



1 Estimating the depth and evolution of intrusions at resurgent 2 calderas: Los Humeros (Mexico)

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

20 Structural field analysis and geological mapping show that Los Potreros area is characterized by several lava domes and
21 cryptodomes (with normal faulting at the top) that suggest multiple deformation sources localized in narrow areas.

22 The analogue experiments simulate the deformation pattern observed in the field, consisting of magma intrusions pushing
23 a domed area with apical graben. To define the possible depth of the intrusion responsible for the observed surface
24 deformations, we apply established relations to our experiments. These relations suggest that the magmatic source
25 responsible for the deformation is present at very shallow depths (hundreds of meters) which is in agreement with the
26 well data and field observations. We therefore propose that the recent deformation at LHVC is not a classical resurgence
27 associated with the bulk inflation of a deep magma reservoir; rather this is related to the ascent of shallow (<1 km) multiple
28 magma bodies. A similar multiple source model of the subsurface structure has been also proposed for other calderas with
29 an active geothermal system (Usu volcano, Japan) suggesting that the model proposed may have a wider applicability.

30 1 Introduction

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



39 estimation of the location, depth and geometry of the magmatic sources is crucial to define the possible geothermal and
40 mineral potential of resurgent calderas, allowing an economically sustainable exploration and exploitation of their resulted
41 natural resources.

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

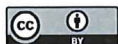
47 This scenario is different from the occurrence of deformation patterns characterized by the widespread and delocalized
48 uplift of several minor portions of the caldera floor, ^{as} due to lava domes and/or cryptodomes, as ^{for example} observed
49 at Usu volcano (Japan, Matsumoto and Nakagawa,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

53 In this regard, the Los Humeros Volcanic Complex (LHVC, Mexico) is an important geothermal target area, consisting
54 of two nested calderas with resurgence within the innermost one (Los Potreros caldera), commonly interpreted as due to
55 the uplift of a resurgence due to the inflation of a deep (several km) magma chamber (Fig. 1a, Norini et al., 2015). ^{This paper}
56 The purpose of this work is to evaluate ^s the depth to the intrusion(s) responsible for the uplift, also explaining the spatio-
57 temporal evolution of the observed deformation of the caldera floor. To achieve this goal, we integrate results from
58 structural field investigations carried out within the Los Potreros caldera with those derived from analogue experiments
59 specifically designed to constrain the depth of the deformation source(s) in volcanic caldera environments. Results
60 document discontinuous and small-scale (< 1 km) surface deformations generated from multiple and shallow (< 1 km)
61 magmatic bodies. These results should be taken into account for planning the future geothermal operations at the LHVC
62 and in other calderas showing similar surface deformation.

63 2 Geological-structural setting

64 LHVC is located at the eastern termination of the Trans Mexican Volcanic Belt (TMVB, see inset in Fig. 1a). The TMVB
65 is the largest Neogene volcanic arc in Mexico (~1000 km long and up to ~300 km wide), resulting from the Cenozoic
66 subduction of the Cocos and Rivera plates beneath the North American plate along the Middle American trench (Ferrari
67 et al., 2012, and references therein). The LHVC consists of two nested calderas formed during the Pleistocene: the outer
68 18 x 16 km Los Humeros caldera and the inner 10 x 8 km Los Potreros caldera (Fig. 1a, Ferriz and Mahood, 1984; Norini
69 et al., 2015; Carrasco-Núñez et al., 2017b).

70 Based on updated stratigraphic and geochronological information, the evolution of the LHVC can be divided ^{into} ~~in~~ three
71 ~~main~~ stages (Carrasco-Núñez et al., 2017b, 2018). ~~The~~ Pre-caldera volcanism extended between ca. 700 and 164 ka (based
72 on U-Th and ³⁹Ar/⁴⁰Ar datings: Carrasco-Núñez et al., 2018), showing evidence for an extended building phase leading
73 to the establishment of the large volume rhyolitic reservoir that fed the 115 km³ caldera-forming Xaltipan ignimbrite
74 eruption. ^A The Caldera stage started at ca. 164 ka with the collapse of the Los Humeros caldera and ended with the eruption
75 of the 15 km³ Zaragoza rhyodacite-andesite ignimbrite at 69 ka, associated with the collapse of the nested Los Potreros
76 caldera. ^{A Post-caldera stage (<69 ka) is interpreted by}
77 Carrasco-Núñez et al. (2018) ~~interprets the Post-Caldera stage (<69 ka)~~ as a Pleistocene resurgent phase, followed by the
78 Holocene activity characterized by intra-caldera basaltic to rhyolitic monogenetic volcanism. This hypothesis discards a



79 configuration of the magmatic plumbing system characterized by a unique, large and homogenized magma reservoir as
80 inferred for the Los Humeros activity during the Caldera ^{stage} (e.g. Ferriz and Mohood, 1984; Verma, 1985) in favour of
81 a heterogeneous multi-layered system vertically distributed in the ~~whole~~ crust, with a deep (ca. 30 km) basaltic reservoir
82 feeding progressively shallower and smaller distinct stagnation layers, pockets and batches up to very shallow conditions
83 (1kbar, ca. 3km) (Lucci et al., under review).

84 ~~In particular,~~ During the early resurgent phase of the Post-Caldera stage, rhyolitic domes were emplaced along the northern
85 rim of the Los Humeros caldera, followed by the emplacement of less evolved lavas of trachyandesitic-trachytic
86 composition (Carrasco-Núñez et al., 2017b). The Holocene ring-fracture and bimodal magmatism is characterized by both
87 explosive and effusive activity, producing several lava flows and domes, as well as periods of dominant explosive activity
88 (e.g. the ca. 7 ka Cuicuiltic Member, Dávila-Harris and Carrasco-Núñez, 2014) from multiple vents located mostly along
89 ~~both~~ the inner and outer caldera ring faults. During this phase, less evolved lavas were erupted (from trachyandesite to
90 basalt) within and outside Los Humeros caldera, one ~~of them~~ ¹⁹¹⁹ corresponds to an olivine-bearing basaltic lava associated
91 with the formation of the Xalapasco crater (Fig. 1a). Trachytic lava flows are the most recent activity recorded ~~by LHVC~~
92 at ca. 2.8 ky (Carrasco-Núñez et al., 2017b).

93 The reconstruction of the shallow stratigraphy in Los Potreros is chiefly derived from ~~the~~ information derived from the
94 available well logs (Figs. 1b-c Carrasco-Núñez et al., 2017a, b). Overall, the ~~Post-caldera~~ units are lithologically
95 dominated by lava flows resting ~~on the~~ ^{on} ignimbrite deposits emplaced during caldera stage. Ignimbrites of the caldera
96 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.,
97 2017a). The subsurface geometry of the pre- and syn-caldera products is better elucidated in Fig. 1b and 1c, which show
98 the in-depth geometry of the different magmatic products that are cross-correlated and projected along the N-S and E-W
99 direction, respectively. The N-S projection shows a constant depth of the top surface of the pre-caldera andesites that is
100 associated with a highly variable depth (up to 400 m) of the top surface of the syn-caldera Xaltipan ignimbrite. The W-E
101 projection shows a high depth variability of both the top surface of the ~~Pre-caldera~~ group (up to 500 m between H-19 and
102 H-25 wells) and that of the Xaltipan ignimbrite (up to 400 m between H-19 and H-10 wells). Within this framework ~~a~~
103 ~~remarkable feature is the presence of both~~ basaltic and rhyolitic-dacitic lavas located at ~~various depths~~ ^{occur} (Carrasco-Núñez
104 et al., 2017a). ~~In particular,~~ the rhyolites-dacites are located mostly at the base (H-20 and H-26 wells) or within (H-05
105 well) the caldera group or ~~within~~ the old andesite sequence (H-25 and H-19 wells). ~~On the other hand,~~ the ~~Basalts~~ are
106 located ~~at various depths~~ only within the pre-caldera andesite sequence, both at its base (in contact with the limestone
107 basement; H-5 and H-8 wells) and at its top (in contact with the base of the caldera sequence; H-10 well). ~~Such bimodal~~
108 lava products, showing an irregular lateral distribution, are interpreted as subaerial ~~volcanic episodes~~ ^{These} (Carrasco-Núñez et
109 al., 2017a).

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

117 The source of the areal uplift ^{has been} is inferred to be the inflation of a saucer or cup shaped deep magmatic source elongated
118 NNW-SSE, upwarping a 8 x 4 km resurgent block, centred in the SE portion of the caldera, delimited to the W by the
119 NNW-SSE main faults, and toward the north, east and south by the caldera rim (Fig. 1a, Norini et al., 2015).



120 The seismic activity ^{between} in the period 1994-2017 is clustered along the Loma Blanca, Los Humeros and Arroyo Grande faults
121 (Lermo et al., 2018; Fig. 1a). Most of the earthquakes show a magnitude (M_w) between 1 and 2.5, and have been mainly
122 interpreted as induced by the geothermal exploitation activity (injection of fluids and hydrofracturing; Lermo et al., 2018).
123 ~~Moreover~~, four major earthquakes ($M_w = 3.2, 3.6, 3.9$ and 4.2 , at a depth of 1, 4, 2.2 and 1.8 km, respectively) have been ^{also}
124 ~~also~~ reported, with focal depths close to the trace of the active faults (Loma Blanca and Los Humeros, Fig. 1a). Such major
125 earthquakes have been interpreted as triggered by fault reactivation due to fluid/brine circulation injected from geothermal
126 wells (Lermo et al., 2018).

127 3 Methods

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

130 3.1 Structural field work

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

139 3.2 Analogue models: experimental set-up and scaling

140 ~~We performed~~ ^{were undertaken,} three experiments simulating the ascent of a viscous intrusion in a brittle overburden ~~with the aim~~ to test
141 existing relationships between the depth of intrusion and the observed surface deformation. The experimental set-up (Fig.
142 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,
143 respectively). In each experiment we imposed a layering using a non-cohesive marine sand below a layer of crushed silica
144 sand (grain size = 40-200 μm , cohesion = 300 Pa), fixing the thickness ratio of the two layers (T_u/T_l) to 1, to simulate the
145 stratigraphy in Los Potreros (stiffer post caldera lava flows above softer and less cohesive ignimbrite deposits emplaced
146 during the caldera collapse stage). At the base of the sand pack, a piston, controlled by an engine, pushes upward the
147 silicone (magma analogue) placed inside a cylinder 8 cm in diameter. The injection rate is fixed for all the experiments
148 to 2 mm/hr and each experiment was stopped at the onset of the silicone extrusion. Both sand and silicone physical
149 properties are listed in Table 1.

150 At the end of each experiment, the surface has been covered with sand to preserve their final topography and were ~~wet~~ ^{wetted.}
151 with water for cutting in sections to appreciate the subsurface deformation. Such sections were used to measure the mean
152 dip of the graben faults (θ) induced by the rising silicone. A digital camera monitored the top view deformation of each
153 experiment at 0.02 fps and a laser scanner, placed next to the camera, provided high-resolution data (maximum error \pm
154 0.5 mm) of the vertical displacement that was used to measure in detail the geometrical features of the deformation i.e.
155 dome diameter (L_d), graben width (L_g) and dome flank mean dip (α). According to the Buckingham- Π theorem (Merle
156 and Borgia 1996 and references therein), ~~our models need 7 independent dimensionless numbers to be properly scaled~~
157 (i.e. 10 variables minus three dimensions, ^{Table 1} table-1). Such dimensionless numbers can be defined as the ratios (Π) listed in

motor?



158 Table 2. ^{Some} ~~Even if the~~ values of Π s differ ^{by} of two orders of magnitude ^{between} in nature and in the experiments (1.8×10^{-8} and $6 \times$
159 10^{-10} , respectively), ^{but most case} ~~they are~~ both largely < 1 , indicating that the ratio is a negligible value in both cases. ??

160 4 Results

161 4.1 Local geology and structural data

162 The outcropping ^Ppost-caldera lithologies within the Los Potreros Caldera consist of: (1) the Cuicuiltic Member, which
163 blankets most of the surface of the upper half of the studied area; (2) basaltic lava flows filling the Xalapasco crater and
164 the NW portion of the caldera; and (3) trachyandesitic and trachytic lava domes and thick flows extending in the southern
165 half of the caldera and rhyolitic domes in its central part (Fig. 3). The more evolved lavas form four elliptical domes,
166 aligned N-S (Figs. 3, 4a): (i) a $2 \text{ long} \times 1.2 \text{ km wide}$ trachytic dome located to the west of the Maztaloya and Los Humeros
167 faults, (ii) a $1 \times 0.7 \text{ km}$ trachyandesitic dome located at the northern tip of the Maztaloya fault, and (iii) two smaller (0.4
168 $\times 0.2 \text{ km}$) rhyolitic domes at the southern tip of the Los Humeros fault (LH-11 in Fig.3). (Qtc?)

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

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

179 4.1.1 Las Papas ^{scarp} lineament (LH-07, LH-08)

180 The E-W trending Las Papas scarp (Fig. 4b) is localised within the Cuicuiltic Member, ^{which here does not} ~~Such lithologies do not~~ show any
181 alteration or significant deformation (LH-07; Fig. 4c). We identified an erosional surface along the scarp, where unaltered
182 and undeformed Cuicuiltic rocks rest above a layered pyroclastic deposit (LH-08, Fig. 4d). The E-W trending
183 morphological lineaments defined by the Las Papas scarp is probably due to differential erosion of the softer layers of the
184 pyroclastic deposits, successively blanketed by the Cuicuiltic Member.

185 4.1.2 Arroyo Grande (LH-09) and Maztaloya ^{scarps}

186 The NE-SW Arroyo Grande scarp (Fig.5a) exposed strongly altered and faulted (NW striking faults, mean attitude
187 $N144^\circ/68^\circ$, $n = 8$) lavas and ignimbrites unconformably covered by the unaltered Cuicuiltic Member (Fig.5b). The throw
188 observed at the outcrop-scale for the single fault strands is ^{ca} ~~in the order of~~ 0.5 m , with a dominant normal dip-slip
189 kinematics (slickenline pitch angle ranging from 99° to 106°). The inferred cumulative displacement at Arroyo Grande ~
190 is 10 m . Similarly, an outcrop on the Maztaloya scarp (in front of well H-6) shows altered trachyandesites covered by
191 unaltered Cuicuiltic rocks (Fig. 5c).

192 4.1.3 Los Humeros (LH-10)

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

200 4.1.4 Loma Blanca (LH-01, LH-02)

201 The Loma Blanca ^f Fault system (LH-01 and LH-02) is located in ^{is} ~~correspondence of~~ an active degassing area, where faults
202 and fractures are frequent.

203 The fault system ^{is} localises on top of an elongated crest (within a graben) of a morphological bulge, ~ 1 km in diameter
204 and 30 m in height. At this location, the Cuicuiltic Member and the underlying trachyandesite lavas are strongly altered.
205 Evidence of stockwork veining and diffuse fracturing of the lavas suggests hydrofracturing and structurally controlled
206 fluid flow and alteration. A set of NNE-SSW striking conjugate extensional faulting and jointing (joint spacing ~1 m;
207 Fig. 5f) is observed. The faults (mean attitude N26°/71°) show a normal dip-slip kinematics (pitch ranging from 82° to
208 104°). Joint systems found in the Cuicuiltic Member strike sub-parallel to the faults (mean attitude N37°/72°, n= 14). The
209 inferred cumulative displacement of the faults, estimated by the depth of the apical graben, is ~ 5 m.

210 ^{In summary} Summing up, the 22 mapped faults in all the structural outcrops of the area show a main NNW-SSE strike (Fig. 5g) with
211 a dominant dip slip movement (mean pitch angle of slickenlines 88°) which is sub-parallel to the N-S elongation of the
212 lava domes and the Xalapasco crater.

213 4.2 Experimental results

214 Here we show two representative experiments with increasing overburden thickness (experiments 5 and 6 with T= 30 and
215 50 mm respectively). Table 3 shows the measured parameters in the experiments.

216 Overall, the experiments show a similar deformation pattern: a first stage characterized by the uplift of a sub-circular
217 dome, bordered by inward dipping reverse faults, and a second stage characterized by the subsidence of the apical part of
218 the dome where normal faulting occurs (graben formation Fig. 6a-f). The reverse and normal faults are ring faults and are
219 associated with the formation of radial fractures from the dome centre.

220 Despite the T/D ratio, all the experiments show that both the dome diameter and graben width increase linearly with the
221 overburden thickness (ranging from 105 to 164 mm and from 14 to 58 mm respectively, Table 3, Fig. 7).

222 The dome diameter increases abruptly with time, becoming almost constant at an early stage of the experiment (Fig. 8a);
223 the graben width shows a similar pattern even if it enlarges slightly with time (after the first abrupt increase) as the silicone
224 rises towards the surface (Fig. 8b), suggesting that the intrusion depth has an higher influence on the graben width, in
225 agreement with Brothelande and Merle (2015).

226 5 Discussion

Why 5+6
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227 The distribution of the alteration patterns and deformation characteristics of the post caldera deposits can be used to infer
228 the origin and extent of the uplift within the LHVC. In particular, ~~the involvement or not of~~ ^{Whether} the 7.4 ka Cuicuiltic Member
229 ~~was involved~~ ^{was involved} in the deformation and alteration ~~allow~~ ^{allow} constraining ~~the~~ ^{the} spatio-temporal evolution of the surficial deformation and
230 associated uplifts in Los Potreros. ~~Indeed,~~ ^{Indeed,} unaltered and undeformed deposits of the Cuicuiltic Member crop out along
231 the E-W Las Papas lineament and unconformably ~~cover~~ ^{cover} altered and faulted lavas and ignimbrites along the Arroyo
232 Grande and Maztaloja scarps. Alteration and deformation of the Cuicuiltic Member occurs along the Los Humeros Fault
233 scarp and within the apical graben of the Loma Blanca bulge. ~~Moreover,~~ ^{Moreover,} the vertical striations of the trachyandesitic plug
234 near the Los Humeros fault scarp suggest that the ascent of the plug induced the uplift, the normal dip-slip faulting and
235 alteration of the Cuicuiltic Member.
236 ~~All these~~ ^{The} observations suggest that Los Potreros is not a classic resurgent caldera (i.e. a caldera characterised by a large-
237 scale process localized in a single area) but is ~~rather~~ ^{rather} characterised by a discontinuous uplifting ~~ing~~ process in space and time,
238 inducing small-scale deformations at each pulse (Fig. 9a-d). In particular, it was active in the south and north-eastern
239 sector of the caldera, at Maztaloja and Arroyo Grande (Fig. 9a), prior to the deposition of the Cuicuiltic Member (~ 7.4
240 ka), and then moved towards N along the Los Humeros and Loma Blanca scarps during and post the eruption of the
241 Cuicuiltic ~~Member~~ ^{Member} (Fig. 9b-d). ~~Concerning the source of the deformation,~~ ^{Concerning the source of the deformation,} the felsic lava found at the Los Humeros Fault scarp
242 shows a similar mineral assemblage ~~of~~ ^{to} the felsic domes located further south (Fig. 3); thus, the Los Humeros scarp may
243 represent the final stage (i.e. effusive eruption of felsic magmas, (Fig. 9c) of the uplift process, which is thus driven by
244 the ascent of relatively narrow (hundreds of meters) and highly viscous felsic magma batches. This is ~~also~~ ^{also} supported by
245 the N-S elongation of the identified lava domes and Xalapasco crater which is sub-parallel to the orientation of the
246 measured fault planes (NNW-SSE), indicating that the observed deformation is closely related to the post-caldera
247 volcanism. The ascent of such ~~magma~~ ^{magma} bodies is inferred here to drive the recent uplift and deformation of the Loma
248 Blanca bulge, as suggested by the active fumaroles and extensive alteration of both the Cuicuiltic pyroclastics and post-
249 caldera lavas (Fig. 9d). The presence of such shallow magma bodies is also suggested by the four major earthquakes
250 recorded in Los Potreros, which have been previously interpreted to be induced by geothermal exploitation (Lermo et al.,
251 2018). However, since the magnitude of the seismic events induced by geothermal exploitation activities is usually lower
252 (i.e. < 3, Evans et al., 2012 and references therein), the higher magnitude (between 3.2 and 4.2) of the earthquakes in Los
253 Potreros suggests that they may be more likely of volcano-tectonic origin due to shallow magma emplacement.
254 ~~In order to~~ ^{In order to} further support ~~the~~ ^{the} above inferences ~~derived from~~ ^{derived from} interpretation of the field observations, analogue models
255 were used to constrain the magma source depth from the geometrical parameters measured in the experiments (L_g , θ , α ,
256 Table 3).
257 Since ~~our~~ ^{our} results confirm that the graben width shows a linear correlation with the source depth (Fig. 7) as estimated in
258 (Brothelande and Merle, 2015), we calculated the theoretical overburden thickness (i.e. the intrusion depth, T_t , Table 3)
259 as follows:
260
$$T_t = \frac{1}{2} L_g \times \frac{\sin(\theta + \alpha)}{\cos \theta} \quad (1)$$

261 Comparing the percentage difference between the imposed experimental (T) and theoretical (T_t) overburden thickness
262 values, we calculate the associated error in the evaluation of the intrusion depth in the models (σ , Table 3, Fig. 7). We then
263 use equation 1 for the evaluation of the heat source depth at the Loma Blanca bulge considering $\sigma \sim 40\%$ (maximum
264 value of the experiments).
265 ~~Considering that for~~ ^{Considering that for} the Loma Blanca bulge $L_g = 286$ m, $\theta = 71^\circ$, $\alpha = 4.5^\circ$, it follows that the estimated intrusion depth is
266 425 ± 170 m. Such relatively shallow depth is within the range of depths of rhyolitic-dacitic domes drilled in geothermal

Much better term



267 wells (spanning from 300 to 1700 m, Fig. 1b-c) and is consistent with the hypothesis that the uplift is driven by small and
268 delocalized magmatic intrusions, as suggested by the field data.

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

278 Summarizing, the combination of field and modelling data support that the uplift in Los Potreros is due to multiple
279 deformation sources in narrow areas that do not represent ^{caldera} a resurgence sensu stricto. Such ^{delocalized} recent deformation
280 within Los Potreros caldera appears to be linked to small magmatic intrusions located at relatively shallow depths (i.e. <
281 1 km) as in Loma Blanca, where the estimated intrusion depth calculated from the experimental data is 425 ± 170 m. ^{This}
282 Such model is ^{slightly} ^{differs} different from the general accepted idea of resurgence in Los Potreros induced by the inflation of
283 a saucer or cup shaped deep magmatic intrusion (Norini et al., 2015). The resurgence is inferred to be centred beneath the
284 sector of the caldera traversed by the E-W lineaments and ^{delimited} by the Maztaloya and Arroyo Grande faults (sector
285 S1 in Norini et al., 2015). The thermal anomalies identified by ^{delimited} Norini et al. (2015) show that the temperatures are
286 unexpectedly cold beneath the inferred centre of the resurgent block, where the highest temperatures should ^{instead} be
287 expected. By contrast, sharp and narrow temperature peaks, spatially coincident with Los Humeros and Loma Blanca
288 faults, are consistent with the presence of shallow and delocalized heat sources. Indeed, the inflation of the deep magma
289 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
290 and 6 km in length (thus coinciding with the Los Humeros caldera rim, Verma et al., 1990), should have resulted in a
291 much wider uplift and with higher magnitude than the one observed in the field. ^{Indeed,} Resurgence resulting from magma
292 remobilization of the deep chamber that produced ^{the} collapse is characterized by a larger-scale surface deformation
293 (thousands of meters of uplift extending for tens of kilometers on the surface) as shown in many large calderas worldwide
294 (Toba, de Silva et al., 2015; Cerro Galan, Folkes et al., 2011; Ischia, Carlino, 2012).

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

297 Such ^a model of the recent uplifting in Los Potreros is ^{also} supported by field-based petrographic-mineralogical analysis
298 showing that the present-day magmatic plumbing system is characterized by multiple magma levels spanning from a deep
299 (30-33 km) basaltic reservoir to very shallow ^{smaller,} (~ 1.5 km) trachyandesitic-trachytic ^{smaller} magma batches (Lucci et al.,
300 under review).

301 A similar model of the plumbing system has been ^{also} proposed to explain the ^{historical} eruptive activity ^(since 1663) of
302 Usu volcano (Japan), ^a post caldera cone of the Toya caldera consisting of a basaltic main edifice surmounted by 3 felsic
303 lava domes and more than 10 cryptodomes. ^{Indeed,} ^{at} petrochemical data suggest the presence of multiple magma batches
304 (i.e. sills) ^{at} in a depth range of 0.25-2 km ^{deep} that originated from partial melting ^{at} ^{at} various degrees of a metagabbro
305 (Matsumoto and Nakagawa, 2010; Tomya et al., 2010).

Needs rewording



306 Our proposed model has ~~crucial~~ ^{siting of} implications for planning ~~the~~ future geothermal exploration: future geothermal wells
307 should consider that the ~~local geothermal gradient may be affected by the~~ presence of shallow heat sources within the
308 caldera ^{may} complicating the pattern of isotherms associated with the deeper heat flow.

309 6 Conclusions

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

313 1. The distribution of the alteration patterns and deformation of the Cuicuiltic Member suggests that the recent (post-
314 caldera collapse) uplift in Los Potreros moved ^{progressively northwards} from the south and north-eastern sector of the caldera ~~towards N~~ along the
315 Los Humeros and Loma Blanca scarps.

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

318 3. The recent uplift in Los Potreros is discontinuous in space and time, inducing small-scale (< 1 km) deformations
319 originating from multiple and shallow (< 1 km) magmatic bodies thus not representing a classic resurgent caldera ~~it~~ ^{which has}
320 large scale (several km) deformation of a single area.

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328 Dipartimenti di Eccellenza, ARTICOLO 1, COMMI 314 – 337 LEGGE 232/2016) is gratefully acknowledged.

329 References

- 330 Acocella, V., Cifelli, F., and Funicello, R.: The control of overburden thickness on resurgent domes, *J. Volcanol. Geoth.*
331 *Res.*, 111, 137–153, [https://doi.org/10.1016/S0377-0273\(01\)00224-4](https://doi.org/10.1016/S0377-0273(01)00224-4), 2001.
- 332 Arellano, V.M., García, A., Barragán, R.M., Izquierdo, G., Aragón, A., and Nieva, D.: An updated conceptual model of
333 the Los Humeros geothermal reservoir (Mexico), *J. Volcanol. Geoth. Res.*, 124, 67–88, [https://doi.org/10.1016/S0377-](https://doi.org/10.1016/S0377-0273(03)00045-3)
334 [0273\(03\)00045-3](https://doi.org/10.1016/S0377-0273(03)00045-3), 2003.
- 335 Brothelande, E., Peltier, A., Got, J.L., Merle, O., Lardy, M., and Garaebiti, E.: Constraints on the source of resurgent
336 doming inferred from analogue and numerical modeling — Implications on the current feeding system of the Yenkahe
337 dome–Yasur volcano complex (Vanuatu), *J. Volcanol. Geoth. Res.*, 322, 225–240,
338 <https://doi.org/10.1016/j.jvolgeores.2015.11.023>, 2016.
- 339 Brothelande, E., and Merle, O.: Estimation of magma depth for resurgent domes: An experimental approach, *Earth Planet.*
340 *Sc. Lett.*, 412, 143–151, <https://doi.org/10.1016/j.epsl.2014.12.011>, 2015.
- 341 Calcagno, P., Evanno, G., Trumpy, E., Carlos Gutiérrez-Negrín, L., Maclás, J.L., Carrasco-Núñez, G., and Liotta, D.:
342 Preliminary 3-D geological models of Los Humeros and Aocolco geothermal fields (Mexico)-H2020 GEMex Project,
343 *Adv. Geosci.*, 45, 321–333, <https://doi.org/10.5194/adgeo-45-321-2018>, 2018.
- 344 Carlino, S.: The process of resurgence for Ischia Island (southern Italy) since 55 ka: The laccolith model and implications
345 for eruption forecasting, *B. Volcanol.*, 74, 947–961. <https://doi.org/10.1007/s00445-012-0578-0>, 2012.



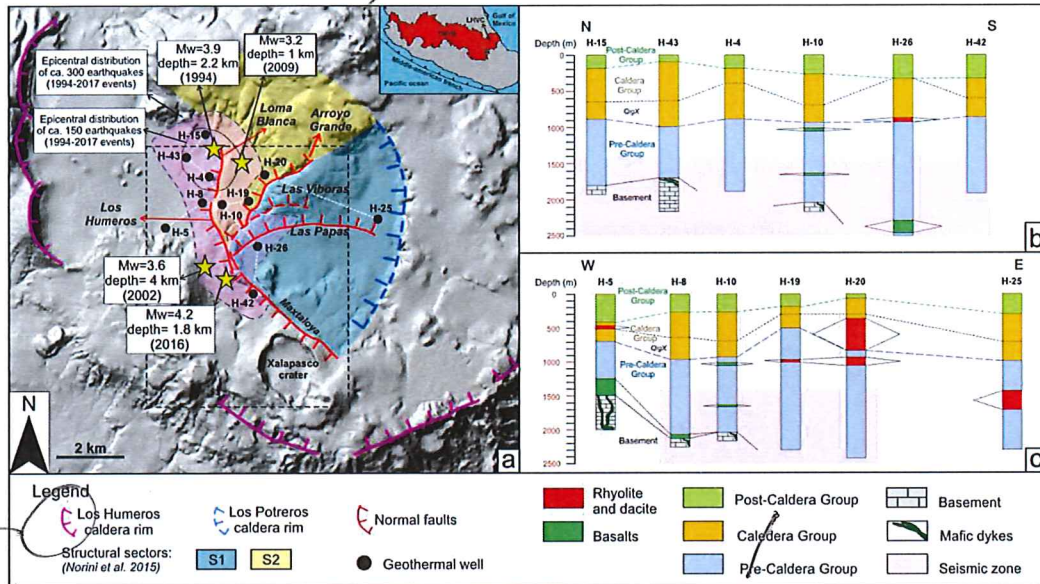
- 346 Carrasco-Núñez, G., and Branney, M.J.: Progressive assembly of a massive layer of ignimbrite with a normal-to-reverse
347 compositional zoning: The Zaragoza ignimbrite of central Mexico, *B. Volcanol.*, 68, 3–20,
348 <https://doi.org/10.1007/s00445-005-0416-8>, 2005.
- 349 Carrasco-Núñez, G., McCurry, M., Branney, M.J., Norry, M., and Willcox, C.: Complex magma mixing, mingling, and
350 withdrawal associated with an intra-Plinian ignimbrite eruption at a large silicic caldera volcano: Los Humeros of central
351 Mexico, *Bull. Geol. Soc. Am.*, 124, 1793–1809, <https://doi.org/10.1130/B30501.1>, 2012.
- 352 Carrasco-Núñez, G., López-Martínez, M., Hernández, J., and Vargas, V.: Subsurface stratigraphy and its correlation with
353 the surficial geology at Los Humeros geothermal field, eastern Trans-Mexican Volcanic Belt, *Geothermics*, 67, 1–17,
354 <https://doi.org/10.1016/j.geothermics.2017.01.001>, 2017a.
- 355 Carrasco-Núñez, G., Hernández, J., De León, L., Dávila, P., Norini, G., Bernal, J.P., Jicha, B., Navarro, M., López-Quiroz,
356 P., and Digitalis, T.: Geologic Map of Los Humeros volcanic complex and geothermal field, eastern Trans-Mexican
357 Volcanic Belt, *Terra Digitalis*, 1, 1–11, <https://doi.org/10.22201/igg.terradigitalis.2017.2.24.78>, 2017b.
- 358 Carrasco-Núñez, G., Bernal, J.P., Dávila, P., Jicha, B., Giordano, G., and Hernández, J.: Reappraisal of Los Humeros
359 volcanic complex by new U/Th zircon and ⁴⁰Ar/³⁹Ar dating: Implications for greater geothermal potential, *Geochem.*
360 *Geophys. Geosy.*, 19, 132–149, <https://doi.org/10.1002/2017GC007044>, 2018.
- 361 Dávila-Harris, P., and Carrasco-Núñez, G.: An unusual syn-eruptive bimodal eruption: The Holocene Cuicuiltic Member
362 at Los Humeros caldera, Mexico, *J. Volcanol. Geoth. Res.*, 271, 24–42, <https://doi.org/10.1016/j.jvolgeores.2013.11.020>,
363 2014.
- 364 de Silva, S.L., Mucek, A.E., Gregg, P.M., and Pratomo, I.: Resurgent Toba - field, chronologic, and model constraints on
365 time scales and mechanisms of resurgence at large calderas, *Front. Earth Sci.*, 3, 1–17,
366 <https://doi.org/10.3389/feart.2015.00025>, 2015.
- 367 Doblás, M.: Slickenside kinematic indicators, *Tectonophysics*, 295, 187–197, <https://doi.org/10.1016/S0040->
368 [1951\(98\)00120-6](https://doi.org/10.1016/S0040-1951(98)00120-6), 1998.
- 369 Evans, K.F., Zappone, A., Kraft, T., Deichmann, N., and Moia, F.: A survey of the induced seismic responses to fluid
370 injection in geothermal and CO₂ reservoirs in Europe, *Geothermics*, 41, 30–54,
371 <https://doi.org/10.1016/j.geothermics.2011.08.002>, 2012.
- 372 Ferrari, L., Orozco-Esquivel, T., Manea, V., and Manea, M.: The dynamic history of the Trans-Mexican Volcanic Belt and
373 the Mexico subduction zone, *Tectonophysics*, 522–523, 122–149, <https://doi.org/10.1016/j.tecto.2011.09.018>, 2012.
- 374 Ferriz, H., and Mahood, G.A.: Eruption Rates and Compositional Trends at Los Humeros Volcanic Center, Puebla,
375 Mexico, *J. Geophys. Res.*, 89, 8511–8524, <https://doi.org/10.1029/JB089iB10p08511>, 1984.
- 376 Folkes, C.B., Wright, H.M., R.A.F. Cas, de Silva, S.L., Lesti, C., and Viramonte, J.G.: A re-appraisal of the stratigraphy
377 and volcanology of the Cerro Galán volcanic system, NW Argentina, *B. Volcanol.*, 73, 1427–1454,
378 <https://doi.org/10.1007/s00445-011-0459-y>, 2011.
- 379 Galetto, F., Acocella, V., and Caricchi, L.: Caldera resurgence driven by magma viscosity contrasts, *Nat. Commun.*, 8, 1–
380 11, <https://doi.org/10.1038/s41467-017-01632-y>, 2017.
- 381 Guillou-Frottier, L., Burov, E.B., and Milési, J.P.: Genetic links between ash-flow calderas and associated ore deposits as
382 revealed by large-scale thermo-mechanical modelling, *J. Volcanol. Geoth. Res.*, 102, 339–361,
383 [https://doi.org/10.1016/S0377-0273\(00\)00246-8](https://doi.org/10.1016/S0377-0273(00)00246-8), 2000.
- 384 Kennedy, B., Wilcock, J., and Stix, J.: Caldera resurgence during magma replenishment and rejuvenation at Valles and
385 Lake City calderas, *B. Volcanol.*, 74, 1833–1847, <https://doi.org/10.1007/s00445-012-0641-x>, 2012.



- 386 Kennedy, B., Stix, J., Hon, K., Deering, C., and Gelman, S.: Magma storage, differentiation, and interaction at Lake City
387 caldera, Colorado, USA, *Bull. Geol. Soc. Am.*, 128, 764–776, <https://doi.org/10.1130/b31305.1>, 2016.
- 388 Lindsay, J., Emmermann, R., Wemmer, K., de Silva, S., and Trumbull, R.: La Pacana caldera, N. Chile: a re-evaluation
389 of the stratigraphy and volcanology of one of the world's largest resurgent calderas, *J. Volcanol. Geoth. Res.*, 106, 145–
390 173, [https://doi.org/10.1016/s0377-0273\(00\)00270-5](https://doi.org/10.1016/s0377-0273(00)00270-5), 2001.
- 391 Lipman, P.W., Zimmerer, M.J., and McIntosh, W.C.: An ignimbrite caldera from the bottom up: Exhumed floor and fill
392 of the resurgent Bonanza caldera, Southern Rocky Mountain volcanic field, Colorado, *Geosphere*, 11, 1902–1947,
393 <https://doi.org/10.1130/GES01184.1>, 2015.
- 394 Lermo, J., Lorenzo, C., Jiménez, N., Ramos, E., Ângulo, J., Israel, J., Téllez, N., Machado, O., Álvarez, I., Torres, R.,
395 Alfaro R.: Analisis de la actividad sismica (1994-2016), su relacion con los pozos inyectoros y productores y aplicación
396 de nuevas tecnicas geofisica para caracterizar las zonas anómalas del campo geotérmico de Los Humeros, CEMIE-GEO,
397 Mexico, Internal Rep., 42 pp., 2018.
- 398 Lucci, F., Carrasco-Núñez, G., Rossetti, F., Theye, T., White, J. C., Urbani, S., Azizi, H., Asahara, Y., and Giordano, G.:
399 Anatomy of the magmatic plumbing system of Los Humeros Caldera (Mexico): implications for geothermal systems,
400 *Solid Earth Discuss.*, <https://doi.org/10.5194/se-2019-86>, in review, 2019.
- 401 Marsh, B.D.: On the mechanics of caldera resurgence, *J. Geophys. Res.*, 89, 8245–8251,
402 <https://doi.org/10.1029/JB089iB10p08245>, 1984.
- 403 Merle, O., Borgia, A.: Scaled experiments of volcanic spreading, *J. Geophys. Res.*, 101, 13805–13817,
404 <https://doi.org/10.1029/95JB03736>, 1996.
- 405 Métrich, N., Allard, P., Aiuppa, A., Bani, P., Bertagnini, A., Shinohara, H., Parello, F., Di Muro, A., Garaebiti, E., Belhadj,
406 O., and Massare, D.: Magma and volatile supply to post-collapse volcanism and block resurgence in Siwi caldera (Tanna
407 Island, Vanuatu arc), *J. Petrol.*, 52, 1077–1105, <https://doi.org/10.1093/petrology/egr019>, 2011.
- 408 Mueller, W.U., Stix, J., Corcoran, P.L., Daigneault, R.: Subaqueous calderas in the Archean Abitibi greenstone belt: An
409 overview and new ideas, *Ore Geol. Rev.*, 35, 4–46, <https://doi.org/10.1016/j.oregeorev.2008.12.003>, 2009.
- 410 Norini, G., Gropelli, G., Sulpizio, R., Carrasco-Núñez, G., Dávila-Harris, P., Pelliccioli, C., Zucca, F., and De Franco, R.:
411 Structural analysis and thermal remote sensing of the Los Humeros Volcanic Complex: Implications for volcano structure
412 and geothermal exploration, *J. Volcanol. Geoth. Res.*, 301, 221–237, <https://doi.org/10.1016/j.jvolgeores.2015.05.014>,
413 2015.
- 414 Matsumoto, A., and Nakagawa, M.: Formation and evolution of silicic magma plumbing system: Petrology of the volcanic
415 rocks of Usu volcano, Hokkaido, Japan, *J. Volcanol. Geoth. Res.*, 196, 185–207,
416 <https://doi.org/10.1016/j.jvolgeores.2010.07.014>, 2010.
- 417 Pribnow, D.F.C., Schütze, C., Hurter, S.J., Flechsig, C., Sass, J.H.: Fluid flow in the resurgent dome of Long Valley
418 Caldera: Implications from thermal data and deep electrical sounding. *J. Volcanol. Geoth. Res.*, 127, 329–345,
419 [https://doi.org/10.1016/S0377-0273\(03\)00175-6](https://doi.org/10.1016/S0377-0273(03)00175-6), 2003.
- 420 Stix, J., Kennedy, B., Hannington, M., Gibson, H., Fiske, R., Mueller, W., Franklin, J.: Caldera-forming processes and the
421 origin of submarine volcanogenic massive sulfide deposits, *Geology*, 31, 375–378, [https://doi.org/10.1130/0091-
422 7613\(2003\)031<0375:CFPATO>2.0.CO;2](https://doi.org/10.1130/0091-7613(2003)031<0375:CFPATO>2.0.CO;2), 2003.
- 423 Tomiya, A., Takahashi, E., Furukawa, N., Suzuki, T.: Depth and evolution of a silicic magma chamber: Melting
424 experiments on a low-K rhyolite from Usu volcano, Japan, *J. Petrol.*, 51, 1333–1354,
425 <https://doi.org/10.1093/petrology/egq021>, 2010.



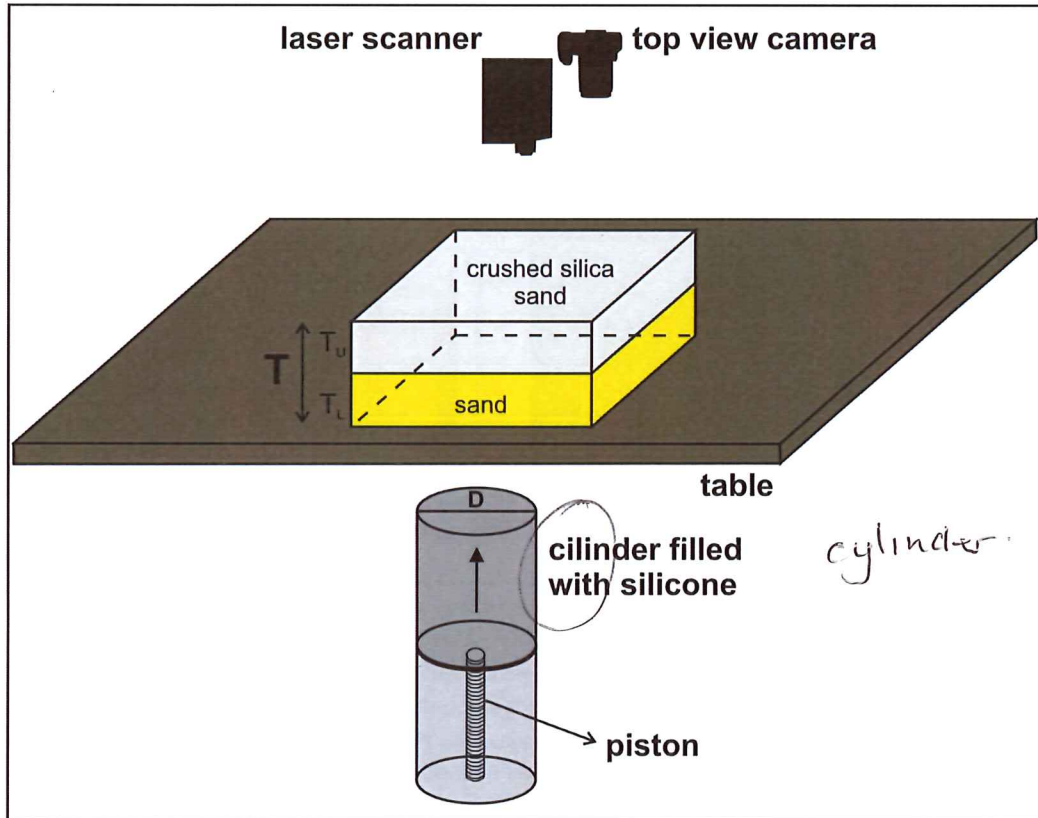
- 426 Verma, M.P., Verma, S.P., and Sanvicente, H.: Temperature field simulation with stratification model of magma chamber
427 under Los Humeros caldera, Puebla, Mexico, *Geothermics*, 19, 187–197, [https://doi.org/10.1016/0375-6505\(90\)90015-](https://doi.org/10.1016/0375-6505(90)90015-4)
428 [4](https://doi.org/10.1016/0375-6505(90)90015-4), 1990.
- 429 Verma, S.P., Gómez-Arias, E., and Andaverde, J.: Thermal sensitivity analysis of emplacement of the magma chamber in
430 Los Humeros caldera, Puebla, Mexico, *Int. Geol. Rev.*, 53, 905–925, <https://doi.org/10.1080/00206810903234296>, 2011.
- 431 Verma, S.P.: Magma genesis and chamber processes at Los Humeros caldera, Mexico - Nd and Sr isotope data, *Nature*,
432 302, 52–55, <https://doi.org/10.1038/302052a0>, 1983.
- 433 Verma, S.P.: Geochemical evidence for a lithospheric source for magmas from Los Humeros caldera, Puebla, Mexico.
434 *Chem. Geol.* 164, 35–60, [https://doi.org/10.1016/S0009-2541\(99\)00138-2](https://doi.org/10.1016/S0009-2541(99)00138-2), 2000.



Too small

435
 436 Figure 1: a) Shaded relief image (illuminated from the NE) obtained from 15 m resolution DEM of the Los Humeros Volcanic
 437 Complex (LHVC) showing the main structural features (faults and caldera rim, modified from Norini et al. (2015); Calcagno et
 438 al. (2018)) and some geothermal wells referred in the text. In depth correlation of lithostratigraphic units along the N-S (b) and
 439 W-E (c) direction (redrawn after Carrasco-Núñez et al. (2017a) and Arellano et al. (2003)). Depth:horizontal distance=1:1.
 440 Location of the correlation line is shown in a). QigX= Xaltipan ignimbrite. The black rectangle indicates the studied area within
 441 the Los Potreros Caldera shown in Figure 3. The inset box show the location of the LHVC (black dot and arrow) within the
 442 eastern sector of the Trans Mexican Volcanic Belt (TMVB). The structural sectors S1 and S2 correspond to the resurgent block
 443 inferred by Norini et al. (2015). Seismicity data from Lermo et al. (2018).

might be better to change colour (yellow?)
 as hard to distinguish from normal
 faults



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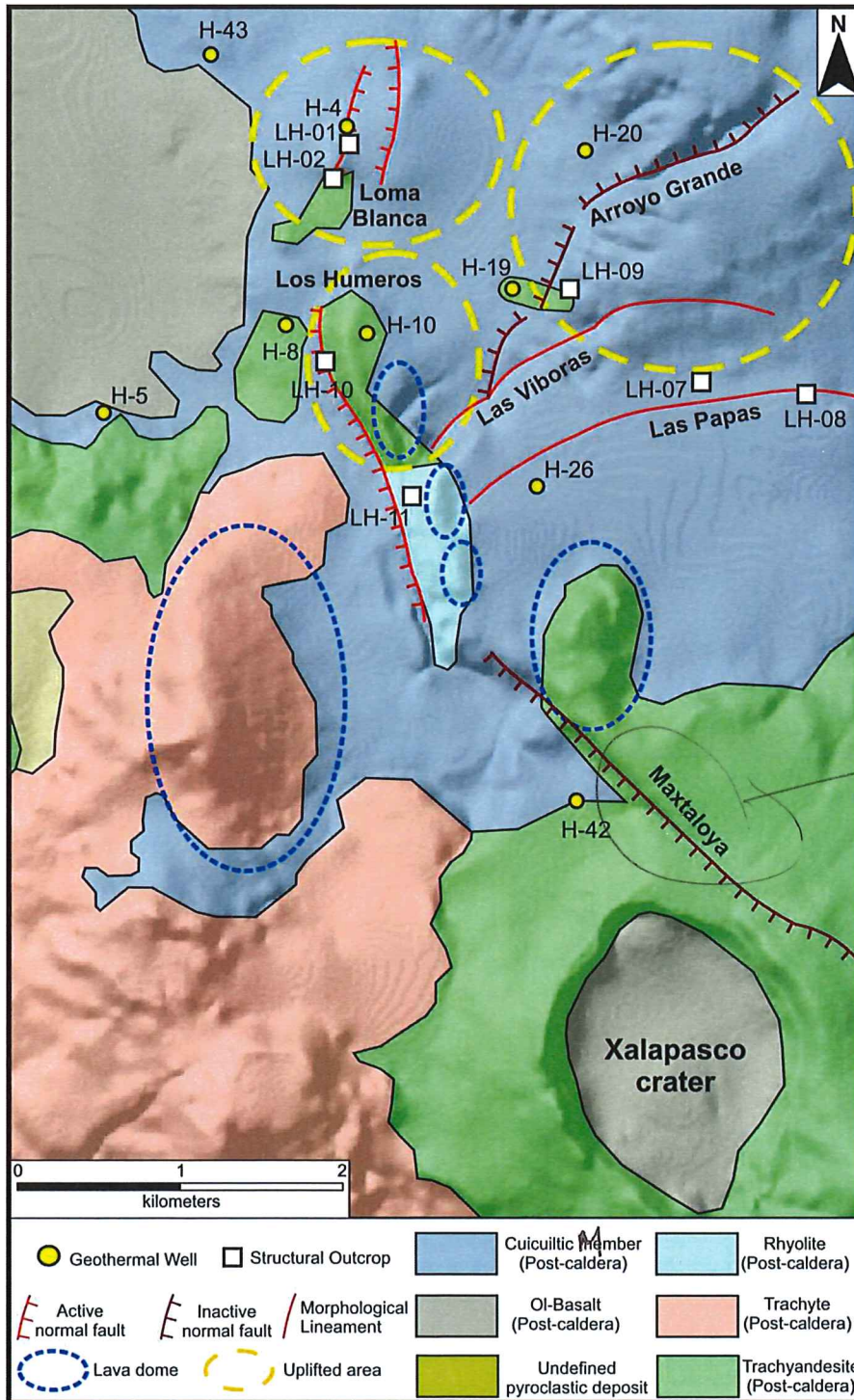
Figure 2: Experimental set-up. D= diameter of the cylinder.



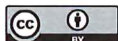
'Los
 Humeros'
 should
 be
 along
 faultt!

Hold
 Obsidian
 Dome?

Mazaloya
 in
 text!



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 467 Figure 3: Simplified geological structural map of the studied area reinterpreted after (Norini et al., 2015; Carrasco- Núñez et
 468 al., 2017b; Calcagno et al., 2018).

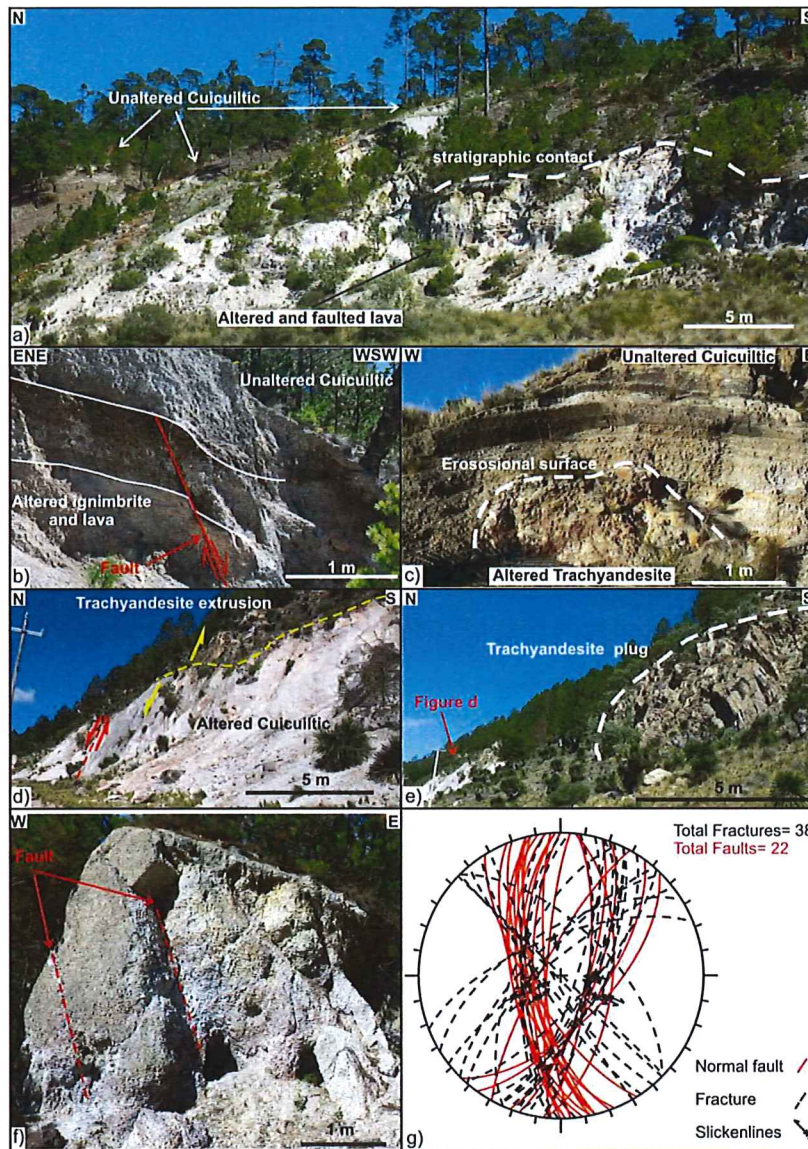


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Add
'Member'
to
'Cuicuiltic'

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470 Figure 4: a) Panoramic view from Xalapasco crater (looking towards N) of the rhyolitic lava domes aligned N-S. b) Panoramic
471 view of the E-W trending Las Papas scarp. c) Unaltered Cuicuiltic (LH-07). d) Unaltered Cuicuiltic covering a layered
472 pyroclastic deposit (LH-08). The erosional surface preceding the deposition of the Cuicuiltic is shown (dashed white line).

Member



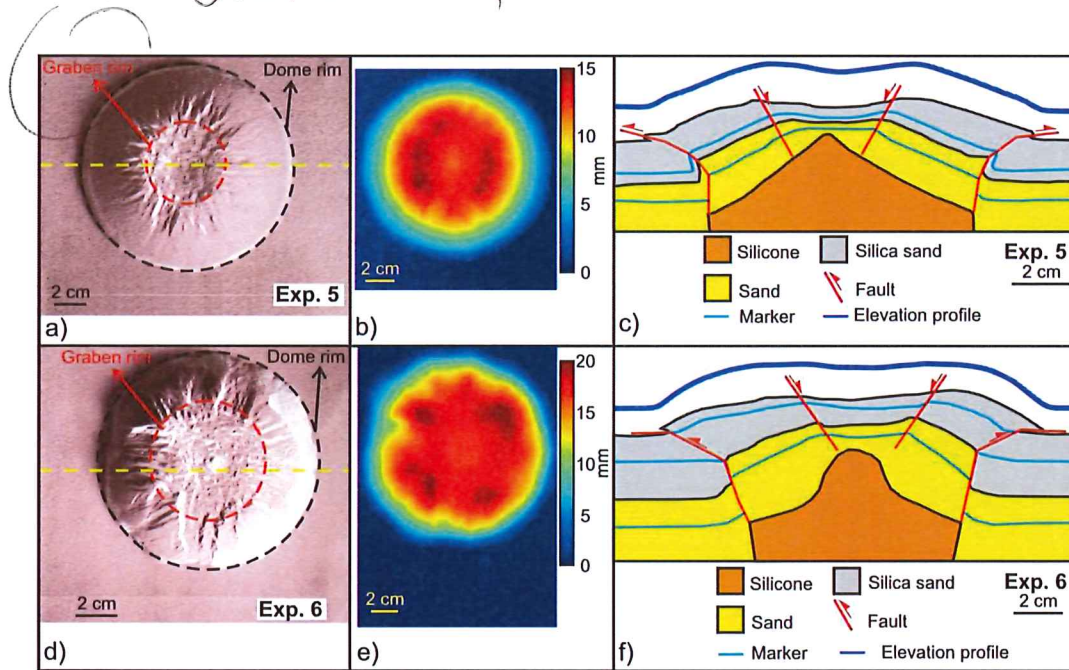
Don't use red on photos for lettering hard to read.

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 474 Figure 5: a) Panoramic view of the Arroyo Grande fault scarp showing the Unaltered Cuicuiltic covering the altered and faulted
 475 ignimbrite and lavas. b) Normal fault affecting the altered ignimbrite deposits unconformably covered by the post-caldera,
 476 unaltered Cuicuiltic deposits (LH-09). Note that the Cuicuiltic deposits are not faulted at this location; the fault can be thus
 477 considered as a fossil fault with respect to the Cuicuiltic deposition. c) Block of altered trachyandesite buried by unaltered
 478 Cuicuiltic layers along the Maztaloia fault scarp. d) Los Humeros fault scarp (LH-10) induced by the ascent of the rhyolitic
 479 extrusion on top of the fault plane. e) Rhyolitic plug cropping out ~150 southward the fault scarp shown in d) (indicated by the
 480 red arrow). f) Normal faulting and alteration of the Cuicuiltic member within the apical graben of the Loma Blanca dome (site
 481 LH-01). g) Equal-area stereo-plot of the attitudes of faults and fractures in all the structural outcrops.

trachyandesite on photo!



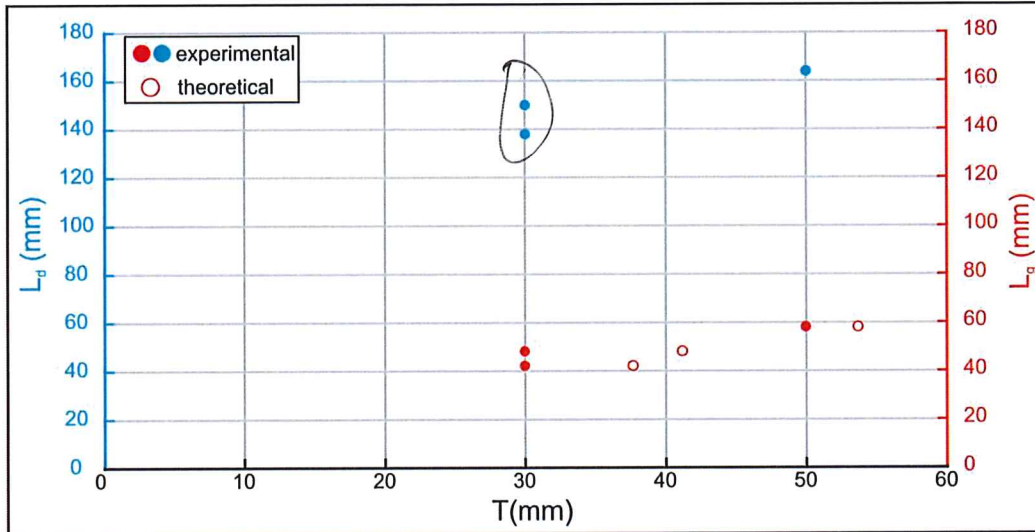
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Why exclude 4?

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 483 Figure 6: a) d) Top view image of the experiments 5 and 6. b) e) cumulative vertical displacement; colour scale is proportional
 484 to the amount of uplift. c) f) Drawing of the cross section view obtained after cutting the section close to the dome center. The
 485 elevation profiles are obtained from laser scanner data. The yellow dashed line in the top view images indicates the trace of the
 486 section views and of the elevation profiles.
 (a) + (c)

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Are there from different experiments?

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511 Figure 7: L_g (graben width) and L_d (dome diameter) versus T . Theoretical values calculated after equation 1 (see discussion
512 section).

apical

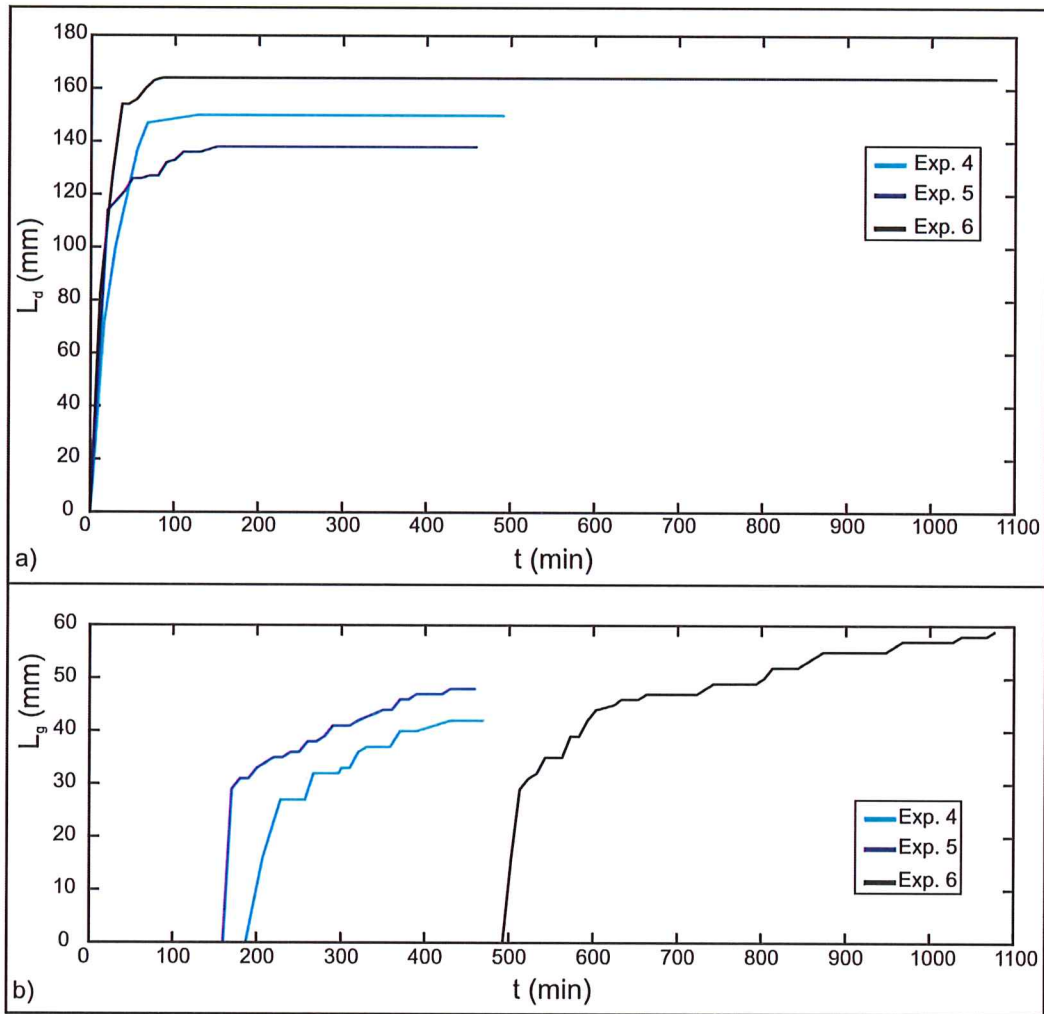
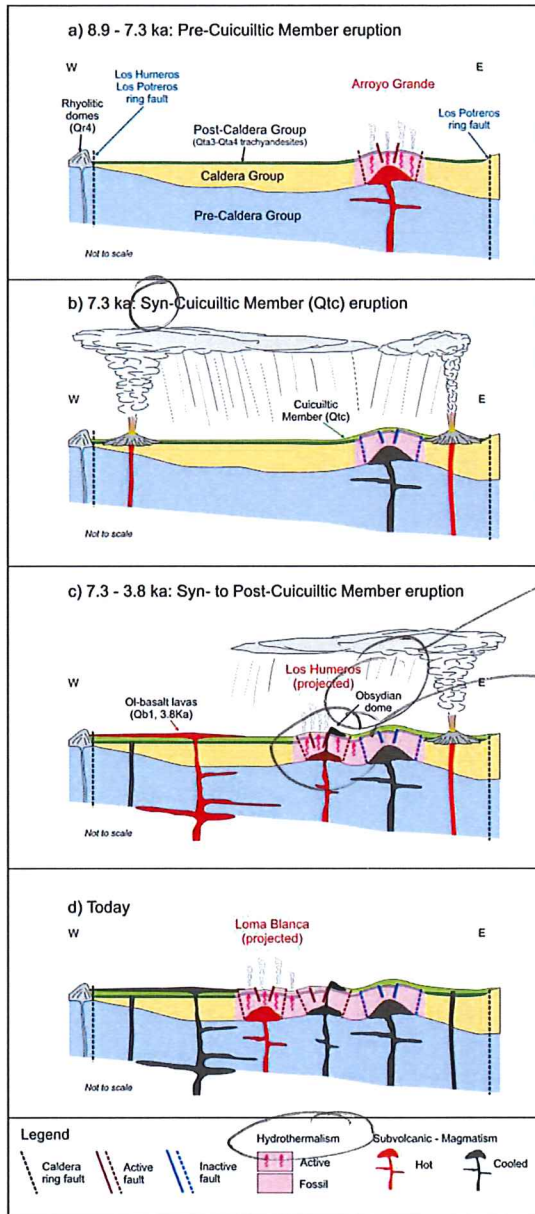


Figure 8: a) L_d versus time b) L_g versus time.

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caption needs expansion!



Obsidian.
 Why 'Projected'?

Hydrothermal alteration

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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 Cuicuiltic 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-Cuicuiltic stage: eruption of the Cuicuiltic Member covering the hydrothermally altered post-caldera trachyandesitic lavas. c) Syn to post Cuicuiltic stage: formation of the Los Humeros fault and extrusion of obsidian lava domes along the fault scarp. As the trachyandesitic domes are covered with Cuicuiltic Member only at his base, the lava extrusion occurred during and post the Cuicuiltic eruption. d) Formation of the Loma Blanca bulge with the current hydrothermal activity and extensional faulting occurring within the apical graben.

eruption

obsidian



Parameter	Definition	Value
T	Thickness of the sand overburden	1.5×10^{-2} m
L_d	Dome diameter	1.6×10^{-1} m
H	Dome height	$1.3-2 \times 10^{-2}$ m
ρ_s	Sand density	1400 kg/m ³
ϕ	Angle of internal friction of sand	25-40°
τ_0	Sand cohesion	300 Pa
ρ_m	Silicone density	1000 kg/m ³
μ_m	Silicone viscosity	10 ⁴ Pa s
g	Gravity	9.8 m/s ²
t	Experiment duration	$2-6.5 \times 10^4$ s

539 Table 1. Geometric and material properties parameters of the experiments.

Dimensionless ratio	Experiments	Nature
$\Pi_1 = T/L_d$	0.1-0.6	0.04-0.6
$\Pi_2 = H/L_d$	0-0.12	0-0.12
$\Pi_3 = \rho_s/\rho_m$	1.4	0.6-1.4
$\Pi_4 = \phi$	35	25-40
$\Pi_5 = \rho_m H^2 / \mu_m t$	6×10^{-10}	1.8×10^{-8}
$\Pi_6 = \rho_m g H t / \mu_m$	1.3×10^3	6.9×10^2
$\Pi_7 = \rho_s g T / \tau_0$	4.57	8.24

540 Table 2. Definition and values of the dimensionless ratios Π in nature and in the experiments.

Exp	T (mm)	L_g (mm)	L_d (mm)	θ	α	T_t (mm)	σ (%)
4	30	42	150	58°	14°	37.7	27
5	30	48	138	56°	18°	41.2	37
6	50	58	164	58°	21°	53.7	7

541 Table 3. Measured parameters in the experiments. T=overburden thickness; L_d =dome diameter; L_g =graben width; θ =graben
 542 fault dip; α =dome flank mean dip; T_t =theoretical overburden thickness calculated with equation 1 (Brothelande and Merle,
 543 2015, see discussion section); σ =percentage difference between T and T_t .

Why 4, 5, 6?

apical apical