Gerencia de Proyectos Geotermoeléctricos, Comisión Federal de Electricidad, 26.

López, H. A., García, G. H., & Arellano, F. G. (1995). *Geothermal exploration at Las Tres Vírgenes, BCS, Mexico*. Proceedings of the World Geothermal Congress (pp. 707–712).

Macías, J. L., Arce, J. L., Garduño, V. H., Avellán, D. R., García, L., Reyes, G., … Navarrete, J. A. (2012). Estudio de estratigrafía y geología del Complejo Volcánico Tres Vírgenes. [Informe Final DEX-DGL-TV-17-11]. *Comisión Federal de Electricidad*, 104 pp.

Martí, J., Groppelli, G., & da Silveira, A. B. (2018). Volcanic stratigraphy: A review. *Journal of Volcanology and Geothermal Research*, *357*, 68–91.

McLean, H. (1988). *Reconnaissance geologic map of the Loreto and part of the San Javier quadrangles, Baja California Sur, Mexico*. U.S. Geological Survey Miscellaneous Field Studies Map, Report No. MF-2000 (p. 10), 1 mapa, escala 1:50,000.

Ortlieb, L. (1978). Reconocimiento de las terrazas marinas cuaternarias en la parte central de Baja California. *Universidad Nacional Autónoma de México. Instituto de Geología*, *2*(2), 200–211.

Ortlieb, L., & Colleta, B. (1984). Síntesis cronoestratigráfica sobre el Neogeno y el Cuaternario marino de la cuenca de Santa Rosalía, Baja Clifornia Sur. In V. Malpica-Cruz, S. Celiz-Gutiérrez, J. Guerrero-García, & L. Ortlieb (Eds.), *Neotectonics a sea level variations in the Gulf of California area, a symposium (Hermosillo, Son., April 21–23)* (pp. 241–268). México, DF: Universidad Nacional Autónoma de México, Instituto de Geología.

Pasquarè, G., Abate, E., Castiglioni, G. B., Merenda, M., Mutti, E., Ortolani, F., … Sassi, F. P. (1992). *Carta geologica d'Italia 1:50.000 Guida al Rilevamento*. Quaderni serie III (Vol. 1, p. 203).

Salvador, A. (1994). *International stratigraphic guide: A guide to stratigraphic classification, terminology, and procedure (No. 30)*. Boulder, CO: Geological Society of America.

Sawlan, M. G. (1991). Magmatic evolution of the Gulf of California rift. In J. P. Dauphin & B. R. Simoneit.

Sawlan, M. G., Ortlieb, L., & Roldan, O. (1981). *Late Cenozoic volcanism in the Tres Vírgenes area*. Proceedings of the Geology of Northwestern Mexico and Southern Arizona Congress (pp. 309–319), Universidad Nacional Autónoma de México, Hermosillo, Sonora, México.

Sawlan, M. G., & Smith, J. G. (1984). *Petrologic characteristics, age and tectonic setting of Neogene volcanic rocks in northern Baja California Sur, Mexico*.

Schmidt, E. K. (1975). *Plate tectonics, volcanic petrology, and ore formation in the Santa Rosalía area, Baja California*. Mexico: The University of Arizona.

Schmitt, A. K., Stockli, D. F., & Hausback, B. P. (2006). Eruption and magma crystallization ages of Las Tres Vírgenes (Baja California) constrained by combined

230Th/238U and (U-Th)/He dating of zircon. *Journal of Volcanology and Geothermal Research*, *158*, 281–295. doi:10.1016/j.jvolgeores.2006.07.005

Schmitt, A. K., Stockli, D. F., Niedermann, S., Lovera, O. M., & Hausback, B. P. (2010). Eruption ages of Las Tres Vírgenes volcano (Baja California): A tale of two helium isotopes. *Quaternary Geochronology*, *5*(5), 503–511.

Umhoefer, P. J., Dorsey, R. J., Willsey, S., Mayer, L., & Renne, P. (2001). Stratigraphy and geochronology of the Comondu Group near Loreto, Baja California Sur, Mexico. *Sedimentary Geology*, *144*(1–2), 125–147.

Wheeler, H. E., & Mallory, V. S. (1953). Designation of stratigraphic units. *AAPG Bulletin*, *37*(10), 2407–2421.

Wilson, I. F. (1948). Buried topography, initial structures, and sedimentation in Santa Rosalia area, Baja California, Mexico. *American Association of Petroleum Geologists Bulletin*, *32*, 1762–1807.

Wilson, I. F., & Rocha, V. S., (1955). Geology and mineral deposits of the Boleo copper district, Baja California, Mexico. Geological Survey Special Paper, 273. Washington, DC: U.S. Government Publishing Office, 140 pp.