Structural studies in active caldera geothermal systems. Reply to Comment on “Estimating the depth and evolution of intrusions at resurgent calderas: Los Humeros (Mexico)” by Norini and Groppelli (2020).

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Abstract Structural studies in active caldera systems are widely used in geothermal exploration to reconstruct volcanological conceptual models. Active calderas are difficult settings to perform such studies mostly because of the highly dynamic environment, dominated by fast accumulation of primary and secondary volcanic deposits, the variable and transient rheology of the shallow volcanic pile, and the continuous feedbacks between faulting, secondary porosity creation and geothermal fluid circulation/alteration/cementation that tend to obliterate the tectonic deformation structures. In addition, deformation structures can be also caused by near- and far-field stress regimes, which include magmatic intrusions at various depths, the evolving topography and regional tectonics. A lack of consideration of all these factors may severely underpin the reliability of structural studies. By rebutting and providing a detailed discussion of all the points raised by the comment of Norini and Groppelli (2020) to the Urbani et al. (2020) paper, we take the opportunity to specify the scientific rationale of our structural fieldwork and strengthen its relevance for geothermal exploration/exploitation in active caldera geothermal systems in general, and, particularly, for the Holocene history of deformation and geothermal circulation in the Los Humeros caldera. At the same time, we identify several major flaws in the approach and results presented in Norini and Groppelli (2020), such as: (1) lack of an appropriate ranking of the deformation structures considering an inventory method for structural analysis; (2) misinterpretation and misquoting of Urbani et al. (2020) and other relevant scientific literature; and (3) irrelevant and contradictory statements within their comment.

1 Introduction

Structural studies in active calderas provide key elements for the exploration of geothermal systems and greatly contribute to the development of conceptual models for their exploitation. We herein reply to the comment by Norini and Groppelli (2020) on our paper Urbani et al. (2020) entitled “Estimating the depth and evolution of intrusions at resurgent calderas: Los Humeros (Mexico)”, giving us the opportunity to further discuss our approach, results and the proposed reconstruction of the Holocene volcano-tectonic evolution of the Los Humeros Volcanic Complex (LHVC; Mexico) and its relevance for understanding of the active geothermal system.

2 Reply to the criticism raised in the comment

The Norini and Groppelli (2020) criticism of the Urbani et al. (2020) paper concentrates on three main aspects: (1) supposed lack of structural field data and supposed geometric and structural inconsistency between the Holocene deformation and the proposed subsurface model; (2) supposed lack of validation of the obtained results with those available from well-logs data; and (3) supposed contradictions with the available stratigraphic reconstruction and radiometric ages.

Here follows a point-by-point discussion of the critical points raised in Norini and Groppelli (2020).

2.1 Las Papas and Las Viboras structures: inventory vs. selective method of structural analysis in active volcanic areas

Norini and Groppelli (2020) question the reinterpretation made by Urbani et al. (2020) of Las Papas and Las Viboras structures as presently inactive morphological scarps, showing small-scale faults in the Cuicuiltic Member (see Fig. 2 of Norini and Groppelli (2020)). They are also critical of the supposedly few data presented. In contrast to the inventory method followed by Norini and Groppelli (2020), where all faults are mixed together without any hierarchy and discussed as unweighted data, in Urbani et al. (2020) we followed a selective method of structural analysis.. By using this method, we ranked faults adopting the following criteria in the field: (i) the topographic expression of the fault, (ii) the amount of displacement of individual fault strands and/or fault systems; (iii) the along-strike persistence of the fault trace; (iv) the presence of clear kinematic indicators; (v) the presence or absence of associated hydrothermal alteration, and (vi) the relative age with respect to the Holocene intracaldera Cuicuiltic Member fall deposit. Regarding this last criteria, the Cuicuiltic Member is regarded as a reference space-time marker to discriminate faults older or younger than 7.3 ka due to its well-known age and distribution within the caldera (Dávila-Harris and Carrasco-Núñez, 2014; Carrasco-Núñez et al., 2017a). Accordingly, in Urbani et al. (2020) we described only selected faults that exhibited clear m-scale offsets, consistent lateral extent and/or evidence of hydrothermal alteration. We therefore strongly reject that our data set is poor, because it deals with structures that, based on the above listed criteria, allowed us to discriminate and rank volcano-tectonic and hydrothermal processes, which are instead missed by the inventory method of unweighted fault dataset adopted by Norini and Groppelli (2020). In terms of geothermal exploration, the faults presented in Norini and Groppelli (2020) are indeed questionable in terms of relevance. For example, the LH17106 and LH62 outcrops shown in Fig. 2c of Norini and Groppelli (2020) are in the same location of outcrop LH-08 shown in Fig. 5c of Urbani et al. (2020), where an erosional surface at the top of undeformed and unaltered pyroclastic deposits of the Xoxoctic Tuff, blanketed by the Cuicuiltic Member is clearly visible. Fig. 1a of this reply shows the same outcrop, where the erosional unconformity at the top of the underlying subhorizontal pyroclastics is sutured by the Cuicuiltic Member fall deposits. The large-scale blanketing geometry of the unaltered Cuicuiltic Member fall deposits across the Las Papas scarp is well visible in Fig. 1b of this reply. This indicates that Las Papas is currently an inactive morphological scarp without evidence of hydrothermal alteration. Whether or not this scarp was associated in origin (prior to 7.3 ka) with a fault trace is not evident in the field nor relevant for our study, focused on present-day relationships between faulting and geothermal circulation. Noteworthy, even Norini et al. (2019; see sections 4 and 6.2) raise doubts on the relevance of the Las Papas structure within the Los Humeros geothermal field, suggesting a weak or no connection with the geothermal reservoir. The same holds for the Las Viboras structure.

In our opinion, the small-scale faults shown by Norini and Groppelli (2020) in their Fig. 2d-e are not at all compelling and may be alternatively interpreted as small-scale normal faults generated by near-field (local) stresses affecting unlithified material (e.g., Wernicke and Birchfiel, 1982; Bridgewater et al., 1985; Branney and Kokelaar, 1994; Gao et al., 2020; Yang and Van Loon, 2016). In particular, Fig. 2d of Norini and Groppelli (2020) is unclear, whereas Fig. 2e does not show any evidence of displacement of the lower white and black pumice beds, as well as on the upper brown beds, suggesting an intraformational readjustment (Fig. 1c) rather than a fault. (e.g. Van Loon and Wiggers, 1975, 1976; Branney and Kokelaar, 1994). Norini and Groppelli (2020) fail to discuss any possible alternative origin for their small-scale faults, which, considering their location is in an active caldera floor, severely impinges the reliability of the inventory dataset presented in Norini and Groppelli (2020) and its relevance for geothermal studies. Reinterpreting the small-scale offsets shown in Fig. 2 on Norini and Groppelli (2020) as minor gravitational structures (i) would justify why they have no connection with the geothermal circulation nor with any thermal anomaly, and (ii) clarifies to the reader why the Urbani et al. (2020) paper instead focused only on faults that were ranked as of first-order importance in terms of displacement, persistence in the field and age of the structurally-controlled hydrothermal fluid circulation.

In summary, we (i) question the use of the inventory method for structural analysis adopted by Norini and Groppelli (2020) when applied to active calderas, which may prove to be inappropriate and unable to discriminate first-order, deep and geothermally relevant, fault systems from small-scale, soft-state deformation structures that are also common in intracaldera domains (e.g., Branney and Kokelaar, 1994); and (ii) consider the selective method of structural analysis used by Urbani et al. (2020) as fully appropriate to rank deformation structures (Fig. 1a-i) when the aim of a structural fieldwork is to characterize the surface deformation related to the recent activity of a caldera, in order to constrain the morphotectonic fingerprints of the resurgence, to evaluate its source and areal extent and, even more importantly, its relevance for the active geothermal system.

2.2 Arroyo Grande and Maxtaloya faults: the importance of tracking fluid path migration in space and time

Norini and Groppelli (2020) state that *"active/fossil alteration doesn't always allow identifying faults or the age of faulting, because it depends also on their depth, life span of the hydrothermal system, spatial relationships, and fluid paths along primary permeability and faults zones (Bonali et al., 2016; Giordano et al., 2016)".* Although geothermal fields may develop also associated with primary porosity (Hurter and Shellschmidt, 2003), the two studies cited by Norini and Groppelli (2020) are in no way at odds with Urbani et al. (2020). The work of Bonali et al. (2016), on the active tectonics at Copahue (Argentina) points out that active fault systems in volcanic settings are responsible for driving hot fluids to the surface. Similarly, the works of Giordano et al. (2013; 2016) on the Tocomar geothermal field (Puna Plateau, Argentina), investigated the evidence of a geothermal field based of the overlapping distribution of hot springs and active fault systems. We thank Norini and Groppelli (2020) for reporting to our attention these two very interesting papers because, along with mainstream literature (e.g. Karaoğlu et al. 2019), they clearly indicate that hydrothermal fluids and associated alteration in volcanic settings are driven/controlled by active fault systems. The relationship between faulting and fluid circulation is well established also in exhumed systems, where it is clear how fault-permeability is affected by the interplay between far-field regional stress field and the near-field stress regime (e.g. Rossetti et al. 2011; Olvera Garcia et al. 2020). Therefore, the cited papers support the proposal of Urbani et al. (2020) to use the distribution and intensity of the hydrothermal alteration within the 7.3 ka Cuicuiltic Member marker beds, that ubiquitously blanket the caldera floor and all the fault scarps, as a valid space-time marker in the field to discriminate active vs. inactive fault segments controlling the upwelling of geothermal fluids (Fig. 1d-i). In contrast to Norini and Groppelli (2020), we conclude that, in agreement with authoritative literature, hydrothermal alteration follows the space-time distribution of structurally-controlled (fault-induced) secondary permeability pathways and its distribution should be used, along with measured fault displacements, persistence and (relative) age, as an indication of fault activity and ranking for geothermal purposes. At Los Potreros, the presence of the 7.3 ka Cuicuiltic Member marker bed allowed us to track the type and intensity of deformation and its association with fluid circulation and alteration in space and time.

2.3 Surface thermal anomalies

Norini and Groppelli (2020) state *"The Maxtaloya fault trace is coincident with a sharp thermal anomaly identified by Norini et al. (2015). Urbani et al. (2020) didn't consider this positive (warm) anomaly when they discussed the thermal remote sensing results published by Norini et al. (2015) (Section 5.3 in Urbani et al., 2020)"*. This statement is not correct, because we did discuss the published remote sensing results as clearly written in section 5.3 of Urbani et al. (2020). Moreover, the sharp and narrow temperature peaks, described by Norini et al. (2015), are spatially coincident with the

Los Humeros and Loma Blanca faults described by Urbani et al. (2020). This scenario is further supported by the recent work of Jentsch et al. (2020; see also Deliverable 4.3 of GEMex, 2019a), where soil temperature anomalies (T > 43°C) are identified only at Los Humeros and at Loma Blanca areas, whereas no thermal anomaly is recognized along other sections of the Maxtaloya fault (see Fig. 5a in Jentsch et al. 2020). We therefore reject the criticism from Norini and Groppelli (2020), who instead failed to consider the recent results presented by Jentsch et al. (2020) and Peiffer et al. (2018).

2.4 Identification and geometry of uplifted areas: topographic data and structural mapping

Norini and Groppelli (2020) criticize the location and geometry of the three uplifted areas of Los Humeros, Loma Blanca and Arroyo Grande identified by Urbani et al. (2020). However, in the topographic profiles across the bulges shown by Norini and Groppelli (2020) in their Fig. 4a-b, the uplifted areas at Loma Blanca, Arroyo Grande and Los Humeros are well visible and the existence of such bulges is unquestionable. Therefore, it is unclear on what basis Norini and Groppelli (2020) question the existence of such uplifted areas. The asymmetry (Arroyo Grande) and tilt of the uplifted areas (Loma Blanca) detailed by Norini and Groppelli (2020) are in no way adversative to the Urbani et al (2020) interpretation. Again, it is unclear why these shapes are reported as counterproof. Asymmetric bulges are common characteristics in many volcanic regions worldwide, in resurgent calderas (e.g. Ischia, Pantelleria, Sierra Negra and Alcedo; Galetto et al. 2017 and references therein) or associated with shallow intrusions, such as Usu (Goto and Tomiya, 2019), Chaine de Puys (van Wyk de Vries et al., 2014; Petronis et al 2019), Bezymianny (Gorshkov, 1959) and Mt St. Helens (Lipman, et al. 1981). Despite being stimulating for future works, investigation of the exact origin of the bulge shapes was far beyond the scope of Urbani et al. (2020), who, for this reason, maintained the same initial and simplified geometric configuration for the analogue models. Therefore, the comment made by Norini and Groppelli (2020) is not relevant for the discussion presented in Urbani et al. (2020).

2.4.1 Apical depression of bulges

The model proposed by Urbani et al. (2020) predicts the formation of an apical depression on the top of a bulge induced by a shallow intrusion. Norini and Groppelli (2020) state that the topography of natural bulges identified by Urbani et al. (2020) does not show well-defined apical depressions in the asymmetric Arroyo Grande and Los Humeros uplifted areas, contradicting the model results. Analogue modeling in Urbani et al (2020) inject symmetric intrusions, a condition appropriate for the morphology of the Loma Blanca bulge, where the apical depression is very well evident (Fig. 2) and measured in the field (Fig. 6f in Urbani et al. 2020). The Arroyo Grande and Los Humeros bulges are instead asymmetrical, and likely developed as trapdoor uplifts (thus without apical depression) associated with asymmetric intrusions and with a deformation amount much larger than that at Loma Blanca and that considered in the analogue models. Therefore, the comment made by Norini and Groppelli (2020) is incorrect regarding the Loma Blanca bulge and not relevant in the other two cases and, consequently, the predictive value of the model proposed by Urbani et al. (2020) is in no way compromised. Indeed, the experiments were designed to ensure the formation of an apical depression not considering the trapdoor uplift/faulting and the asymmetric bulges are not directly modeled. .

2.4.3 Reverse faults bounding uplifted areas

Norini and Groppelli (2020) state that Urbani et al. (2020) do not provide independent validation of the proposed multiple magmatic intrusion model, such as field evidence of reverse faults predicted by the analogue modeling results. Exposure of faults in active caldera floors depends on many factors: (i) elastic vs. anelastic response to deformation source, its location, intensity and duration, (ii) nucleation depth and surface propagation and (iii) burial vs. exhumation rates. Therefore, while reverse faults accompanying both large-scale resurgence and local uplifts are expected by analogue models, the scarcity of visible and measurable reverse faulting in no way disproves the hypothesis related to the intrusion of cryptodomes and resurgence (Bonanza, Lipman et al., 2015; Long Valley, Hildreth et al., 2017; Kutcharo, Goto and McPhie, 2019). Therefore, the statement by Norini and Groppelli (2020) claiming that the locations of such reverse faults "*are a fundamental feature of their model*" is incorrect. In addition, Norini and Groppelli (2020) show the traces of inferred reverse faults at the periphery of the Loma Blanca bulge, just where the Urbani et al. 2020 model predicts (see Fig. 2), making Norini and Groppelli 2020 own statements contradictory.

2.5 Validation of the proposed model: geothermal wells log data

2.5.1 Lithology of intrusions

Norini and Groppelli 2020 invoke the thermal profile and the stratigraphy of just one well log (H4 well, drilled on the top of the Loma Blanca bulge) to claim the lack of validation of the models proposed in Urbani et al. (2020). First, we would like to emphasize that the proposed reinterpretation of the subsurface stratigraphy presented in Urbani et al. (2020) is not just based on the H4 well. A great part of section 2 ("Geological-structural setting") and Figs. 2a-b presented in Urbani et al. (2020) discuss in detail the published data from twelve well logs (including the H4 well log) as presented in Arellano et al. (2003) and in Carrasco-Núñez et al. (2017a, 2017b). The model evaluation of the intrusion depths, as derived from the equation of Brothelande and Merle (2015), are valid within the modelling assumptions and are within the depth range of some rhyolitic-dacitic bodies drilled in geothermal wells, wherein they are simply described texturally as lavas (Carrasco-Núñez et al., 2017b and references therein). The lithologic definition of "lava" is associated with aphanitic to phaneritic textures that are not only restricted to subaerial environments and may be impossible to distinguish from textures of sub-volcanic/hypabyssal bodies. Hypabyssal rocks are characterized by a rapid cooling and their textures are fine grained or glassy, and mostly resemble those of volcanic rocks (Phillpots and Ague, 2009). One of the most famous examples of felsic hypabyssal intrusions in intracaldera ignimbrite deposits is in Long Valley Caldera (California). At Long Valley, the well logs revealed ca. 300 m cumulative thick succession of aphanitic to phyric rhyolitic intrusions emplaced during the post-caldera stage, into the older, ca. 1200 m thick, intracaldera Bishop Tuff (McConnell et al., 1995). We therefore reject the criticism by Norini and Groppelli (2020) as the interpretation is based not only on the H-4 well but also on stratigraphic reconstructions derived from 12 published well logs

2.5.2 Geometry of caldera fill

The reinterpretation proposed by Urbani et al. (2020) of some of the rhyolitic-dacitic bodies of the Los Potreros subsurface as hypabyssal intrusives is not simply based on their lithology, but also on their geometry, stratigraphic position, as well as the whole geometry of the caldera fill; all elements neither considered nor discussed in Norini and Groppelli (2020). When correlating the stratigraphic well-logs, Urbani et al. (2020) documented (in section 2 at p. 530 and Fig. 2) the irregular geometry of both the top of the Xaltipan intracaldera ignimbrite and the post-caldera units, as well as the lack of a clear topography filling geometry: a stratigraphic setting that can be hardly reconciled with an intracaldera setting unless the emplacement of intrusive bodies has occurred in the shallow crust. Noteworthy, the main geometric anomalies of the caldera fill appear right in correspondence with the possible location of a felsic intrusion. For example, a 600 m-thick rhyolitic-dacitic body showing all the petrographic features of a hypabyssal intrusion is reported to the west of Arroyo Grande in the H20 well at 470-1060 m of depth from the surface (see also Carrasco-Núñez et al. (2017b). It is located at the top of the pre-caldera andesites, intrudes both the intracaldera and the post-caldera units, and shows no lateral continuity. Similar felsic bodies were also drilled in H5, H26, H19 and H25 wells. Furthermore, Norini and

Groppelli (2020) completely misinterpreted and misquoted a recent work by Cavazos-Alvarez et al. (2020), which only deals with the reinterpretation of andesitic layers within the Xaltipan intracaldera ignimbrite (see blue ellipses in wells: H10-Fig. 3a; H20-Fig. 3b; and H42-Fig. 3e) and does not question the interpretation of the rhyolite bodies proposed by Urbani et al. (2020) as small intrusions located above and below the Xaltipan ignimbrite. With regard to these rhyolite bodies, Cavazos-Alvarez et al. (2020) not only confirm their existence in wells H20 and H26 (red ellipses in Figs. 3b and 3d of this reply), but also identify previously unrecognized (i) ca. 400 m cumulative thick rhyolite layers (between ca. 500-1000 m below the surface) in well H25 (Fig. 3c), and (ii) a ca. 50 m thick rhyolite layers (between 850-900 m below the surface) in well H42 (Fig. 3e). The depths of these rhyolitic layers are compatible with the estimated intrusion depth of 425 ±170 m proposed by Urbani et al. (2020) for the emplacement of small cryptodomes within the volcanic sequence. It should be emphasized that the presence of rhyolitic bodies within the volcanic sequence in the Los Potreros intracaldera domain is also reported in the geological cross-section included in the recently updated geological map of Los Humeros (Carrasco-Núñez et al. 2017a). Summarizing, we have demonstrated the agreement between the works of Carrasco-Núñez et al. (2017a, 2017b), Urbani et al. (2020) and Cavazos-Alvarez et al. (2020) for what concerns the subsurface stratigraphy of the Los Potreros intracaldera domain, and therefore we reject the criticism of Norini and Groppelli (2020).

2.5.3 Thermal gradient

The statement by Norini and Groppelli (2020) on the absence of an in-depth sharp increase of the temperature and geothermal gradient in the H4 well (considered to remain constant at ca. 20 °C/km; see Fig. 3d in Norini and Groppelli (2020)) is not correct. The existing published in-depth temperature profiles of the H4 well (Fig. 4a; after Torres-Rodriguez, 1995; Prol-Ledesma, 1988, 1998; Martinez-Serrano, 2002) show a clear sharp temperature increase (+150 °C) in less than 200 m, up to 300 °C at 1000 m below the surface. The temperature profile is then characterized by a progressive temperature decrease down to ca. 200 °C at 2000 m depth. Such temperature profile is not observed in the very close H43 well (Fig. 4a, after Lorenzo-Pulido, 2008). Significantly, on the top of the Loma Blanca bulge, very close to the H4 well, Norini et al. (2019) and also Norini and Groppelli (2020) report *"a warm normal fault"* in the Cuicuiltic Member deposits and documented it through a thermal image (Fig. 5b in Norini et al., 2019; Fig. 3 in Norini and Groppelli (2020), Figs. 1e-g in this reply), confirming the active thermal activity in the Loma Blanca area. Furthermore, 300 m away from the H4 well, at the southern termination of the Loma Blanca fault, Jentsch et al. (2020) measured the highest surface temperature (91.3 °C) of the whole Los Potreros caldera, corresponding to an active solfatara (Figs. 1h-I, 4b).

2.6 Validation of the proposed model: stratigraphic and radiometric data

2.6.1 Age of the domes along Los Humeros fault

Norini and Groppelli (2020) question the presence of domes younger than 7.3 ka based on stratigraphic and radiometric data presented in Carrasco-Núñez et al. (2018). Fig. 5 shows, in agreement with the geological map of Carrasco-Núñez et al. (2017a), a perspective view of the Los Potreros caldera floor across the Maxtaloya and Los Humeros faults. The images show the presence of lava domes and flows of variable composition both covered by and emplaced above the 7.3 ka Cuicuiltic Member. Older lavas include those associated with the "Resurgent Phase" (50.7-44.8 ka; "Qr1" in Carrasco-Núñez et al., 2018 and references therein). Younger lavas show absence of the 7.3 ka Cuicuiltic member cover and a morphology poorly or unaffected by evidence of faulting. It should be noted in Fig. 5 that the Obsidian dome is also the site of a sample whose magmatic zircon crystallization age was U-Th dated at 44.8 ka in Carrasco-Nunez et al. 2017. At the same time, the dome is largely not covered by the Cuicuiltic member. As the dated sample was taken at the base of the dome, this can be interpreted in various ways: one is that the dome is polyphased and its upper part is younger than 7.3 ka resting above the Cuicuiltic member; the other is that the dome was exhumed after 7.3ka. The emplacement/exhumation of the obsidian dome and the nearby faulting of the Cuicuiltic member by tens of meters of displacement at the site of the Los Humeros fault indicates that this section of the fault was active later than 7.3 ka. By contrast, the fault displacement drastically reduces southward along the Maxtaloya fault. This in our opinion supports our interpretation of the Maxtaloya-Los Humeros faults as segmented and diachronous during Holocene, in agreement with the Urbani et al 2020 interpretation.

2.6.2 Recent history of caldera floor uplift

Norini and Groppelli (2020) misquote Urbani et al. (2020), attributing to them the interpretation of a northward shift in volcanic activity within the Los Potreros caldera, which was neither declared nor intended in the paper. Urbani et al (2020) simply summarize field evidence stating "*the recent (post-caldera collapse) uplift in the Los Potreros caldera moved progressively northwards, from the south and north-eastern sector of the caldera towards the north along the Los Humeros and Loma Blanca scarps*". Urbani et al. (2020) did not discuss the causes of such northward shift and even less attributed it to a shift in "the volcanic feeding system" as erroneously and unjustifiably reported by Norini and Groppelli (2020). The fate of a magma intrusion, i.e. whether it will erupt or stop in the crust, depends on many factors, such as its buoyancy (density contrast with host rocks), the initial gas content, the rise speed and style of decompression-degassing, the rheology of the magma and of the intruded crust, including its layering, structure and so forth. The evolution over time and space of intrusions in a caldera may see different phases and have many different causes, partly depending on feedbacks existing between the evolving configuration of the magmatic plumbing system and the evolving rheology and structure of the caldera roof rocks. The plumbing system of the last 10 ka at Los Humeros has been reconstructed in detail by Lucci et al (2020). This study documents a multistorey magmatic complex, which allows the eruption along the Los Potreros caldera floor of both deep-sourced (>30 km) olivine basalts and shallow-differentiated (< 3 km) felsic trachytes and rhyolites. The results of Lucci et al. (2020), curiously neither cited nor discussed by Norini and Groppelli (2020), highlight the absence of the classic large volume, single magma chamber and suggest that the activation of magma sources at different depths appear not to have followed any specific pattern during the Holocene. A corollary of the present absence below Los Humeros of a single large magma chamber/crystal mush able to form a rheological barrier to the rise of basalts directly from lower crustal depths severely impinges upon the model of classic resurgence supported by Norini and Groppelli (2020), which requires the existence of a voluminous viscous layer accommodating magma recharge and acting as a pressure source for resurgence (Galetto et al. 2017).

3. Summary and implications for the Los Humeros geothermal system

Understanding the anatomy of magma plumbing systems of active volcanic systems, from deeper reservoirs to subsurface ephemeral batches, is crucial to define temperature, depth and geometry of the heat sources for geothermal exploration. The Pleistocene-Holocene Los Humeros Volcanic Complex (LHVC), located in the eastern Trans-Mexican Volcanic Belt (central Mexico), represents one of the most important exploited geothermal fields in Mexico, with ca. 95 MW of produced electricity. Geological investigations at LHVC started at the end of the '70 of the last century and culminated with the production of (i) the first comprehensive geological map (Fig. 6a; after Ferriz and Mahood (1984), (ii) a structural map of the intracaldera domain (Fig. 6b after Alcantara et al., 1988), (iii) the proposal of a petrological conceptual model of the plumbing system made of a single voluminous (ca. 1200 km^3) melt-dominated and zoned magma chamber at shallow depths (ca. 5 km, Fig. 6c, after Verma, 1985), and (iv) the proposal of an inflation-deflation caldera episodic/cyclic model (Fig. 6d, after Campos-Enriquez and Arredondo-Fragoso, 1992) connected to the activity of the single voluminous conventional magma chamber of Verma (1985). Since these main studies, up to the most recent published works, the understanding of the Los Humeros volcanic complex has been incremental, never questioning the consolidated model of the single zoned magma chamber where all petrologic, volcanologic and deformation processes originate (i.e., Ferriz and Mahood, 1984; Alcantara et al., 1988; Verma, 1985; Campos-Enriquez and Arredondo-Fragoso, 1992). Structural work by Norini et al. (2015, 2019), produced updates and refined versions (Figs. 6e and 6f) of the original structural map by Alcantara et al. (1988). Based on the assumption of the existence of an active single voluminous magma chamber as proposed in the early '1980s (Verma, 1985), post-caldera deformation has been interpreted uniquely as due to a classic mechanism of resurgence (e.g., Fig. 6g after Norini et al., 2019) that much (or completely) resemble the first proposal of Campos-Enriquez and Arredondo-Fragoso (1992). However, such conceptual model is now under stress as the geothermal anomalies appear very localized, mainly confined along the NNW-SSE-trending "Maxtaloya-Los Humeros-Loma Blanca-Los Conejos" corridor and corresponding to the almost unique, narrow thermal anomaly recognized within the Los Potreros caldera (Norini et al., 2015; Peiffer et al., 2018; Jentsch et al., 2020), rapidly declining away. This geothermal configuration is reflected in the relatively low number of productive geothermal wells (ca. 25 out of ca. 60; Gutierrez-Negrín et al. 2019; 2020) but is difficult to reconcile with the existence of a single, deep-seated, large-volume magmatic source that should instead generate widespread and sustained thermal anomalies in the caldera floor, such as in active resurgent calderas like Ischia (Carlino et al., 2014).

A step-change of paradigm in the reconstruction of the Holocene magmatic plumbing system at Los Humeros has been proposed in Lucci et al. (2020) and GEMex (2019c), which nevertheless their important implications for the understanding of the present-day geothermal system were not even cited by Norini and Groppelli (2020). Lucci et al. (2020) carried out a thermobarometric study of all exposed Holocene lavas, demonstrating that the scattered intracaldera monogenetic activity reflects the ascent of magmas from basaltic to trachytic in composition from sources located at depths comprised between > 30 km (basalts) to < 3 km (trachytes), and for variably evolved compositions, with complex histories of ascent and stalling at various depths, depicting a multistorey plumbing system (e.g. Cashman and Giordano, 2014; Cashman et al. 2017; Sparks et al. 2019). This innovative reconstruction of the plumbing system suggests that the large volume magma chamber at 5 km depth that produced the caldera collapses at the time of the eruption of the Xaltipan ignimbrite (164 ka) and Zaragoza ignimbrite (69 ka) does not exist anymore as a single melt-dominated volume, allowing the rise to surface of mantle-derived magmas as well as differentiation processes at various depths of small batches of magma through the entire crust. Urbani et al. (2020) performed a structural fieldwork based on a selective method approach combined with analogue models, showing that, at least during the Holocene, the classic resurgence model (e.g. Norini et al. 2019) does not explain the fault-ranks and the spatio-temporal evolution of the deformation/alteration. This change of paradigm at Los Humeros implies: (i) the inadequacy of the hypothesis of a single, large and voluminous shallow magmatic chamber homogeneously distributed beneath the caldera; (ii) the proposal of an innovative scenario, characterized by a complex magmatic plumbing system vertically distributed across the entire crust, from a deeper residence zone for basalts to a shallower magmatic plexus made of small single-charge ephemeral pockets of heterogeneous magmas localized beneath the Los Humeros nested caldera (Fig. 7a, after Lucci et al., 2020), and (iii) the interpretation of the recent deformation at Los Humeros volcanic complex not as a classical resurgence associated with the bulk inflation of a deep magma reservoir, but as the response to the ascent and emplacement of multiple, small-volume magma batches at shallow crustal conditions (< 1km depth) (Fig. 7b, after Urbani et al., 2020). These results bear important consequences on the geothermal exploration/exploitation and siting of future geothermal wells, where shallow magma bodies can act as scattered and localized short-lived heat sources complicating the pattern of isotherms related to deeper reservoirs. At the same time, the evidence of absence during the Holocene of an actively recharged large and melt-dominated magma chamber located at 5 km depth (i.e. the Xaltipan/Zaragoza magma chamber) may help understanding the localized nature of the thermal anomalies at Los Humeros.

Data availability

All the data presented in this paper are available upon request.

Author contributions

All the authors contributed equally to the preparation of this reply.

Competing interests

The authors declare that they have no conflict of interest.

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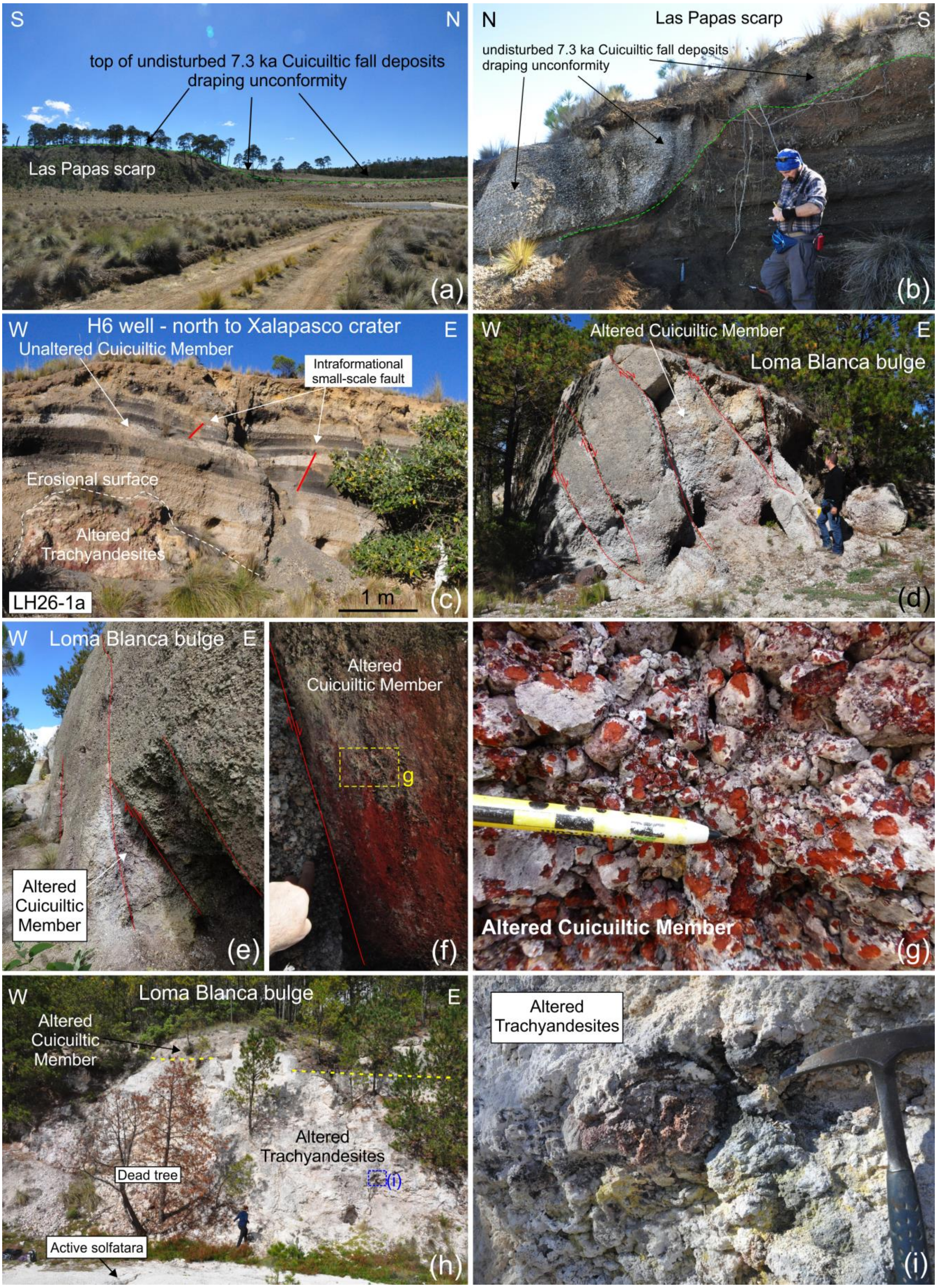

Figure 1: a) Panoramic view showing the top of the draping unconformity surface (green dashed line) of the Cuicuiltic Member fall deposit covering the Las Papas scarp. b) Outcrop image along the Las Papas scarp showing the unaltered and underformed

Cuicuiltic Member uncomfomably lying on the Xoxotic Tuff. c) Outcrop scale image of the LH26-1a site, investigated by both Urbani et al. (2020) and Lucci et al. (2020), showing an altered trachyandesite lava covered by unaltered Cuicuiltic Member layers along the Maxtaloya scarp close to the H6 well. Intraformational penecontemporaneous small-scale faults are visible in upper layers of the Cuicuiltic Member deposit. d-g) Hydrothermal alteration associated with normal faults and joints within the apical depression of the Loma Blanca bulge. f) NNE-SSW-striking Loma Blanca main fault showing reddish alteration on its plane. g) Detail of the reddish hydrothermal alteration. h-i) Outcrop images of the active solfatara located 300 m away from the H4 well, at the southern termination of the Loma Blanca fault, showing hydrothermal alteration of both post-caldera trachyandesites and overlying Cuicuiltic Member fall deposit.

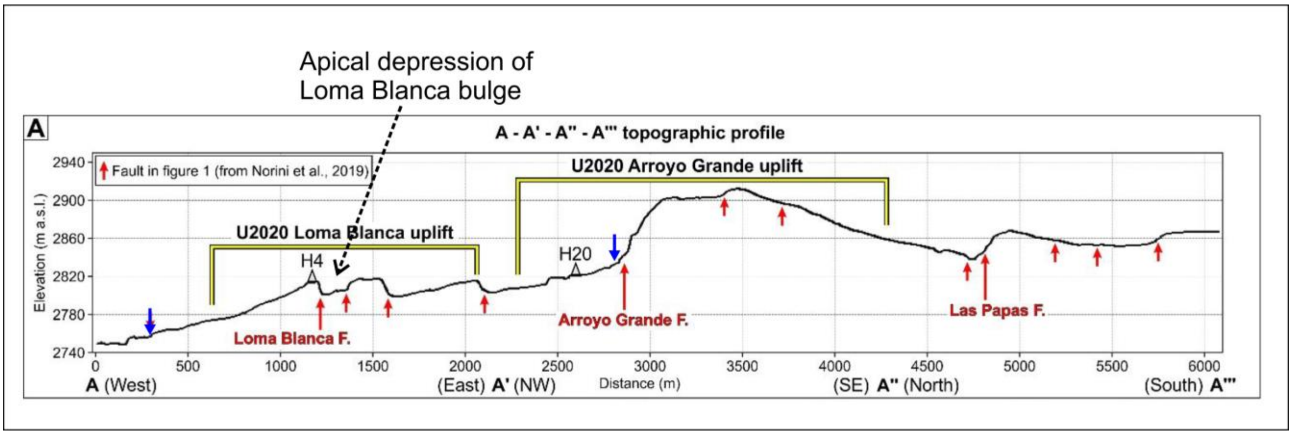

Figure 2: Trace of the A-A'-A''-A''' topographic profile of Norini and Groppelli (2020) showing the apical depression of the Loma Blanca bulge and reverse faults (blue arrows) at the base of the Arroyo Grande and Loma Blanca bulges identified by (Norini et al., 2019). Modified from Fig. 4a of Norini and Groppelli (2020).

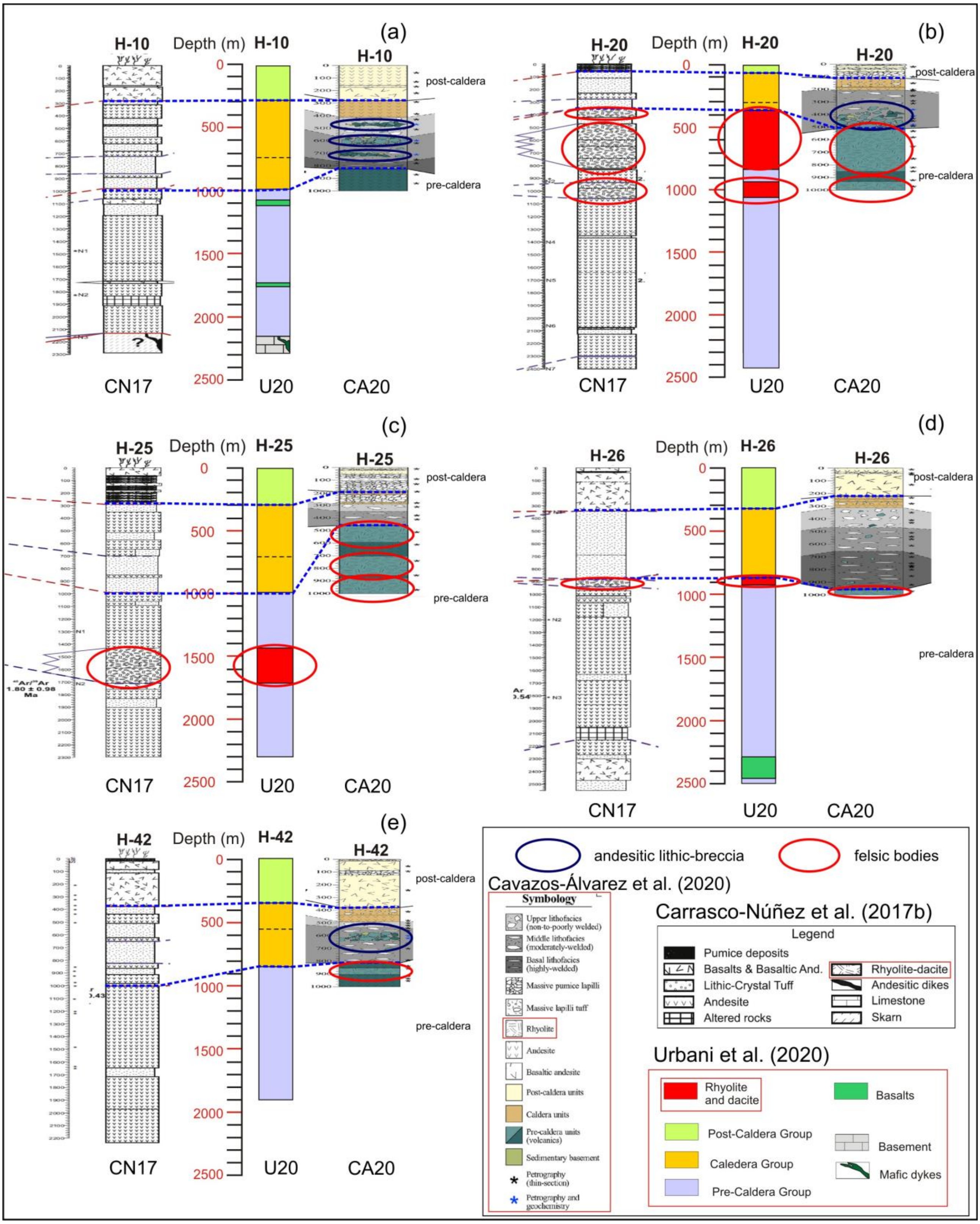

Figure 3: Lithostratigraphic columns of the wells a) H10, b) H20, c) H25, d) H26 and e) H42 as proposed by Carrasco-Núñez et al. (2017b; CN17 in figure), Urbani et al. (2020; U20 in figure) and Cavazos-Alvarez et al. (2020; CA20 in figure). Felsic or rhyolitic bodies within the volcanic sequence are indicated by red ellipses, whereas the newly identified andesitic lithic-breccias within the intracaldera Xaltipan Ignimbrite deposits (Cavazos-Alvarez et al., 2020) are indicated by blue ellipses.

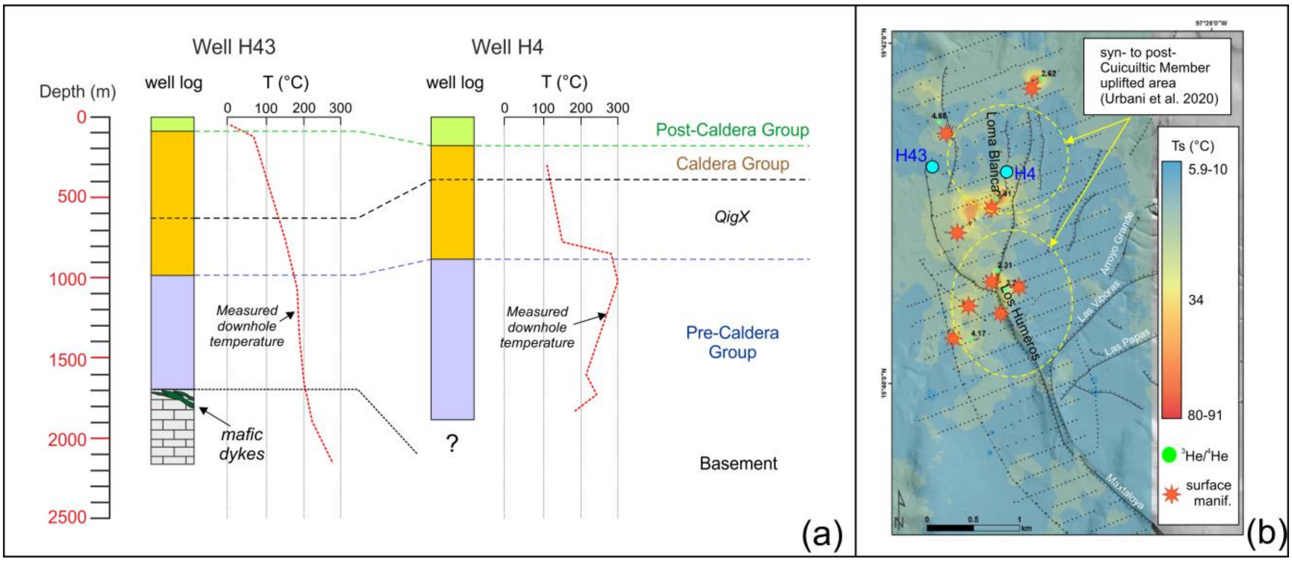

Figure 4: a) In-depth correlation of lithostratigraphic units for H4 and H43 geothermal wells (after Areallano et al., 2003; Carrasco-Núñez et al., 2017b; Urbani et al., 2020). Measured downhole temperature profiles for well H4 (Torres-Rodriguez, 1995; Prol-Ledesma, 1988, 1998; Martinez-Serrano, 2002) and well H43 (Lorenzo-Pulido, 2008) are reported. b) Interpolation map of soil temperatures measured at Los Potreros Caldera (modified after Jentsch et al., 2020; GEMex, 2019a). Orange stars showing locations of hydrothermal surface manifestations are after Jentsch et al. (2020). Geothermal wells H4 and H43 are also reported. Yellow dashed ellipses indicate the syn- to post-Cuicuiltic Member eruption uplifted area as proposed by Urbani et al. (2020).

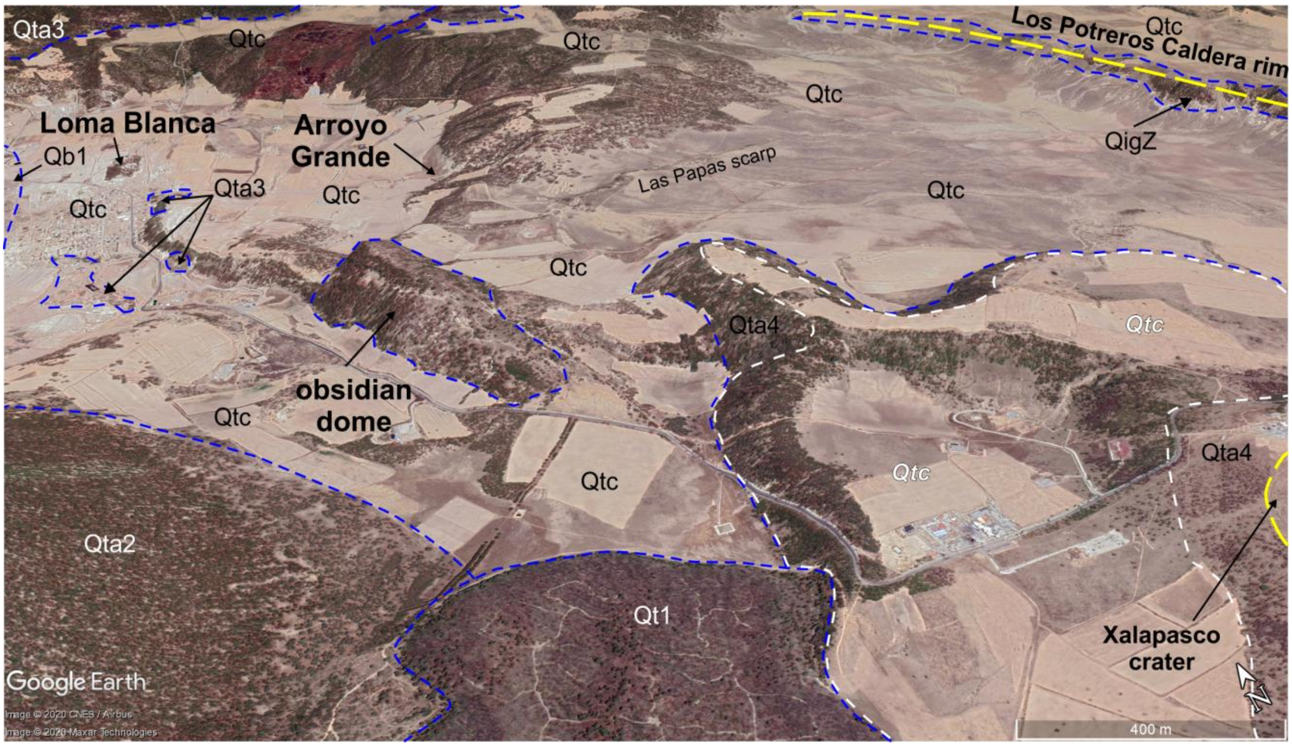

Figure 5: Perspective view from a satellite image of the Los Potreros Caldera floor (Image Landsat from Google Earth Pro, 2020, Inegi-Maxar Technologies; courtesy of Google). The dashed blue lines outline the lava domes and flows (Qta2, Qta3, Qb1, Qta4, Qt1) mapped by Carrasco-Núñez et al. (2017a) whereas the dashed white lines outline the mapping of the Cuicuiltic Member (Qtc) from Urbani et al. (2020).

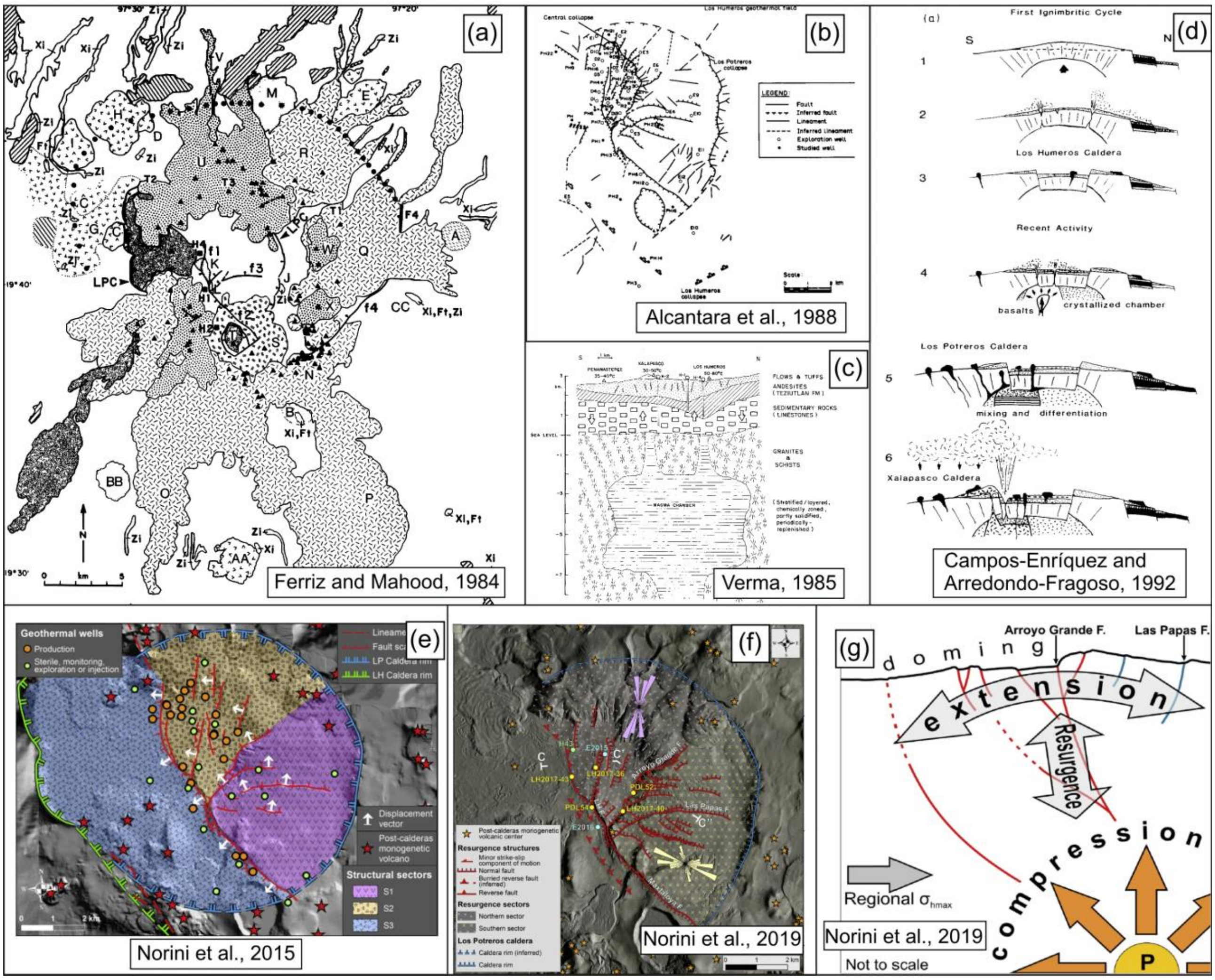

Figure 6: a) The simplified geological map of the Los Humeros volcanic center as proposed by Ferriz and Mahood (1984). b) Schematic map of the Los Potreros caldera showing the main structures and the exploration wells drilled before the 1988. This map was presented by Alcantara et al. (1988) based on unpublished map by CFE. c) Conceptual model of the single voluminous magma chamber underlying the Los Humeros volcanic center as proposed by Verma (1985). d) Schematic representation of the evolution of Los Humeros volcanic complex by Campos-Enriquez and Arredondo-Fragoso (1992) where magmatism, eruptive styles, inflation and deflation phenomena are all correlated to the activity of the single voluminous and shallow-seated magma chamber of Verma (1985). e) Morphostructural map of the Los Potreros caldera with interpretation of the sectorial resurgence as proposed by Norini et al. (2015). f) Morphostructural map of the Los Potreros caldera with interpretation of the sectorial resurgence as proposed by Norini et al. (2019). g) Schematic not to scale structural interpretation of the post-caldera resurgence at Los Humeros induced by a unique pressure source at depth as proposed by Norini et al. (2019).

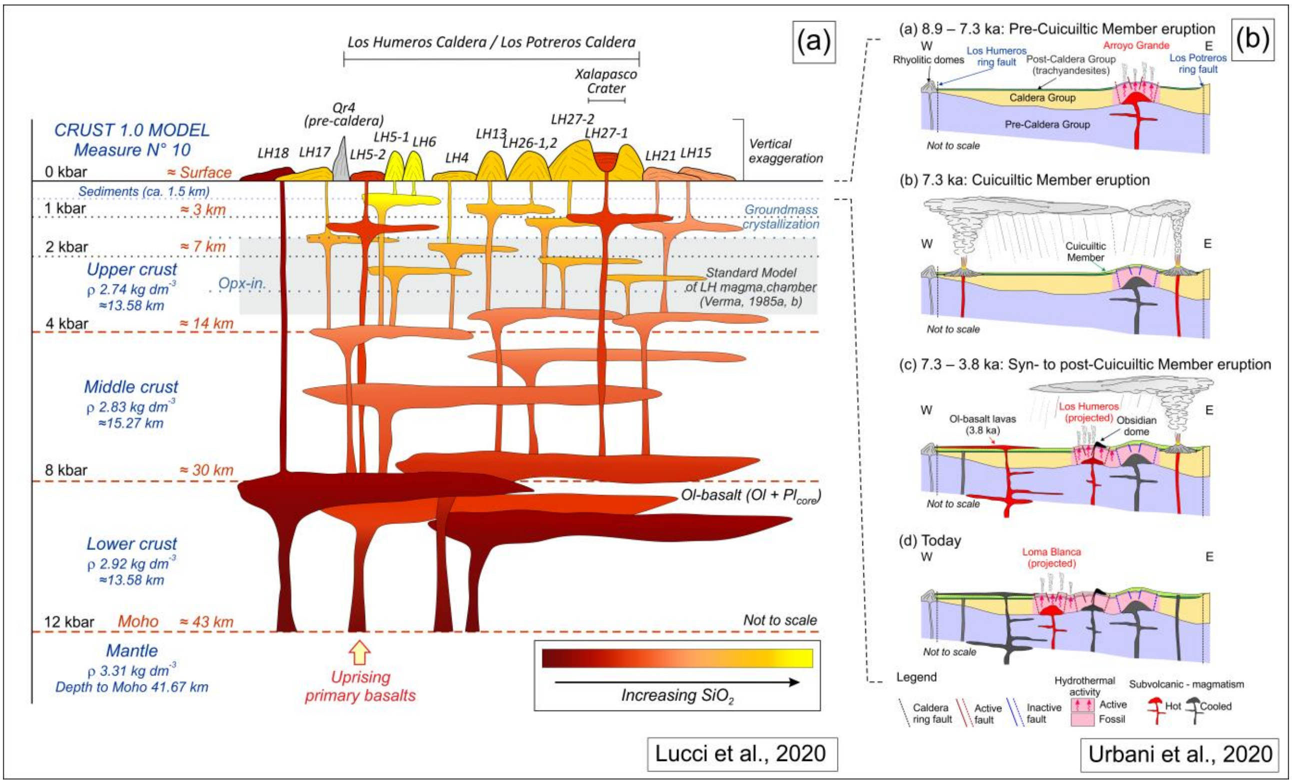

Figure 7: a) Schematic representation (not to scale), by Lucci et al. (2020), of the magmatic plumbing system feeding the Los Humeros post-caldera stage activity, beneath the Los Humeros Caldera, as derived by pressure-temperature estimates obtained from mineral-liquid thermobarometry models. The model is integrated with the crustal structure (see Lucci et al., 2020, for further explanations). b) Schematic model, by Urbani et al. (2020), of the evolution and of the subsurface structure of the Los Potreros caldera floor. Multiple magmatic intrusions located at relatively shallow depth (< 1km) are responsible for the localized bulging of the caldera floor (Arroyo Grande, Los Humeros, and Loma Blanca uplifted areas). The Cuicuiltic Member eruption is assumed as a time-marker in the intracaldera domain.