Estimating the depth and evolution of intrusions at resurgent calderas: Los Humeros (Mexico)

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Abstract. Resurgent calderas represent a target with high potential for geothermal exploration, as they are associated with the shallow emplacement of magma, resulting in a widespread and long lasting hydrothermal activity. Therefore, evaluating the thermal potential of resurgent calderas may provide important insights for geothermal exploitation. Resurgence is classically attributed to the uplift of a block or dome resulting from the inflation of the collapse-forming magma chamber due to the intrusion of new magma. The Los Humeros volcanic complex (LHVC; Mexico), consisting of two nested calderas (the outer Los Humeros and the inner, resurgent, Los Potreros), represents an area of high interest for geothermal exploration to optimize the current exploitation of the active geothermal field. Here we aim at better define the characteristics of the resurgence in Los Potreros, by integrating field work with analogue models, evaluating the spatio-temporal evolution of the deformation and the depth and extent of the intrusions responsible for the resurgence and which may represent also the local heat source(s).

Structural field analysis and geological mapping show that Los Potreros area is characterized by several lava domes and cryptodomes (with normal faulting at the top) that suggest multiple deformation sources localized in narrow areas. The analogue experiments simulate the deformation pattern observed in the field, consisting of magma intrusions pushing a domed area with apical graben. To define the possible depth of the intrusion responsible for the observed surface deformations, we apply established relations to our experiments. These relations suggest that the magmatic source responsible for the deformation is present at very shallow depths (hundreds of meters) which is in agreement with the well data and field observations. We therefore propose that the recent deformation at LHVC is not a classical resurgence associated with the bulk inflation of a deep magma reservoir; rather this is related to the ascent of shallow (<1 km) multiple magma bodies. A similar multiple source model of the subsurface structure has been also proposed for other calderas with an active geothermal system (Usu volcano, Japan) suggesting that the model proposed may have a wider applicability.

1 Introduction

Caldera resurgence consists of the uplift of part of the caldera floor. It is attributed to the emplacement of silicic magma at different depth levels under limited viscosity contrasts with regard to the previously emplaced magma (Marsh, 1984; Galetto et al., 2017). Resurgence is often associated with hydrothermal and ore forming processes, since the circulation pattern and temperature gradients of geothermal fluids are structurally-controlled by the space-time distribution of faults and fractures and by the depth and shape of the magmatic sources (e.g. Guillou Frottier et al., 2000; Printecoff et al., 2003; Stix et al., 2003; Mueller et al., 2009). Therefore, the characterisation of the magma that drives resurgence (location, depth and size) and of the factors controlling the release of the heat (permeability, fracture patterns, and fluid flow) have important implications for the exploration and exploitation of renewable geothermal energy resources. In particular, the
estimation of the location, depth and geometry of the magmatic sources is crucial to define the possible geothermal and mineral potential of resurgent calderas, allowing an economically sustainable exploration and exploitation of their natural resources.

On this regard, the intrusion of magma at different crustal depths has been proposed as the driving mechanism for resurgence in many calderas worldwide (Lindsay et al., 2001; Metrich et al., 2011; Kennedy et al., 2012, 2016; Lipman et al., 2015; Brothelander et al., 2016). These cases may show different uplift styles (resurgent blocks or domes, Accella et al., 2001) and rates (from mm to cm per year), depending on the depth, volume and size of the magmatic sources, but they share a common feature that is a coherent uplift of a significant part of the caldera floor.

This scenario is different from the occurrence of deformation patterns characterized by the widespread and delocalized uplift of several minor portions of the caldera floor, due to lava domes and/or cryptodomes, as for example observed at Usu volcano (Japan, Matsumoto and Nakagawa, 2010; Tsona et al., 2010). A different depth and extent of the responsible source(s) and, consequently, a different subsurface structure of the volcano is therefore suggested. A better assessment of the subsurface structure in such cases has crucial implications for geothermal exploration, in order to maximize the geothermal production.

In this regard, the Los Humeros Volcanic Complex (LHVC, Mexico) is an important geothermal target area, consisting of two nested calderas with resurgence within the innermost one (Los Potreros caldera), commonly interpreted as due to the uplift of a resurgence due to the inflation of a deep (several km) magma chamber (Fig. 1a, Norini et al., 2015).

The purpose of this work is to evaluate the depth to the intrusion(s) responsible for the uplift, also explaining the spatio-temporal evolution of the observed deformation of the caldera floor. To achieve this goal, we integrate results from structural field investigations carried out within the Los Potreros caldera with those derived from analogue experiments specifically designed to constrain the depth of the deformation source(s) in volcanic caldera environments. Results document discontinuous and small-scale (< 1 km) surface deformations generated from multiple and shallow (< 1 km) magmatic bodies. These results should be taken into account for planning the future geothermal operations at the LHVC and in other calderas showing similar surface deformation.

2 Geological-structural setting

LHVC is located at the eastern termination of the Trans Mexican Volcanic Belt (TMVB, see inset in Fig. 1a). The TMVB is the largest Neogene volcanic arc in Mexico (~1000 km long and up to ~300 km wide), resulting from the Cenozoic subduction of the Cocos and Rivera plates beneath the North American plate along the Middle American trench (Ferrari et al., 2012, and references therein). The LHVC consists of two nested calderas formed during the Pleistocene: the outer 18 x 16 km Los Humeros caldera and the inner 10 x 8 km Los Potreros caldera (Fig. 1a, Ferriz and Mahood, 1984; Norini et al., 2015; Carrasco-Núñez et al., 2017b).

Based on updated stratigraphic and geochronological information, the evolution of the LHVC can be divided into three main stages (Carrasco-Núñez et al., 2017b, 2018). Pre-caldera volcanism extended between ca. 700 and 164 ka (based on U-Th and 39Ar/40Ar datings: Carrasco-Núñez et al., 2018), showing evidence for an extended building phase leading to the establishment of the large volume rhyolitic reservoir that fed the 115 km³ caldera-forming Xaltipan ignimbrite eruption. The Caldera stage started at ca. 164 ka with the collapse of the Los Humeros caldera and ended with the eruption of the 15 km³ Zaragoza rhyodacite-andesite ignimbrite at 69 ka, associated with the collapse of the nested Los Potreros caldera. A post-caldera stage (< 69 ka) is interpreted by Carrasco-Núñez et al. (2018) as the reoccupation of the post-caldera stage (< 69 ka) as a Pleistocene resurgence phase, followed by the Holocene activity characterized by intra-caldera basaltic to rhyolitic monogenetic volcanism. This hypothesis discards a
configuration of the magmatic plumbing system characterized by a unique, large and homogenized magma reservoir as inferred for the Los Humeros activity during the Caldera stage (e.g. Ferriz and Mohood, 1984; Verma, 1985) in favour of a heterogeneous multi-layered system vertically distributed in the crust, with a deep (ca. 30 km) basaltic reservoir feeding progressively shallower and smaller distinct stagnation layers, pockets and bunches up to very shallow conditions (1 kb, ca. 3 cm) (Lucci et al., under review).

In particular, during the early resurgence phase of the Post-caldera stage, rhyolitic domes were emplaced along the northern rim of the Los Humeros caldera, followed by the placement of less evolved lavas of trachyanidesitic-trachytic composition (Carrasco-Núñez et al., 2017b). The Holocene ring-fracture and bimodal magmatism is characterized by both explosive and effusive activity, producing several lava flows and domes, as well as periods of dominant explosive activity (e.g. the ca. 7 ka Cuicuilco Member, Dávila-Harris and Carrasco-Núñez, 2014) from multiple vents located mostly along both the inner and outer caldera ring faults. During this phase, less evolved lavas erupted (from trachyanidesite to basalt) within and outside Los Humeros caldera, one of which corresponds to an olivine-bearing basaltic lava associated with the formation of the Xalapanco crater (Fig. 1a). Trachytic lava flows are the most recent activity recorded by LHVC at ca. 2.8 ky (Carrasco-Núñez et al., 2017b).

The reconstruction of the shallow stratigraphy in Los Potreros is chiefly derived from information derived from the available well logs (Figs. 1b-c Carrasco-Núñez et al., 2017a, b). Overall, the post-caldera units are lithologically dominated by lava flows resting on andesitic ignimbrite deposits emplaced during caldera stage. Ignimbrites of the caldera stage rest in turn on a thick sequence dominated by old andesite lavas dated at ca. 1.4-2.8 Ma (Carrasco-Núñez et al., 2017a). The subsurface geometry of the pre- and syn-caldera products is better elucidated in Fig. 1b and c, which show the in-depth geometry of the different magmatic products that are cross-correlated and projected along the N-S and E-W direction, respectively. The N-S projection shows a constant depth of the top surface of the pre-caldera andesites that is associated with a highly variable depth (up to 400 m) at the top surface of the syn-caldera Xalapamco ignimbrite. The W-E projection shows a high depth variability of both the top surface of the pre-caldera group (up to 500 m between H-19 and H-25 wells) and that of the Xalapamco ignimbrite (up to 400 m between H-19 and H-10 wells). Within this framework, a remarkable feature in the presence of both basaltic and rhyolitic-dacitic lavas located at various depths (Carrasco-Núñez et al., 2017a), in particular, the rhyolites-dacites are located mostly at the base (H-20 and H-26 wells) or within (H-05 well) the caldera group or within the old andesite sequence (H-25 and H-19 wells). On the other hand, the basalts are located at various depths only within the pre-caldera andesite sequence, both at its base (in contact with the limestone basement; H-5 and H-8 wells) and at its top (in contact with the base of the caldera sequence, H-10 well). Small bimodal lava products, showing an irregular lateral distribution, are interpreted as subaerial quasianteporos (Carrasco-Núñez et al., 2017a).

The structure of the LHVC is controlled by a network of active extensional fault systems consisting of NNW-SSE, N-S, NE-SW and E-W fault strands cutting across the Los Potreros caldera floor, in particular, the following main faults were recognised (Norini et al., 2015; Calcagno et al., 2018) (Fig. 1a): (i) Mazaltaya (NNW-SSE striking), (ii) Los Humeros and Loma Blanca (N-S striking), (iii) Arroyo Grande (NE-SW striking), (iv) Las Viñoraz and Las Papanas (E-W striking). Such active fault system is interpreted as due to the recent/active resurgence of the Los Potreros Caldera, since the faults do not show continuity beyond the caldera border, their scarps decrease in height towards the periphery of the caldera and the dip-slip displacement vectors show a semi-radial pattern (Norini et al., 2015).

The source of the areal uplift is inferred to be the inflation of a saucer or cup shaped deep magmatic source elongated NNW-SSE, upwarping a 8 x 4 km resurgence block, centred in the SE portion of the caldera, delimited to the W by the NNW-SSE main faults, and toward the north, east and south by the caldera rim (Fig. 1a, Norini et al., 2015).
The seismic activity in the period 1994-2017 is clustered along the Loma Blanca, Los Humeros and Arroyo Grande faults (Lermo et al., 2018; Fig. 1a). Most of the earthquakes show a magnitude (Mw) between 1 and 2.5, and have been mainly interpreted as induced by the geothermal exploitation activity (injection of fluids and hydrofracturing; Lermo et al., 2018). Also, four major earthquakes (Mw= 3.2, 3.6, 3.9 and 4.2, at a depth of 1, 4, 2.2 and 1.8 km, respectively) have been reported, with focal depths close to the trace of the active faults (Loma Blanca and Los Humeros, Fig. 1a). Such major earthquakes have been interpreted as triggered by fault reactivation due to fluid injection from geothermal wells (Lermo et al., 2018).

3 Methods

The scientific rationale adopted in this study is based on structural field work, combined with analogue models aimed to constrain the depth of the deformation sources in the caldera domain.

3.1 Structural field work

Structural field work was carried out to evaluate the surface deformation related to the recent activity of the Los Potros caldera, in order to constrain the morphotectonic fingerprints of the resurgence. The geometry and distribution of the observable faults and joints were defined at the outcrop scale by measuring their attitudes (strike and dip with the right-hand rule) and spacing. Fault kinematics was assessed through classical criteria on slickensides fault surfaces, such as Riedel shears and sheltering trails (Doblas, 1998). The geological-structural mapping of the studied area aims at reconstructing the relationships between the post-caldera volcanic products and the structural features at the surface to constrain the source and extent of the resurgence. The proposed interpretation is based on a published geological map (Carrasco-Núñez et al., 2017b) and geothermal well data has been also used.

3.2 Analogue models: experimental set-up and scaling

We performed three experiments simulating the ascent of a viscous intrusion in a brittle overburden to test existing relationships between the depth of intrusion and the observed surface deformation. The experimental set-up (Fig. 2) consists of a 31 × 31 cm glass box filled with a sand pack (crust analogue) of variable thickness (T, of 30 and 50 mm, respectively). In each experiment we imposed a layering using a non-cohesive marine sand below a layer of crushed silica sand (grain size = 40-200 μm, cohesion = 300 Pa), fixing the thickness ratio of the two layers (T1/T2) to 1, to simulate the stratigraphy in Los Potros (stiffer post caldera lava flows above softer and less cohesive ignimbrite deposits emplaced during the caldera collapse stage). At the base of the sand pack, a piston, controlled by a motor, pushes upward the silicone (magma analogue) placed inside a cylinder 8 cm in diameter. The injection rate is fixed for all the experiments to 2 mm/hr and each experiment was stopped at the onset of the silicone extrusion. Both sand and silicone physical properties are listed in Table 1.

At the end of each experiment, the surface has been covered with sand to preserve their final topography and were wetted with water for cutting in sections to appreciate the subsurface deformation. Such sections were used to measure the mean dip of the graben faults (θ) induced by the rising silicone. A digital camera monitored the top view deformation of each experiment at 0.02 fps and a laser scanner, placed next to the camera, provided high-resolution data (maximum error ± 0.5 mm) of the vertical displacement that was used to measure in detail the geometrical features of the deformation i.e. dome diameter (D), graben width (W) and dome flank mean dip (α). According to the Buckingham-II theorem (Merle and Borgia 1996 and references therein), our models need 7 independent dimensionless numbers to be properly scaled (i.e. 10 variables minus three dimensions). Such dimensionless numbers can be defined as the ratios (θ) listed in Table 4.
Table 2. Even if the values of $T_k$ differ by two orders of magnitude in nature and in the experiments ($1.8 \times 10^4$ and $6 \times 10^{10}$, respectively), they are both largely $<1$, indicating that the ratio is a negligible value in both cases.

4 Results

4.1 Local geology and structural data

The outcropping post-caldera lithologies within the Los Potreros Caldera consist of: (1) the Cuicuilco Member, which blankets most of the surface of the upper half of the studied area; (2) basaltic lava flows filling the Xalapasco crater and the NW portion of the caldera; and (3) trachyandesitic and trachytic lava domes and thick flows extending in the southern half of the caldera and rhyolitic domes in its central part (Fig. 3). The more evolved lavas form four elliptical domes, aligned N-S (Figs. 3, 4a): (i) a 2 km wide trachytic dome located to the west of the Mazteyza and Los Humeros faults, (ii) a 1 km wide trachyandesitic dome located at the northern tip of the Mazteyza fault, and (iii) two smaller (0.4 km x 0.2 km) rhyolitic domes at the southern tip of the Los Humeros fault (LH-11 in Fig. 3).

We identified three uplifted areas corresponding to the surface expression of the Loma Blanca, Arroyo Grande and Los Humeros faults (labeled 1-2, 9 and 10 respectively in Fig. 3). The observed structures in these uplifted areas (joints and faults) affect the deposits of the post-caldera phase. Based on field evidence, we also propose a revised interpretation of the surface structures identified by previous studies (Norris et al., 2015) distinguishing between lineaments (morphological linear features which are not associated with significant deformation and alteration at the outcrop scale), active and inactive faults, associated with active and fossil alteration respectively (Fig. 3).

We present below a description of the structures mapped in the studied area, highlighting their temporal and spatial relationships with the post-caldera geological formations. We identified two inactive faults (Mazteyza and Arroyo Grande), a morphological lineament (Las Papas) and two currently active faults (Los Humeros and Loma Blanca). The data number at each location is hereafter indicated with “n”.

4.1.1 Las Papas lineament (LH-07, LH-08)

The E-W trending Las Papas scarps (Fig. 4b) is located within the Cuicuilco Member. Such lithologies do not show any alteration or significant deformation (LH-07; Fig. 4c). We identified an erosional surface along the scarp, where unaltered and undeformed Cuicuilco rocks rest above a layered pyroclastic deposit (LH-08, Fig. 4d). The E-W trending morphological lineaments defined by the Las Papas scarps are probably due to differential erosion of the softer layers of the pyroclastic deposits, successively blanketed by the Cuicuilco Member.

4.1.2 Arroyo Grande (LH-09) and Mazteyza (LH-10)

The NE-SW Arroyo Grande scarp (Fig. 5a) exposed strongly altered and faulted (NW striking faults, mean attitude N144°/68°, n = 8) lavas and ignimbrites unconformably cover by the unaltered Cuicuilco Member (Fig. 5b). The throw observed at the outcrop-scale for the single fault strands is in the order of 0.5 m, with a dominant normal dip-slip kinematics ( slickenline pitch angle ranging from 99° to 106°). The inferred cumulative displacement at Arroyo Grande is 10 m. Similarly, an outcrop on the Mazteyza scarp (in front of well H-6) shows altered trachyandesites covered by unaltered Cuicuilco rocks (Fig. 5c).

4.1.3 Los Humeros (LH-10)

Dashes this have a name?
The fault scarp of the N-S striking (mean attitude N174°/73°, n = 8) Los Humeros Fault is defined by the altered portions of the Cuicuilco Member. Fault population analysis reveals a dominant normal dip-slip (mean pitch angle 84°, n = 8) kinematics, as documented by both Riedel shears and carbonate-quartz growth steps. The main fault plane is surmounted by a trachyandesitic extrusion (Fig. 5d), localised along an aligned N-S dome (LH-11 in Fig. 3). Moreover, ~150 m southward from the outcrop of the fault scarp, a 5 x 3 m trachyandesitic plug shows vertical striation on its surface due to a subsurface vertical flow of the trachyandesite (Fig. 5e). The observed displacement at the outcrop scale, as indicated by the height of the fault scarp, is ~10 m.

4.1.4 Loma Blanca (LH-01, LH-02)

The Loma Blanca fault system (LH-01 and LH-02) is located in correspondence of an active degassing area, where faults and fractures are frequent. The fault system localizes on top of an elongated crest (within a graben) of a morphological bulge, ~1 km in diameter and 30 m in height. At this location, the Cuicuilco Member and the underlying trachyandesite lavas are strongly altered. Evidence of stockwork veining and diffuse fracturing of the lavas suggests hydrofracturing and structurally controlled fluid flow and alteration. A set of NNE-SSW striking conjugate extensional faulting and jointing (joint spacing ~1 m; Fig. 5f) is observed. The faults (mean attitude N26°/71°) show a normal dip-slip kinematics (pitch ranging from 82° to 104°). Joint systems found in the Cuicuilco Member strike sub-parallel to the faults (mean attitude N37°/72°, n = 14). The inferred cumulative displacement of the faults, estimated by the depth of the apical graben, is ~5 m.

Summarizing, the 22 mapped faults in all the structural outcrops of the area show a main NNW-SSE strike (Fig. 5g) with a dominant dip slip movement (mean pitch angle of slickenlines 88°) which is sub-parallel to the N-S elongation of the lava domes and the Xalapaasco crater.

4.2 Experimental results

Here we show two representative experiments with increasing overburden thickness (experiments 5 and 6 with T = 30 and 50 mm respectively). Table 3 shows the measured parameters in the experiments. Overall, the experiments show a similar deformation pattern: a first stage characterized by the uplift of a sub-circular dome, bordered by inward dipping reverse faults, and a second stage characterized by the subsidence of the apical part of the dome where normal faulting occurs (carbon formation Fig. 6a-f). The reverse and normal faults are ring faults and are associated with the formation of radial fractures from the dome centre. Despite the T/D ratio, all the experiments show that both the dome diameter and graben width increase linearly with the overburden thickness (ranging from 105 to 164 mm and from 14 to 58 mm respectively, Table 3, Fig. 7). The dome diameter increases abruptly with time, becoming almost constant at an early stage of the experiment (Fig. 8a); the graben width shows a similar pattern even if it enlarges slightly with time (after the first abrupt increase) as the silicone rises towards the surface (Fig. 8b), suggesting that the intrusion depth has a higher influence on the graben width, in agreement with Berthelot and Merle (2015).

5 Discussion
The distribution of the alteration patterns and deformation characteristics of the post-caldera deposits can be used to infer the origin and extent of the uplift within the LIHVC. In particular, the involvement of the 7.4 ka Cuicuilco Member in the deformation and alteration likely constraining the spatio-temporal evolution of the surficial deformation and associated uplifts in Los Potreros—indeed, altered and undeformed deposits of the Cuicuilco Member crop out along the E-W Las Papas lineament and unconfornmably cover altered and faulted lavas and ignimbrites along the Arroyo Grande and Mazatlaya scarps. Alteration and deformation of the Cuicuilco Member occurs along the Los Humeros Fault scarps and within the apical graben of the Loma Blanca bulge. Moreover, the vertical striations of the trachyandesitic plug near the Los Humeros fault scarp suggest that the ascent of the plug induced the uplift, the normal dip-strike faulting and alteration of the Cuicuilco Member.

All these observations suggest that Los Potreros is not a classic resurgent caldera (i.e., a caldera characterised by a large-scale process localized in a single area) but is better characterised by a discontinuous uplift process in space and time, inducing small-scale deformations at each pulse (Fig. 9a-d). In particular, it was active in the south and north-eastern sector of the caldera, at Mazatlaya and Arroyo Grande (Fig. 9a), prior to the deposition of the Cuicuilco Member (~ 7.4 ka), and then moved towards N along the Los Humeros and Loma Blanca scarps during and post the eruption of the Cuicuilco (Fig. 9b-d). Concerning the source of deformation, the felsic lava found at the Los Humeros Fault scarp shows a similar mineral assemblage of the felsic domes located further south (Fig. 3), thus, the Los Humeros scarp may represent the final stage (i.e., effusive eruption of felsic magmas, Fig. 9c) of the uplift process, which is thus driven by the ascent of relatively narrow (hundreds of meters) and highly viscous felsic magma batches. This is also supported by the N-S elongation of the identified lava domes and Xalapasso crater which is sub-parallel to the orientation of the measured fault planes (NNW-SSE) indicating that the observed deformation is closely related to the post-caldera volcanism. The ascent of such magma bodies is inferred here to drive the recent uplift and deformation of the Loma Blanca bulge, as suggested by the active fumaroles and extensive alteration of both the Cuicuilco pyroclastics and post-caldera lavas (Fig. 9d). The presence of such shallow magma bodies is also suggested by the four major earthquakes recorded in Los Potreros, which have been previously interpreted to be induced by geothermal exploitation (Lemo et al., 2018). However, since the magnitude of the seismic events induced by geothermal exploitation activities is usually lower (i.e. < 3, Evans et al., 2012 and references therein), the higher magnitude (between 3.2 and 4.2) of the earthquakes in Los Potreros suggests that they may be more likely of volano-tectonic origin due to shallow magma emplacement.

In order to further support the above inference derived from interpretation of the field observations, analogue models were used to constrain the magma source depth from the geometrical parameters measured in the experiments (L, b, a, Table 3).

Since our results confirm that the graben width shows a linear correlation with the source depth (Fig. 7) as estimated in (Brotheland and Merle, 2015), we calculated the theoretical overburden thickness (i.e. the intrusion depth, Ti, Table 3) as follows:

\[ T_i = \frac{1}{2} t g \left( \frac{\sin(\theta + \phi)}{\cos \theta} \right) \]

Comparing the percentage difference between the imposed experimental (T) and theoretical (Ti) overburden thickness values, we calculate the associated error in the evaluation of the intrusion depth in the models (a, Table 3, Fig. 7). We then use equation 1 for the evaluation of the heat source depth at the Loma Blanca bulge considering σ = 40 % (maximum value of the experiments).

Considering that for the Loma Blanca bulge L = 286 m, θ = 71°, α = 45°, it follows that the estimated intrusion depth is 425 ± 170 m. Such relatively shallow depth is within the range of depths of phylilitic-dacitic domes drilled in geothermal
wells (spanning from 300 to 1700 m, Fig. 1b-c) and is consistent with the hypothesis that the uplift is driven by small and delocalized magmatic intrusions, as suggested by the field data.

Even if these rhyolite-dacites have been previously interpreted as subaerial origin (Carrasco-Núñez et al., 2017a), we suggest that such lavas can be reinterpreted as intrusion of felsic cryptodomes based on the following considerations: i) the occurrence of rhyolite-dacite lava bodies within the thick pre-caldera old andesite sequence is unusual and does not have a subaerial counterpart; ii) the intracaldera ignimbrite sequence does not level out the paleotopography; in facts the "topographic high" formed by the rhyolite body in well H-20 (Fig. 1c) persists during the post-caldera emplacement controlling the reduced thickness of lavas of the post caldera stage at that locality; iii) the high depth variation of the top of the Xaltipa ignimbrite not associated with an equal variation of the pre-caldera andesite (Fig. 1b) highlighting a local and discontinuous deformation and uplifting of the Xaltipa ignimbrite. These evidences can be more easily reconciled with the intrusion of felsic cryptodomes within the volcanic sequence, respect to a regular layer cake stratigraphy.

Summarizing, the combination of field and modelling data support that the uplift in Los Potreros is due to multiple deformation sources in narrow areas that do not represent resurgence sensu stricto. Such localized recent deformation within Los Potreros caldera appears to be linked to small magmatic intrusions located at relatively shallow depths (i.e. < 1 km) as in Loma Blanca, where the estimated intrusion depth calculated from the experimental data is 425 ± 170 m.

Such model is slightly different from the general accepted idea of resurgence in Los Potreros induced by the inflation of a saucer or cup shaped deep magmatic intrusion (Norini et al., 2015). The resurgence is inferred to be centred beneath the sector of the caldera traversed by the E-W lineaments and delimited by the Mazataloa and Arroyo Grande faults (sector S1 in Norini et al., 2015). The thermal anomalies identified by Norini et al. (2015) show that the temperatures are unexpectedly cold beneath the inferred centre of the resurgent block, where the highest temperatures should instead be expected. By contrast, sharp and narrow temperature peaks, spatially coincident with Los Humeros and Loma Blanca faults, are consistent with the presence of shallow and delocalized heat sources. Indeed, the inflation of the deep magma chamber of the LHVC, inferred to be at 5 to 7-8 km of depth (Verma, 1983, 2000, 2011) and extending 9 km in radius and 6 km in length (thus coinciding with the Los Humeros caldera rim, Verma et al., 1990), should have resulted in a much wider uplift and with higher magnitude than the one observed in the field. Indeed, resurgence resulting from magma remobilization of the deep chamber that produced collapse is characterized by a larger-scale surface deformation (thousands of meters of uplift extending for tens of kilometers at the surface) as shown in many large calderas worldwide (Toba, de Silva et al., 2015; Cerro Galan, Folkes et al., 2011; Ischia, Carlin, 2012).

It is therefore unlikely that the replenishment of new magma in the caldera forming deep magma chamber accounts for the magnitude (few tens of meters) and discontinuous spatial distribution of the deformation in Los Potreros.

Such model of the recent uplifting in Los Potreros is supported by field-based petrographic-mineralogical analysis showing that the present-day magmatic plumbing system is characterized by multiple magma levels spanning from a deep (30-33 km) basaltic reservoir to very shallow (< 1.5 km) trachyandesitic-trachytic (shelled) magma batches (Lucchi et al., under review).

A similar model of the plumbing system has been proposed to explain the historical eruptive activity since 1663 of Usu volcano (Japan) by a post caldera cone of the Toya caldera consisting of a basaltic main edifice surmounted by 3 felsic lava domes and more than 10 cryptodomes. Indeed, petrochemical data suggest the presence of multiple magma batches (i.e. sills) at depths ranging of 0.25-2 km that originated from partial melting at various degrees of a metagabbro (Matsumoto and Nakagawa, 2010; Tonya et al., 2010).
Our proposed model has implications for planning future geothermal exploration. Future geothermal wells should consider that the local geothermal gradient may be affected by the presence of shallow heat sources within the caldera, complicating the pattern of isotherms associated with the deeper heat flow.

6 Conclusions

This study, integrating field work with analogue models, allowed us to reconstruct the spatio-temporal evolution of the recent formation in Los Potreros and estimate the depth of intrusions representing the local heat sources for geothermal exploitation. Our results suggest the following:

1. The distribution of the alteration patterns and deformation of the Cuicuilco rim suggests that the recent (post-caldera collapse) uplift in Los Potreros moved from the south and north-eastern sector of the caldera towards the south along the Los Humeros and Loma Blanca scarp.

2. The estimated depth of the intrusions responsible for such uplift is very shallow, as calculated from the experimental data for the Loma Blanca bulge (425 ± 170 m).

3. The recent uplift in Los Potreros is discontinuous in space and time, inducing small-scale (< 1 km) deformations originating from multiple and shallow (< 1 km) magma bodies thus not representing a classic resurgent caldera (by which is meant large scale deformation of a single area).

Acknowledgements

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References


Figure 1: a) Shaded relief image (illuminated from the NE) obtained from 15 m resolution DEM of the Los Humeros Volcanic Complex (LHVC) showing the main structural features (faults and caldera rim, modified from Norini et al. 2015, Calcagno et al. 2018) and some geothermal wells referred to in the text. In depth correlation of lithostratigraphic units along the N-S (b) and W-E (c) direction (redrawn after Carrasco-Núñez et al. 2017) and Arellano et al. (2003). Depth: horizontal distance = 1:1. Location of the correlation line is shown in a). QigX= Xaltipan ignimbrite. The black rectangle indicates the studied area within the Los Potreros Caldera shown in Figure 3. The inset box shows the location of the LHVC (black dot and arrow) within the eastern sector of the Trans Mexican Volcanic Belt (TMVB). The structural sectors S1 and S2 correspond to the resurgent block inferred by Norini et al. (2015). Seismicity data from Lerma et al. (2018).

might be better to change colours (yellow?) as heat to distinguish from normal faults.
Figure 2: Experimental set-up. $D =$ diameter of the cylinder.
Figure 3: Simplified geological structural map of the studied area reinterpreted after Norini et al., 2015; Carrasco-Núñez et al., 2017b; Calcagni et al., 2018.
Figure 4: a) Panoramic view from Xalapasco crater (looking toward N) of the rhyolitic lava domes aligned N-S. b) Panoramic view of the E-W trending Las Papas scarp. c) Unaltered Cuicuilco (LL-07). d) Unaltered Cuicuilco covering a layered pyroclastic deposit (LH-08). The erosional surface preceding the deposition of the Cuicuilco is shown (dashed white line).
Figure 5: a) Panoramic view of the Arroyo Grande fault scarp showing the Unaltered Cuicuilco covering the altered and faulted ignimbrite and lavas. b) Normal fault affecting the altered ignimbrite deposits unconformably covered by the post-caldera, unaltered Cuicuilco deposits (LH-09). Note that the Cuicuilco deposits are not faulted at this location; the fault can be thus considered as a fossil fault with respect to the Cuicuilco deposition. c) Block of altered trachyandesite buried by unaltered Cuicuilco layers along the Mazatoya fault scarp, d) the Humeros fault scarp (LH-10) induced by the ascent of the rhyolitic extrusion on top of the fault plane. e) Rhyolitic plug cropping out ~150 southward the fault scarp shown in d) (indicated by the red arrow). f) Normal faulting and alteration of the Cuicuilco member within the apical graben of the Loma Blanca dome (site LH-01). g) Equal-area stereo-plot of the attitudes of faults and fractures in all the structural outcrops.
Figure 6: a) d) Top view image of the experiments 5 and 6. b) c) e) f) Vertical displacement; colour scale is proportional to the amount of uplift. g) h) Drawing of the cross section view obtained after cutting the section close to the dome center. The elevation profiles are obtained from laser scanner data. The yellow dashed line in the top view images indicates the trace of the section views and of the elevation profiles.
Figure 7: $L_a$ (crabon width) and $L_d$ (dome diameter) versus $T$. Theoretical values calculated after equation 1 (see discussion section).
Figure 8: a) $L_d$ versus time b) $L_v$ versus time.

caption needs expansion!
Figure 9: Schematic model of the evolution of the sub-surface structure of the Los Potreros caldera floor. Multiple magmatic intrusions located at relatively shallow depth (<1 km) are responsible for the localized bulging of the caldera floor (Loma Blanca, Los Humeros and Arroyo Grande uplifted areas). a) Pre-Cuiculitic stage: emplacement of a felsic intrusion at shallow depth and formation of the Arroyo Grande bulge characterized by extensional faulting at its top, reverse faulting at its base and hydrothermalism. b) Syn-Cuiculitic stage: eruption of the Cuiculitic member covering the hydrothermally altered post-caldera trachyandesitic lavas. c) Syn to post-Cuiculitic stage: formation of the Los Humeros fault and extrusion of obsidian lava domes along the fault scarp. As the trachyandesitic domes are covered with Cuiculitic member only at its base, the lava extrusion occurred during and post the Cuiculitic eruption. d) Formation of the Loma Blanca bulge with the current hydrothermal activity and extensional faulting occurring within the apical graber.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>Value</th>
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<tr>
<td>T</td>
<td>Thickness of the sand overburden</td>
<td>1.5 X 10^2 m</td>
</tr>
<tr>
<td>L_d</td>
<td>Dome diameter</td>
<td>1.16 X 10^1 m</td>
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<tr>
<td>H</td>
<td>Dome height</td>
<td>1.32 X 10^2 m</td>
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<tr>
<td>ρ_s</td>
<td>Sand density</td>
<td>1400 kg/m^3</td>
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<tr>
<td>φ</td>
<td>Angle of internal friction of sand</td>
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<td>τ_0</td>
<td>Sand cohesion</td>
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<td>ρ_m</td>
<td>Silicone density</td>
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<tr>
<td>μ_m</td>
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<tr>
<td>g</td>
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<tr>
<td>t</td>
<td>Experiment duration</td>
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Table 1. Geometric and material properties parameters of the experiments.

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<th>Experiments</th>
<th>Nature</th>
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<tr>
<td>Π_1 = T/L_d</td>
<td>0.1-0.6</td>
<td>0.04-0.6</td>
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<td>Π_2 = H/L_d</td>
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<td>0-0.12</td>
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<td>Π_3 = ρ_s/ρ_m</td>
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<td>0.6-1.4</td>
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<td>Π_4 = φ</td>
<td>35</td>
<td>25-40</td>
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<tr>
<td>Π_5 = ρ_m H^2/μ_m a</td>
<td>6 X 10^10</td>
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<td>Π_6 = ρ_m g H / μ_m</td>
<td>1.3 X 10^3</td>
<td>6.9 X 10^3</td>
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<td>Π_7 = ρ_s g T / τ_0</td>
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Table 2. Definition and values of the dimensionless ratios Π in nature and in the experiments.

<table>
<thead>
<tr>
<th>Exp.</th>
<th>T (mm)</th>
<th>L_d (mm)</th>
<th>L_s (mm)</th>
<th>θ</th>
<th>α</th>
<th>T_r (mm)</th>
<th>σ (%)</th>
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<tbody>
<tr>
<td>4</td>
<td>30</td>
<td>42</td>
<td>50</td>
<td>150</td>
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<td>14°</td>
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<td>50</td>
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Table 3. Measured parameters in the experiments. T = overburden thickness; L_d = dome diameter; L_s = caldera width; θ = caldera fault dip; α = dome flank mean dip; T_r = theoretical overburden thickness calculated with equation T_r (Brosh et al. 2013). σ = percentage difference between T and T_r.